Catalog of Recommended Pavement Design Features

Final Report

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Prepared by:

Michael I. Darter
Harold Von Quintus
Y. Jane Jiang
Emmanuel B. Owusu-Antwi
Brian M. Killingsworth

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ERES CONSULTANTS, INC.

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Report Preparation

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This catalog was prepared in part through consensus building between the research team and a resource group consisting of knowledgeable engineers from state, Federal, consultants, industry and academia. Much appreciation is expressed to this group for their assistance.

CATALOG OF RECOMMENDED PAVEMENT DESIGN FEATURES

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SECTION 1 INTRODUCTION

This document presents a catalog of "good practice" recommendations for design features of highway pavements for highway engineers, administrators, and others in an easy to use format. This document is **NOT** a pavement design manual and must **NOT** be used for project-level pavement design. Guidelines are provided for three main site conditions: traffic loadings, subgrade support, and climate. Based on these inputs, design feature recommendations are provided in "design cells" including the pavement cross section, structural design, materials, and other features required to meet minimum performance requirements. This catalog of recommended pavement design features is a relatively simple but effective mode of presentation of an underlying pavement design methodology that includes both empirical and mechanistic components.

This printed catalog is supplemented by a prototype microcomputer-oriented, knowledge-based expert system (KBES). The limited prototype KBES provides users with additional assistance in determining site conditions, a computerized version of the printed catalog, and limited explanations and background knowledge on the recommended design features to assist in difficult design situations (see Appendix H).

There are several potential uses for this catalog, as listed below:

- Obtain information on recommended design features for comparative purposes.
- Train personnel.
- Update aspects of agencies' current design procedures.
- Review or check current pavement design features.
- Remind pavement engineers of design feature alternatives they might consider for a given set of conditions.

This catalog of recommended design features could be adapted to fit an agency's own cross-section designs, thickness design procedure, materials specifications, mix designs, and other standards.

1.1 Description of Catalog

The contents of this *Catalog of Recommended Pavement Design Features* for highway pavements include the following:

- Recommended (good practice) design features for highway engineers, administrators, and others in a format that is easy to use and understand.
- A model catalog presentation format for potential usage by agencies.
- Recommended consensus on many design features for varying site conditions.

The design catalog is organized into the following sections:

Section 1	An introduction to the catalog.
Section 2	How to use the catalog and design criteria.
Section 3	Project site condition inputs (climate, traffic, and subgrade).
Section 4	Guidelines on recommended design features for alternative pavement structures that will meet the minimum performance requirements of the site condition cell.
Section 5	Special subsurface conditions.
References	
Glossary	Definition of terms used in catalog.
Appendices	Detailed information on inputs, design examples, design check models, notes on design recommendations, and the prototype KBES.

1.2. Scope of Catalog

The catalog provides recommendations on design features for highways ranging from heavily trafficked Interstate and primary highways to secondary highways. The specific pavement types included in the catalog are as follows:

<u>**Flexible Pavements**</u>

- Asphalt concrete pavement with a crushed aggregate base.
- Asphalt concrete pavement with an asphalt treated base.
- Asphalt concrete pavement with a cement treated base.

- Asphalt concrete full-depth pavement.

Rigid Pavements

- Jointed plain concrete pavements (JPCP).
- Jointed reinforced concrete pavements (JRCP).
- Continuously reinforced concrete pavements (CRCP).

This catalog, as it stands, is NOT intended for direct use in pavement design. Design feature recommendations are provided in the form of acceptable ranges within each cell of site conditions and, thus, is NOT suitable for use in design. The catalog will, however, provide recommendations that are adequate to identify design features for flexible and rigid pavements that will help guide highway authorities in checking designs to ensure that the proposed design is within certain bounds of reasonableness that have been established by consensus.

The catalog is applicable to project site conditions and construction practices encountered in the United States with guidelines provided for the appropriate adjustments for special sub-surface conditions. In general, the catalog provides ranges of recommended design features that meet specific minimum performance requirements for a given set of site conditions.

The pavement design dilemma (as stated by a former state pavement design engineer): "There is a large amount of knowledge about pavement design available that is not being used. Much of this knowledge resides with experienced engineers, in FHWA and State highway agency manuals, pavement performance databases, and in research publications. A large percentage of experienced engineers and contractors have retired leaving pavement design and construction to far less experienced engineers. New engineers entering the highway field often do not have the barest knowledge about pavements. Technical support from industry has been decreased. Existing design manuals and procedures address thickness design, but do not directly consider many important details that affect performance and future rehabilitation needs. Many of these "details" are specified in agency "standards" which are seldom improved or updated consistently. This Catalog of Recommended Pavement Design Features attempts to bring more of the available knowledge directly into the pavement design process, especially for relatively inexperienced engineers.

1.3 Basis for the Catalog

The catalog recommendations are based on many sources, however, the most significant source is the recommendations achieved by consensus of a resource group of pavement design experts from Federal, state, industry, consulting, and academia. The resource group met for an entire week and debated and revised many proposed recommendations until a consensus was reached.[1] Contributions were also made by the NCHRP panel based on reviews of the documents. In addition, use was made of current SHA design practices [2], FHWA design manuals [20], the 1993 *AASHTO Guide for Design of Pavement Structures* [3], and mechanistic-empirical performance models that were used to limit the occurrence of key distress types for flexible and rigid pavements and adjusted as needed to limit key distress types within specified performance criteria (see Appendices E and F).

Limitations of AASHTO Guide

The AASHTO design procedure, used correctly with proper inputs, provides pavement structures that carry a specified amount of mixed traffic loadings between an initial serviceability level and a terminal serviceability level, at a specified level of design reliability. The design models are based on data from one climate; thus, the procedure is not directly applicable to other climatic regions of the country.

Since the AASHTO procedure is based on full-scale field testing of flexible and rigid pavements over a 2-year period only, the method does not include "aging" effects beyond two years. Aging is defined as any process that causes damage (reduction in serviceability) to a pavement other than traffic loads.

As aging damage occurs, traffic loading may result in more rapid deterioration because of the existing fractures or softening or disintegration of materials and other effects (dynamic loads). The effects of aging are mostly a durability issue and relate heavily to materials selection, mixture design, and the subgrade. Some examples include the following for all pavement types: frost heave, swelling soils, settlements from the consolidation of saturated soils, and disintegration of any pavement layer from freeze-thaw effects. For flexible pavements specifically, hardening of asphalt binder resulting in thermal or shrinkage-related cracking, reflection cracking from treated bases, and stripping of asphalt resulting in raveling, rutting, and shoving are all examples of aging effects. For rigid pavements, examples include incompressibles that result in joint spalling, and corrosion of steel that results in various problems. Material durability problems would include "D" cracking and reactive aggregates.

None of the AASHO Road Test pavements received any maintenance or rehabilitation during the time they were considered in test. The application of maintenance or rehabilitation may, therefore, extend the design life of any pavement designed by the AASHTO procedure.

Because of aging effects and possible differences in maintenance, two pavements having the same design ESAL capacity (either two different flexible pavements, two different rigid pavements, or one flexible and one rigid pavement) would not necessarily perform the same (i.e. experience the same trend in serviceability) if one pavement were trafficked over a 2-year time period and the other over a 20-year period. The pavement trafficked over the 20-year period may develop a lot of aging damage that could reduce the serviceability and cause the pavement to reach a terminal level long before the design traffic was applied. Maintenance or rehabilitation may be needed to extend the pavement's life until it carries the design traffic.

Structural Sections in this Catalog

This catalog has attempted to overcome these limitations through the use of considerable engineering experience and mechanistic-empirical models to check the designs. Appendix A of reference 1 and Appendix G provide information on the consensus building process.

This catalog provides structural sections that are expected to carry a specified amount of mixed traffic that has been projected to occur over a given design period within selected performance criteria. Differing amounts of maintenance and rehabilitation may be required to reach the end of the design period, and of course life-cycle costs may vary between structural sections.

1.4 Advantages and Limitations

Advantages of a Catalog of Recommended Pavement Design Features

Ease of obtaining design features. The catalog requires obtaining inputs for future traffic loading, subgrade support, and climate. These inputs are used to identify the appropriate catalog design cell of site conditions. Section 3 and Appendices A, B, and C provide guidance on obtaining these inputs. Within each design cell, recommended design features are provided for each pavement type.

Technology transfer. The catalog of recommended design features is a good training tool to learn more about pavement design.

Improvement of the efficiency of the pavement design process. All information required is included in a single document, which may lead to some efficiency. A computerized KBES has the potential for even greater efficiency in design by making more information and explanations easily available.

Check of pavement designs. The catalog can be used to check designs to see if they meet minimum performance criteria.

Enhanced pavement design communication with administrators and construction personnel. This is a distinct advantage of a design catalog due to its graphical display of design features for each cell of site conditions.

As a long-range planning tool for roadway management. The catalog can be used as an expedient method of developing approximations of pavement construction/reconstruction costs. This application could be especially useful to the local resident engineer who has little pavement design expertise available. Such approximate design should never be used for actual construction without prior review by a pavement design engineer.

<u>**Disadvantages of A "Customized" Agency Pavement Design Catalog**</u>

Gives engineers and management too simplified a view of design. Because the catalog of recommended designs is in a relatively simple presentation format, it may give a false impression that pavement design is a relatively simple activity, even though the catalog can represent any underlying design procedure no matter how sophisticated or complex. The user is strongly cautioned that pavement design is not a simple engineering activity. It is very complex and there are many details that if not properly chosen, can lead to premature and rapid failure. This document is **NOT** a pavement design manual.

Provides new engineers with a false sense of security. New engineers may think that pavement design is as simple as the catalog format, and may be tempted to make decisions without adequate guidance or experience. Pavement design requires a detailed and comprehensive process. This catalog provides guidance on recommended ranges of design features for given site conditions that are useful in checking designs.

SECTION 2 GENERAL INFORMATION

2.1 How to Use the General Catalog

This catalog is NOT suitable for pavement design, but it can be used for training personnel, comparing design agency features with the recommended features in the general catalog under the same design cell, updating certain aspects of an agency's current design procedure, and approximate checking of pavement designs.

For example, the process of using this catalog to check an agency design can be summarized as follows:

1. Select pavement type to be checked.
2. Identify the site condition design cell for the project under consideration through estimation of traffic, subgrade, and climate inputs.
3. Obtain the recommended design features from the design cell.
4. Compare each of the recommended design features in the catalog with those of the pavement under design and identify any feature that is significantly different.
5. Investigate the reasons for significant differences between the design features. Assess the consequences of any difference, and modify the design if a deficiency exists.

2.2 General Design Criteria

There are general criteria common to each pavement type that must be considered during the design of the pavement. They include items such as design life, design reliability, performance criteria (initial and terminal serviceability, maximum rutting [flexible only], fatigue cracking, joint faulting [rigid only], deteriorated transverse cracks [JRCP only] and punchouts [CRCP only]), number of traffic lanes, width of traffic lanes (and slabs) and shoulders, cross-slope, curb and gutter, and others. The general design inputs used in this catalog are discussed in this section.

Design Life

Design life must be specified so that traffic loadings can be estimated over this period. This catalog uses the number of equivalent 18-kip single axle loads (ESALs) over the design life as the traffic loading input. The design life commonly used ranges from 10 to 50 years, however, the impact of materials durability should be fully considered (i.e., if a given material has a durability life of only 20 years, then this should be the design life.)

Reliability and Overall Standard Deviation*

Design reliability varies with traffic level as shown in table 1. Overall standard deviations include both performance and traffic uncertainties: 0.49 for flexible pavements is recommended; 0.39 for rigid pavements is recommended.

Initial and Terminal Serviceability (Smoothness)*

Initial serviceability: 4.5
Terminal serviceability: 2.5 minimum

Other Suggested Performance Criteria Used for Checking Designs*

Fatigue cracking ACP: 45 percent of the wheel path area maximum.
Rutting ACP (mean): 0.5 in maximum.
Slab fatigue cracking JPCP: 50 percent slabs maximum.
Slab crack deterioration JRCP: 25 deteriorated transverse cracks/mile maximum.
Joint faulting JPCP (mean): 0.10 in maximum.
Joint faulting JRCP (mean): 0.20 in maximum.
Localized failures (punchouts in CRCP): 5/mile maximum.

Table 1. Recommended levels of design reliability.*

Flexible ESALs (million)	Rigid ESALs (million)	Design Reliability
<1.0	<1.5	75
1.0 - 2.0	1.5 - 3.0	85
2 - 4	3.0 - 6.0	90
>4	>6.0	95

* Note: All items marked with an asterisk (*) were achieved through consensus. See appendix G for further information.

SECTION 3 PROJECT SITE CONDITION INPUTS

This section provides guidelines for the determination of traffic loadings, subgrade and climatic site condition inputs. Recommended pavement design features are keyed to these site condition inputs. For a given project site, traffic and subgrade site conditions identify a unique "design cell" in the factorial matrix in Section 4. Climatic site conditions are included within design cells for specific design features that vary with climate, and they are part of determining the recommended subgrade input (through seasonal weighting). Pavement design feature recommendations can then be obtained for the identified site condition cell.

3.1 Traffic

General

Repetitive traffic loading is an important factor in establishing the pavement design features. Pavement damage from traffic loadings depends on many variables, including: types of axles, weight distribution of each axle type, speed of loading, tire characteristics such as air pressure and type (dual or wide single). Over time, other factors include the rate of growth of truck volume, changes in axle types, growth in axle weights, directional distribution of trucks, lane distribution of trucks, and lateral distribution of trucks within lanes.

Equivalent Single Axle Load

A large majority of the SHAs use the 80-kN (18-kip) equivalent single axle load (ESAL) to characterize traffic loading [2] and it has become widely used. ESALs actually represent the number of axle loads, weighted by equivalency factors derived at the AASHO Road Test. [3] The main factors that are taken into account in ESAL calculation over the design period include the following:

- Average daily traffic (ADT).
- Average daily truck traffic (ADTT).
- Truck volume growth rate.
- Weight and number of each axle type.
- Truck weight growth rate.

- Directional distribution for truck traffic .
- Lane distribution for truck traffic.

The total number of predicted future 80-kN (18-kip) ESALs in the design lane over the design period is the traffic input that defines the design feature cells. Table 2 shows the traffic loading ranges selected for the design feature cells of this catalog.

Table 2. Traffic ranges for factorial matrix (note: the comparison of flexible and rigid ESALs are very approximate and are only intended for illustration, they must be computed individually for the traffic stream under consideration).

ESAL Ranges For Design, millions	
Flexible Pavements	**Rigid Pavements**
0.5 - 1	0.75 - 1.5
1 - 2	1.5 - 3
2 - 4	3 - 6
4 - 8	6 - 12
8 - 12	12 - 18
12 - 20	18 - 30
20 - 36	30 - 54
36 - 60	54 - 90
60 - 100	90 - 150

The different design ESAL traffic levels for flexible and rigid pavements are a result of the differences between the AASHTO equivalency factors [3] for flexible and rigid pavements used to calculate 80-kN ESALs from the exact same mixed traffic stream. This means, for example, that a flexible pavement design for 20 million flexible ESALs would show approximately the same loss of serviceability as a rigid pavement designed for 30 million rigid ESALs for a typical axle load distribution. Thus, the design of a flexible pavement requires the computation of "flexible" ESALs and the design of a rigid type pavement requires the computation of "rigid" type ESALs separately.

Procedures For ESAL Estimation

Computation procedures for design ESALs are provided in appendix A. Total ESALs over the design period can be estimated using varying levels of complexity. A relatively simplified method is provided in appendix A. A more comprehensive method is provided in appendix D of the 1993 AASHTO Design Guide.[3]

- **Simplified Approach:** The total design ESALs are estimated by multiplying the total number of trucks (over the design period) by a mean truck equivalency factor (18-kip ESALs/truck) that represents all trucks for the highway class under consideration. This method is very approximate in that the mean truck equivalency factor represents an entire highway class and pavement type, is not site specific, is assumed to be constant over time, and does not consider vehicle classifications for that site.

  Note that a more comprehensive method would be to estimate the mean truck equivalency factor for each of the FHWA truck classifications for the highway class, and then use these values along with site specific vehicle classifications for the project under design to estimate the total design ESALs.

- **Comprehensive Approach:** The axle load distributions (numbers and weights) of single, tandem and tridem axles must be known (as can be obtained from weigh-in-motion equipment). This data is converted to total design ESALs through use of the axle load equivalency factors obtained from the AASHTO Design Guide and truck volume growth factors.[3]

The use of site specific traffic classification and weigh-in-motion axle weight distribution data will provide for greatly increased accuracy in estimating the design ESALs.

3.2 Subgrade

Proper preparation of the subgrade is extremely important to a long lasting and well performing pavement. Therefore, this catalog emphasizes this aspect by providing detailed guidelines on achieving an adequate subgrade on which to build the pavement structure. These guidelines, which discuss subgrade preparation, improvement, swelling soils, frost heave, and other aspects, are given in Sections 4 and 5.

This section describes the specific inputs for the structural design of the pavement. The stiffness of the subgrade under repeated loading is an important factor related to pavement performance and, thus, is an essential input to this pavement design catalog. The design inputs required to characterize the subgrade for structural design include the following:

- Resilient modulus (laboratory value) for flexible pavements—seasonally weighted
- Elastic k-value for rigid pavements—seasonally weighted.

Several methods to estimate these inputs are provided in this section. The required input is the mean seasonally weighted effective resilient modulus or elastic k-value consistent with the AASHTO Design Guide.[3] Climate is thus considered through seasonally weighting these values.

Resilient Modulus For Flexible Pavement Design

The laboratory resilient modulus of the subgrade soil is used to represent the modulus of elasticity of the top of the finished roadbed soil or embankment upon which the subbase, base and/or asphalt or cement treated bases will eventually be constructed. This input is consistent with the laboratory determined resilient modulus required in the AASHTO Design Guide.[3]

Table 3 provides a summary of the range of laboratory resilient moduli that are typical for different types or groups of soils. The design subgrade laboratory resilient modulus required for use of this catalog can be estimated by different methods. Detailed procedures are provided in Appendix B.

- **METHOD A - Correlations with Soil Type, Other Soil Properties, and Tests**. The laboratory resilient modulus can be estimated from previously developed correlations using soil classification data, dry density, CBR, R-Value and other physical property tests. The resilient modulus can then be seasonally weighted. See Table 3.

- **METHOD B - Deflection Testing and Backcalculation of an Equivalent Elastic Modulus of the Subgrade**. This is the most commonly used method, because many tests can be conducted along a roadway and these tests are conducted on the in situ pavement. The resilient modulus or equivalent elastic moduli are computed at each test point, and averaged along each design section. The backcalculated resilient modulus must then be converted to a laboratory resilient modulus (appendix B) and seasonally weighted before use in this catalog. For new designs, the pavements and subgrade soils tested must be similar to the conditions expected after construction.

- **METHOD C - Laboratory Resilient Modulus Test on Recompacted or Undisturbed Samples of the Subgrade Soils**. Repeated load triaxial compression tests performed in accordance with AASHTO T294-92 (Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils —SHRP Protocol P46) or other equivalent procedures are used to determine the laboratory resilient moduli of the subgrade soils for the associated pavement structure. The specific procedure is summarized in Appendix B. This method is not often used by highway agencies due to its high cost, time requirements, and predictions of seasonal variations under the pavement. This value must also be seasonally weighted.

All three methods can be used for both new construction and reconstruction of existing roadways. However, Method B is primarily used for reconstruction and Method C for new construction. Method A, based solely on correlations, is the least accurate, while Methods B and C require much more effort, but are more accurate and reliable.

Elastic k-Value For Rigid Pavement Design

The elastic modulus of subgrade reaction (k-value) is defined as that measured or estimated on top of the finished roadbed soil or embankment upon which the subbase, base and/or concrete slab will eventually be constructed. Note that the elastic k-value used in this catalog for design is that of the subgrade; it does not represent the composite "top of the base course" k-value. The effect of the base course on increasing the k-value was already considered in determining the recommended slab thicknesses provided in the catalog.

The k-Value input defined. The mean static elastic k-value on top of the subgrade or embankment is the required design input. Only the elastic component of this deformation is considered representative of the response of the subgrade to moving traffic loads on the pavement.

Table 3. Recommended laboratory resilient modulus and elastic k-value ranges for various soil types.

AASHTO Class	Description	Unified Class	Dry Density (lb/ft^3)	CBR (percent)	k-value (psi/in)	Lab Resilient Modulus (psi)
Coarse-grained soils:						
A-1-a, well graded	gravel	GW, GP	125 - 140	60 - 80	300 - 450	10000 - 20000
A-1-a, poorly graded			120 - 130	35 - 60	300 - 400	10000 - 20000
A-1-b	coarse sand	SW	110 - 130	20 - 40	200 - 400	6000 - 15000
A-3	fine sand	SP	105 - 120	15 - 25	150 - 300	5000 - 12000
A-2 soils (granular materials with high fines):						
A-2-4, gravelly	silty gravel	GM	130 - 145	40 - 80	300 - 500	10000 - 30000
A-2-5, gravelly	silty sandy gravel					
A-2-4, sandy	silty sand	SM	120 - 135	20 - 40	300 - 400	10000 - 20000
A-2-5, sandy	silty gravelly sand					
A-2-6, gravelly	clayey gravel	GC	120 - 140	20 - 40	200 - 450	8000 - 20000
A-2-7, gravelly	clayey sandy gravel					
A-2-6, sandy	clayey sand	SC	105 - 130	10 - 20	150 - 350	5000 - 15000
A-2-7, sandy	clayey gravelly sand					
Fine-grained soils:*						
A-4	silt	ML, OL	90 - 105	4 - 8	25 - 165	2000 - 6000
	silt/sand/ gravel mixture		100 - 125	5 - 15	40 - 220	4000 - 8000
A-5	poorly graded silt	MH	80 - 100	4 - 8	25 - 190	2000 - 6000
A-6	plastic clay	CL	100 - 125	5 - 15	25 - 255	2000 - 10000
A-7-5	moderately plastic elastic clay	CL, OL	90 - 125	4 - 15	25 - 215	2000 - 10000
A-7-6	highly plastic elastic clay	CH, OH	80 - 110	3 - 5	40 - 220	4000 - 10000

* Elastic k-value and resilient modulus of fine-grained soil are highly dependent on degree of saturation.

1 lb/ft^3 =16.018 kg/m^3, 1 psi/in = 0.271 kPa/mm

Steps in determining design k-value. The mean elastic k-value (seasonally weighted) input required for this design method is determined by the following steps. Detailed procedures are provided in appendix B.

Step 1. Estimate a mean subgrade k-value for each season, using any of the following three methods, or a combination of these methods.

Method A Correlations with soil type and other soil properties or tests. Subgrade k-value can be estimated using soil classification, moisture level, dry density, CBR, or Dynamic Cone Penetrometer (DCP) data. See Table 3.

Method B Deflection testing (Falling Weight Deflectometer) and backcalculation of subgrade k-value. This is the most highly recommended method because many tests can be conducted along the project, the k-value is readily computed at each test point, and it is conducted on the in situ pavement. The static elastic k-value used in this catalog is determined by dividing the FWD backcalculated value by 2.[4]

Method C Plate bearing tests on the subgrade. Repetitive static plate loading (AASHTO T221, ASTM D1195) or nonrepetitive static plate loading (AASHTO T222, ASTM D1196) may be used with specific k value computation procedures. This method is rarely used due to its excessive cost and time requirements.

A combination of Methods A and B usually provide the most effective method to estimate seasonally weighted elastic k-values.

Step 2. Determine a seasonally adjusted effective k-value. The effective k-value is obtained by combining the seasonal k-values into a single "effective" value for use in design.[3]

Step 3. Adjust the seasonally adjusted effective k-value for effects of a shallow rigid layer, if present, and/or an embankment of better material above the natural subgrade, if present. This step is only needed if k-value was determined using Method A (estimated using soil type or tests).

Note that this catalog utilizes the mean elastic k-value of the subgrade along the project, not the lowest value measured or some other conservative value. A large variation in subgrade soils is often a major problem faced in pavement design. The data should first be scrutinized for outliers or errors. If the data shows a significant change in k-value throughout the design project, then it may be cost-effective to divide the project into two or more lengths for pavement design.

Summary

Subgrade preparation and/or improvement is very important for a well performing pavement. Guidelines for subgrade preparation are given in Sections 4 and 5. **Uniformity is perhaps the most important aspect of all in the upper portion of the subgrade relative to textural classification, moisture, and density.**

Specific subgrade inputs to the structural design include the laboratory resilient modulus and the elastic k-value, which are used to characterize the subgrade support for flexible and rigid pavements, respectively, in the design cells. Both the laboratory resilient modulus and the elastic (static) k value can be estimated using different procedures as described. Table 4 shows the ranges for subgrade support selected for use in this catalog.

Table 4. Subgrade support values for factorial matrix (note: the comparison of resilient modulus and k value are very approximate and must be determined separately.

Soil Class	Resilient Modulus (Lab test), Flexible Pavement Design, psi	Elastic k-Value Rigid Pavement Design, psi/in	General Description
Very Soft	<4,500 (3,000 midpoint)	<100 (75 midpoint)	Silts and/or clays of high plasticity
Weak-Fair	4,500-12,000 (5,000 and 9,000 midpoints)	100-200 (150 midpoint)	Clay silts or silty-sandy clays of moderate plasticity
Strong	>12,000 (14,000 midpoint)	>200 (300 midpoint)	Clayey, silty sands and/or gravelly clays, sands, gravels

3.3 Climate

An important but complex factor that affects pavement performance is climate. This is especially true in the United States, which is a very large country that encompasses a wide range of climates. To select the variables for characterization of the effect of climate and to select the levels of the variables to use in the catalog, several pavement studies involving a factorial matrix design were reviewed, including the Long-Term Pavement Performance (LTPP) study [5] and the Moisture Accelerated Distress (MAD) identification study [6]. The pavement design practices of several State highway agencies (SHAs) were also examined [2].

Climatic Factors

The climatic factors that were identified for use in characterizing climatic conditions include the following:

- Freezing Index (degree-days below freezing, frost action, frost heave).
- Average annual maximum daily temperature.
- Average annual minimum daily temperature.
- Number and length of freeze-thaw cycles.
- Average daily high temperature during the month of construction.
- Average low temperature for the coldest month of the pavement life .
- Average annual frost depth.
- Annual or monthly precipitation.
- Thornthwaite Moisture Index .
- Concentration of summer thermal efficiency (C.S.T.E.).
- Days of precipitation greater than 0.01 inch.

Correlation Of Climatic Variables

Evaluation of the information obtained indicated that practically all temperature-related variables are strongly correlated (i.e., annual temperature correlates strongly with the freezing index). Similarly, many moisture-related variables are correlated (i.e., annual precipitation correlates strongly with the number of days of precipitation greater than 0.01 inch). These correlations are given in appendix C. Therefore, because of these strong correlations, it is possible to select general climatic zones based on temperature and moisture variables that can be considered for a reasonable representation of the effect of climate on pavement design and performance.

Four Climatic Zones

The four climatic zones used in the LTPP studies were selected to characterize climatic effects (see figure 1). Typical climatic variables for the climatic zones are given in table 5.

Table 5. Typical climate factor levels for the LTPP climatic zones.

Climatic Zone	Climatic Variable			
	Mean Freezing Index*	Mean Monthly Temp, °F	Temp. Range, °F**	Mean Annual Precip., in
Wet-freeze	200 to 1,000	52	82	33
Dry-freeze	200 to 1,000	45	70	15
Wet-nonfreeze	0	66	63	49
Dry-nonfreeze	0	66	68	16

* Degree-days F below freezing.

** Difference between mean maximum monthly July temperature and mean minimum monthly January temperature.

Climate Effects on Pavement Designs

Climate effects on flexible and rigid pavement structural designs are directly considered through the seasonally adjusted resilient modulus and elastic k-value which are the required subgrade input. For example, for the same soil resilient modulus or k-value at a given moisture content and density, projects located in areas with deep frost penetration would have lower seasonally weighted effective values, and thus, the pavement structure would be increased.

Climate effects on other flexible and rigid pavement design features are considered within each of the design cells through the climatic zones. For example, the following design features vary by climatic zone: maximum joint spacing for JPCP, asphalt binder selection, subdrainage design, material requirements, reinforcement content for JRCP and CRCP, and provision of non-frost susceptible layers.

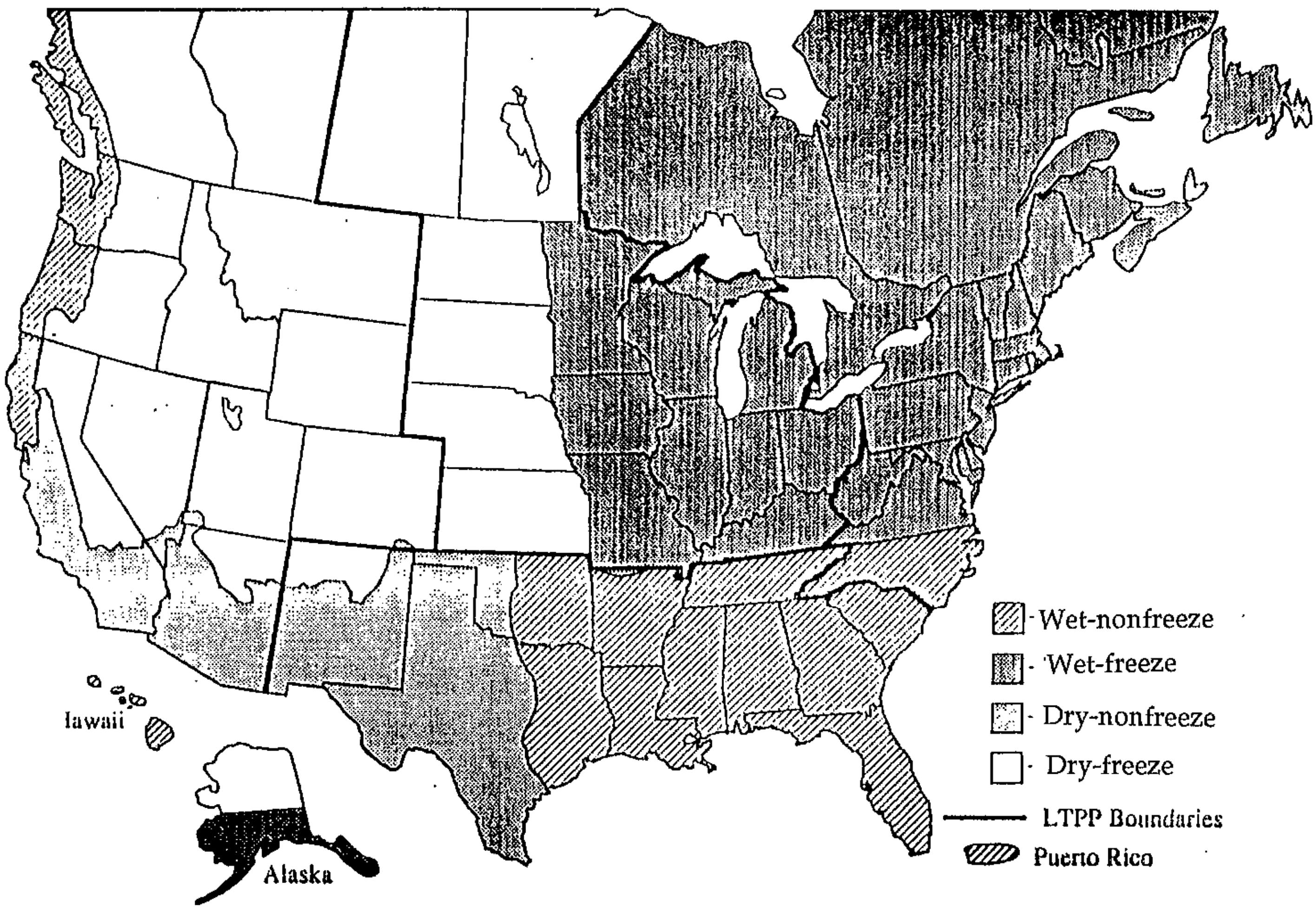


Figure 1. SHRP/LTPP climatic zones.

3.4 Recommended Design Site Condition Cells

Based on the classes of subgrade support (weighted by climatic season) and traffic loading, a unique design site condition cell can be defined for a given project site. Within each design cell the climatic zone may be directly considered for various design features, such as asphalt binder selection, maximum joint spacing for JPCP, etc. The recommended design features provided in this catalog are keyed to those cells. Design examples are given in appendix D. Materials requirements are described in Sections 4A, 4B, and 4C for each pavement type.

SECTION 4 PAVEMENT DESIGN FEATURE RECOMMENDATIONS

Section 4A Flexible Pavements

The recommended design features for flexible pavements are presented in this section. The catalog recommendations are based on many sources, however, the most significant source was the recommendations achieved by consensus of a large group of pavement engineers from Federal, state, industry, consulting, and academia.[1] In addition, use was made of current SHA design practices [2], FHWA Pavements Notebook [20], the 1993 *AASHTO Guide for Design of Pavement Structures* [3], and selected mechanistic and empirical performance models to limit the occurrence of fatigue cracking and permanent subgrade deformation (See Appendix E).

The sections included are as follows:

- Section 4A.1 Flexible Pavement Cross Sections and Shoulder Design Features
- Section 4A.2 Flexible Pavement Structural Design Features for Site Condition Cells
- Section 4A.3 Material Design Features for Flexible Pavements
- Section 4A.4 Selection of Binder for Bituminous Mixtures
- Section 4A.5 Base Drainage for Flexible Pavements
- Section 4A.6 Joint Construction in Placing Hot-Mixed Asphalt Concrete Mixtures

4A.1 Flexible Pavement Cross Sections and Shoulder Design Features

The cross section of a highway pavement is made up of several elements, each varying with the type of highway facility needed to fulfill the needs of the section under consideration. Both urban and rural sections of highway are considered as the typical section varies with the service to adjacent development, costs, right-of-way acquisition, traffic volumes, access

control, and pedestrian activities. Table 6 provides a summary of the cross-sections that are considered appropriate for each traffic level.

Pavement Cross Sections

Cross sectional design elements include pavement and shoulder cross slopes, lane and shoulder widths, side slopes, and curbs. Figures 2 through 13 show typical cross section design features for flexible pavements. Drainage considerations are shown in the cross-sections as optional, because these features are site dependent. Refer to Section 4C for specific details regarding drainage recommendations for each pavement cross-section.

As shown in the pavement cross sections, the underlying pavement base, subbase and improved subgrade layers should be extended beyond the edge of the outside or traffic lane. The reason for extending the underlying structure is to reduce the moisture change potential in the supporting subgrade soils that are highly expansive; thus, reducing the occurrence of longitudinal edge cracking in the travel lanes (requiring maintenance) from the shrink and swell of the soils along the pavement's edge. The benefit of this practice is the significant reduction or elimination of the need to seal the longitudinal edge cracks and the acceleration of fatigue cracks caused by edge cracks. This is discussed in more detail in Section 5.

Although moisture variations can and do occur beneath pavement structures in all areas of the United States, those areas with large differences in seasonal rainfall amounts are known to have greater fluctuations in the moisture content of the supporting subgrade soils. These areas are those with low to relatively high amounts of rainfall (10 to 40 inches). Table 7 provides the minimum desirable added width of the underlying layers in environments and conditions where significant moisture variations are expected to occur.

Table 6. Alternate cross-sections and shoulder types considered appropriate for the different traffic classifications used for structural design of flexible pavement.

Flexible ESAL Ranges for Design Millions	Highway Classification											
	Rural								Urban			
	Surface Cross Slope											
	Crown				Uniform				Crown		Uniform	
	Shoulder Type											
	Sod/ Turf	Gravel	Surface Treatment	Paved	Sod/ Turf	Gravel	Surf. Treatment	Paved	No Shoulder	Paved	No Shoulder	Paved
<1.0	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1.0-2.0		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
2.0-4.0		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
4.0-8.0			✓	✓			✓	✓	✓	✓	✓	✓
8.0-12.0				✓				✓	✓	✓	✓	✓
12.0-20.0				✓				✓		✓		✓
20.0-36.0				✓				✓		✓		✓
36.0-60.0				✓				✓		✓		✓
60.0-100.0				✓				✓		✓		✓

Table 7. Recommended minimum widths to extend the underlying layers beyond the pavement's edge.

Soil Type	Plasticity Index	Minimum Desirable Added Width or Extension, ft	
		Annual Rainfall 10 - 40 in	Annual Rainfall < 10 or > 40 in
Gravely and sandy soils and low plasticity silts & clays	0-20	1	1
Inorganic silts and clays of low to medium plasticity, lean clays, and organic silts and silt-clays	5-20	2	1
	20-30	3	1
Inorganic and elastic silts, inorganic clays of medium to high plasticity, fat clays, and organic clays of medium to high plasticity	36-40	4	2
	>40	6	3

Turf or Sod Shoulders
Rural Roadways
Site Condition Cells 1-4

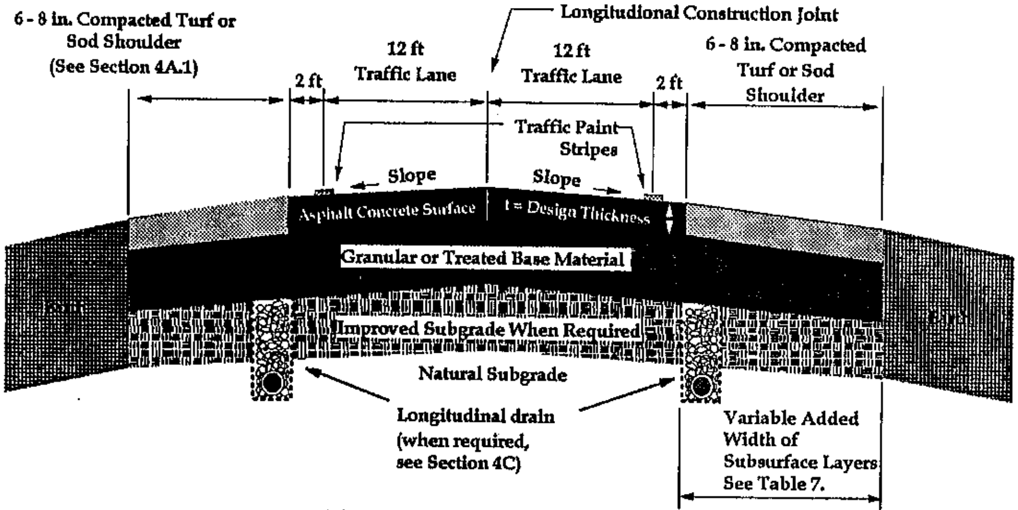


Figure 2. Crowned Surface
(Two Directional Traffic) with Turf or Sod Shoulders

Figure 2. Crowned surface (two directional traffic).

Turf or Sod Shoulders
Rural Roadways
Site Condition Cells 1-4

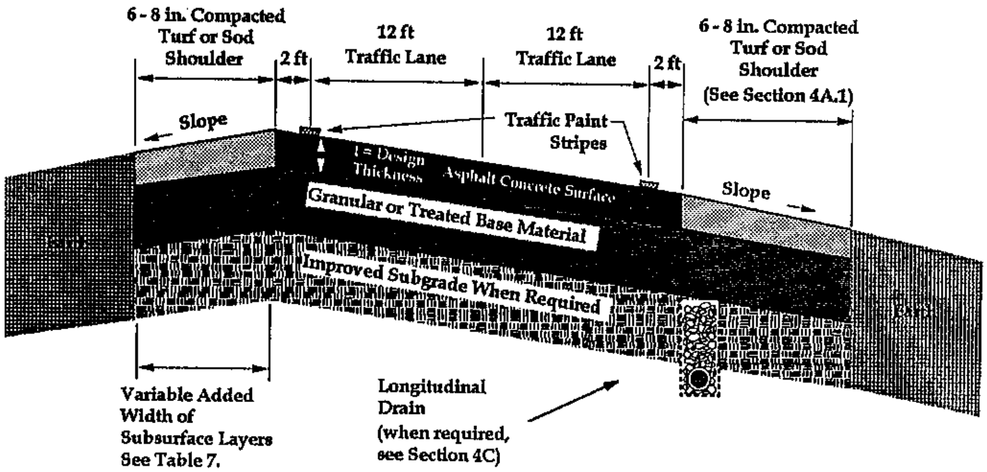


Figure 3. Uniform Surface
(Two Directional Traffic) with Turf or Sod Shoulders

Figure 3. Uniform surface (two directional traffic).

Gravel Shoulders
Rural Roadways
Site Condition Cells 1-12

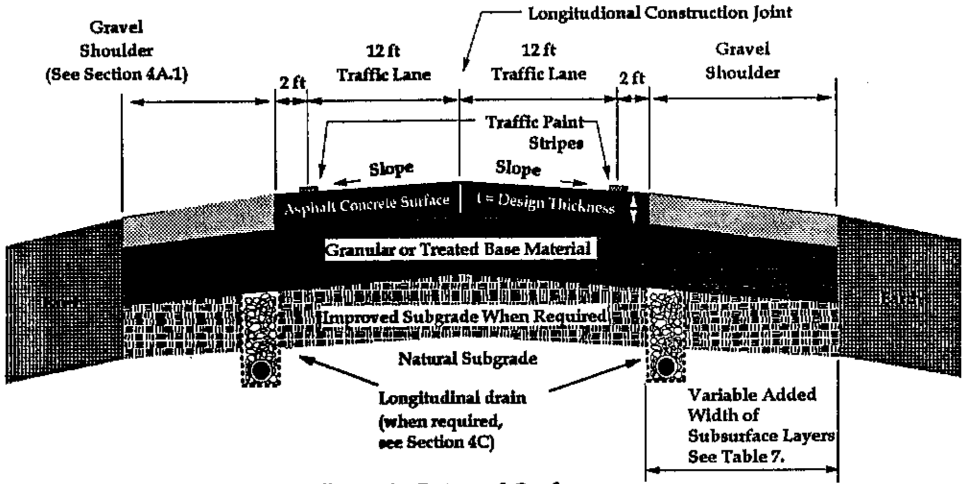


Figure 4. Crowned Surface (One or Two Directional Traffic) with Gravel Shoulders

Figure 4. Crowned surface (one or two directional traffic).

Gravel Shoulders
Rural Roadways
Site Condition Cells 1-12

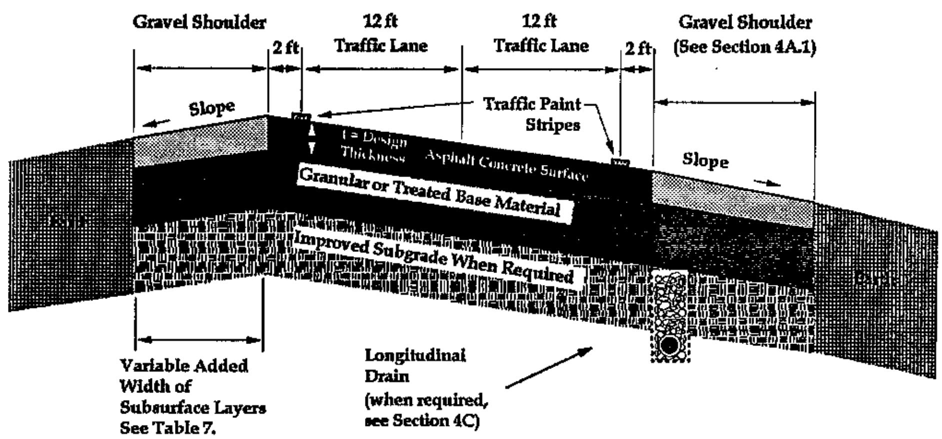


Figure 5. Uniform Surface (One or Two Directional Traffic) with Gravel Shoulders

Figure 5. Uniform surface (one or two directional traffic).

Surface Treatment Shoulders
Rural Roadways
Site Condition Cells 1-16

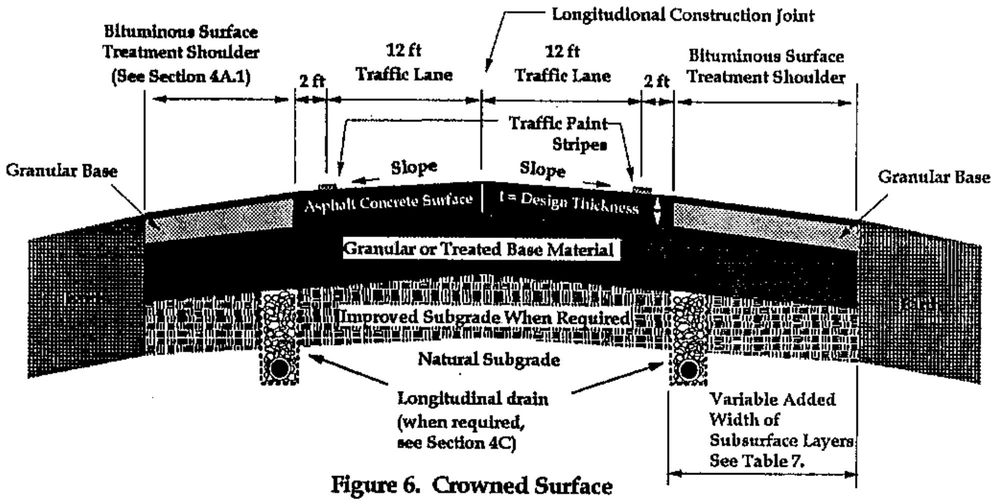


Figure 6. Crowned Surface
(One or Two Directional Traffic)
with Bituminous Surface Treatment Shoulders

Figure 6. Crowned surface (one or two directional traffic).

Surface Treatment Shoulders
Rural Roadways
Site Condition Cells 1-16

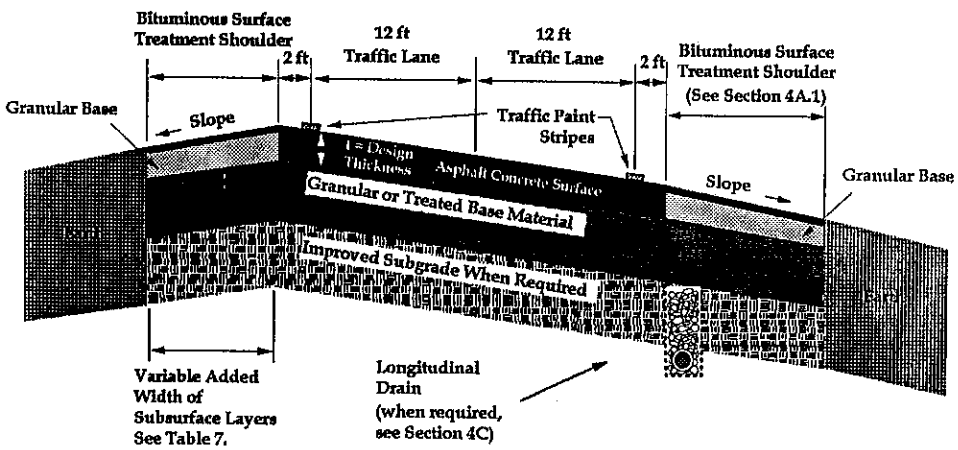


Figure 7. Uniform Surface
(One or Two Directional Traffic) with Bituminous Surface Treatment Shoulders

Figure 7. Uniform surface (one or two directional traffic).

Paved Shoulders
Rural Roadways
Site Condition Cells 1-36

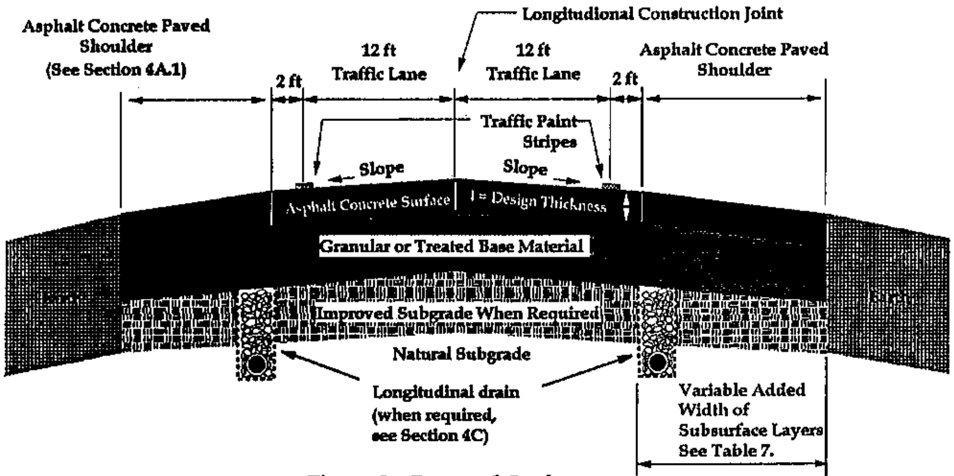
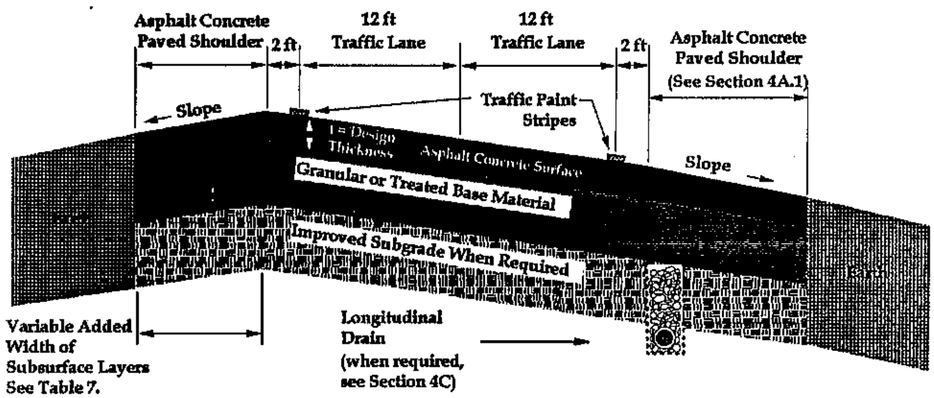


Figure 8. Crowned Surface
(One or Two Directional Traffic)
with Paved Shoulders

Figure 8. Crowned surface (one or two directional traffic).

Paved Shoulders
Rural Roadways
Site Condition Cells 1-36



Note: Edge Taper with a Hydraulic Screed extension can be used to place a variable width shoulder with a different cross-slope.

Figure 9. Uniform Surface
(One or Two Directional Traffic) with Paved Shoulders

Figure 9. Uniform surface (one or two directional traffic).

Urban Roadways
Site Condition Cells 1-20

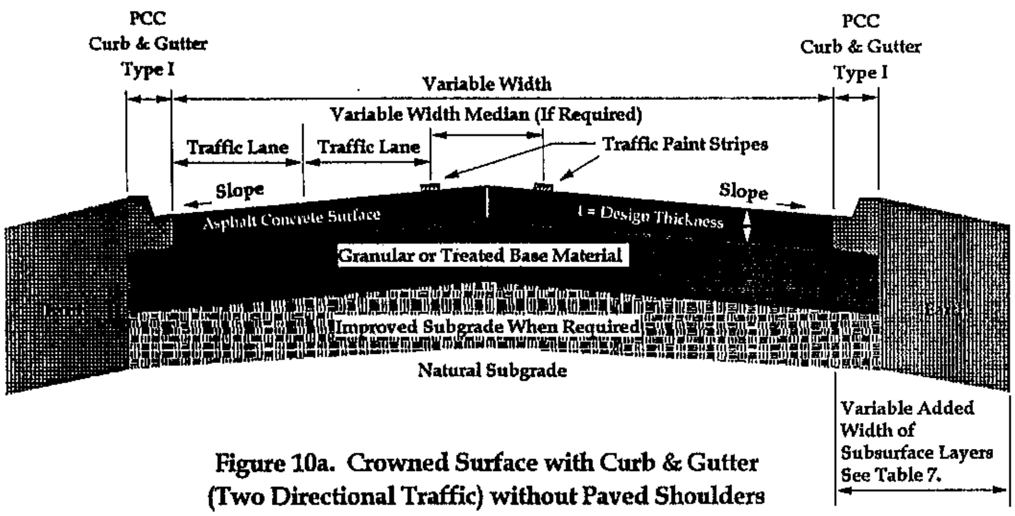


Figure 10a. Crowned Surface with Curb & Gutter
(Two Directional Traffic) without Paved Shoulders

Figure 10a. Crowned surface with curb & gutter (two directional traffic).

Urban Roadways
Site Condition Cells 1-20

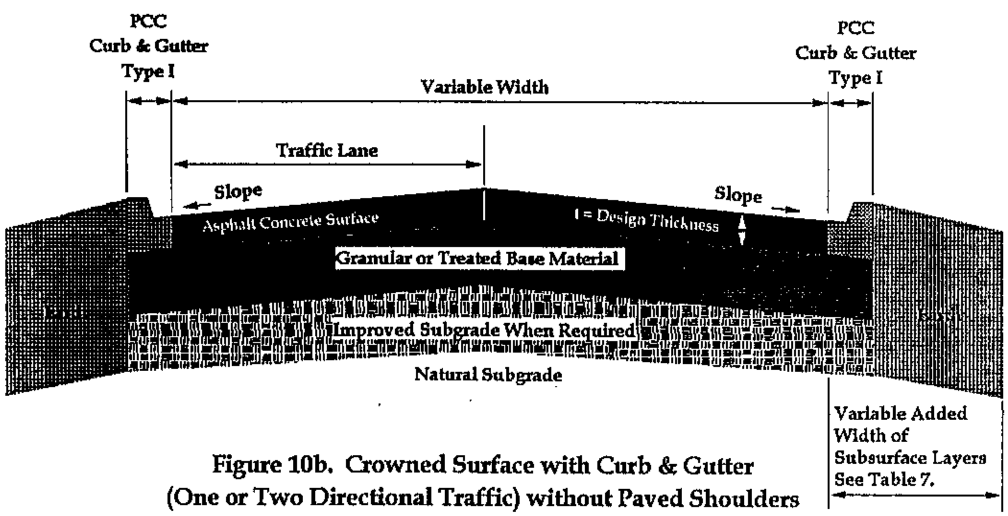


Figure 10b. Crowned Surface with Curb & Gutter
(One or Two Directional Traffic) without Paved Shoulders

Figure 10b. Crowned surface with curb & gutter (one or two directional traffic).

Paved Shoulders
Urban Roadways
Site Condition Cells 1-36

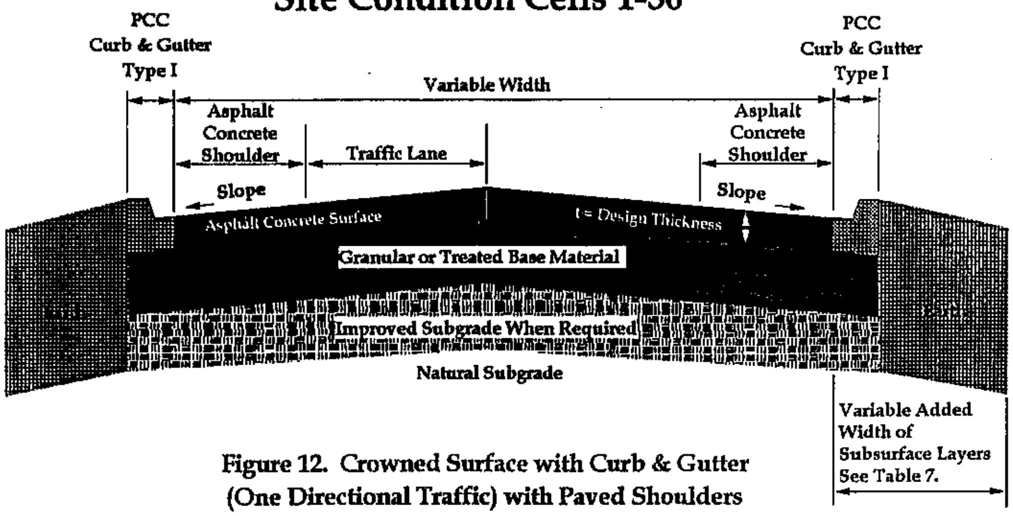


Figure 12. Crowned Surface with Curb & Gutter (One Directional Traffic) with Paved Shoulders

Figure 11. Crowned surface with curb & gutter (two directional traffic).

Paved Shoulders
Urban Roadways
Site Condition Cells 1-36

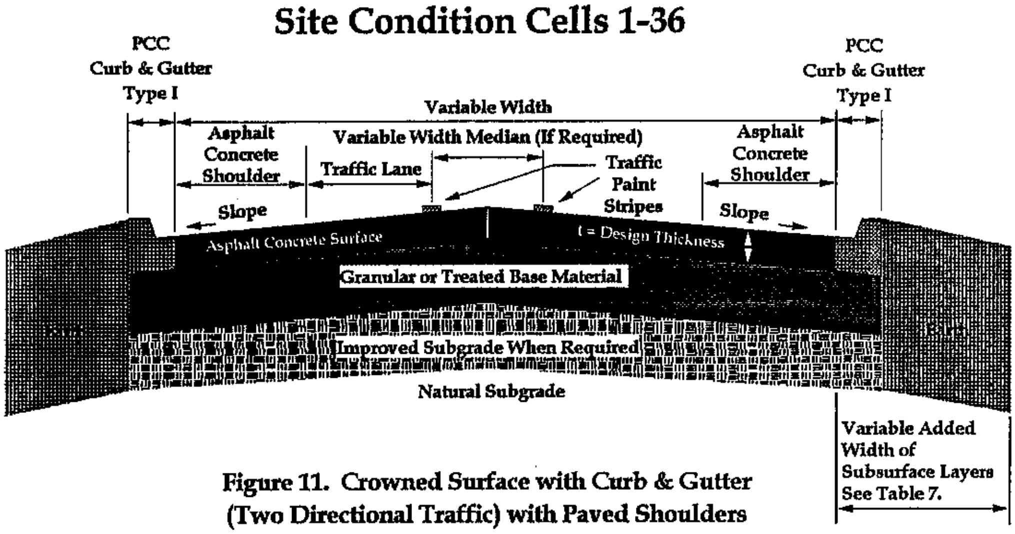
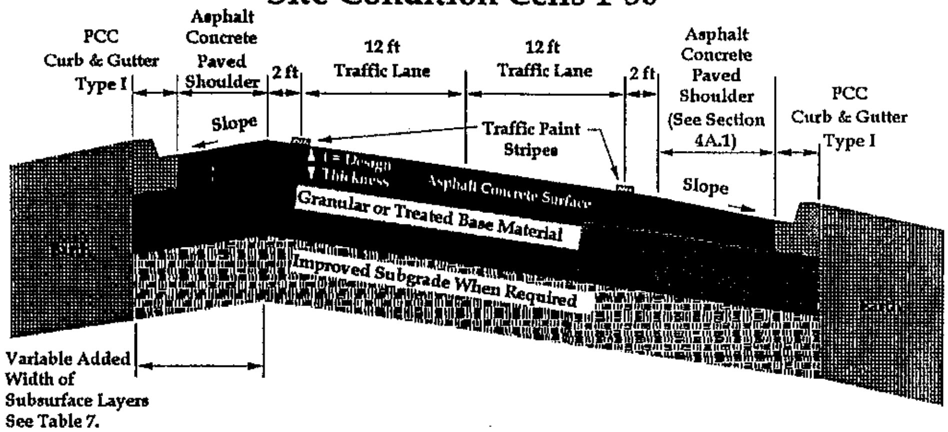


Figure 11. Crowned Surface with Curb & Gutter (Two Directional Traffic) with Paved Shoulders

Figure 12. Crowned surface with curb & gutter (one directional traffic).

Paved Shoulders
Urban Roadways
Site Condition Cells 1-36



Note: Edge Taper with a Hydraulic Screed extension can be used to place a variable width shoulder adjacent to a curb and gutter with an opposite cross-slope from the main traffic lanes.

Figure 13. Uniform Surface with Curb & Gutter (One or Two Directional Traffic)

Figure 13. Uniform surface with curb & gutter (one or two directional traffic).

Shoulders

Wide, surfaced shoulders provide a suitable, all-weather area for stopped vehicles to stand clear of the travel lanes. When used, shoulders must have an all-weather surface and structural capability of supporting vehicles that may need to use the shoulders. In addition, surfacing material can provide a contrast color and/or texture for easy distinction from the travel lanes. Turf or sod filled shoulders should only be used on very low volume roadways (typically those roadways with a two-way ADT less than 500).

Paved shoulders are preferred as being more reliable than aggregate shoulders and generally require less maintenance. Paved shoulders should be provided on all high volume facilities, as shown in Table 6, and are of considerable value on high speed facilities, such as for rural highways and some suburban arterials. Shoulders, in addition to serving as emergency parking areas, lend lateral support to the travel lane pavement structure, provide a maneuvering area, and increase sight distance on horizontal curves. Design shoulder widths for rural 2-lane highways with moderate and high volumes are:

Desirable Width = 10 ft
Minimum Width = 8 ft

Facilities with low volumes or low design speeds may have lesser width shoulders that are right-of-way dependent. Multi-lane divided rural highways normally have outside shoulders as well as inside shoulders. Outside shoulders are designed the same as for a moderate or high volume 2-lane highway. As such, the design widths are:

Desirable Width = 10 ft
Minimum Width = 8 ft

Inside shoulders on divided highway with two lanes in each direction are normally 4 ft wide so as not to encourage parking of vehicles on the inside. On divided highways with three or more lanes in each direction, inside shoulders can be the same width as outside shoulders.

Although urban roadways and streets normally use curb and gutter sections and, if necessary, provide parking lanes, there are instances where shoulders are constructed within urban areas. In such instances, the rural standards for shoulder width can apply equally to urban roadways and streets.

Pavement and Shoulder Cross Slope

The operating characteristics of vehicles on crowned pavements is such that on cross slopes up to ¼ inch per foot the effect on steering is barely perceptible. A reasonably steep lateral slope is desirable to minimize water ponding on flat sections of uncurbed pavements due to imperfections or unequal settlement. With curbed pavements, a steep cross slope is desirable to contain the flow of water adjacent to the curb or towards the pavement's edge. The recommended cross slopes for all types of pavement and shoulder sections are indicated below, and must be consistent and in accordance with AASHTO - A Policy on Geometric Design of Highways and Streets.

Type of Surface	Cross Slope in Inches per Foot	
	Desirable	Maximum
Asphalt Concrete/ Concrete	3/16	¼
Asphalt Surface Treatment	¼	5/16

On multi-lane divided highways, pavements with three or more lanes inclined in the same direction should have greater slope across the outside lane(s) than across the two interior lanes. This increase in slope in the outer lane should be approximately 1/16 inch per foot. In general, on

divided highways on tangent, each pavement should have a uniform cross slope with the high point at the edge nearest the median. On rural sections with a wide depressed median, the high point of the crown may be placed at the centerline of the pavement and sloped toward the edges at a uniform rate. At intersections, interchange ramps or in unusual situations, the high point of the crown position may vary depending upon surface drainage or other controls.

Type of Shoulder	Slope in Inches per Foot of Width	
	Desirable	**Maximum**
Asphalt Concrete/ Concrete	½	⅝
Asphalt Surface Treatment	½	⅝
Gravel or Crushed Stone	⅝	¾
Turf or Sod	¾	1

4A.2 Flexible Pavement Structural Design Features for Site Condition Cells

This section presents a catalog of recommended flexible (or asphalt concrete surfaced) pavement structural design features that vary with site conditions, i.e., traffic and subgrade. These site condition design cells are identified by the different traffic classes and subgrade conditions, previously defined in Section 3. Climate conditions are not used to define the site condition cells, however, the effective (seasonally adjusted) subgrade resilient modulus may vary with climatic zone, so there is an indirect effect on the structural design features. In addition, binder selection varies with climatic zone.

General Inputs Used to Develop Structural Designs

The general design inputs used in the AASHTO Design Guide [3] for determining the structural design features are noted below:

- Initial Serviceability = 4.5*
- Terminal Serviceability = 2.5*
- Overall Standard Deviation = 0.49*
- Reliability = Traffic Dependent (75% - 95%), Refer to Table 1 in Section 2.2
- Elastic Modulus of Asphalt Concrete Surface = 450 ksi

- Drainage Coefficient = 1.0*

* Note: All variables determined by consensus are indicated by an asterisk (*). See appendix G for further information.

As listed above, an AASHTO drainage coefficient (m-value) of 1.0 for all appropriate layers was used in determining the layer thickness requirements for each site condition cell. As such, it is inherently assumed that each pavement structure will have adequate surface and subsurface drainage features to ensure that the pavement materials will not become saturated for extended periods of time.. Refer to Section 4C for specific details regarding drainage recommendations for each pavement cross-section.

Design Checks

The structural designs for each flexible pavement type were initially based on the 1993 AASHTO Design Guide (which is based on serviceability or smoothness). All designs were then checked using two additional mechanistic/empirical design criteria:

- Fatigue cracking of the asphalt bound and cement treated layers.
- Permanent subgrade deformation.

The response parameters include asphalt concrete tensile strain, cement-treated base tensile stress, and subgrade vertical compressive strain.[7-14] Detailed information are presented in Appendix E. When the designs failed to meet the other design criteria, the structural designs were adjusted, such that all three design criteria were met for each pavement type and site condition cell. The resulting layer thicknesses satisfying each design criteria are included in this section of the catalog for each site condition cell.

Marginal Designs

The word "marginal" is used as an additional description of selected pavement types within specific site condition cells. Those pavement types noted as marginal represent pavements that have been used with reasonable success in some areas of the U.S., but have required extensive maintenance in other areas. The performance of those pavements noted as marginal under selected cells are highly dependent on the materials used, but are not necessarily confined to a specific area, environment or support conditions.

Subdrainage for Flexible Pavements

Section 4C contains recommendations on the level of subdrainage for each design cell for flexible pavements.

Subgrade Improvement

Subgrade uniformity and support are very important considerations in pavement design. Subgrade as used herein refers to the natural, processed, or fill soil foundation on which a pavement structure is placed. Uniformity of the upper portion of the subgrade is critical. This catalog recommends either an "improvement" for all subgrades identified as Very Soft (see Section 3, Subgrade), or provides an alternative with a thicker structural section. Subgrade improvement should also be considered for subgrades identified as Weak. Subgrade improvement is defined as either of the following techniques:

- Granular layer: Placement and compaction of a 6 to 12 in granular layer to 95 percent or greater of maximum density as defined by AASHTO T180, over the existing subgrade.

- Stabilization: The stabilization of the top 6 to 12 in of the subgrade generally with hydrated lime or cement. Subgrade improvement in terms of stabilization is discussed in greater detail in Section 5.6.

Benefits of subgrade improvement include provision of a construction platform so that pavement layers can be properly placed and compacted, increased uniform support along the project and a granular layer (with a controlled amount of fines) provides slow seepage of excess moisture out of the pavement structure. See Section 5 for further guidelines.

Subgrade Preparation

It is recommended that all subgrades that are not improved (as defined above) be "prepared" as described in Section 5 and summarized below to achieve a high degree of uniformity.

- Fill Sections. All granular fill materials should be compacted to at least 95% of the maximum density, as defined by AASHTO T180. Cohesive fill materials should be compacted to no less than 95% of the maximum density as defined by AASHTO T99.

- Cut Sections. In cuts, the depth and degree of compaction required varies with the pavement or subgrade elevation of the different soils that are encountered along a highway project. Uniformity of the upper portion of the subgrade is critical relative to

textural classification, moisture, and density. Specific guidance on compaction depth is given in Section 5. When existing subgrade soils do not meet minimum compaction requirements, consider the following alternatives:

(1) Compact soils from the surface.
(2) Remove and process soil to attain the approximate optimum moisture and replace and compact.
(3) Replace subgrade soil with suitable borrow materials.
(4) Raise the grade so that existing natural densities meet required values.

Special Subsurface Conditions
The pavement cross-sections and layer thicknesses included in the next section for each site condition cell are not intended to provide all alternatives and/or requirements for all subsurface conditions and problem soils that may be encountered along a highway project. The different treatments or techniques suggested for special subsurface conditions and/or problem soils are included in Section 5 - Special Subsurface Conditions.

Design Matrix Cells With Recommendations
Recommended design features are provided for four basic flexible or asphalt concrete surfaced pavements for the different site condition cells. These flexible pavement types are:

- Conventional Unbound Granular Base Pavements, both with and without improved subgrades.
- Full-Depth Asphalt Concrete
- Asphalt Treated Base, both with and without improved subgrades
- Cement Treated Base, both with and without improved subgrades.

Feasible flexible pavement types, key structural design inputs, structural layer thicknesses, and other design features are presented in table 8 for 36 site condition cells. Recommendations for each of the 36 cells are provided in the pages that follow.

A range of structural thicknesses are provided for each cell. These thicknesses were determined considering the range of traffic, holding the subgrade resilient moduli at their mean values. Climatic site condition is not directly included in the site condition cell definition. However, the "effective" (seasonally adjusted) resilient modulus is dependent on the soil type

and climate and the type of binder used in the asphalt concrete wearing and base layers is dependent on climate.

Table 8. Site condition design cells and alternatives for flexible pavement catalog.

Flexible Traffic ESALs millions	Subgrade Strength Class (Resilient Modulus, ksi)			
	M1: <4.5 (Very Soft)	M2: 4.5-9.0 (Weak)	M3: 9.0-14.0 (Fair)	M4: >14.0 (Strong)
T1: 0.5 - 1	Cell 1: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 2: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 3: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base	Cell 4: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base
T2: 1 - 2	Cell 5: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 6: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 7: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base	Cell 8: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base
T3: 2 - 4	Cell 9: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 10: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 11: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base	Cell 12: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base
T4: 4 - 8	Cell 13: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 14: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 15: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base	Cell 16: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base
T5: 8 - 12	Cell 17: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 18: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 19: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base	Cell 20: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base
T6: 12 - 20	Cell 21: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 22: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 23: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base	Cell 24: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base
T7: 20 - 36	Cell 25: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 26: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 27: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base	Cell 28: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base
T8: 36 - 60	Cell 29: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 30: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 31: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base	Cell 32: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base
T9: 60 - 100	Cell 33: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 34: Conventional Unbound Granular Base Asphalt Treated Base Cement Treated Base	Cell 35: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base	Cell 36: Conventional Unbound Granular Base Full-Depth Asphalt Concrete Asphalt Treated Base Cement Treated Base

Flexible
Cell 1

Traffic: 0.5-1.0 million flexible ESALs
Subgrade: Very soft (Resilient Modulus < 4.5 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	3 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	75%		

Note: Subgrade is very soft; some type of improvement is strongly recommended (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.5	4.0-5.5
Crushed Stone Aggregate Base Thickness, in.	12.0	12.0
Granular/Aggregate Subbase Thickness, in.	14.0-16.0 Crushed Stone	14.0-16.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades(see Section 5).

- ■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- ■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.0	4.0-5.0
Crushed Stone Aggregate Base Thickness, in.	8.0	8.0
Granular/Aggregate Subbase Thickness, in.	9.0-11.0 Crushed Stone	10.0-12.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

- ■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions.

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.5 - 4.5	3.5 - 4.5
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	9.0-10.0	9.0-10.0
Prepared Subgrade (See Section 5)		

■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	2.5-3.5	2.5-3.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	9.0	9.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

■ Controlled by AASHTO -PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.5 - 4.5	3.5 - 4.5
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	6.0	6.0
Prepared Subgrade (See Section 5)		

■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	2.5-3.5	2.5-3.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	6.0	6.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.0	4.0-5.0
Cement Treated Base Thickness, in.	7.0	7.0
Granular/Aggregate Subbase Thickness, in.	7.0 Crushed Stone	8.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Layer	
Dense Graded Asphalt Concrete Surface Thickness, in.	3.5-4.5
Cement Treated Base Thickness, in.	9.0
Improved Subgrade, in.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions.

Flexible Cell 2

Traffic: 0.5-1.0 million flexible ESALs
Subgrade: Weak (Resilient Modulus, 4.5 ksi-9.0 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	5 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	75%		

Note: Subgrade is weak; some type of improvement is should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.0	4.0-5.0
Crushed Stone Aggregate Base Thickness, in.	9.0	9.0
Granular/Aggregate Subbase Thickness, in.	10.5-11.5 Crushed Stone	11.0-12.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5-4.5	3.5-4.5
Crushed Stone Aggregate Base Thickness, in.	7.0	7.0
Granular/Aggregate Subbase Thickness, in.	8.0-9.0 Crushed Stone	9.0-10.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-4.0	3.0-4.0
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	7.0	7.0
Prepared Subgrade(See Section 5)		

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	2.5-3.0	2.5-3.0
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	6.0	6.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-4.0	3.0-4.0
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	6.0	6.0
Prepared Subgrade (See Section 5)		

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

~~Loads~~

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	2.5-3.0	2.5-3.0
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	5.5	5.5
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

- Controlled by AASHTO-PSI Criteria
- Controlled by Subgrade Vertical Compressive Strain Between Wheel

Structural Layer Thickness - Cement Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-3.5	3.0-3.5
Cement Treated Base Thickness, in.	6.0	6.0
Granular/Aggregate Subbase Thickness, in.	7.0 Crushed Stone	8.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- Controlled by AASHTO-PSI Criteria

Layer	
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-4.0
Cement Treated Base Thickness, in.	7.0
Improved Subgrade , in.	6.0 - 12.0

- Controlled by AASHTO-PSI Criteria

Flexible Cell 3

Traffic: 0.5-1.0 million flexible ESALs
Subgrade: Fair (Resilient Modulus 9.0 - 14.0 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	9 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	75%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

	■	■
Dense Graded Asphalt Concrete Surface Thickness, in.	3.5-4.5	3.5-4.5
Crushed Stone Aggregate Base Thickness, in.	6.0	6.0
Granular/Aggregate Subbase Thickness, in.	8.0-9.0 Crushed Stone	9.0-10.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- ■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- ■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

	■
Dense Graded Asphalt Concrete Surface Thickness, in.	3.5
Dense Graded Asphalt Concrete Base Thickness, in.	4.0-4.5
Prepared Subgrade (See Section 5)	

- ■ Controlled by Subgrade Vertical Compressive Strain Under Wheel loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0 - 3.5	3.0 - 3.5
Asphalt Treated Base Thickness, in.	5.0 (Plant mixed)	6.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	5.0-6.0	5.0-6.0
Prepared Subgrade (See Section 5)		

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0 - 3.5	3.0 - 3.5
Asphalt Treated Base Thickness, in.	5.0 (Plant mixed)	6.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	5.0-5.5	5.0-5.5
Prepared Subgrade (See Section 5)		

- Controlled by AASHTO-PSI Criteria
- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Layer	
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-3.5
Cement Treated Base Thickness, in.	7.0
Prepared Subgrade(See Section 5)	

- Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Flexible Cell 4

Traffic: 0.5-1.0 million flexible ESALs
Subgrade: Strong (Resilient Modulus, > 14.0 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	14 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	75%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5-4.5	3.5-4.5
Crushed Stone Aggregate Base Thickness, in.	5.0	5.0
Granular/Aggregate Subbase Thickness, in.	5.0 Crushed Stone	6.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	2.5-3.0
Dense Graded Asphalt Concrete Base Thickness, in.	4.0
Prepared Subgrade (See Section 5)	

- Controlled by AASHTO-PSI criteria

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0	3.0
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	7.5 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	5.0	5.0
Prepared Subgrade (See Section 5)		

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	2.5-3.0	2.5-3.0
Asphalt Treated Base Thickness, in.	4.0 (Plant mixed)	4.5 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	5.0	5.0
Prepared Subgrade (See Section 5)		

- Controlled by AASHTO-PSI Criteria
- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Layer	
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-3.5
Cement Treated Base Thickness, in.	5.0
Prepared Subgrade (See Section 5)	

- Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Flexible Cell 5	Traffic: 1-2 million flexible ESALs Subgrade: Very Soft (Resilient Modulus, < 4.5 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	3 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	85%		

Note: Subgrade is very soft; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	5.0-6.5	5.0-6.5
Crushed Stone Aggregate Base Thickness, in.	12.0	12.0
Granular/Aggregate Subbase Thickness, in.	14.5-16.5 Crushed Stone	15.0-17.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades(See Section 5).

- ■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- ■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-6.0	4.5-6.0
Crushed Stone Aggregate Base Thickness, in.	8.0	8.0
Granular/Aggregate Subbase Thickness, in.	11.0-12.0 Crushed Stone	12.0-13.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

- ■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions.

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, In.	3.5 - 4.5	3.5 - 4.5
Asphalt Treated Base Thickness, In.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	12.0-13.0	12.0-13.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	4.0-5.0	4.0-5.0
Asphalt Treated Base Thickness, In.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	10.0	10.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	3.5 - 4.5	3.5 - 4.5
Asphalt Treated Base Thickness, In.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, In.	5.5	5.5
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	6.0-7.0	6.0-7.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

Dense Graded Asphalt Concrete Surface Thickness, In.	4.0-5.0	4.0-5.0
Asphalt Treated Base Thickness, In.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	6.0	6.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, In.	4.5-5.5	4.5-5.5
Cement Treated Base Thickness, In.	9.0	9.0
Granular/Aggregate Subbase Thickness, In.	7.5-8.0 Crushed Stone	8.0-8.5 Pit Run Gravel
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	4.5-6.0
Cement Treated Base Thickness, In.	10.0
Improved Subgrade , In.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions.

Flexible Cell 6

Traffic: 1-2 million flexible ESALs
Subgrade: Weak (Resilient Modulus, 4.5-9.0 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	5 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	85%		

Note: Subgrade is weak; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	5.0-6.0	5.0-6.0
Crushed Stone Aggregate Base Thickness, in.	9.0	9.0
Granular/Aggregate Subbase Thickness, in.	9.5-10.5 Crushed Stone	10.0-11.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5	4.5-5.5
Crushed Stone Aggregate Base Thickness, in.	7.0	7.0
Granular/Aggregate Subbase Thickness, in.	8.0-9.0 Crushed Stone	9.0-10.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-4.0	3.0-4.0
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	9.0	9.0
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	3.0-4.0	3.0-4.0
Asphalt Treated Base Thickness, In.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	7.0	7.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-4.0	3.0-4.0
Asphalt Treated Base Thickness, In.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, In.	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	5.0	5.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	3.0-4.0	3.0-4.0
Asphalt Treated Base Thickness, In.	5.0 (Plant mixed)	6.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	5.0	5.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	3.5-4.5	3.5-4.5
Cement Treated Base Thickness, In.	7.0	7.0
Granular/Aggregate Subbase Thickness, In.	7.0 Crushed Stone	8.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Layer	
Dense Graded Asphalt Concrete Surface Thickness, In.	3.5-4.5
Cement Treated Base Thickness, In.	9.0
Improved Subgrade , In.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Flexible
Cell 7

Traffic: 1-2 million flexible ESALs
Subgrade: Fair (Resilient Modulus, 9-14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	9 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	85%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-55	4.5-55
Crushed Stone Aggregate Base Thickness, in.	8.0	8.0
Granular/Aggregate Subbase Thickness, in.	9.0 Crushed Stone	10.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5
Dense Graded Asphalt Concrete Base Thickness, in.	5.0-5.5
Prepared Subgrade (See Section 5)	

- Controlled by Subgrade Vertical Compressive Strain Under Wheel Loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0 - 3.5	3.0 - 3.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	6.0	6.0
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0 - 3.5	3.0 - 3.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	5.5	5.5
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Layer	
Dense Graded Asphalt Concrete Surface Thickness, in.	3.5-4.0
Cement Treated Base Thickness, in.	8.0
Prepared Subgrade (See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Flexible Cell 8	Traffic: 1-2 million flexible ESALs Subgrade: Strong (Resilient Modulus, > 14.5 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	14 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	85%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

	■	■
Dense Graded Asphalt Concrete Surface Thickness, In.	4.0-5.5	4.0-5.5
Crushed Stone Aggregate Base Thickness, In.	6.0	6.0
Granular/Aggregate Subbase Thickness, In.	7.0 Crushed Stone	8.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, In.	3.5
Dense Graded Asphalt Concrete Base Thickness, In.	4.0
Prepared Subgrade (See Section 5)	

■ Controlled by Subgrade Vertical
■ Compressive Strain Under Wheel
Loads Controlled by AASHTO-PSI Criteria

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	3.0	3.0
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	7.5 (Roadway Mixed)
Prepared Subgrade (See Section 5)	6.0	6.0

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-3.5
Cement Treated Base Thickness, in.	7.0
Prepared Subgrade(See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Flexible
Cell 9

Traffic: 2-4 million flexible ESALs
Subgrade: Very Soft (Resilient Modulus, < 4.5 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	3 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	90%		

Note: Subgrade is very soft; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	6.0-7.5	6.0-7.5
Crushed Stone Aggregate Base Thickness, in.	14.0	14.0
Granular/Aggregate Subbase Thickness, in.	15.0-17.0 Crushed Stone	16.0-18.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-7.0	5.5-7.0
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	11.0-12.0 Crushed Stone	12.0-13.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade condition.

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, In.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	14.0-15.0	14.0-15.0
Prepared Subgrade(See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, In.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	12.0	12.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, In.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, In.	7.0	7.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	6.0-7.0	6.0-7.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, In.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	6.0	6.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	4.5-5.5	4.5-5.5
Cement Treated Base Thickness, In.	12.0	12.0
Granular/Aggregate Subbase Thickness, In.	7.0-8.0 Crushed Stone	8.0-9.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Layer	
Dense Graded Asphalt Concrete Surface Thickness, In.	5.0-6.5
Cement Treated Base Thickness, In.	12.0
Improved Subgrade , In.	6.0 -12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions.

Flexible Cell 10

Traffic: 2-4 million flexible ESALs
Subgrade: Weak (Resilient Modulus, 4.5-9.0 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	5 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	90%		

Note: Subgrade is very weak; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5	6.5-7.5
Crushed Stone Aggregate Base Thickness, in.	8.0	8.0
Granular/Aggregate Subbase Thickness, in.	11.0-12.0 Crushed Stone	12.0-13.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.5	5.5-6.5
Crushed Stone Aggregate Base Thickness, in.	8.0	8.0
Granular/Aggregate Subbase Thickness, in.	9.0-10.0 Crushed Stone	10.0-11.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5-4.5	3.5-4.5
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	12.0	12.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.0	4.0-5.0
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	9.0	9.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5-4.5	3.5-4.5
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	6.0	6.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.0	4.0-5.0
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	8.0	8.0
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.0	4.0-5.0
Cement Treated Base Thickness, in.	9.0	9.0
Granular/Aggregate Subbase Thickness, in.	7.0 Crushed Stone	8.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5
Cement Treated Base Thickness, in.	10.0
Improved Subgrade , in.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Flexible Cell 11

Traffic: 2-4 million flexible ESALs
Subgrade: Fair (Resilient Modulus, 9-14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	9 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	90%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.5	5.5-6.5
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	8.0-9.0 Crushed Stone	10.0-11.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- ■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- ■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5
Dense Graded Asphalt Concrete Base Thickness, in.	6.0-6.5
Prepared Subgrade (See Section 5)	

- ■ Controlled by Subgrade Vertical Compressive Strain Under Wheel Loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5)

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	3.0 - 4.0	3.0 - 4.0
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	9.0	9.0
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-4.0	3.0-4.0
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	8.0	8.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5
Cement Treated Base Thickness, in.	6.0
Prepared Subgrade (See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Flexible Cell 12

Traffic: 2-4 million flexible ESALs
Subgrade: Strong (Resilient Modulus, > 14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	14 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	90%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	5.0-6.5	5.0-6.5
Crushed Stone Aggregate Base Thickness, in.	6.0	6.0
Granular/Aggregate Subbase Thickness, in.	8.0 Crushed Stone	10.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5
Dense Graded Asphalt Concrete Base Thickness, in.	4.5-5.0
Prepared Subgrade	

- Controlled by AASHTO-PSI criteria

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-3.5	3.0-3.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular (Aggregate Pit Run Gravel) Subbase Thickness, in.	6.0	6.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	3.0-3.5	3.0-3.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Base Thickness, in.	5.0	5.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Layer	
Dense Graded Asphalt Concrete Surface Thickness, in.	3.5-4.5
Cement Treated Base Thickness, in.	8.0
Prepared Subgrade (See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Flexible
Cell 13

Traffic: 4-8 million flexible ESALs
Subgrade: Very Soft (Resilient Modulus, < 4.5 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	3 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is very weak; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	7.5-8.5	7.5-8.5
Crushed Stone Aggregate Base Thickness, in.	14.0	14.0
Granular/Aggregate Subbase Thickness, in.	17.0-18.0 Crushed Stone	18.0-19.0 Pit Run Gravel
Prepared Subgrade See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Dense Graded Asphalt Concrete Surface Thickness, in.	7.0-8.0	7.0-8.0
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	13.0-14.0 Crushed Stone	14.0-15.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the subgrade conditions.

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, In.	5.5-6.5	5.5-6.5
Asphalt Treated Base Thickness, In.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	13.0-14.0	13.0-14.0
Prepared Subgrade(See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	5.5-6.5	5.5-6.5
Asphalt Treated Base Thickness, In.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	14.0	14.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	5.5-6.5	5.5-6.5
Asphalt Treated Base Thickness, In.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, In.	7.0	7.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	5.0-6.0	5.0-6.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	5.5-6.5	5.5-6.5
Asphalt Treated Base Thickness, In.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	7.0	7.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, In.	6.5-7.5	6.5-7.5
Cement Treated Base Thickness, In.	12.0	12.0
Granular/Aggregate Subbase Thickness, In.	7.0-8.0 Crushed Stone	8.0-9.0 Pit Run Gravel
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	6.5-8.0
Cement Treated Base Thickness, In.	13.0
Improved Subgrade , In.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 14

Traffic: 4-8 million flexible ESALs
Subgrade: Weak (Resilient Modulus, 4.5-9.0 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	5 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is very weak; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	7.0-8.5	7.0-8.5
Crushed Stone Aggregate Base Thickness, in.	9.0	9.0
Granular/Aggregate Subbase Thickness, in.	15.0-16.0 Crushed Stone	16.0-17.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5	6.5-7.5
Crushed Stone Aggregate Base Thickness, in.	9.0	9.0
Granular/Aggregate Subbase Thickness, in.	11.0-12.0 Crushed Stone	12.0-13.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.5	4.0-5.5
Asphalt Treated Base Thickness, in.	9.0 (Plant mixed)	10.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	12.0	12.0
Prepared Subgrade(See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	14.0	14.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.5	4.0-5.5
Asphalt Treated Base Thickness, in.	9.0 (Plant mixed)	10.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	6.0	6.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	12.0	12.0
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.5	5.5-6.5
Cement Treated Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	7.0 Crushed Stone	8.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	5.0-6.5
Cement Treated Base Thickness, in.	12.0
Improved Subgrade , in.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 15

Traffic: 4-8 million flexible ESALs
Subgrade: Fair (Resilient Modulus, 9-14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	9 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-8.0	6.5-8.0
Crushed Stone Aggregate Base Thickness, in.	9.0	9.0
Granular/Aggregate Subbase Thickness, in.	11.0-12.0 Crushed Stone	12.0-13.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5
Dense Graded Asphalt Concrete Base Thickness, in.	7.5-8.5
Prepared Subgrade (See Section 5)	

■ Controlled by Subgrade Vertical Compressive Strain Under Wheel loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.0	4.0-5.0
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	11.0-12.0	11.0-12.0
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.0	4.0-5.0
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	5.0-6.0	5.0-6.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.5
Cement Treated Base Thickness, in.	9.0
Prepared Subgrade(See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 16

Traffic: 4-8 million flexible ESALs
Subgrade: Strong (Resilient Modulus, > 14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	14 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5	6.5-7.5
Crushed Stone Aggregate Base Thickness, in.	7.0	7.0
Granular/Aggregate Subbase Thickness, in.	8.0 Crushed Stone	10.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5
Dense Graded Asphalt Concrete Base Thickness, in.	5.5-6.5
Prepared Subgrade (See Section 5)	

- Controlled by AASHTO-PSI criteria

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-4.5	4.0-4.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular (Aggregate Pit Run Gravel) Subbase Thickness, in.	7.0	7.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-4.5	4.0-4.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase Thickness, in.	6.0	6.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5
Cement Treated Base Thickness, in.	8.0
Prepared Subgrade (See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 17

Traffic: 8-12 million flexible ESALs
Subgrade: Very Soft (Resilient Modulus, < 4.5 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	3 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is very soft; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	8.5-9.5	8.5-9.5
Crushed Stone Aggregate Base Thickness, in.	15.0	15.0
Granular/Aggregate Subbase Thickness, in.	17.0-18.0 Crushed Stone	18.0-19.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

- Controlled by Subgrade Vertical Compressive Strain Under Wheel Loads
- Controlled by Asphalt Concrete Tensile Strain Between Wheel Load

Dense Graded Asphalt Concrete Surface Thickness, in.	8.0-8.5	8.0-8.5
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	15.0-16.0 Crushed Stone	16.0-17.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade condition.

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	6.0-7.0	6.0-7.0
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	15.0-16.0	15.0-16.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	6.0-7.0	6.0-7.0
Asphalt Treated Base Thickness, in.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	16.0	16.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	6.0-7.0	6.0-7.0
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	8.0-9.0	8.0-9.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	6.0-7.0	6.0-7.0
Asphalt Treated Base Thickness, in.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	7.0	7.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	8.0	8.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	7.0-8.0	7.0-8.0
Cement Treated Base Thickness, in.	13.0	13.0
Granular/Aggregate Subbase Thickness, in.	7.0-8.0 Crushed Stone	8.0-9.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Layer	
Dense Graded Asphalt Concrete Surface Thickness, in.	7.5-8.5
Cement Treated Base Thickness, in.	14.0
Improved Subgrade , in.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 18

Traffic: 8-12 million flexible ESALs
Subgrade: Weak (Resilient Modulus, 4.5-9.0 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	5 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is weak; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	8.5-9.5	8.5-9.5
Crushed Stone Aggregate Base Thickness, in.	9.0	9.0
Granular/Aggregate Subbase Thickness, in.	15.0-16.0 Crushed Stone	16.0-17.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Load

Dense Graded Asphalt Concrete Surface Thickness, in.	7.5-8.5	7.5-8.5
Crushed Stone Aggregate Base Thickness, in.	9.0	9.0
Granular/Aggregate Subbase Thickness, in.	13.0-14.0 Crushed Stone	14.0-15.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	12.0	12.0
Prepared Subgrade(See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.0	5.5-6.0
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	13.0	13.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	6.0	6.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.0	5.5-6.0
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	6.0	6.0
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.0	5.5-6.0
Cement Treated Base Thickness, in.	13.0	13.0
Granular/Aggregate Subbase Thickness, in.	7.0 Crushed Stone	8.0 Pit Run Gravel
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	7.0-7.5
Cement Treated Base Thickness, in.	11.03
Improved Subgrade , in.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible
Cell 19

Traffic: 8-12 million flexible ESALs
Subgrade: Fair (Resilient Modulus, 9-14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	9 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	7.5-8.5	7.5-8.5
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	11.0-12.0 Crushed Stone	12.0-13.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5
Dense Graded Asphalt Concrete Base Thickness, in.	8.5-9.5
Prepared Subgrade (See Section 5)	

■ Controlled by Subgrade Vertical Compressive Strain Under Wheel Loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.0	4.5-5.0
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	12.0-13.0	12.0-13.0
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.0	4.5-5.0
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	6.0-7.0	6.0-7.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Layer	
Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.0
Cement Treated Base Thickness, in.	11.0
Prepared Subgrade (See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 20

Traffic: 8-12 million flexible ESALs
Subgrade: Strong (Resilient Modulus, < 4.5 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	14 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	7.0-8.0	7.0-8.0
Crushed Stone Aggregate Base Thickness, in.	8.0	8.0
Granular/Aggregate Subbase Thickness, in.	10.0-12.0 Crushed Stone	12.0-13.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- Controlled by Asphalt Concrete Tensile Strain Under Wheel Load

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5
Dense Graded Asphalt Concrete Base Thickness, in.	6.5-7.0
Prepared Subgrade (See Section 5)	

- Controlled by AASHTO-PSI criteria

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-4.5	4.0-4.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Granular (Aggregate Pit Run Gravel) Subbase Thickness, in.	10.0	10.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-4.5	4.0-4.5
Asphalt Treated Base Thickness, in.	6.0 (Plant mixed)	7.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase Thickness, in.	8.0	8.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	5.0-5.5
Cement Treated Base Thickness, in.	9.0
Prepared Subgrade (See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 21

Traffic: 12-20 million flexible ESALs
Subgrade: Very Soft (Resilient Modulus, < 4.5 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	3 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is very soft; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	9.5-10.5	9.5-10.5
Crushed Stone Aggregate Base Thickness, in.	16.0	16.0
Granular/Aggregate Subbase Thickness, in.	17.0-18.0 Crushed Stone	18.0-19.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

- ■ Controlled by Subgrade Vertical Compressive Strain Under Wheel Loads
- ■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

Dense Graded Asphalt Concrete Surface Thickness, in.	8.5-10.0	8.5-10.0
Crushed Stone Aggregate Base Thickness, in.	11.0	11.0
Granular/Aggregate Subbase Thickness, in.	16.0-17.0 Crushed Stone	16.0-17.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

- ■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the subgrade conditions.

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	7.0-8.0	7.0-8.0
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	16.0-17.0	16.0-17.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5	6.5-7.5
Asphalt Treated Base Thickness, in.	9.0 (Plant mixed)	10.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	16.0	16.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	7.0-8.0	7.0-8.0
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	7.0	7.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	8.0-9.0	8.0-9.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator is recommended between the subbase and very soft subgrades (See Section 6).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5	6.5-7.5
Asphalt Treated Base Thickness, in.	9.0 (Plant mixed)	10.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	7.0	7.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	8.0	8.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	7.5-8.5	7.5-8.5
Cement Treated Base Thickness, in.	14.0	14.0
Granular/Aggregate Subbase Thickness, in.	7.0-8.0 Crushed Stone	8.0-9.0 Pit Run Gravel
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	8.5-9.5
Cement Treated Base Thickness, in.	14.0
Improved Subgrade , in.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible
Cell 22

Traffic: 12-20 million flexible ESALs
Subgrade: Weak (Resilient Modulus, < 4.5-9.0 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	5 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is weak; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	9.0-10.5	9.0-10.5
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	15.0-16.0 Crushed Stone	16.0-17.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

Dense Graded Asphalt Concrete Surface Thickness, in.	8.5-9.5	8.5-9.5
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	13.0-14.0 Crushed Stone	14.0-15.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	5.0-6.0	5.0-6.0
Asphalt Treated Base Thickness, In.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	14.0-15.0	14.0-15.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	5.5-6.5	5.5-6.5
Asphalt Treated Base Thickness, In.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	12.0	12.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	5.0-6.0	5.0-6.0
Asphalt Treated Base Thickness, In.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, In.	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	7.0-8.0	7.0-8.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	5.5-6.5	5.5-6.5
Asphalt Treated Base Thickness, In.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase Thickness, In.	5.0	5.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	6.0	6.0
Improved Subgrade Thickness, In.	6.0-12.0	6.0-12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	5.5-6.5	5.5-6.5
Cement Treated Base Thickness, In.	13.0	13.0
Granular/Aggregate Subbase Thickness, In.	7.0 Crushed Stone	8.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Layer	
Dense Graded Asphalt Concrete Surface Thickness, In.	7.5-8.5
Cement Treated Base Thickness, In.	11.0
Improved Subgrade , In.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible
Cell 23

Traffic: **12-20 million flexible ESALs**
Subgrade: **Fair (Resilient Modulus, 9-14 ksi)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	9 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	8.5-9.5	8.5-9.5
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	13.0-14.0 Crushed Stone	14.0-15.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5
Dense Graded Asphalt Concrete Base Thickness, in.	8.5-10
Prepared Subgrade (See Section 5)	

■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	13.0-14.0	13.0-14.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	6.0-7.0	6.0-7.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.5
Cement Treated Base Thickness, in.	12.0
Prepared Subgrade(See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible
Cell 24

Traffic: 12-20 million flexible ESALs
Subgrade: Strong (Resilient Modulus, > 14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	14 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	8.0-8.5	8.0-8.5
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	11.0-12.0 Crushed Stone	12.0-13.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	3.5
Dense Graded Asphalt Concrete Base Thickness, in.	8.0-9.0
Prepared Subgrade (See Section 5)	

- Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-4.5	4.0-4.5
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Granular (Aggregate Pit Run Gravel) Subbase Thickness, in.	10.0	10.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-4.5	4.0-4.5
Asphalt Treated Base Thickness, in.	7.0 (Plant mixed)	8.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase Thickness, in.	9.0	9.0
Prepared Subgrade (See Section 5).		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	5.0-5.5
Cement Treated Base Thickness, in.	9.0
Prepared Subgrade(See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible
Cell 25

Traffic:	**20-36 million flexible ESALs**
Subgrade:	**Very Soft (Resilient Modulus, < 4.5 ksi)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	3 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is very soft; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

A conventional unbound base without an improved subgrade is not recommended for this site condition cell.

Dense Graded Asphalt Concrete Surface Thickness, in.	9.5-11.0	9.5-11.0
Crushed Stone Aggregate Base Thickness, in.	12.0	12.0
Granular/Aggregate Subbase Thickness, in.	16.0-18.0 Crushed Stone	18.0-19.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	7.5-8.5	7.5-8.5
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	17.0-18.0	18.0-19.0
Prepared Subgrade(See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	7.0-8.0	7.0-8.0
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	16.0	16.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	7.5-8.5	7.5-8.5
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	8.0	8.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	8.0-9.0	9.0-10.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	7.0-8.0	7.0-8.0
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	7.0	7.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	8.0	8.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	8.0-9.0	8.0-9.0
Cement Treated Base Thickness, in.	15.0	15.0
Granular/Aggregate Subbase Thickness, in.	7.0-8.0 Crushed Stone	8.0-9.0 Pit Run Gravel
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	8.5-9.5
Cement Treated Base Thickness, in.	16.0
Improved Subgrade , in.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible
Cell 26

Traffic: 20-36 million flexible ESALs
Subgrade: Weak (Resilient Modulus, 4.5-9.0 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	5 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is weak; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	10-11.5	10-11.5
Crushed Stone Aggregate Base Thickness, in.	12.0	12.0
Granular/Aggregate Subbase Thickness, in.	15.0-16.0 Crushed Stone	16.0-17.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

Dense Graded Asphalt Concrete Surface Thickness, in.	9.0-10.5	9.0-10.5
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	14.0-15.0 Crushed Stone	16.0-17.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, In.	5.5-6.5	5.5-6.5
Asphalt Treated Base Thickness, In.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	15.0-16.0	16.0-17.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	6.0-7.0	6.0-7.0
Asphalt Treated Base Thickness, In.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	15.0	16.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	5.5-6.5	5.5-6.5
Asphalt Treated Base Thickness, In.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, In.	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	8.0-9.0	9.0-11.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	6.0-7.0	6.0-7.0
Asphalt Treated Base Thickness, In.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase Thickness, In.	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	8.0	8.0
Improved Subgrade Thickness, In.	6.0-12.0	6.0-12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, In.	6.0-7.0	6.0-7.0
Cement Treated Base Thickness, In.	14.0	14.0
Granular/Aggregate Subbase Thickness, In.	7.0 Crushed Stone	8.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	8.0-9.0
Cement Treated Base Thickness, In.	12.0
Improved Subgrade., In.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible
Cell 27

Traffic: 20-36 million flexible ESALs
Subgrade: Fair (Resilient Modulus, 9-14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	9 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	9.5-11.0	9.5-11.0
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	15.0-16.0 Crushed Stone	16.0-17.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5
Dense Graded Asphalt Concrete Base Thickness, in.	9.0-10.0
Prepared Subgrade (See Section 5)	

■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, in.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	14.0-15.0	14.0-15.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, in.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	7.0-8.0	7.0-8.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5
Cement Treated Base Thickness, in.	12.0
Prepared Subgrade(See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 28

Traffic: 20-36 million flexible ESALs
Subgrade: Strong (Resilient Modulus, > 14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	14 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	8.5-10.0	8.5-10.0
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	12.0-13.0 Crushed Stone	13.0-14.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5
Dense Graded Asphalt Concrete Base Thickness, in.	7.0-8.5
Prepared Subgrade (See Section 5)	

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.0	4.0-5.0
Asphalt Treated Base Thickness, in.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Granular (Aggregate Pit Run Gravel) Subbase Thickness, in.	10.0	10.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	4.0-5.0	4.0-5.0
Asphalt Treated Base Thickness, in.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase Thickness, in.	9.0	9.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Layer	
Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.5
Cement Treated Base Thickness, in.	11.0
Prepared Subgrade(See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 29

Traffic: 36-60 million flexible ESALs
Subgrade: Very Soft (Resilient Modulus, < 4.5 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	3 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is very soft; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

A conventional unbound base without an improved subgrade is not recommended for this site condition cell.

Dense Graded Asphalt Concrete Surface Thickness, in.	10.5-12	10.5-12
Crushed Stone Aggregate Base Thickness, in.	14.0	14.0
Granular/Aggregate Subbase Thickness, in.	16.0-18.0 Crushed Stone	18.0-19.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	7.5-9.0	7.5-9.0
Asphalt Treated Base Thickness, in.	12.0 (Plant mixed)	13.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	17.0-18.0	18.0-19.0
Prepared Subgrade(See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	8.0-9.0	8.0-9.0
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	17.0	17.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	7.5-9.0	7.5-9.0
Asphalt Treated Base Thickness, in.	12.0 (Plant mixed)	13.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	8.0	8.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	8.0-9.0	9.0-10.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	8.0-9.0	8.0-9.0
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	7.0	7.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	9.0	9.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	8.5-10.0	8.5-10.0
Cement Treated Base Thickness, in.	16.0	16.0
Granular/Aggregate Subbase Thickness, in.	7.0-8.0 Crushed Stone	8.0-9.0 Pit Run Gravel
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, in.	8.5-10.0
Cement Treated Base Thickness, in.	18.0
Improved Subgrade , in.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 30

Traffic: 36-60 million flexible ESALs
Subgrade: Weak (Resilient Modulus, 4.5-9.0 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	5 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is weak; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

A conventional unbound base without an improved subgrade is not recommended for this site condition cell.

Dense Graded Asphalt Concrete Surface Thickness, in.	10.5-12	10.5-12
Crushed Stone Aggregate Base Thickness, in.	11.0	11.0
Granular/Aggregate Subbase Thickness, in.	16.0-18.0 Crushed Stone	18.0-19.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5	6.5-7.5
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	15.0-16.0	16.0-17.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5	6.5-7.5
Asphalt Treated Base Thickness, in.	9.0 (Plant mixed)	10.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	15.0	15.0
Improved Subgrade Thickness, in.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5	6.5-7.5
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, in.	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	8.0-9.0	9.0-11.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and weak subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5	6.5-7.5
Asphalt Treated Base Thickness, in.	9.0 (Plant mixed)	10.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase Thickness, in.	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	8.0	8.0
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5	6.5-7.5
Cement Treated Base Thickness, in.	15.0	15.0
Granular/Aggregate Subbase Thickness, in.	7.0 Crushed Stone	8.0 Pit Run Gravel
Prepared Subgrade(See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Layer	
Dense Graded Asphalt Concrete Surface Thickness, in.	8.5-9.5
Cement Treated Base Thickness, in.	13.0
Improved Subgrade , in.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible
Cell 31

Traffic: 36-60 million flexible ESALs
Subgrade: Fair (Resilient Modulus, 9-14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	9 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	11.0-12.0	11.0-12.0
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	15.0-16.0 Crushed Stone	16.0-17.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5
Dense Graded Asphalt Concrete Base Thickness, in.	10.0-11.5
Prepared Subgrade (See Section 5)	

■ Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads
■ Controlled by asphalt concrete tensile strain between wheel loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	5.0-6.0	5.0-6.0
Asphalt Treated Base Thickness, In.	9.0 (Plant mixed)	10.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	14.0-15.0	14.0-15.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	5.0-6.0	5.0-6.0
Asphalt Treated Base Thickness, In.	9.0 (Plant mixed)	10.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, In.	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	7.0-8.0	7.0-8.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Layer	
Dense Graded Asphalt Concrete Surface Thickness, In.	7.5-8.5
Cement Treated Base Thickness, In.	12.0
Prepared Subgrade (See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 32

Traffic: 36-60 million flexible ESALs
Subgrade: Strong (Resilient Modulus, > 14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	14 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	10-11.5	10-11.5
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	14.0-15.0 Crushed Stone	15.0-16.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5
Dense Graded Asphalt Concrete Base Thickness, in.	8.5-10
Prepared Subgrade (See Section 5)	

- Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads
- Controlled by Subgrade Vertical Compressive Strain Between Wheel Loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, in.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	12.0	12.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5-5.5	4.5-5.5
Asphalt Treated Base Thickness, in.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase Thickness, in.	5.0	5.0
Granular/Aggregate (Pit Run Gravel Subbase Thickness, in.	6.0	6.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	6.0-6.5
Cement Treated Base Thickness, in.	12.0
Prepared Subgrade (See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 33

Traffic: 60-100 million flexible ESALs
Subgrade: Very Soft (Resilient Modulus, < 4.5 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	3 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is very soft; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

A conventional unbound base without an improved subgrade is not recommended for this site condition cell.

Dense Graded Asphalt Concrete Surface Thickness, in.	12-13.5	12-13.5
Crushed Stone Aggregate Base Thickness, in.	15.0	15.0
Granular/Aggregate Subbase Thickness, in.	18.0 Crushed Stone	20.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	8.5-10.0	8.5-10.0
Asphalt Treated Base Thickness, In.	12.0 (Plant mixed)	13.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	18.0-19.0	19.0-20.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	9.0-10.0	9.0-10.0
Asphalt Treated Base Thickness, In.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	18.0	18.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	8.5-10.0	8.5-10.0
Asphalt Treated Base Thickness, In.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, In.	8.0	8.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	9.0-10.0	9.0-10.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	9.0-10.0	9.0-10.0
Asphalt Treated Base Thickness, In.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	8.0	8.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	9.0	9.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, In.	9.5-10.5	9.5-10.5
Cement Treated Base Thickness, In.	17.0	17.0
Granular/Aggregate Subbase Thickness, In.	7.0-8.0 Crushed Stone	8.0-9.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Layer	
Dense Graded Asphalt Concrete Surface Thickness, In.	9.5-11.0
Cement Treated Base Thickness, In.	18.0
Improved Subgrade , In.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible
Cell 34

Traffic: 60-100 million flexible ESALs
Subgrade: Weak (Resilient Modulus, 4.5-9.0 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	5 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: Subgrade is weak; some type of improvement should be considered (See Section 5).
Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

A conventional unbound base without an improved subgrade is not recommended for this site condition cell.

Dense Graded Asphalt Concrete Surface Thickness, in.	11.5-13	11.5-13
Crushed Stone Aggregate Base Thickness, in.	12.0	12.0
Granular/Aggregate Subbase Thickness, in.	16.0-18.0 Crushed Stone	18.0-19.0 Pit Run Gravel
Improved Subgrade Thickness, in.	6.0-12.0	6.0-12.0

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

Structural Layer Thickness - Full-Depth Asphalt Concrete

A full-depth asphalt concrete pavement is not recommended for this site condition cell.

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, In.	6.5-7.5	6.5-7.5
Asphalt Treated Base Thickness, In.	12.0 (Plant mixed)	13.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	15.0-16.0	16.0-17.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator) is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	7.0-8.0	7.0-8.0
Asphalt Treated Base Thickness, In.	9.0 (Plant mixed)	10.0 (Roadway Mixed)
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	17.0	17.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	6.5-7.5	6.5-7.5
Asphalt Treated Base Thickness, In.	12.0 (Plant mixed)	13.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase, In.	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	8.0-9.0	9.0-11.0
Prepared Subgrade (See Section 5)		

Note: A filter layer (or separator is recommended between the subbase and very soft subgrades (See Section 5).

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	7.0-8.0	7.0-8.0
Asphalt Treated Base Thickness, In.	9.0 (Plant mixed)	10.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase	7.0	7.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, In.	9.0	9.0
Improved Subgrade Thickness, In.	6.0 - 12.0	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, In.	7.0-8.5	7.0-8.5
Cement Treated Base Thickness, In.	16.0	16.0
Granular/Aggregate Subbase Thickness, In.	7.0 Crushed Stone	8.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

Dense Graded Asphalt Concrete Surface Thickness, In.	8.5-10.0
Cement Treated Base Thickness, In.	15.0
Improved Subgrade , In.	6.0 - 12.0

■ Controlled by AASHTO-PSI Criteria

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 35

Traffic: 60-100 million flexible ESALs
Subgrade: Fair (Resilient Modulus, 9-14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	9 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	12-13	12-13
Crushed Stone Aggregate Base Thickness, in.	12.0	12.0
Granular/Aggregate Subbase Thickness, in.	15.0-16.0 Crushed Stone	16.0-17.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5
Dense Graded Asphalt Concrete Base Thickness, in.	11.5-12.5
Prepared Subgrade (See Section 5)	

■ Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.5	5.5-6.5
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Granular Aggregate (Pit Run Gravel) Subbase Thickness, in.	14.0-15.0	14.0-15.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-6.5	5.5-6.5
Asphalt Treated Base Thickness, in.	10.0 (Plant mixed)	11.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase Thickness, in.	6.0	6.0
Granular/Aggregate (Pit Run Gravel Subbase Thickness, in.	7.0-8.0	7.0-8.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Dense Graded Asphalt Concrete Surface Thickness, in.	7.5-8.5
Cement Treated Base Thickness, in.	14.0
Prepared Subgrade (See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

Flexible Cell 36

Traffic: 60-100 million flexible ESALs
Subgrade: Strong (Resilient Modulus, > 14 ksi)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of surface HMAC	450 ksi
Terminal Serviceability	2.5	Resilient modulus of subgrade	14 ksi
Overall standard deviation	0.49	Drainage coefficient, m	1.00
Reliability	95%		

Note: See Sections 4A.2 through 4A.5 for detailed guidelines on other asphalt concrete pavement design features.

Structural Layer Thickness - Conventional Unbound Granular Base

Dense Graded Asphalt Concrete Surface Thickness, in.	11.5-12.5	11.5-12.5
Crushed Stone Aggregate Base Thickness, in.	10.0	10.0
Granular/Aggregate Subbase Thickness, in.	14.0-16.0 Crushed Stone	16.0-17.0 Pit Run Gravel
Prepared Subgrade (See Section 5)		

- Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A conventional Unbound Granular Base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Full-Depth Asphalt Concrete

Dense Graded Asphalt Concrete Surface Thickness, in.	4.5
Dense Graded Asphalt Concrete Base Thickness, in.	10.0-11.0
Prepared Subgrade (See Section 5)	

- Controlled by Vertical Compressive Subgrade Strain Between Wheel Loads
- Controlled by Asphalt Concrete Tensile Strain Between Wheel Loads

A full depth asphalt concrete pavement with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Asphalt Treated Base

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-7.0	5.5-7.0
Asphalt Treated Base Thickness, in.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Granular Aggregate (Pit Run Gravel) Subbase Thickness, in.	13.0	13.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Layer		
Dense Graded Asphalt Concrete Surface Thickness, in.	5.5-7.0	5.5-7.0
Asphalt Treated Base Thickness, in.	8.0 (Plant mixed)	9.0 (Roadway Mixed)
Crushed Stone Aggregate Subbase Thickness, in.	6.0	6.0
Granular/Aggregate (Pit Run Gravel) Subbase Thickness, in.	6.0	6.0
Prepared Subgrade (See Section 5)		

■ Controlled by AASHTO-PSI Criteria

An asphalt treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Structural Layer Thickness - Cement Treated Base

Layer	
Dense Graded Asphalt Concrete Surface Thickness, in.	6.5-7.5
Cement Treated Base Thickness, in.	12.0
Prepared Subgrade (See Section 5)	

■ Controlled by AASHTO-PSI Criteria

A cement treated base with an improved subgrade is not usually needed for this site condition cell (See Section 5).

Note: The site condition cells that are shaded represent designs that have been used, but are considered "marginal" and may not be able to sustain the expected traffic for the given subgrade conditions (performance is highly dependent on materials).

4A.3 Material Design Features for Flexible Pavements

This section of the catalog includes general comments and minimum material requirements to define the materials used for flexible pavements; however, it is not intended to provide detailed material production and construction specifications. AASHTO, ASTM, local agency, and/or federal construction specifications should be used to prepare complete materials specifications for use in preparing the final design.

Dense Graded Asphalt Concrete Surface and/or Base Mixtures
Asphalt concrete is a high-quality mixture of asphalt cement and well-graded, high-quality aggregate that has been thoroughly compacted into a uniform mass. Asphalt concrete mixes can be designed to serve as either a wearing, binder, or base course. The asphalt concrete must also exhibit adequate load distribution properties and as a surface or wearing course must also resist the polishing effects of heavy traffic and the effects of aging or weathering and other environment influences.

For determining the layer thicknesses of each pavement type included in the catalog portion of this manual, the structural design properties listed in Table 9 were used for dense-graded hot-mix asphalt concrete surface and base mixtures.

Table 9. Structural design properties for dense-graded hot-mix asphalt concrete materials.

Layer Type	AASHTO Structural Layer Coefficient	Total Resilient Modulus, Ksi
AC Wearing Surface	0.42*	450*
AC Binder and Base Layers	0.42*	450*

* Consensus values, appendix G.

<u>Aggregate Requirements</u>. The coarse aggregate may consist of crushed stone, crushed slag, crushed gravel, or lightweight aggregate. The fine aggregate may consist of natural sand, stone screenings, or slag screenings, or combinations of these. Basic or alkaline rocks (limestone, dolomite) provide better adhesion with asphaltic films than do acidic or silicious rocks (granite, quartzite). Where acidic rocks are used, the addition of an anti-stripping agent

or hydrated lime may be required. The aggregate used in the asphalt concrete mixture should also be durable and resistant to degradation under freeze/thaw cycles.

The coarse and fine aggregates used in the surface courses should be crushed to ensure high stability and performance. Asphalt concrete base courses, however, may include natural materials in the fine fractions. Since the type and quality of mineral filler affects the mixture stability, the mineral filler used in surface courses should be limestone dust, portland cement, or other inert materials. At least two thirds of the material passing the No. 200 sieve in a dense-graded asphalt concrete mixture should be nonplastic material meeting the requirements of AASHTO M17 (ASTM D242).

The aggregates used in a dense-graded asphalt concrete mixture should meet the general requirements of ASTM D692 and AASHTO M29 (ASTM D1073) for coarse and fine aggregates, respectively. Mineral filler, when required, should conform to AASHTO M17 (ASTM D242). Both coarse and fine aggregates, as well as mineral filler, if used, must meet the standard materials quality specifications, such as soundness, abrasion, and cleanliness. In addition, friction resistance requirements should be carefully considered to select aggregates to be used in asphalt concrete wearing surfaces that will maintain adequate or a minimum friction number over the design period.

The minimum acceptable aggregate properties were also defined by the Strategic Highway Research Program (SHRP) Asphalt Research Program for higher volume roadways. These aggregate requirements are documented in the following report and are recommended for use in establishing minimum material requirements.

"Level One Mix Design: Materials Selection, Compaction, and Conditioning," Report No. SHRP-A-408, Strategic Highway Research Program, National Research Council, Washington, DC, 1994.

Table 10 summarizes the desirable aggregate properties for dense-graded asphalt concrete mixtures.

Table 10. Summary of desirable aggregate properties for dense graded asphalt concrete mixtures.*

Flexible ESALs, Millions	Coarse Aggregate Angularity, * Depth from Surface		Fine Aggregate Angularity, Depth from Surface		Sand Equiva-lent Value Minimum %	Thin Elongated Particles Max. %	Dust Propor-tion	Los Angeles Abrasion Max.	
	< 4"	> 4"	< 4"	> 4"				Surface Mix	Base Mix
<1	65/-	-/-	40	-	40	-	0.6-1.2	45	50
1-4	76/-	50/-	40	40	40	10	0.6-1.2	40	45
4-12	85/80	60/-	45	40	45	10	0.6-1.2	40	45
12-36	95/90	80/75	45	40	45	10	0.6-1.2	40	40
36-100	100/100	95/100	45	45	50	10	0.6-1.2	40	40

*85/80 means 85% one fractured face, 80% two fractured faces

- **Maximum Coarse Aggregate Size**. In general, the maximum aggregate size for wearing courses should not exceed ¾ inches. For binder, intermediate and/or base courses, the maximum aggregate size should not exceed ⅔ of the compacted lift thickness.

- **Coarse Aggregate Angularity**. Coarse aggregate angularity is defined as the percent by weight of aggregate particles larger than No. 4 sieve with one or more fractured faces. A fractured face is defined as a fractured surface larger than 25% of the maximum aspect ratio of the aggregate particle. Coarse aggregate angularity is to be measured on the coarse particles of the blended aggregates. Desirable values for coarse aggregate angularity are traffic dependent and are shown in Table 10. It is recommended that all wearing or surface mixtures on roadways with heavy wheel loads and/or at intersections consisting of a minimum of 85% crushed aggregate, based on the total coarse and fine aggregate.

- **Fine Aggregate Angularity**. Fine aggregate angularity is defined as the percent air voids of loosely compacted aggregate as measured in the National Aggregate Association Test Method A. This test is done on the portion of blended aggregates passing the No. 8 sieve. Desirable values for fine aggregate angularity are traffic dependent and are shown in Table 10.

- **Aggregate Toughness**. Aggregate toughness is defined as percentage loss from the Los Angeles abrasion test. The test is used during mix design to determine aggregate acceptability and can be used as a parameter for acceptance control of an aggregate source. Specifying agencies should confirm the requirement for an aggregate toughness criteria in their local situation and apply that criteria or determine acceptable levels for the local situation. Desirable values of aggregate toughness (LA Abrasion) are shown in Table 10.

- **Aggregate Soundness**. Aggregate soundness is defined as percentage degradation from the sodium or magnesium soundness test. The test can be used in the laboratory during mix design to determine aggregate acceptability and/or can be used for source acceptance control. Specifying agencies should determine the requirement for an aggregate soundness criteria based on their local materials and apply that criteria as they are currently using or determine acceptable levels for the local situation.

- **Aggregate Deleterious Materials**. Deleterious material is defined as the percentage by weight of undesirable contaminants. Aggregate contaminants vary widely according to geographic location. Typical contaminants include soft shale, coal, wood and mica. Specifying agencies should determine the requirements for a deleterious criteria for their local materials and sources and apply that criteria as they may be currently using or determine acceptable levels for their local situation. The test is used during mix design to determine the aggregate source acceptability or as a parameter for acceptance control of an aggregate source.

- **Clay Content**. Clay content is measured using the sand equivalent test which is done on the portion of blended aggregate passing the No. 8 sieve. The test is used to determine aggregate acceptability during mix design, but can also be used as a field control tool to monitor aggregate production. Minimum desirable values are shown in Table 10.

- **Thin Elongated Particles**. Thin, elongated particles are defined as the percentage by weight of coarse aggregate particles which have a ratio of maximum to minimum dimensions greater than five. Thin elongated particles are measured using ASTM D4791, which is done on the portion of blended aggregates passing the No. 4 sieve. The test may be used during mix design to determine aggregate acceptability but can also be used as a method of source qualification. Maximum desirable values are shown in Table 10.

- **Dust Proportion**. Dust proportion is defined as the percentage by weight ratio of material passing the No. 200 sieve to the percentage of "effective" asphalt binder. Dust proportion is calculated in the laboratory during mix design to determine acceptability. The dust to asphalt ratio should be between 0.6 and 1.2 for all dense-graded, hot-mixed asphalt concrete mixtures.

Asphalt Binder Requirements. The asphalt cement should meet the standard specification requirements as noted in ASTM D3515 for viscosity, penetration and ductility. The selected grade of asphalt cement should satisfy the environmental and traffic loads applied to the pavement. Section 4A.4 includes different methods for selecting the proper type or grade of asphalt cement.

Asphalt Concrete Mixture Requirements. The asphalt concrete mix used as either a surface or base material should be designed according to accepted mix design procedures. The Asphalt Institute's MS-2 manual or AASHTO R-12 are suggested for defining the mix design criteria and procedures for hot-mix dense-graded asphalt concrete mixtures. The mix must meet the required gradation, stability, flow, air voids and other criteria. ASTM D3515 (Standard Specifications for Hot-Mixed, Hot-Laid Bituminous Paving mixtures) can be used for specifying those materials. Another document that defines the material and mix design minimum parameters is the FHWA Technical Advisory T5040.27, dated March 10, 1988, and entitled "Asphalt Concrete Mixture Requirements."

The SHRP Asphalt Research Program also defined minimum asphalt concrete mixture requirements for higher volume roadways. These suggested mixture requirements are documented in the following reports.

Cominsky, Ronald J. Et al, "The Superpave Mix Design Manual for New Construction and Overlays," Publication No. SHRP-A-407, Strategic Highway Research Program, National Research Council, Washington, DC, 1994.

McGennis, R.B., R.M. Anderson, T.W. Kennedy, and M. Solaimanian, "Background of SUPERPAVE: Asphalt Mixture Design and Analysis," Publication No. FHWA-SA-95-003, Federal Highway Administration, Washington, DC, November 1994.

Table 11 summarizes the desirable mixture properties for dense graded asphalt concrete mixtures.

Table 11. Summary of desirable asphalt concrete mixture properties.

Flexible ESALs, Millions	Design Air Void Content, %	Voids Filled with Asphalt, %	Minimum Moisture Damage Ratio, TSR & MRR*		Voids in the Mineral Aggregate	Minimum Stability Marshall/ Hveem	
			Depth From Surface				
			<4"	>4"		Surface	Base
<1	4	65-80	0.75	0.75	See Table 13	1800/45	1200/37
1-4	4	65-80	0.80	0.80		1800/45	1500/40
4-12	4	65-75	0.80	0.80		1800/45	1800/45
12-36	4	65-75	0.85	0.80		1800/45	1800/45
36-100	4	65-75	0.90	0.80		1800/45	1800/45

*TSR = Tensile Strength Ratio; MRR = Resilient Modulus Ratio

- **Aggregate Blend/Gradation**. One of the most important elements of an asphalt concrete mix is the aggregate structure, as defined by the aggregate blend or gradation. Unfortunately, the upper and lower limits of the aggregate blend vary considerably from agency to agency. Table 12 shows the typical limits or values for the different sieve sizes and the corresponding limits of the asphalt content. As these values vary significantly from one agency to another, the gradation controls defined by the SHRP Asphalt Research Program are considered appropriate and more universal than any of the other procedures. However, the SHRP dense-graded asphalt concrete mix design method (entitled Superpave, as documented in the following report) should not be used interchangeably with the Marshall, Hveem or other agency mix design criteria.

  "The Superpave Mix Design Manual for New Construction and Overlays", Report No. SHRP-A-407, Strategic Highway Research Program, National Research Council, Washington, DC, 1994.

Table 12. Limits for gradation control and suggested bitumen content for each gradation, bituminous road mixes (surfaces).

Maximum Particle Size (in)	Recommended Asphalt Content, %	Percent Passing Each Sieve (by Weight)								
		Sieve Designation								
		1"	¾"	½"	⅜"	No. 4	No. 10	No. 40	No. 80	No. 200
1	5.0-8.0	100	85-100	---	61-90	43-79	30-65	16-38	10-24	2-10
¾	5.0-8.5	---	100	82-100	68-93	48-82	32-68	17-44	11-28	2-10
½	5.0-9.0	---	---	100	82-100	57-88	38-74	18-46	11-30	2-10

The term used to describe the cumulative frequency distribution of aggregate particle sizes is the *"design aggregate structure"*. A design aggregate structure that lies between the control points and avoids the restricted zone meets the requirements of SHRP with respect to gradation. To specify gradation, the 0.45 power gradation chart is used to define a permissible gradation. This chart uses a unique graphing technique to judge the cumulative particle size distribution of a blend of aggregate. The ordinate of the chart is percent passing. The abscissa is an arithmetic scale of sieve size in millimeters, raised to the 0.45 power (See Figure 14).

An important feature of this chart is the maximum density gradation. This gradation plots as a straight line from the maximum aggregate size through the origin. SHRP used a standard set of ASTM sieves and the following definitions with respect to aggregate size:

Maximum Size:	One sieve size larger than the nominal maximum size
Nominal maximum Size:	One sieve size larger than the first sieve to retain more than 10%.

The maximum density gradation represents a gradation in which the aggregate particles fit together in their densest possible arrangement. Theoretically, this is a gradation to avoid, because there is very little aggregate space to develop sufficiently thick asphalt films for a durable mixture. Figure 14 shows a 0.45 power gradation chart with a maximum density gradation for a 19 mm (⅜ inch) maximum aggregate size and 12.5 mm (½ inch) nominal maximum size.

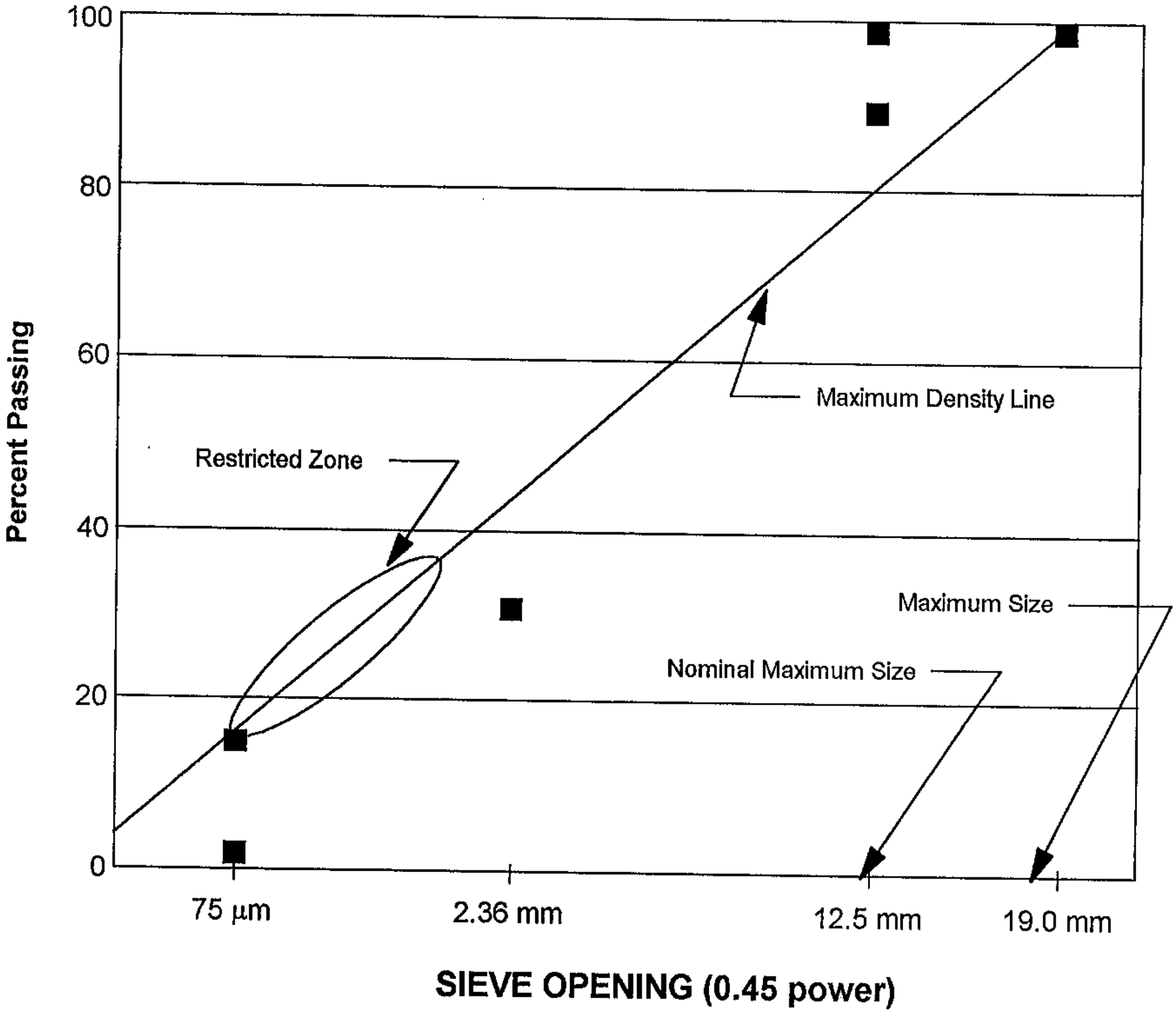


Figure 14. Typical gradation control for 12.5 mm (1/2 in) mix.

To specify aggregate gradation, two additional features are added to the 0.45 power chart: control points and a restricted zone. Control points function as master ranges through which gradations must pass. They are placed on the nominal maximum size, an intermediate size, No. 8 sieve (2.36 mm) and the dust size, No. 200 sieve (0.075 mm).

The restricted zone resides along the maximum density gradation between the intermediate size (either No. 4 or No. 8 sieve, 4.75 or 2.36 mm) and the No. 50 sieve (0.3 mm size). It forms a band through which gradations are not permitted to pass. Gradations that pass through the restricted zone have often been called "humped gradations", because of the characteristic hump in the grading curve that passes through the restricted zone. In most cases, a humped gradation indicates a mixture that possesses too much fine sand in relation to total sand. This gradation generally results in tender mix behavior. A tender mix is difficult to compact during construction and offers reduced resistance to permanent deformation during its performance life. Gradations that violate the restricted zone generally have weak aggregate skeletons that depend too much on asphalt binder stiffness to achieve mixture shear strength. These mixtures are also very sensitive to asphalt content and can easily become plastic, resulting in accelerated rutting and shoving.

SHRP recommends, but does not require, mixtures to be graded below the restricted zone. It also recommends that as traffic level increases, gradations move closer to the coarse control points. It should be noted, however, that the SHRP gradation control requirements were not intended to be applied to special purpose mix types such as stone matrix asphalt or open graded mixtures, and should not be used for these types of mixtures.

- **Air Voids**. Air voids are defined as the total volume of air between the coated aggregate particles throughout a compacted mix, expressed as a percent of the bulk volume of the compacted mix. The test is to be used in the laboratory during mix design to select the proper asphalt content. It is also typically used in the field to monitor the production of the mix.

  The design air void content suggested for use of all dense-graded asphalt concrete mixtures is 4%. It is desirable that the compaction air void requirements for construction range from 6% to 8%. To require a lower void content at construction would be impractical realizing the difficulty of achieving lower air voids while still satisfying all other requirements for the mix. For example, to attain a lower void content, it would be necessary to increase the asphalt content, but the consequences of that decision could be

a less stable mix (lower stabilities and strengths) and perhaps bleeding at the pavement surface.

- **Voids in Mineral Aggregate (VMA)**. Voids in mineral aggregate (VMA) are defined as the percent by volume of effective asphalt binder plus air voids in a compacted aggregate asphalt mix. Voids in mineral aggregate are calculated using bulk specific gravity of the aggregate. The test is used in the laboratory during mix design to determine acceptability. However, it can also be used as a field control tool to monitor production of mix.

  For the mixture to have an adequate asphalt cement content without bleeding, there must be sufficient air voids in the compacted mixture. These volumetric requirements are determined through VMA. Changes in the VMA are made by adjusting the aggregate gradation, and the VMA should be checked for each mix used. Acceptable values are listed in Table 13 by nominal aggregate size.

Table 13. Voids in mineral aggregate criteria.

Nominal Maximum Size of Aggregate, Inches	Voids in the Mineral Aggregate, %
0.125	15.0
0.25	14.0
0.375	13.0
0.50	12.0
0.75	11.0
2.0	10.5

- **Voids Filled with Asphalt (VFA)**. Voids filled with asphalt (VFA) is defined as percent of the VMA filled with asphalt. Voids filled with asphalt is calculated from values of air voids and VMA. Desirable VFA values are shown in Table 11.

- **Moisture Damage Ratios**. Moisture interacts with some aggregates to produce adverse effects on material properties, which results in significant damage to the asphalt concrete. These moisture interactions affect the adhesion between the asphalt cement and the aggregate. Alkaline rocks provide better adhesion to asphalt in the presence of water than

do acid or silicious rocks. When acid rocks are used in asphalt concrete, addition of an anti-stripping agent, such as hydrated lime may be required. In determining the moisture-induced damage of the asphalt concrete mixture, AASHTO T 283 is recommended. A strength and modulus reduction should not be greater than 25%. Table 11 lists the minimum tensile strength and resilient modulus moisture damage ratios for asphalt concrete mixtures.

Unbound Granular Materials

The granular base and subbase material consists of aggregates such as crushed stone, crushed slag, crushed or uncrushed gravel, and sand, or of combinations of these materials. Specifications for base course materials are generally much more stringent than for subbase materials in requirements for strength, plasticity and gradation. The specification presented in AASHTO M-147 is typical of the gradation and quality of untreated base and subbase aggregates. Additional requirements for quality of base materials, based on test procedures used by the specifying agency, may also be included in materials or construction specifications.

For determining the layer thicknesses presented in the catalog, the following structural design criteria were used for the unbound granular base and subbase materials:*

Layer	AASHTO Structural Layer Coefficient	Total Resilient Modulus, ksi
Crushed stone base materials	0.14	See Figure 15
Pit run gravel (sandy gravel) subbase	0.10	See Figure 15

*See appendix G.

The modulus of these materials is dependent not only on moisture content and density, but also on the state of stress to which the material is subjected. For most granular materials, the resilient modulus increases as the bulk stress increases. Repeated load triaxial compression tests performed in accordance with AASHTO T294-92 entitled "Resilient Modulus of Unbound Granular Base/Subbase and Subgrade Soils—SHRP Protocol P46" can be used to measure the resilient modulus of the unbound based and subbase materials.

More importantly, the insitu resilient modulus of any unbound material is also dependent on the modulus of the underlying material. For the design checks and criteria discussed in Appendix

E, Figure 15 presents the limiting modulus of the unbound granular base and subbase layers that were used to check and adjust the layer thicknesses presented in the catalog.

All unbound granular base materials included in the catalog include crushed stones with a limit of 15% passing the No. 200 sieve. Significantly higher amounts of minus 200 material can have a detrimental effect on the shear strength of the material.

The granular subbase materials were considered sandy gravels or pit run gravels to crushed stone. The unbound granular base and subbase material are materials that meet the grading and other requirements described in the AASHTO M147 or ASTM D2940. It is recommended that, for base materials, a 1.5 inch top size aggregate be used.

All unbound granular base and subbase materials should be compacted to 100% of the maximum density, as defined by AASHTO T180. Table 14 summarizes some of the desirable properties for unbound aggregate bases and subbase layers.

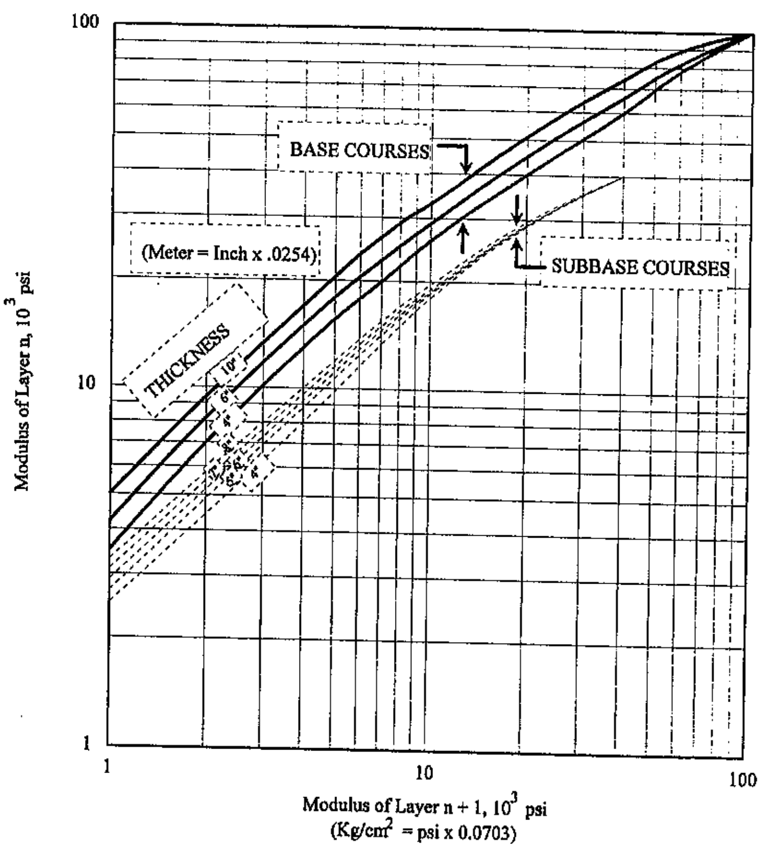


Figure 15. Limiting modulus of unbound granular base and subbase layers.

Table 14. Summary of desirable aggregate properties for unbound granular base and subbase materials.

Property	Base Material	Subbase Material
Minimum Sand Equivalent Value	35	---*
Aggregate toughness, Maximum LA Abrasion	45	50
Maximum liquid limit	25	30*
Maximum plasticity index	4	6*
Minimum strength value		
CBR	80	40
R-Value	80	60
Minimum (laboratory) resilient modulus, ksi	80 (15 psi/10 psi)**	40 (10 psi/5 psi)**
Suggested Grading, % Passing Sieve Size:		AASHTO M147
1½ "	100	Gradings A, B,
¾ "	70-90	C, D, E, or F
½ "	55-80	
⅜ "	20-50	
No. 4	35-60	
No. 10	20-40	
No. 40	10-25	
No. 200	5-15	

* If the subbase layer or material is within the probable depth of frost penetration (see Section 5), then the material requirements for an unbound base material should apply to the subbase layer.

** The numbers included in the (__/__) represent the repeated vertical applied stress and confining pressures used in the laboratory, respectively.

For environments where frost is expected to penetrate the pavement structure, a maximum of 8% passing the No. 200 sieve is recommended to ensure that the material will not be susceptible to frost action. (The effects of frost action are discussed in Section 5.)

Treated Base Materials

Two types of treated base materials are considered in the flexible pavement design catalog: asphalt and cement treated base materials. In summary, these mixtures are granular base materials (see Table 14) that have been treated with a bituminous or cementitious binder to improve strength and stiffness characteristics. Table 15 summarizes some of the desirable properties for the asphalt and cement treated bases used in the site condition cells.

Table 15. Summary of desirable asphalt and cement treated base materials.

Property	Asphalt Treated		Cement Treated
	Roadway Mixed	Plant Mixed	
Binder Type	Emulsified Asphalt (Asphalt Institute MS-19 Manual, or ASTM D4215)	Asphalt Cement (Asphalt Institute MS-19 Manual or ASTM D4215 or D3515)	Portland Cement Types I, II or III
Percent Binder	3-6% by wt.	3-6% by wt.	>5.0% by wt. or 3-8% by volume
Design Air Voids	3-5%	3-5%	4-7%
Minimum VMA	13	13	NA
Minimum Stability, Marshall/Hveem	1000/35	1200/37	NA
Minimum 28-day Compressive Strength	NA	NA	750 psi
Compaction	100% AASHTO T180	100% AASHTO T180 or 95% AASHTO T209	100% AASHTO T134 or 95% AASHTO T180

- **Bituminous or Asphalt Treated Base Mixtures** consist of a uniform mixture of mineral aggregate and bituminous material. The Asphalt Institute's Manual No. MS19 (a basic asphalt emulsion manual) can be used to define the design criteria and procedures for asphalt treated base mixtures. In addition, asphalt cement can also be used as the bituminous binder in these type of materials. Normally, an HFMS-2h asphalt emulsion is used for hot plant mixtures, whereas an SS or CSS grade of emulsified asphalt is used for cold laid-plant mix asphalt emulsion.

  For treated stabilized base mixes, the percent crushed bases should exceed 65%, and the sand equivalent value should be greater than 35. The following material strength/modulus values were used in determining the layer thicknesses presented in the catalog for an asphalt-treated base (which can include cold-mix base materials):

Plant Mixed	Roadway Mixed
0.25*	0.23*
100 ksi	80 ksi

*See appendix G.

- **Cement-Treated Base Mixtures** are suggested for use in some cases as a treated base with an asphalt concrete surface. These types of structures are sometimes defined as composite pavements.

  This material must be designed to provide adequate load distribution properties and to resist any adverse environmental effects. Current mixture designs for cement-treated bases require a minimum percent cement from 3.0 to as much as 10% by the total weight of aggregate. The material type and specifications for cement-treated bases materials are generally the same as for asphalt-treated base materials. The coarse aggregate may be crushed stones, crushed or uncrushed gravel and slag. The fine aggregate may be that naturally contained in the coarse aggregate material or may be sand from a separate source. The aggregate durability, hardness, cleanliness, and so on should be that for normal unbound aggregate base specifications (discussed in a previous section, See Table 14).

  The cement used to treat the unbound base material should be a standard brand that conforms to ASTM requirements. The water should be clean and free of

substances that will adversely affect the mix. The curing material can be an asphalt emulsion, or other curing materials used for PCC surfaces. To determine layer thicknesses within this catalog, the cement-treated base should be proportioned to produce a mix with a minimum 28 day compressive strength of 750 psi. A compressive strength of 750 psi can generally be produced in the laboratory within the amount of portland cement as identified above. All mix proportions and properties should be well defined in the mix designs completed prior to beginning construction.

The following material strength/modulus design values were used in determining the layer thicknesses presented in the catalog for a cement-treated base material:

AASHTO Structural Layer Coefficient	-	0.22*
Modulus of Elasticity	-	500 ksi

*See appendix G.

Improved Subgrades or Subgrade Soil Stabilization and Prepared Subgrade

It is sometimes necessary to treat and/or stabilize the subgrade to obtain a proper platform for construction of the other pavement layers. Subgrade as used herein refers to the natural or fill soil foundation on which a pavement structure is placed. Prepared subgrade as used in the site condition cells simply refers to the grade work to establish the proper elevation, scarification of the surficial soils, and compaction to achieve proper densities and moisture contents of the subgrade. Improved and/or stabilized subgrades refers to strengthening the subgrade by some physical methods.

Guidelines on improving the subgrades (including stabilization) especially where swelling soils are present, are provided in Section 5 - Special Subsurface Conditions. The method for stabilization of subgrade soils is affected by changes in moisture content, density and variations in the stress state. Stabilizing agents used generally include cement and lime. Note that in lieu of subgrade stabilization with cement or lime, a thick layer of select granular fill or embankment over the roadbed soil may be adequate.

The elevation of the subgrade is normally determined for many roadway construction projects by balancing the cut and fill requirements. In other words, the depths and/or volume of soil cut to a specified elevation is used as fill material in areas where the elevation needs to be raised.

All subgrade soils (whether in a cut or full section) should be compacted to at least 95% of the maximum density, as defined by AASHTO T180, for granular or noncohesive soils and to at least 95% of the maximum density, as defined by AASHTO T99, for those cohesive soils.

4A.4 Selection of Binder for Bituminous Surface and Base Mixtures

As for aggregate gradation, specification and use of the grade and type of asphalt vary extensively from agency to agency for surface and base mixtures. The selected asphalt cement grade should be of the proper viscosity grade to satisfy the environmental and traffic loads applied. Figure 16 shows a gross summary of the typical types of asphalt cement (both penetration and viscosity graded asphalts) used for dense-graded asphalt concrete surface mixtures in the U.S. In general, the asphalt cement shall meet all of the standard specification requirements such as viscosity, penetration, and ductility. AASHTO M20 can be used for penetration graded asphalt cements, and AASHTO M226 can be used for viscosity graded asphalt cements.

One factor that can severely limit the performance of an asphalt concrete pavement is the effect of the environment on asphalt cement properties. The Thin Film Oven Test and Rolling Thin Film Oven Tests give an indication of how the asphalt will harden with time. Asphalt hardening produces raveling and a brittle mixture. When the penetration of the in-service asphalt is 30 or less, or when the viscosity at 140ºF exceeds 35 kilopoise, the pavement becomes extremely susceptible to cracking. In such situations the rate of asphalt hardening can be reduced by reducing the voids content to about 2%. Since bleeding becomes a problem at these low void contents, some compromise is necessary; therefore, most mix design criteria limit the in-service voids to 3% to 5%. Asphalt cements exhibiting severe hardening as measured by the Thin Film Oven Test should not be used in the surface mixtures.

As for the aggregate gradation requirements, SHRP developed a new asphalt binder specification with a new set of tests. The performance-based specification for asphalt binders within the SHRP system is designed to quantify and maximize the performance of the binder in reducing the occurrence of permanent deformation, fatigue cracking, and low-temperature cracking. The new system for specifying asphalt binders is unique in that it is a performance based specification. It specifies binders on the basis of the climate and attendant pavement temperatures in which the binder is expected to serve. In other words, physical property

requirements remain the same, but the temperature at which the binder must attain the properties changes.

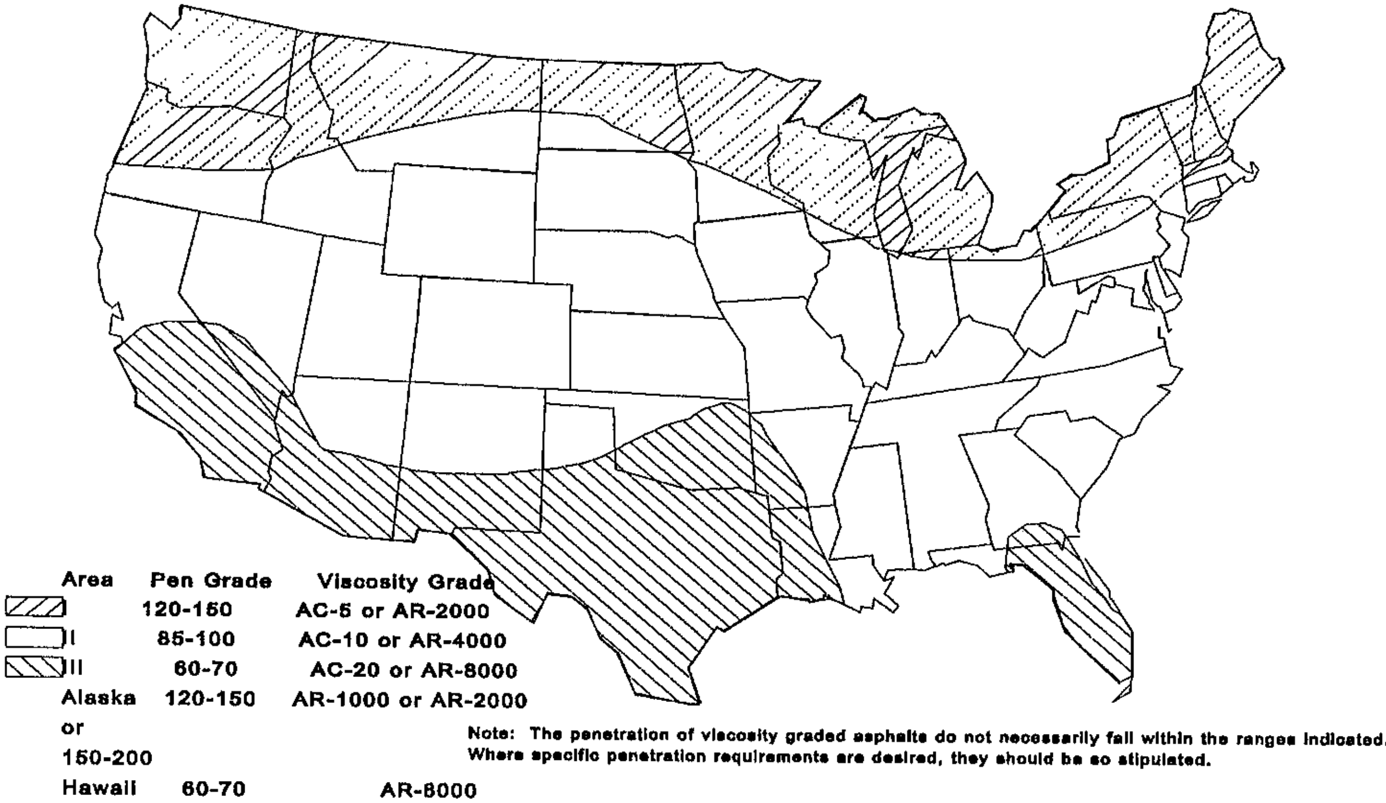


Figure 16. Selection guide for asphalt cement.

Performance graded (PG) binders are graded such as PG 64-22. The first number, 64, is called the "high temperature grade". This means that the binder would possess adequate physical properties at least up to 64ºC (147ºF). This would be the high pavement temperature corresponding to the climate in which the binder is actually expected to serve. Likewise, the second number (-22) is often called the "low temperature grade" and means that the binder would possess adequate physical properties in pavements at least down to -22ºC (-8ºF). Additional consideration is given to the time of loading (open highway, city streets, intersections, etc.) and magnitude of loads (heavy trucks).

The choice of asphalt binder grade alone will not eliminate permanent deformation, which is strongly dependent upon the aggregate properties and the volumetric properties of the as-constructed paving mix, or fatigue cracking, which is also highly dependent upon pavement structure. However, selecting the proper grade asphalt binder essentially eliminates low-temperature cracking. The SHRP mix design system facilitates selecting asphalt binders that provide different levels of protection or reliability. The following references provide more discussion on the new procedures for selecting and defining the binder required for a specific environment and roadway, and are recommended for use in specifying the minimum requirements of the asphalt binder.

"The Superpave Mix Design Manual for New Construction and Overlays", Report No. SHRP-A-407, Strategic Highway Research Program, National Research Council, Washington, DC, 1994.

"The Superpave Mix Design System: Manual of Specifications, Test Methods, and Practices", Report No. SHRP-A-379, Strategic Highway Research Program, National Research Council, Washington, DC, 1994.

4A.5 Base Drainage for Flexible Pavements

The performance of flexible pavements is highly dependent on maintaining adequate base and/or subbase strength during periods of increased moisture. Consider the use of a base course drainage system wherever the following conditions exist:

(1) Where ground water levels approach the bottom of the base.

(2) Where frost action penetrates the subgrade.
(3) In sag vertical curves where the subgrade soil has low permeability.

Refer to Section 4C for specific details regarding subsurface drainage recommendations.

4A.6 Joint Construction in Placing Hot-Mixed Asphalt Concrete Mixtures

The proper placement and compaction of transverse and longitudinal joints in asphalt concrete mixtures (especially surface mixtures) are critically important to ensure long term performance of asphalt concrete pavements. In general, as few transverse and longitudinal joints should be used as possible. Screed and auger extensions should be used whenever practical and possible to increase the paving widths, to reduce the number of longitudinal joints across the pavement's width. In addition, longitudinal joints should not be located in the wheelpaths or in the center of wheelpaths.

Proper mix placement procedures and paver operation should be adhered to in placing each lift to ensure that the mix has adequate density at the joints. Lower densities at longitudinal and transverse joints (as well as in other portions of the lift) can cause premature surface deterioration in the form of raveling and cracking. The following document is a good source and reference for the proper production, placement and compaction of asphalt concrete mixtures.

> Hot-Mix Asphalt Paving Handbook, Federal Aviation Administration Advisory Circular AC 150/5370-14 and U.S. Army Corps of Engineers Publication Un-13 (CEMP-ET), Library of Congress Catalog Card Number LC 91-74090, 31 July 1991.

SECTION 4 PAVEMENT DESIGN FEATURE RECOMMENDATIONS

Section 4B Rigid Pavements

The recommended design features for rigid pavements are presented in this section. The catalog recommendations are based on many sources, however, the most significant source was the recommendations achieved by consensus of a group of pavement design experts from Federal, state, industry, consulting, and academia. [1] In addition, use was made of current SHA design practices [2], FHWA Pavements Notebook, [20], the 1993 *AASHTO Guide for Design of Pavement Structures* [3], and mechanistic-empirical performance models to limit the occurrence of JPCP fatigue cracking, JRCP crack deterioration, CRCP punchouts, doweled and non-doweled joint faulting, and roughness (see appendix F).

The sections included are as follows:

- **Section 4B.1** Rigid Pavement Cross Sections and Shoulder Design Features
- **Section 4B.2** Rigid Pavement Structural Design Features for Site Condition Cells
- **Section 4B.3** Transverse Joints for JPCP and JRCP
- **Section 4B.4** Load Transfer Design (Dowel Bars)
- **Section 4B.5** Longitudinal Joints and Tie Bars
- **Section 4B.6** Expansion Joint Design
- **Section 4B.7** Joint Sealant Reservoir and Joint Sealants
- **Section 4B.8** Reinforcement Design for JRCP
- **Section 4B.9** Reinforcement Design for CRCP
- **Section 4B.10** Terminal Anchorage for CRCP
- **Section 4B.11** PCC Slab Material Properties
- **Section 4B.12** Base and Subbase Material Properties

4B.1 Rigid Pavement Cross Sections and Shoulder Design Features

A pavement cross section must be carefully developed to insure that each of the design features will function successfully as well as the entire cross-section as a whole. There are many possible alternative cross-sections, based on variations in the following features:

- Cross slope of the traffic lanes: uniform or crown.
- Traffic direction: a simple two lane (two directional) highway or multiple lanes in one direction.
- Shoulders or curbs: tied concrete, HMAC/granular surfaced, or tied or integral concrete curb. (See section 4B.2 for shoulder support definition).
- Concrete slab thickness: uniform or tapered thickness (trapezoidal).
- Width of heaviest truck lane slab: conventional or extra wide.
- Subdrainage system: none, longitudinal edge drains, total subdrainage system with permeable base layer (provided in Section 4C only).

Cross Sections

Several alternative cross sections are provided. Selection of the best section for a given project depends on the type of highway (rural or urban), geometric policy (uniform or crowned cross slope), traffic direction (one way or two way traffic), construction costs, and various construction considerations. Alternative cross sections and recommendations for their usage are provided in this section. Uniformity across the section was a major objective of each cross section to minimize problems associated with subdrainage, frost heave, and swelling soils.

- **Rural highway with two or more traffic lanes in one direction (conventional width slabs) (Figure 17).**
  Section 1A: Uniform surface slope and slab thickness, tied concrete shoulders.
  Section 1B: Crown surface slope, uniform slab thickness, tied concrete shoulders.
  Recommendations: These uniform layer cross sections provide good performance and low maintenance and water infiltration. Design thickness is reduced as the shoulder load transfer capability increases. Note: Sections with conventional lane width and HMAC shoulders are not recommended due to problems at the PCC lane and HMAC shoulder joint, where settlements and extensive deterioration commonly occur that requires maintenance. Also, a large majority of runoff water enters the pavement section through the PCC/HMAC lane/shoulder joint.

- **Rural highway with two traffic lanes in one direction (widened slab) (Figures 18 and 19).**
  Section 2A: Uniform surface slope and slab thickness, widened slab, tied concrete shoulders.
  Section 2B: Crown surface slope, uniform slab thickness, widened slab, tied concrete shoulders.
  Section 3A: Uniform surface slope and slab thickness, HMAC shoulders.
  Section 3B: Crown surface slope, uniform slab thickness, HMAC shoulders.

  Recommendations: Widened slab pavements have provided excellent performance with lower faulting and cracking levels for jointed pavements and reduced edge punchouts for CRCP.[15] Widened lanes have no problem with loss of longitudinal joint load transfer. These pavements have been built by several states in the U.S. and in several European and other countries with great success.[26] Keeping heavy traffic loads away from the free longitudinal edge and slab corner reduces deflections and stresses and thus improved performance and lower maintenance. Widened slab pavements are applicable whenever there exists heavy traffic in the lane. Slab thickness is reduced for this cross section design due to Type II and Type I shoulders. (See section 4B.2).

- **Rural highway with two traffic lanes in one direction with trapezoidal cross-section (Figure 20).**
  Section 4: Uniform surface slope, widened slab, HMAC shoulders.
  Recommendations: Trapezoidal cross section provides for optimization of materials and the reduction in critical stresses and deflections along the longitudinal joint. They are applicable only where there exists a large lateral variation in truck traffic across multiple traffic lanes. Trapezoidal sections have been used in France and in Chile for both new construction and concrete overlays for many years with good success.[26,46]

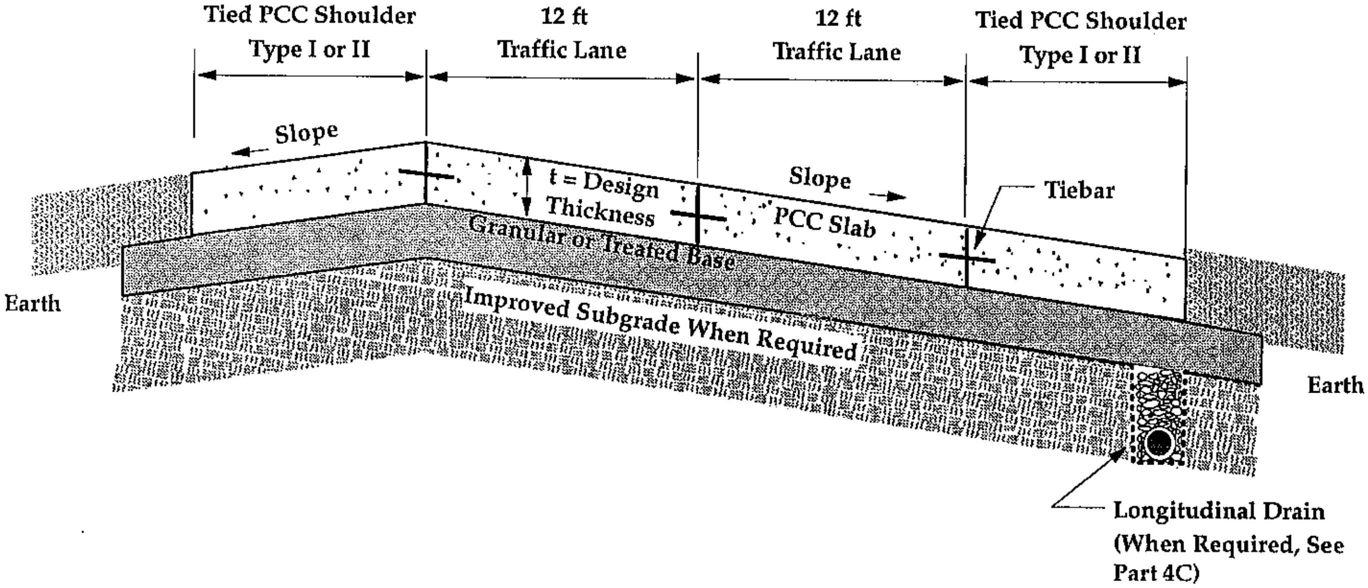
- **Rural highway with two way traffic (Figure 21).**
  Section 1B: Crown surface slope, conventional slab width, tied concrete shoulders.
  Recommendations: See note under Section 1.
  Section 5A: Crown surface slope, widened slab, tied concrete shoulders.
  Section 5B: Crown surface slope, widened slab, HMAC shoulders.
  Recommendations: See note under Section 3. Widened slabs on two lane highways provide the same benefit as they do on multilane highways by keeping heavy loads away from the free edges.

- **Urban highway with multiple lanes and two way traffic (Figure 22).**
  Section 6: Crown surface slope, conventional slab width, tied concrete curb.
  Recommendations: Urban cross section with a tied or integral concrete curb has about the same effect as a tied shoulder or widened slab section. This design feature reduces tensile stresses in the slab and deflections at corners.

Shoulders

Thickness of PCC shoulders are the same as the traffic lane as shown in the cross-sections of Figures 17, 18, 21, and 22. Thickness of HMAC shoulders as shown in the cross-sections of Figures 19, 20, and 21 should be determined as a function of traffic in the outer lane. Recommended design traffic ranges from 2 to 10 percent of main line traffic, which is the range specified by several states for shoulder design.(2) Thickness of the HMAC should be determined from the flexible pavement Section 4A of this catalog. Locations with substantial shoulder parking (i.e., interchange ramps) should be designed toward the top of this range or higher.

Section 1A. Uniform Surface
(One Directional Traffic)



Section 1B. Crown Surface
(One or Two Directional Traffic)

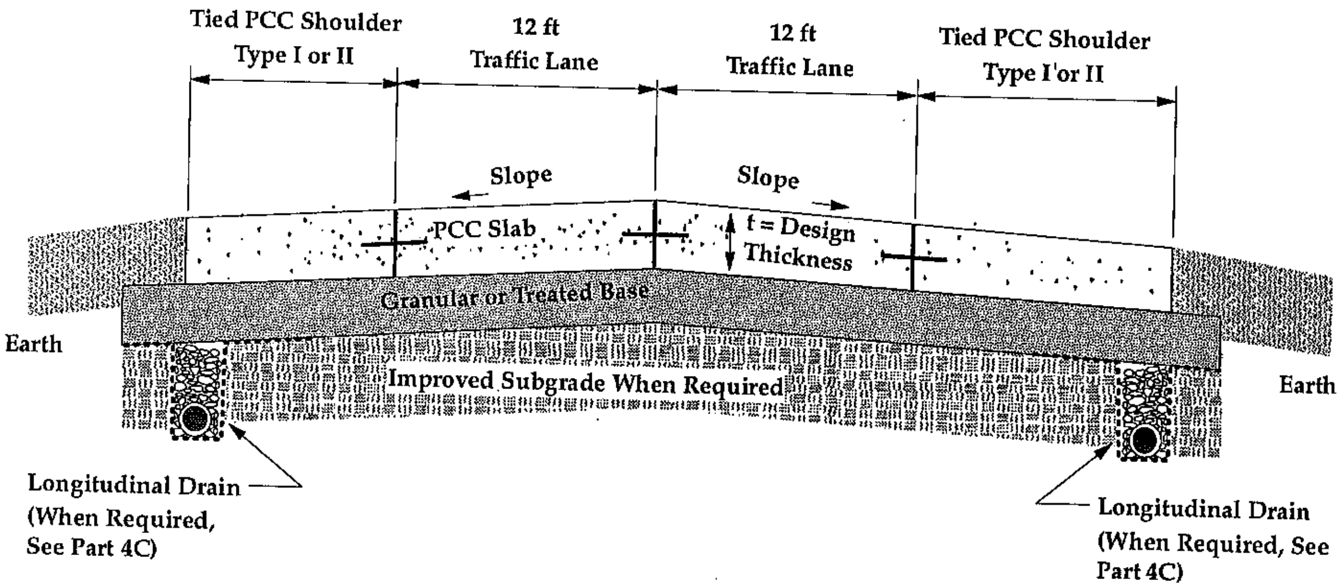
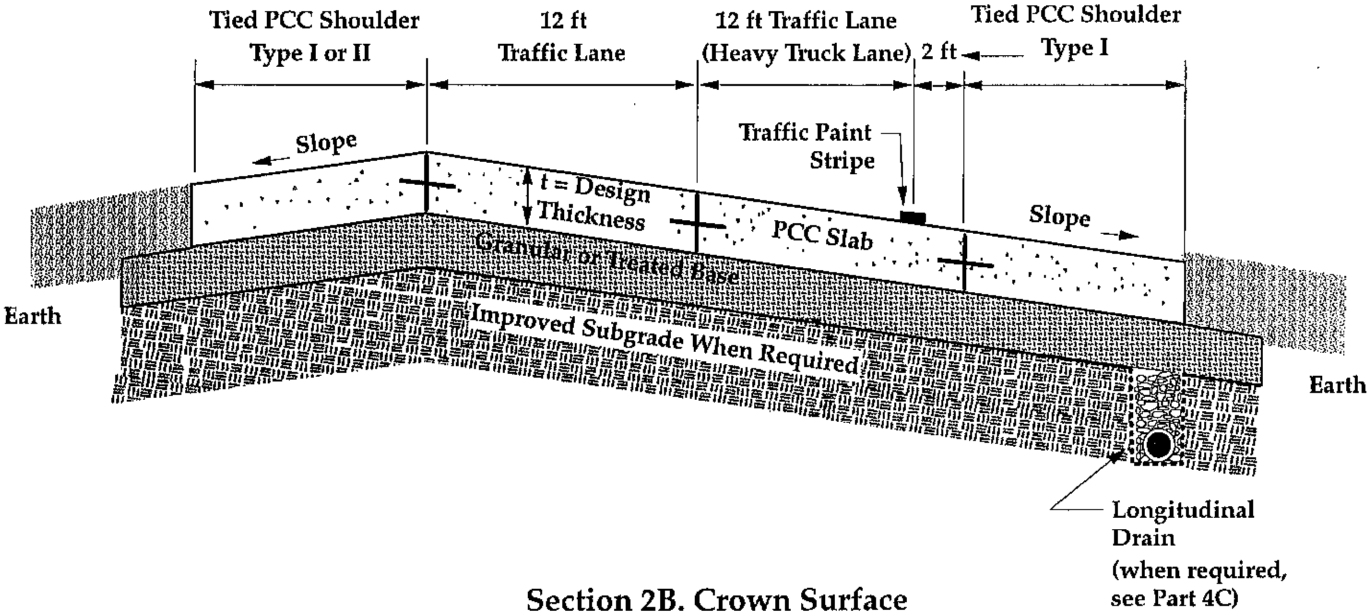


Figure 17. Cross section for rural highway with two or more lanes in one direction (crown section for both one and two direction traffic), conventional slab width, tied concrete shoulders, and uniform slab thickness pavement (Sections 1A and 1B).

Section 2A. Uniform Surface
(One Directional Traffic)



Section 2B. Crown Surface
(One Directional Traffic)

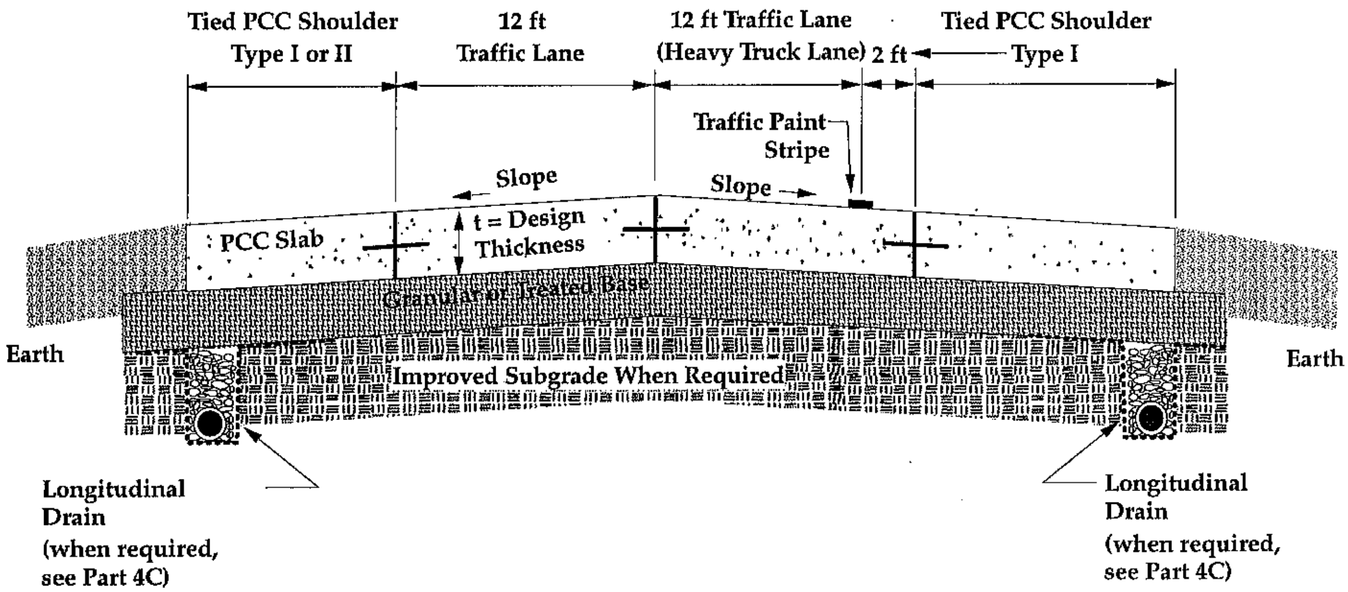
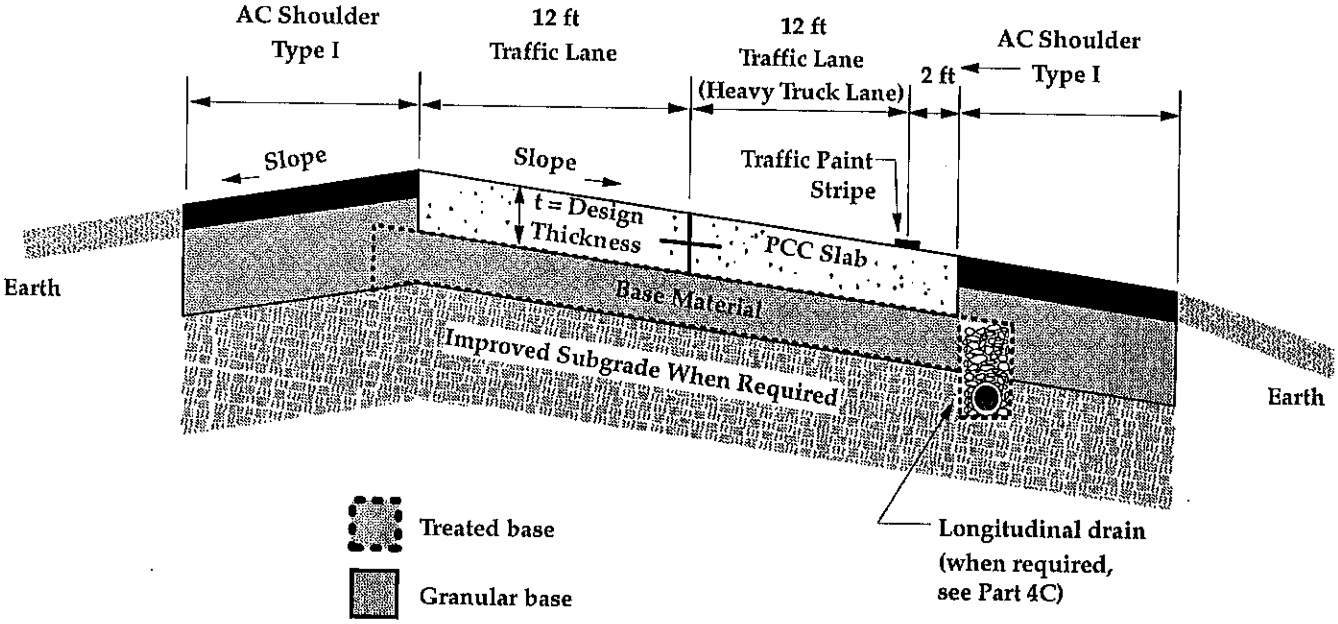


Figure 18. Cross section for rural highway, two or more lanes in one direction, widened slab, tied concrete shoulders, and uniform slab thickness pavement (Sections 2A and 2B).

Section 3A. Uniform Surface (One Directional Traffic)



Section 3B. Crown Surface (One Directional Traffic)

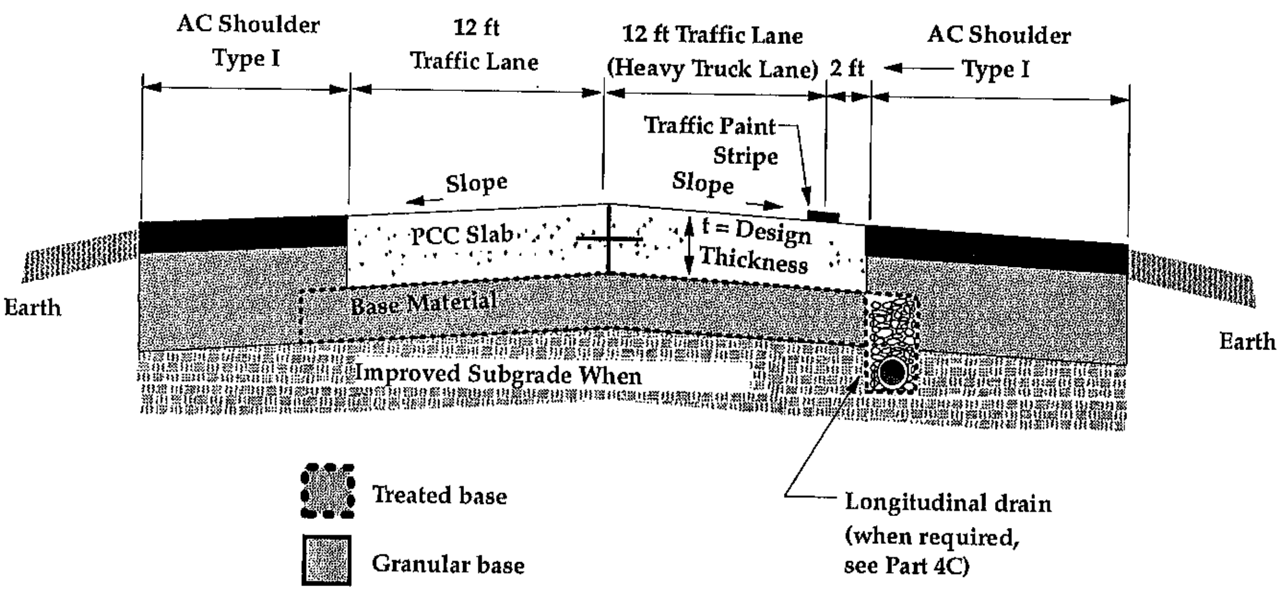


Figure 19. Cross section for a rural highway, two or more lanes in one direction, widened slab, HMAC shoulders, and uniform slab thickness pavement (Sections 3A and 3B).

Section 4. Uniform Surface
(One Directional Traffic)

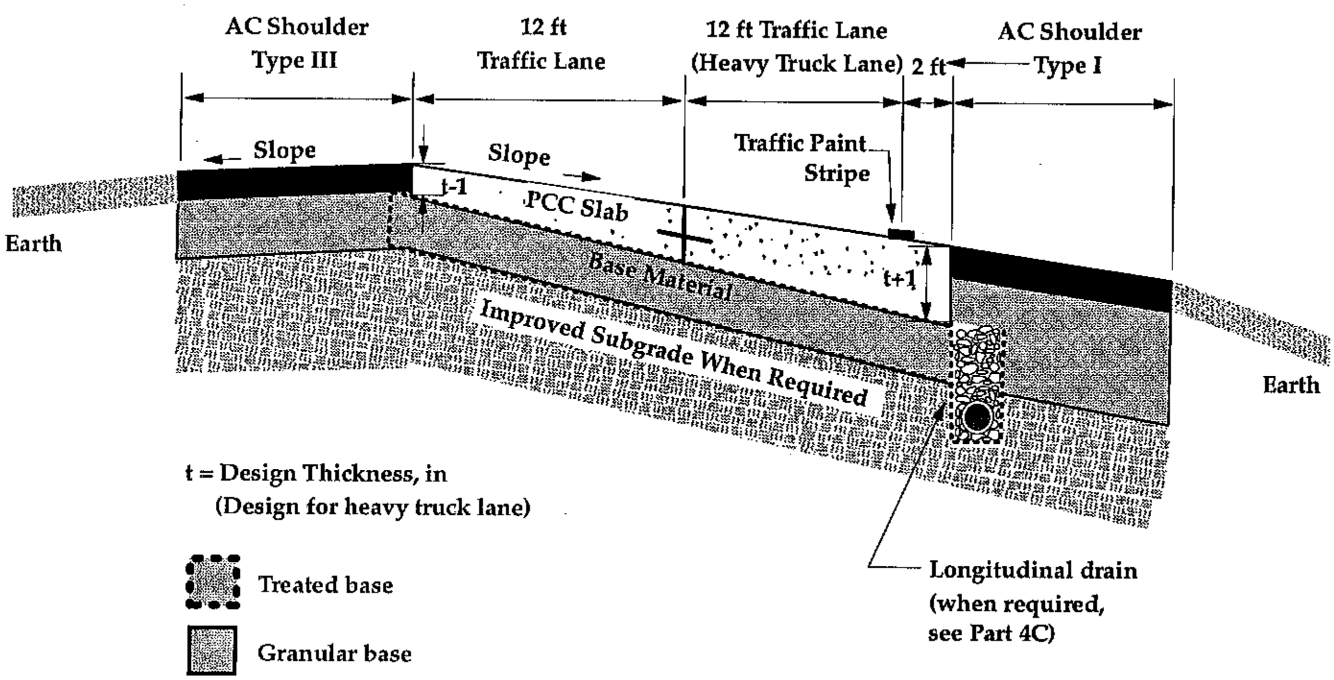
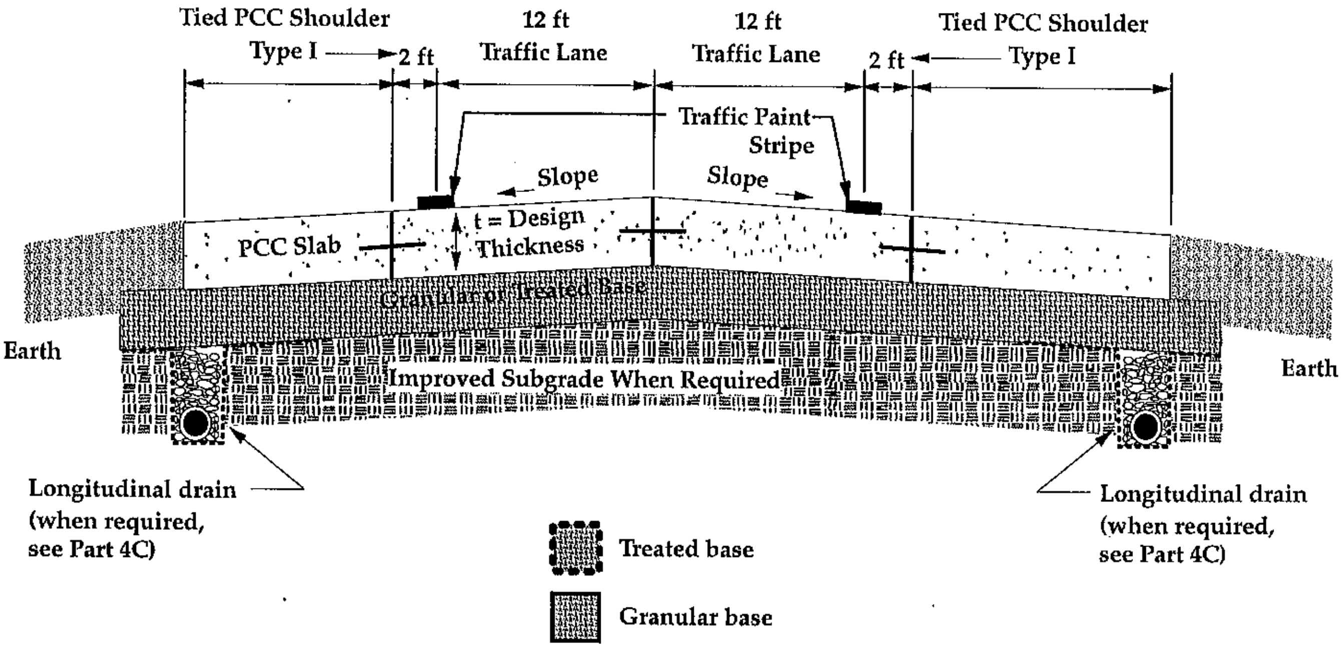


Figure 20. Cross section for a rural highway, two or more lanes in one direction, conventional slab width, HMAC shoulders, and trapezoidal slab thickness (Section 4).

Section 5A. Crowned Surface (Two Directional Traffic)



Section 5B. Crowned Surface (Two Directional Traffic)

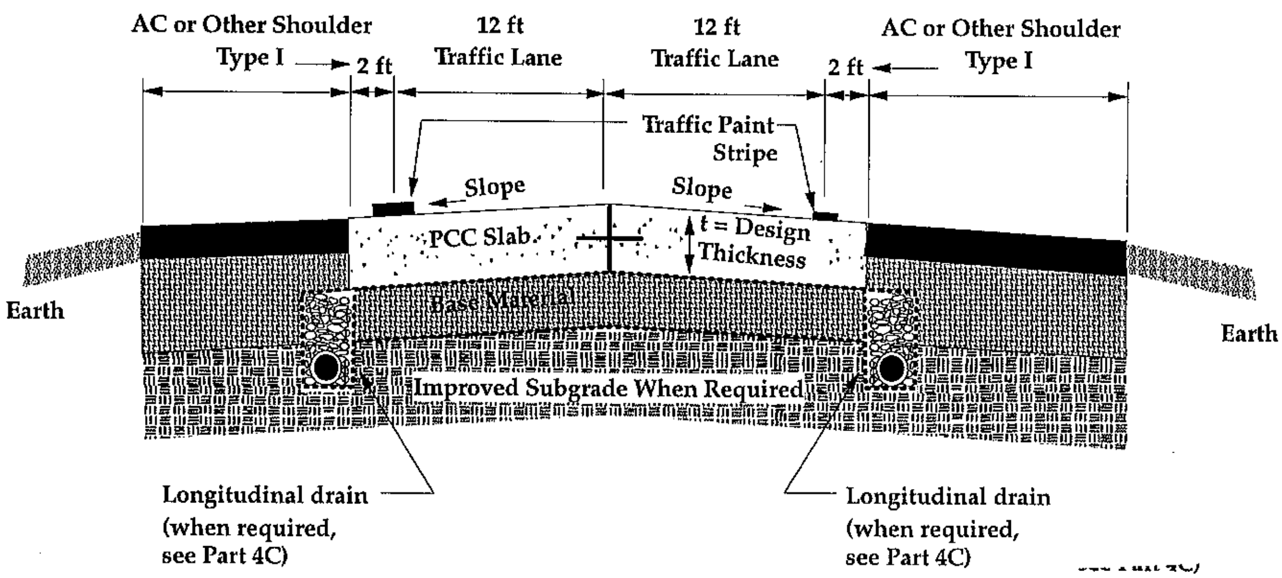
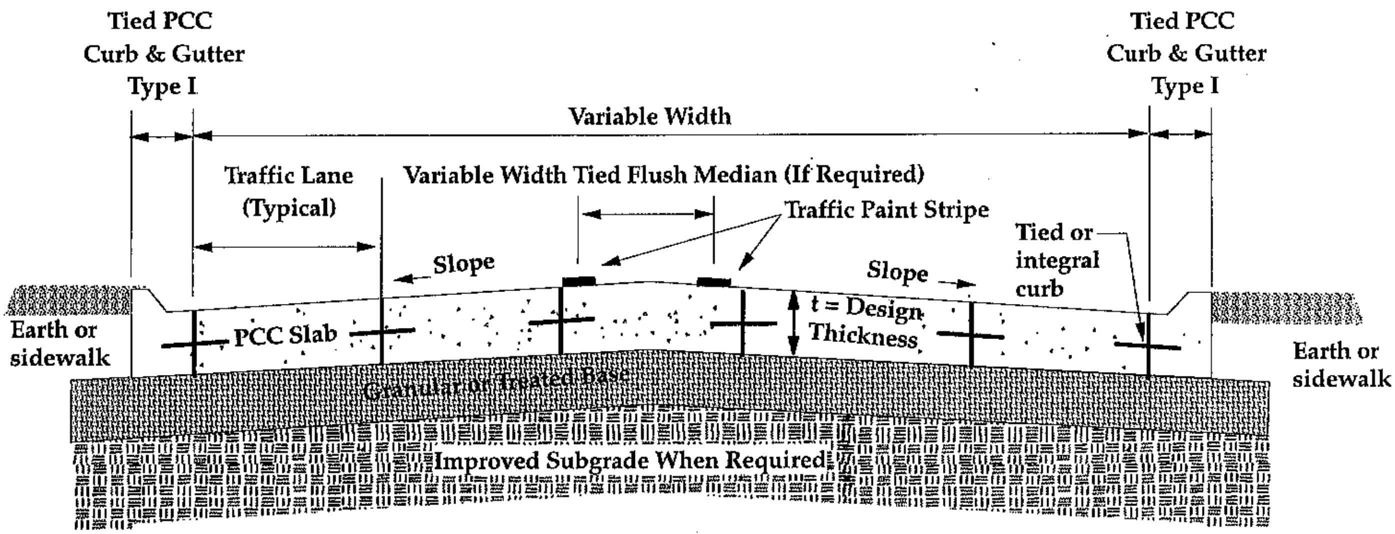


Figure 21. Cross sections showing rural two-lane highway, widened slab, and concrete or HMAC shoulders (Sections 5A and 5B).

Section 6. Tied Curb & Gutter (Two Directional Traffic)



Note: Raised Median with Tied PCC Curb & Gutter May Be Used in Lieu of Flush Median.

Figure 22. Cross section for an urban multi-lane highway, with tied or integral concrete curbs (Section 6).

4B.2 Rigid Pavement Structural Design Features for Site Condition Cells

Recommended rigid pavement structural design features that vary with site conditions are provided in this section. General background on the developmental process is first summarized.

General Inputs Used To Develop Structural Designs

Initial serviceability = 4.5*

Design reliability = See Table 16

Mean flexural strength = 650 psi*

Drainage coefficient, Cd = See Table 16*

Terminal serviceability = 2.5*

Overall standard deviation = 0.39*

Elastic modulus of PCC = 4,000,000 psi

Load transfer, J = See Table 17*

Table 16. Inputs varying with traffic loadings.*

Rigid ESAL (millions)	R %	Edge drain?	Drainage coefficient
<1.5	75%	No	1.00
1.5 - 3.0	85%	No	1.00
3-6	90%	Yes	1.05
> 6	95%	Yes	1.05

* Note: all items marked with an asterisk (*) were achieved through consensus. See appendix G for further information.

Traffic Lane Edge Support

The tie between the lane and shoulder is critical to any benefit of the tied shoulder. The most effective tie occurs when the outside traffic lane and shoulder are constructed at the same time (monolithic construction), deformed steel tiebars are properly placed in the plastic concrete across the joint, and the longitudinal joint is sawed to the proper depth (defined as Type I). Another form of excellent lane edge support is a widened slab (also Type I). Placement of the shoulder after the traffic lane has been placed will not provide the same level of load transfer (Type II). Other types of shoulders do not provide any load transfer (Type III). Required slab thickness is decreased as the longitudinal joint load transfer is improved.

Type I: Monolithically constructed tied PCC shoulder (traffic lane and shoulder included in same placement), or widened slab, or integral curb.

Type II: Tied PCC shoulder with longitudinal joint not monolithically placed (shoulder placed after traffic lanes placed).

Type III: Gravel, soil, AC or non-tied PCC shoulder.

Table 17. Load transfer coefficient, J-value.*

Pavement type	Joint load transfer	Edge support	J-value
JPCP/JRCP	**Doweled**	**Type I**	2.7
		Type II	3.0
		Type III	3.2
	Non-Doweled	**Type I**	3.7; if ESAL<1.5 mill: 3.4
		Type II	3.9; if ESAL<1.5 mill: 3.6
		Type III	4.1; if ESAL<1.5 mill: 3.8
CRCP	**Not Applicable**	**Type I**	2.6
		Type II	2.9
		Type III	3.1

***See appendix G.**

Design Checks

The initial designs were developed using the 1993 AASHTO Design Guide with the general inputs listed. Performance models were then used to check the structural designs against specific criteria for key distresses and roughness listed below.

- Non-doweled joint faulting [15].
- Doweled joint faulting [15].
- JPCP slab cracking [15].
- JRCP crack deterioration [15].
- CRCP localized failure [16].
- Terminal serviceability index (smoothness) [18].

Modifications were made to the design recommendations if the criteria listed in Section 2.3 were not met (as indicated in the cells). It should be noted that in the higher traffic cells, the slab thicknesses for JPCP were always more than adequate to prevent slab cracking or joint faulting. The checks showed that a JPCP thickness of 13 in is adequate to handle the joint spacing, subgrade, climate, and highest traffic level included in this catalog.

Marginal Designs

Some design cells are labeled as "marginal". These designs are considered "marginal" in that they have performed well in some locations but not as well in others. The designer should carefully consider local performance when selecting these designs.

Base Course

All designs require either an untreated dense graded aggregate or dense graded treated (cement, asphalt, lean concrete) base just beneath the slab, except if the slab is placed directly on grade for design rigid ESALs less than 3 million. See Sections 4B.12 and 4C for information on base materials.

Alternative designs for permeable bases are not provided in this section because they are still considered as experimental and their benefits and potential risks have not been fully established (See Reference 1, Appendix A). Recommendations on their use in concrete pavements is provided in Section 4C. The structural effect of the base course was considered by providing an increased k value for determining the slab thickness. A minimum of 6 in* should be used for an aggregate base course if the base is to be used as a working platform. Specific material requirements are given in Section 4C.

Subgrade Improvement

Subgrade uniformity and support is a very important consideration in pavement performance. Subgrade as used herein refers to the natural, processed, or fill soil foundation on which a pavement structure is placed. Uniformity of the upper portion of the subgrade is critical. This catalog recommends an "improvement" for all subgrades identified as Very Soft (see Section 3.2, Subgrade). Subgrade improvement should also be considered for subgrades identified as Weak. Subgrade improvement is defined as either of the following techniques:

- Granular layer: Placement and compaction of a 6 to 12 in granular layer to 95 percent or greater of maximum density, as defined by AASHTO T180, over the existing subgrade.

- Stabilization: The stabilization of the top 6 to 12 in of the subgrade generally with hydrated lime or cement. Subgrade improvement in terms of stabilization is discussed in greater detail in Section 5.6.

Benefits of an improved subgrade include provision of a construction platform for placement and compaction of pavement layers and help in achieving a smoother pavement, increased uniform support of the pavement structure, and when a granular layer is used beneath a treated base it reduces the amount erosion from pumping and a slow seepage of water out of the base course (bottom seepage). See Section 5 for further guidelines.

The structural effect of the improved subgrade was considered by providing an increased k value for determining the slab thickness (the k-value of the "Weak-Fair" subgrade was used).

Subgrade Preparation
It is recommended that all subgrades that are not improved (as defined above) be "prepared" as described in Section 5 and summarized below to achieve a high degree of uniformity.

- Fill Sections. All granular fill materials should be compacted to at least 95% of maximum density as defined by AASHTO T180. Cohesive fill materials should be compacted to no less than 95% of the maximum density as defined by AASHTO T99.

- Cut Sections. In cuts, the depth and degree of compaction required varies with the pavement or subgrade elevation of the different soils that are encountered along a highway project. Uniformity of the upper portion of the subgrade is critical relative to textural classification, moisture, and density. Specific guidance on compaction depth is given in Section 5. When existing subgrade soils do not meet minimum compaction requirements, consider the following alternatives:

  (1) Compact soils from the surface.
  (2) Remove and process soil to attain the approximate optimum moisture and replace and compact.
  (3) Replace subgrade soil with suitable borrow materials.
  (4) Raise the grade so that existing natural densities meet required values.

Special Subsurface Conditions
The pavement cross-sections and layer thicknesses included in the next section for each site condition cell are not intended to provide all alternatives and/or requirements for all subsurface

conditions and problem soils that may be encountered along a highway project. The different treatments or techniques suggested for special subsurface conditions and/or problem soils are included in Section 5 - Special Subsurface Conditions.

Subdrainage

Recommendations on the level of subdrainage are provided on each cell design sheet. More detailed recommendations are given in Section 4C.

Design Matrix Cells With Recommendations

The recommended features are keyed to specific design cells of a matrix defined by traffic levels and subgrade levels as shown in table 18. Climatic effects are considered both in the determination of the subgrade level (through the effective seasonally adjusted k value) and by specific climatic variables specified within each design cell. The design thickness and other features for all rigid pavement type alternatives are shown on 27 cell charts on succeeding pages.

A range of structural thicknesses are provided for each cell. These thicknesses were determined considering the range of traffic, holding the subgrade k value at their mean values. The range of base thickness is based on typical current practice.

Concrete Strength

All of the designs are developed for a mean 28-day flexural strength (third point load) of 650 psi. See Section 4B.11 for procedure to adjust thickness to other strengths.

Table 18. Site condition cells and design alternatives for the rigid pavement.

Rigid Traffic ESALs **	Subgrade Condition					
	Very Soft (k-value 50-100 psi/in)		Weak-Fair (k-value 100-200 psi/in)		Strong (k-value 200-400 psi/in)	
T1(0.75-1.5 million)	Cell 1:	Non doweled JPCP	Cell 2:	Non doweled JPCP	Cell 3:	Non doweled JPCP
T2 (1.5-3 million)	Cell 4:	Non doweled JPCP Doweled JPCP/JRCP	Cell 5:	Non doweled JPCP Doweled JPCP/JRCP	Cell 6:	Non doweled JPCP Doweled JPCP/JRCP
T3 (3-6 million)	Cell 7:	Non doweled JPCP Doweled JPCP/JRCP CRCP	Cell 8:	Non doweled JPCP Doweled JPCP/JRCP CRCP	Cell 9:	Non doweled JPCP Doweled JPCP/JRCP CRCP
T4 (6-12 million)	Cell 10:	Doweled JPCP/JRCP CRCP	Cell 11:	Doweled JPCP/JRCP CRCP	Cell 12:	Doweled JPCP/JRCP CRCP
T5 (12-18 million)	Cell 13:	Doweled JPCP/JRCP CRCP	Cell 14:	Doweled JPCP/JRCP CRCP	Cell 15:	Doweled JPCP/JRCP CRCP
T6 (18-30 million)	Cell 16:	Doweled JPCP/JRCP CRCP	Cell 17:	Doweled JPCP/JRCP CRCP	Cell 18:	Doweled JPCP/JRCP CRCP
T7 (30-54 million)	Cell 19:	Doweled JPCP/JRCP CRCP	Cell 20:	Doweled JPCP/JRCP CRCP	Cell 21:	Doweled JPCP/JRCP CRCP
T8 (54-90 million)	Cell 22:	Doweled JPCP/JRCP CRCP	Cell 23:	Doweled JPCP/JRCP CRCP	Cell 24:	Doweled JPCP/JRCP CRCP
T9 (90-150 million)	Cell 25:	Doweled JPCP/JRCP CRCP	Cell 26:	Doweled JPCP/JRCP CRCP	Cell 27:	Doweled JPCP/JRCP CRCP

Note: Climatic site condition is considered in both the determination of the subgrade seasonally adjusted k-value and by specific climatic variables specified within each design cell.

** Cumulative in design lane over design period.

Rigid Cell 1

Traffic: 0.75-1.5 million rigid ESALs

Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	**Elastic modulus of PCC**	4,000,000 psi
Terminal serviceability	2.5	**PCC mean flexural strength**	650 psi
Overall standard deviation	0.39	**Load transfer coef, J-value**	Varies w/ edge support type
Reliability	75%	**Drainage coef, Cd**	1.0

Structural Layer Thickness - NonDoweled JPCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	6.5-7.5	6.5-7.5	7-8	6-7	6-7.5	6.5-7.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Transverse Joint Design

Maximum Joint spacing, ft.

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	12-14	12-14	12-14
WNF	12	12-13	12-13
DNF	12	12	12

Joint reservoir and other joint design features
For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 1 - Seal joints and cracks (over time), see Section 4C.

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 2

Traffic: 0.75-1.5 million rigid ESALs
Subgrade: Weak/Fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	**Elastic modulus of PCC**	4,000,000 psi
Terminal serviceability	2.5	**PCC mean flexural strength**	650 psi
Overall standard deviation	0.39	**Load transfer coef, J-value**	Varies w/ edge support type
Reliability	75%	**Drainage coef, Cd**	1.0

Structural Layer Thickness - NonDoweled JPCP

	Aggregate base			Treated base			No base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	6-7	6-7.5	6.5-7.5	5.5-7	6-7	6-7.5	6-7	6.5-7.5	6.5-7.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6			
Prepared Subgrade (See Section 5)									

Marginal Design (No base)

Transverse Joint Design

Maximum Joint spacing, ft.

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	12-14	12-14	12-14
WNF	12-14	12	12-13
DNF	12-13	12	12

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 1 - Seal joints and cracks (over time), see Section 4C.

Note: See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 3	
Traffic:	0.75-1.5 million rigid ESALs
Subgrade:	Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	**Elastic modulus of PCC**	4,000,000 psi
Terminal serviceability	2.5	**PCC mean flexural strength**	650 psi
Overall standard deviation	0.39	**Load transfer coef, J-value**	Varies w/ edge support type
Reliability	75%	**Drainage coef, Cd**	1.0

Structural Layer Thickness - NonDoweled JPCP

	Aggregate base			Treated base			No base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	6.5-6.5	5.5-7	6-7	5-6.5	5-6.5	5.5-7	6.5-6.5	6-7	6-7.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6			
Prepared Subgrade									

Marginal Design (No base)

Transverse Joint Design

Maximum Joint spacing, ft.

JPCP:

	Edge support		
Climate	Type I	Type II	Type III
WF, DF	12	12	12
WNF	12	12	12
DNF	12	12	12

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 1 - Seal joints and cracks (over time), see Section 4C.

Note: See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 4

Traffic: 1.53-3 million rigid ESALs

Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	85%	Drainage coef, Cd	1.0

Structural Layer Thickness - NonDoweled JPCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	7.5-9	8-9	8-9.5	7-8.5	7.5-9	8-9
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Transverse Joint Design

Maximum Joint spacing, ft.

JPCP:

	Edge support		
Climate	Type I	Type II	Type III
WF, DF	14-16	14-16	15-17
WNF	12-15	13-15	14-16
DNF	12-13	12-13	12-14

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 2 - Non-erodible materials (see Section 4C).

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 4

Traffic: 1.5-3 million rigid ESALs

Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi (28 days)
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	85%	Drainage coef, Cd	1.0

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	6.5-7.5	6.5-8	7-8	6-7	6.5-7.5	6.5-8
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved Subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	12-14	13-15	13-16
WNF	12-13	12-14	12-14
DNF	12	12	12-13

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 2 - Non-erodible materials (see Section 4C).

Minimum % reinforcement content for JRCP: 0.15%-0.17%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 5

Traffic: 1.5-3 million rigid ESALs
Subgrade: Weak/Fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	**Elastic modulus of PCC**	4,000,000 psi
Terminal serviceability	2.5	**PCC mean flexural strength**	650 psi
Overall standard deviation	0.39	**Load transfer coef, J-value**	Varies w/ edge support type
Reliability	85%	**Drainage coef, Cd**	1.0

Structural Layer Thickness - NonDoweled JPCP

	Aggregate base			Treated base			No base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	7.5-9	8-9	8-9.5	7-8.5	7.5-9	8-9	7.5-9	8-9	8-9.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6			
Prepared Subgrade (See Section 5)									

Marginal Design

Transverse Joint Design

Maximum Joint spacing, ft.

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	14-16	14-16	15-17
WNF	12-15	13-15	14-16
DNF	12-13	12-13	12-14

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 2 - Non-erodible materials (see Section 4C).

Note: See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 5

Traffic: 1.5-3 million rigid ESALs

Subgrade: Weak/Fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varied w/ edge support type
Reliability	85%	Drainage coef, Cd	1.0

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base			No base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	6.5-7.5	6.5-8	7-8	6-7	6.5-7.5	6.5-8	6.5-7.5	7-8	7-8.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6			
Prepared subgrade (See Section 5)							Marginal Design		

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	12-14	13-15	13-16
WNF	12-13	12-14	12-14
DNF	12	12	12-13

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 2 - Non-erodible materials (see Section 4C).

Minimum % reinforcement content for JRCP: 0.15%-0.17%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Cell 6
Rigid

Traffic:	**1.5-3 million rigid ESAL*s***
Subgrade:	**Strong (k-value of 200-400 psi/in)**

General Structural Design Inputs

Initial serviceability	4.5	**Elastic modulus of PCC**	4,000,000 psi
Terminal serviceability	2.5	**PCC mean flexural strength**	650 psi
Overall standard deviation	0.39	**Load transfer coef, J-value**	Varies w/ edge support type
Reliability	85%	**Drainage coef, Cd**	1.0

Structural Layer Thickness - NonDoweled JPCP

	Aggregate base			Treated base			No base		
Edge support type	**Type I**	**Type II**	**Type III**	**Type I**	**Type II**	**Type III**	**Type I**	**Type II**	**Type III**
PCC slab thickness, in	7-8.5	7.5-9	8-9	7-8	7.5-8.5	7.5-9	7.5-8.5	7.5-9	8-9
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6			
Prepared Subgrade									

Marginal Design (No base)

Transverse Joint Design

Maximum Joint spacing, ft.

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	12-13	12-14	12-14
WNF	12	12-13	12-13
DNF	12	12	12

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 1 - Seal joints and cracks (see Section 4C).

Note: See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 6	
Traffic:	1.5-3 million rigid ESALs
Subgrade:	Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	85%	Drainage coef, Cd	1.0

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base			No base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	6-7	6.5-7.5	6.5-8	6.5-6.5	6-7	6-7.5	6-7	6.5-7.5	6.5-8
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6			
Prepared subgrade							Marginal Design		

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	12	12	12-13
WNF	12	12	12
DNF	12	12	12

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B. 8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Subdrainage design: Level 2 - Non-erodible materials (see Section 4C).

Minimum % reinforcement content for JRCP: 0.15%-0.17%

Tie bar design: No.5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 7	
Traffic:	3-6 million rigid ESALs
Subgrade:	Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	**Elastic modulus of PCC**	4,000,000 psi
Terminal serviceability	2.5	**PCC mean flexural strength**	650 psi
Overall standard deviation	0.39	**Load transfer coef, J-value**	Varies w/ edge support type
Reliability	90%	**Drainage coef, Cd**	1.05

Structural Layer Thickness - NonDoweled JPCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	9-10.5	9.5-10.5	9.5-11	8.5-10	9-10.5	9.5-10.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Transverse Joint Design

Maximum Joint spacing, ft.

JPCP:

	Edge support		
Climate	Type I	Type II	Type III
WF, DF	16-18	16-18	17-19
WNF	14-16	14-16	16-17
DNF	13-15	13-15	14-16

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: **Dry Climate: Level 2 - Non-erodible materials (see Section 4C).**
Wet Climate: Level 3 - Edge drains and non-erodible materials (see Section 4C).

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 7

Traffic: 3-6 million rigid ESALs

Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi (28 days)
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	90%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	7.5-8.5	8-9	8.5-9.5	7-8.5	7.5-9	8-9
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved Subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	14-16	14-16	15-17
WNF	12-15	13-15	14-16
DNF	12-13	12-13	12-14

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Dry climate: Level 1 - Seal joints and cracks.
Wet climate: Level 2 - Non-erodible materials (see Section 4C).

Minimum % reinforcement content for JRCP: 0.16%-0.18%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid
Cell 7

Traffic: 3-6 million rigid ESALs

Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	**Elastic modulus of PCC**	4,000,000 psi
Terminal serviceability	2.5	**PCC mean flexural strength**	650 psi
Overall standard deviation	0.39	**Load transfer coef, J-value**	Varies w/ edge support type
Reliability	90%	**Drainage coef, Cd**	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	7.5-8.5	8-9	8-9.5	7-8.5	7.5-8.5	8-9
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Reinforcement Design

Reinforcement content for CRCP, %

Climate	Base Type: Aggregate	Base Type: Treated
No Freeze	0.60	0.60
Freeze	0.70	0.70

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Dry climate: Level 1 - Seal joints and cracks.
Wet climate: Level 2 - Non-erodible materials (see Section 4C).

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 8

Traffic: 3-6 million rigid ESALs

Subgrade: Weak/Fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	**Elastic modulus of PCC**	4,000,000 psi
Terminal serviceability	2.5	**PCC mean flexural strength**	650 psi
Overall standard deviation	0.39	**Load transfer coef, J-value**	Varies w/ edge support type
Reliability	90%	**Drainage coef, Cd**	1.05

Structural Layer Thickness - NonDoweled JPCP

Edge support type

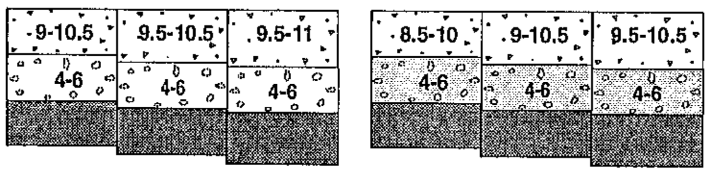
PCC slab thickness, in

Base thickness, in

Prepared subgrade (See Section 5)

Aggregate base — Type I, Type II, Type III

Treated base — Type I, Type II, Type III



Transverse Joint Design

Maximum Joint spacing, ft.

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	16-18	16-18	17-19
WNF	14-16	14-16	16-17
DNF	13-15	13-15	14-16

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: **Dry Climate:** Level 1 - Seal joints and cracks.
Wet Climate: Level 3 - Edge drains and non-erodible materials (treated base required) (see Section 4B).

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 8

Traffic:	**3-6 million rigid ESALs**
Subgrade:	**Weak/Fair (k-value of 100-200 psi/in)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	90%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	7.5-8.5	8-9	8.5-9.5	7-8.5	7.5-9	8-9
Base thickness	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade, in (See Section 5)						

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

	Edge support		
Climate	**Type I**	**Type II**	**Type III**
WF, DF	14-16	14-16	15-17
WNF	12-15	13-15	14-16
DNF	12-13	12-13	12-14

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Dry climate: Level 1 - Joint and crack reseal.
Wet climate: Level 2 - Non-erodible materials (see Section 4C).

Minimum % reinforcement content for JRCP: 0.16%-0.18%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 8	Traffic: 3-6 million rigid ESALs Subgrade: Weak/Fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	90%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

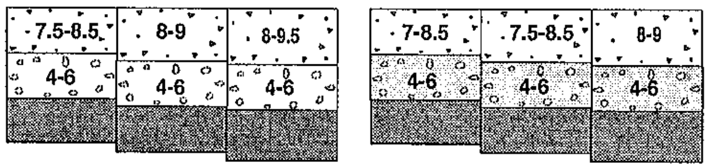
Edge support type

PCC slab thickness, in

Base thickness, in

Prepared subgrade (See Section 5)

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III



Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.60	0.60
Freeze	0.70	0.70

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Dry climate: Level 1 - Joint and crack reseal.
Wet climate: Level 2 - Non-erodible materials (see Section 4C).

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 9	
Traffic:	3-6 million rigid ESALs
Subgrade:	Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	**Elastic modulus of PCC**	4,000,000 psi
Terminal serviceability	2.5	**PCC mean flexural strength**	650 psi
Overall standard deviation	0.39	**Load transfer coef, J-value**	Varies w/ edge support type
Reliability	90%	**Drainage coef, Cd**	1.05

Structural Layer Thickness - NonDoweled JPCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	8.5-10	9-10.5	9-10.5	8.5-9.5	8.5-10	9-10.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

Transverse Joint Design

Maximum Joint spacing, ft.

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	13-15	13-16	14-16
WNF	12-14	12-14	13-14
DNF	12	12-13	12-13

Joint reservoir and other joint design features
For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Dry Climate: Level 2 - Non-erodible materials.
Wet Climate: Level 2 - Non-erodible materials (treated base required).

Note: See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 9	Traffic: 3-6 million rigid ESALs Subgrade: Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	90%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	7-8.5	7.5-9	8-9	6.5-8	7.5-8.5	7.5-9
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:	Edge support		
Climate	Type I	Type II	Type III
WF, DF	12-13	12-14	12-14
WNF	12	12-13	12-13
DNF	12	12	12

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B. 8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Dry climate: Level 1 - Joint and crack reseal.
Wet climate: Level 2 - Non-erodible materials (see Section 4C).

Minimum % reinforcement content for JRCP: 0.16%-0.18%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 9

Traffic: 3-6 million rigid ESALs

Subgrade: Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	90%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	7-8	7.5-8.5	7.5-9	6.5-8	7-8.5	7.5-8.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

Reinforcement Design

Reinforcement content for CRCP, %

Climate	Base Type: Aggregate	Base Type: Treated
No Freeze	0.60	0.60
Freeze	0.70	0.70

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Dry climate: Level 1 - Joint and crack reseal.
Wet climate: Level 2 - Non-erodible materials (see Section 4C).

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 10	Traffic: 6-12 million rigid ESALs Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	8.5-10	9-10.5	9.5-11	8.5-10	9-10.5	9.5-10.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.70

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No.5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 10

Traffic: 6-12 million rigid ESALs

Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi (28 days)
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	9-10	9.5-11	9.5-11	8.5-10	9-10.5	9.5-11
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved Subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Edge support Type II	Edge support Type III
WF, DF	16-18	16-19	17-19
WNF	14-16	15-17	16-17
DNF	13-14	13-16	14-16

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.18%-0.20%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 11

Traffic: 6-12 million rigid ESALs

Subgrade: Weak/Fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	**Type I**	**Type II**	**Type III**	**Type I**	**Type II**	**Type III**
PCC slab thickness, in	8.5-10	9-10.5	9.5-11	8.5-10	9-10.5	9.5-10.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade (See Section 5)						

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.70

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No.5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid
Cell 11

Traffic:	**6-12 million rigid ESALs**
Subgrade:	**Weak/fair (k-value of 100-200 psi/in)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	9-10	9.5-11	9.5-11	8.5-10	9-10.5	9.5-11
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP:	45 ft			
JPCP:		**Edge support**		
	Climate	**Type I**	**Type II**	**Type III**
	WF, DF	16-18	16-19	17-19
	WNF	14-16	15-17	16-17
	DNF	13-14	13-16	14-16

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.18%-0.20%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 12	
Traffic:	6-12 million rigid ESALs
Subgrade:	Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	8.5-9.5	9-10.5	9-10.5	8-9.5	8.5-10	9-10.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade (See Section 5)						

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.70

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No.5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid
Cell 12

Traffic:	**6-12 million rigid ESALs**
Subgrade:	**Strong (k-value of 200-400 psi/in)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	8.5-10	9-10.5	9.5-11	8-9.5	9-10	9-10.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP:	45 ft			
JPCP:		**Edge support**		
	Climate	**Type I**	**Type II**	**Type III**
	WF, DF	12-15	13-16	14-16
	WNF	12-14	12-14	13-15
	DNF	12	12-13	12-13

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Minimum % reinforcement content for JRCP: 0.17%-0.20%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 13	**Traffic:** 12-18 million rigid ESALs **Subgrade:** Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi (28 days)
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	10-11	10.5-11.5	11-12	9.5-10.5	10-11	10.5-11.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved Subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Edge support Type II	Edge support Type III
WF, DF	17-19	18-20	18-20
WNF	16-17	16-18	17-19
DNF	14-16	15-16	15-17

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.19%-0.21%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid
Cell 13

Traffic: 12-18 million rigid ESALs

Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	10-10.5	10.5-11.5	10.5-11.5	9.5-10.5	10-11	10.5-11.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.70

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No.5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 14	
Traffic:	12-18 million rigid ESALs
Subgrade:	Weak/Fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	10-11	10.5-11.5	11-12	9.5-10.5	10.11	10.5-11.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade (See Section 5)						

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft				
JPCP:		Edge support		
	Climate	Type I	Type II	Type III
	WF, DF	17-19	18-20	18-20
	WNF	16-17	16-18	17-19
	DNF	14-16	15-16	15-17

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.19%-0.21%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid

Cell 14

Traffic: 12-18 million rigid ESALs

Subgrade: Weak/Fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	10-10.5	10.5-11.5	10.5-11.5	9.5-10.5	10.11	10.5-11.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade (See Section 5)						

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.70

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No.5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid

Cell 15

Traffic: 12-18 million rigid ESALs

Subgrade: Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	10-10.5	10-11	10.5-11.5	9.5-10	10-11	10.5-11.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:	Edge support		
Climate	**Type I**	**Type II**	**Type III**
WF, DF	14-16	15-16	15-17
WNF	13-14	14-15	14-15
DNF	12-13	12-13	12-14

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Minimum % reinforcement content for JRCP: 0.19%-0.21%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 15	
Traffic:	**12-18 million rigid ESALs**
Subgrade:	**Strong (k-value of 200-400 psi/in)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	9.5-10.5	10-11	10.5-11.5	9-10	9.5-10.5	10-11
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.70

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No.5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid

Cell 16

Traffic: 18-30 million rigid ESALs

Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi (28 days)
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	10.5-11.5	11-12.5	11.5-13	10.5-11.5	11-12	11.5-12.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved Subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	18-20	19-20	20
WNF	17-18	17-19	18-20
DNF	15-16	16-17	16-18

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.20%-0.22%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 16

Traffic: 18-30 million rigid ESALs

Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	10-10.5	11-12	11.5-13	10-11	10.5-12	11-12.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.70

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid

Cell 17

Traffic:	**18-30 million rigid ESALs**
Subgrade:	**Weak/Fair (k-value of 100-200 psi/in)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	10.5-11.5	11-12.5	11.5-13	10.5-11.5	11-12	11.5-12.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade (See Section 5)						

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Edge support Type II	Edge support Type III
WF, DF	18-20	19-20	20
WNF	17-18	17-19	18-20
DNF	15-16	16-17	16-18

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B. 8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.20%-0.22%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 17	
Traffic:	**18-30 million rigid ESALs**
Subgrade:	**Weak/fair (k-value of 100-200 psi/in)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	10.5-11.5	11-12	11.5-13	10-11	10.5-12	11-12.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.70

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 18

Traffic: 18-30 million rigid ESALs
Subgrade: Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	10.5-11.5	11-12	11.5-12.5	10-11	10.5-12	11-12
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	15-17	16-17	16-18
WNF	14-15	14-16	15-16
DNF	12-14	13-14	13-14

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B. 8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Minimum % reinforcement content for JRCP: 0.19%-0.22%

Dowel bar design: 1.25 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid

Cell 18

Traffic: 18-30 million rigid ESALs

Subgrade: Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	10-11	10.5-12	11-12.5	9.5-11	10.5-11.5	11-12
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.75

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid
Cell 19

Traffic: 30-54 million rigid ESALs

Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi (28 days)
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	**Type I**	**Type II**	**Type III**	**Type I**	**Type II**	**Type III**
PCC slab thickness, in	11.5-13*	12-13.5*	12.5-14*	11.5-12.5	12-13.5*	12-13.5*
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

*** Maximum slab thickness of 13 in required by checks.**

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Edge support Type II	Edge support Type III
WF, DF	20	20	20
WNF	18-20	19-20	19-20
DNF	16-18	17-18	17-19

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B. 8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.21%-0.23%

Dowel bar design: 1.5 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 19	Traffic: 30-54 million rigid ESALs Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	11.5-12.5	12-13.5*	12.5-14*	11-12.5	11.5-13	12-13.5*
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

* Maximum slab thickness of 13 in required by checks.

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	Aggregate	Treated
No Freeze	0.65	0.65
Freeze	0.70	0.75

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 20	
Traffic:	30-54 million rigid ESALs
Subgrade:	Weak/fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	11.5-13*	12-13.5*	12.5-14*	11.5-12.5*	12-13.5*	12-13.5*
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

* Maximum slab thickness of 13 in required by checks.

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	20	20	20
WNF	18-20	19-20	19-20
DNF	16-18	17-18	17-19

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B. 8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.21%-0.23%

Dowel bar design: 1.5 in diameter corrosion-resistant dowel bars spaced at 12 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 20

Traffic: 30-54 million rigid ESALs
Subgrade: Weak/Fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	11.5-12.5*	12-13.5*	12.5-14*	11-12.5*	11.5-13*	12-13.5*
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade (See Section 5)						

*** Maximum slab thickness of 13 in required by checks.**

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.75

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 21	
Traffic:	30-54 million rigid ESALs
Subgrade:	Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	11-12.5	12-13	12.5-13.5	11-12	11.5-13	12-13.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

* Maximum slab thickness of 13 in required by checks.

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP:	45 ft			
JPCP:		Edge support		
	Climate	Type I	Type II	Type III
	WF, DF	16-18	17-18	17-19
	WNF	15-16	15-17	15-17
	DNF	13-14	14-15	14-15

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B. 8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Minimum % reinforcement content for JRCP: 0.20%-0.23%

Dowel bar design: 1.5 in diameter corrosion-resistant dowel bars spaced at 12 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid
Cell 21

Traffic: 30-54 million rigid ESALs

Subgrade: Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	11-12.5	11.5-13	12-13.5	10.5-12	11.5-12.5	12-13
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

*** Maximum slab thickness of 13 in required by checks.**

Reinforcement Design

Reinforcement content for CRCP, %

Climate	Base Type: Aggregate	Base Type: Treated
No Freeze	0.65	0.65
Freeze	0.70	0.75

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No.5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid

Cell 22

Traffic: 54-90 million rigid ESALs

Subgrade: Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi (28 days)
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP

	Aggregate base			Treated base		
Edge support type	**Type I**	**Type II**	**Type III**	**Type I**	**Type II**	**Type III**
PCC slab thickness, in	12.5-14*	13.5-14.5	13.5-15	12.5-13.5	13-14.5	13.5-15
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

*** Maximum slab thickness of 13 in required by checks.**

Transverse Joint Design

Maximum Joint spacing, ft.

		Edge support		
JRCP: 45 ft				
JPCP:	**Climate**	**Type I**	**Type II**	**Type III**
	WF, DF	20	20	20
	WNF	19-20	20	20
	DNF	17-19	18-19	18-20

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B. 8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.22%-0.23%

Dowel bar design: 1.5 in diameter corrosion-resistant dowel bars spaced at 12 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 22	
Traffic:	**54-90 million rigid ESALs**
Subgrade:	**Very Soft (k-value of 50-100 psi/in)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	12.5-13.5*	13-14.5	13.5-15	12-13.5	12.5-14	13-14.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

*** Maximum slab thickness of 13 in required by checks.**

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.75

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid

Cell 23

Traffic:	**54-90 million rigid ESALs**
Subgrade:	**Weak/Fair (k-value of 50-100 psi/in)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	12.5-14*	13.5-14.5*	13.5-15*	12.5-13.5*	13-14.5*	13.5-15*
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade (See Section 5)						

*** Maximum slab thickness of 13 in required by checks.**

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	20	20	20
WNF	19-20	20	20
DNF	17-19	18-19	18-20

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.22% - 0.23%

Dowel bar design: 1.625 in diameter corrosion-resistant dowel bars spaced at 12 in

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 23	
Traffic:	**54-90 million rigid ESALs**
Subgrade:	**Weak/Fair (k-value of 100-200 psi/in)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	12.5-13.5	13-14.5	13.5-15	12-13.5	12.5-14	13-14.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade (See Section 5)						

*** Maximum slab thickness of 13 in required by checks.**

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.75

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 24

Traffic: 54-90 million rigid ESALs

Subgrade: Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/edge support type
Reliability	95%	Drainage coef, Cd	1.05

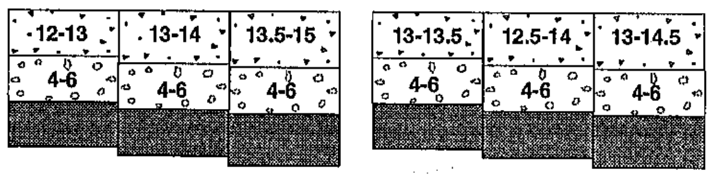
Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III

PCC slab thickness, in

Base thickness, in

Prepared subgrade
See Section 5



*** Maximum slab thickness of 13 in required by checks.**

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Edge support Type II	Edge support Type III
WF, DF	17-19	18-19	18-20
WNF	16-17	16-18	17-18
DNF	14-15	14-16	15-17

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Minimum % reinforcement content for JRCP: 0.21% - 0.23%

Dowel bar design: 1.5 in diameter corrosion-resistant dowel bars spaced at 12 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid

Cell 24

Traffic: 54-90 million rigid ESALs

Subgrade: Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	12-13.5	12.5-14	13-14.5	11.5-13	12.5-14	13-14.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade (See Section 5)						

*** Maximum slab thickness of 13 in required by checks.**

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.75

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid **Cell 25**	**Traffic:** 90-150 million rigid ESALs **Subgrade:** Very Soft (k-value of 50-100 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi (28 days)
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	13.5-15*	14.5-15.5*	15-16.5*	13.5-14.5*	14-15.5*	14.5-16*
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade, in (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

*** Maximum slab thickness of 14 in required by checks.**

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	20	20	20
WNF	20	20	20
DNF	18-20	19-20	19-20

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.23%

Dowel bar design: 1.625 in diameter corrosion-resistant dowel bars spaced at 12 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 25	
Traffic:	**90-150 million rigid ESALs**
Subgrade:	**Very Soft (k-value of 50-100 psi/in)**

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	**Type I**	**Type II**	**Type III**	**Type I**	**Type II**	**Type III**
PCC slab thickness, in	13.5-14.5	14-15.5	14.5-16	13-14.5	14-15	14.5-15.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Improved subgrade (See Section 5)	6-12	6-12	6-12	6-12	6-12	6-12

*** Maximum slab thickness of 14 in required by checks.**

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.75

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 26

Traffic: 90-150 million rigid ESALs

Subgrade: Weak/fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	13.5-15	14.5-15.5	15-16.5	13.5-14.5	14-15.5	14.5-16
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

* Maximum slab thickness of 14 in required by checks.

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	20	20	20
WNF	20	20	20
DNF	18-20	19-20	19-20

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Minimum % reinforcement content for JRCP: 0.23%

Dowel bar design: 1.625 in diameter corrosion-resistant dowel bars spaced at 12 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid
Cell 26

Traffic: 90-150 million rigid ESALs

Subgrade: Weak/Fair (k-value of 100-200 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

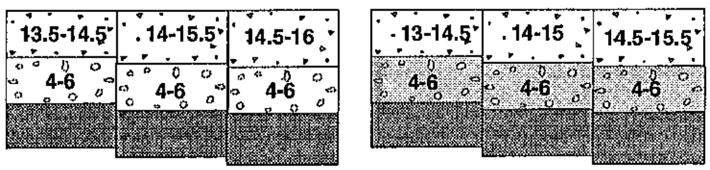
Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III

PCC slab thickness, in

Base thickness, in

Prepared subgrade (See Section 5)



*** Maximum slab thickness of 14 in required by checks.**

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.75

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drains and non-erodable treated base, or
Level 4 - Full subdrainage system with permeable base.

Note See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.

Rigid Cell 27

Traffic: 90-150 million rigid ESALs
Subgrade: Strong (k-value of 200-400 psi/in)

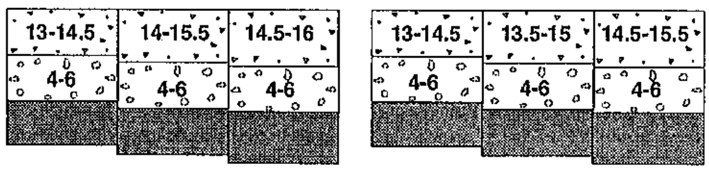
General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - Doweled JPCP/JRCP

Edge support type
PCC slab thickness, in
Base thickness, in
Prepared subgrade

Aggregate base — Type I, Type II, Type III
Treated base — Type I, Type II, Type III



* Maximum slab thickness of 14 in required by checks.

Transverse Joint Design

Maximum Joint spacing, ft.

JRCP: 45 ft

JPCP:

Climate	Edge support Type I	Type II	Type III
WF, DF	18-20	19-20	20
WNF	17-18	17-19	18-19
DNF	15-16	15-17	19-20

Joint reservoir and other joint design features

For recommended transverse joint reservoir width and other transverse joint design details, see Section 4B.8, "Joint Sealant Reservoir and Joint Sealants" and Section 4B.4, "Transverse Joints for JPCP and JRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Minimum % reinforcement content for JRCP: 0.22% - 0.23%

Dowel bar design: 1.625 in diameter corrosion-resistant dowel bars spaced at 12 in

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

Rigid Cell 27

Traffic: 90-150 million rigid ESALs

Subgrade: Strong (k-value of 200-400 psi/in)

General Structural Design Inputs

Initial serviceability	4.5	Elastic modulus of PCC	4,000,000 psi
Terminal serviceability	2.5	PCC mean flexural strength	650 psi
Overall standard deviation	0.39	Load transfer coef, J-value	Varies w/ edge support type
Reliability	95%	Drainage coef, Cd	1.05

Structural Layer Thickness - CRCP

	Aggregate base			Treated base		
Edge support type	Type I	Type II	Type III	Type I	Type II	Type III
PCC slab thickness, in	13-14.5	14-15	14-15.5	12.5-14	13.5-15	14-15.5
Base thickness, in	4-6	4-6	4-6	4-6	4-6	4-6
Prepared subgrade						

*** Maximum slab thickness of 14 in required by checks.**

Reinforcement Design

Reinforcement content for CRCP, %

	Base Type	
Climate	**Aggregate**	**Treated**
No Freeze	0.65	0.65
Freeze	0.70	0.75

Longitudinal reinforcement bar size

For recommended longitudinal deformed uncoated reinforcement bar sizes, see Section 4B.10, "Reinforcement Design for CRCP".

Other Design Features

Tie bar design for longitudinal joints: No. 5 (0.625 in diameter) deformed reinforcing bars spaced at 30 in

Subdrainage design: Level 3 - Edge drain and non-erodible materials.

Note **See Sections 4B.2 through 4B.12 for additional detailed guidelines on all the rigid pavement design features.**

4B.3 Transverse Joints For JPCP And JRCP

JPCP. Closely spaced transverse joints are required for JPCP to avoid transverse cracking from thermal gradients and from moisture gradients that occur through the slab. The climatic region, traffic level, slab thickness, base stiffness, and subgrade stiffness must all be considered in selection of the transverse joint spacing for JPCP. Past experience has often resulted in too long joint spacing that leads to transverse cracking.

Maximum joint spacing recommendations were initially established through setting the ratio of the joint spacing (L) to the radius of relative stiffness (l) for each climatic zone. These limits were 4.5 for dry-nonfreeze climates, 5.0 for wet-nonfreeze climates, and 5.5 for dry or wet freeze climates. These criteria were selected after evaluating a substantial amount of field data [15,17].

The recommendations shown in table 19 have been checked in a comprehensive fatigue analysis that considered traffic loading, temperature gradients, base stiffness, slab thickness, and subgrade stiffness to control fatigue cracking, using the comprehensive mechanistic model from reference 15. Modifications were made where necessary to limit fatigue cracking to 50 percent slabs. A maximum of 20 ft* and a minimum of 12 ft* are specified for practical reasons. (* See Appendix G.)

These joint spacing recommendations are to be considered only as general guidelines because this design feature also depends on other factors not considered here; local experience must be fully considered when selecting joint spacing.

JRCP. Longer joint spacing is possible because transverse cracking is designed for by providing reinforcing steel to hold transverse cracks tight when they occur. Past JRCP designs have not contained adequate longitudinal steel reinforcement, and many transverse cracks have opened up and spalled and faulted.

Also, past JRCP have not had adequate joint sealants to prevent incompressibles from entering and causing spalling after several years. A maximum joint spacing of 45 feet is recommended. This joint spacing is based on consensus group recommendations, but includes substantially increased steel content to hold cracks very tight. Recommendations for adequate reinforcement and joint sealants is provided below.

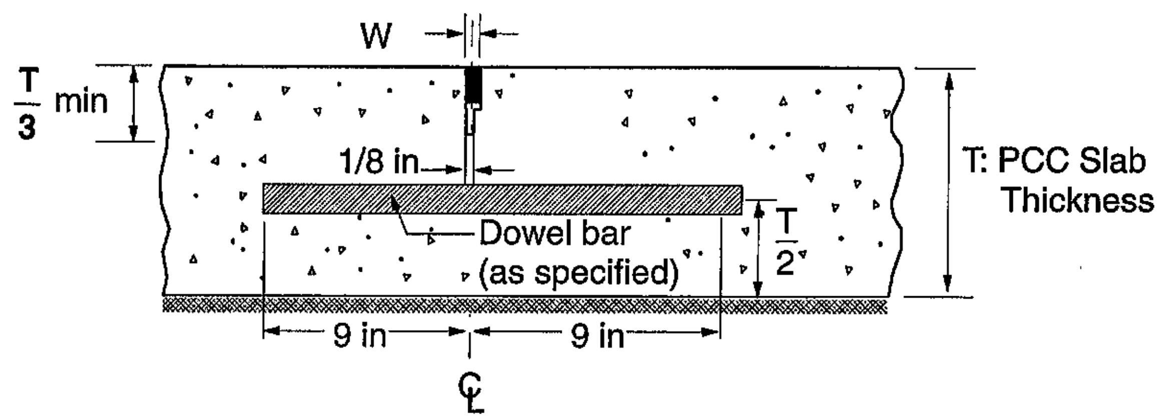
Table 19. Recommended maximum joint spacing (ft) for JPCP.

Slab thickness (in)	Subgrade k-value (psi/in)								
	75			150			300		
	Climatic Region								
	WF, DF	WNF	DNF	WF, DF	WNF	DNF	WF, DF	WNF	DNF
5	13	12	12	12	12	12	12	12	12
5.5	14	12	12	12	12	12	12	12	12
6	14	13	12	12	12	12	12	12	12
6.5	15	14	13	13	12	12	12	12	12
7	16	15	13	14	12	12	12	12	12
7.5	17	16	14	14	13	12	12	12	12
8	18	16	15	15	14	12	13	12	12
8.5	19	17	15	16	14	13	13	12	12
9	20	18	16	16	15	13	14	13	12
9.5	20	19	17	17	16	14	14	13	12
10	20	19	17	18	16	15	15	14	12
10.5	20	20	18	18	17	15	16	14	13
11	20	20	19	19	17	16	16	15	13
11.5	20	20	19	20	18	16	17	15	14
12	20	20	20	20	19	17	17	16	14
12.5	20	20	20	20	19	17	18	16	14
13	20	20	20	20	20	18	18	17	15
13.5	20	20	20	20	20	18	19	17	15
14	20	20	20	20	20	19	19	18	16
14.5	20	20	20	20	20	19	20	18	16
15	20	20	20	20	20	20	20	18	17
15.5	20	20	20	20	20	20	20	19	17
16	20	20	20	20	20	20	20	19	17

General Guidelines for Joint Design [see also Reference 57]

- Sawed joints are recommended that are cut to a minimum of one-quarter* the slab thickness and one-third* the slab thickness, respectively, for pavements on granular base and treated base. They should be sawed as soon as the concrete gains adequate strength to carry sawing equipment and to avoid saw raveling. The minimum depth of saw-cut for green sawing is 1 in*. The recommended design for transverse contraction joints is shown in figure 23. (* See Appendix G.)
- Random spacing has been used to minimize resonant vehicle responses when faulting develops. Adequately designed joints will not develop significant faulting, so random joint spacing is not recommended when dowels are used. For non-doweled joints, the maximum slab length should be that specified in design. For example, some States have successfully used a non-doweled random spacing of 12-15-14-13 ft for JPCP where the maximum desired is 15 ft.
- Skewed joints have been used to provide a smoother ride after faulting develops, and there is some evidence that skewing reduces faulting. At two different sites that were directly comparable, faulting was approximately 50 percent less for the skewed joints versus perpendicular joints. [15] Adequately designed doweled load transfer joints will not develop significant faulting, so skewed joints are not recommended when dowel bars are used.
- For JPCP, when either cement-treated base or lean concrete bases are used, it is recommended that transverse (and longitudinal) joints be formed in the base beneath the joints in the slab. The slab can then be allowed to bond with the base course, reducing the potential for erosion between these two layers. This practice will reduce the potential for random cracking and provide for uniform cracking and opening of cracks in the JPCP slab. [26]
- When an asphalt stabilized base is used, no efforts should be made to break the bond with the slab. This bonding and friction is highly desirable to form the cracks at the transverse and longitudinal joints for JPCP and JRCP, to form sufficient cracks in CRCP, and to minimize erosion at the slab/base interface.

TRANSVERSE CONTRACTION JOINT - Sawed



DOWEL BAR SPACING, in

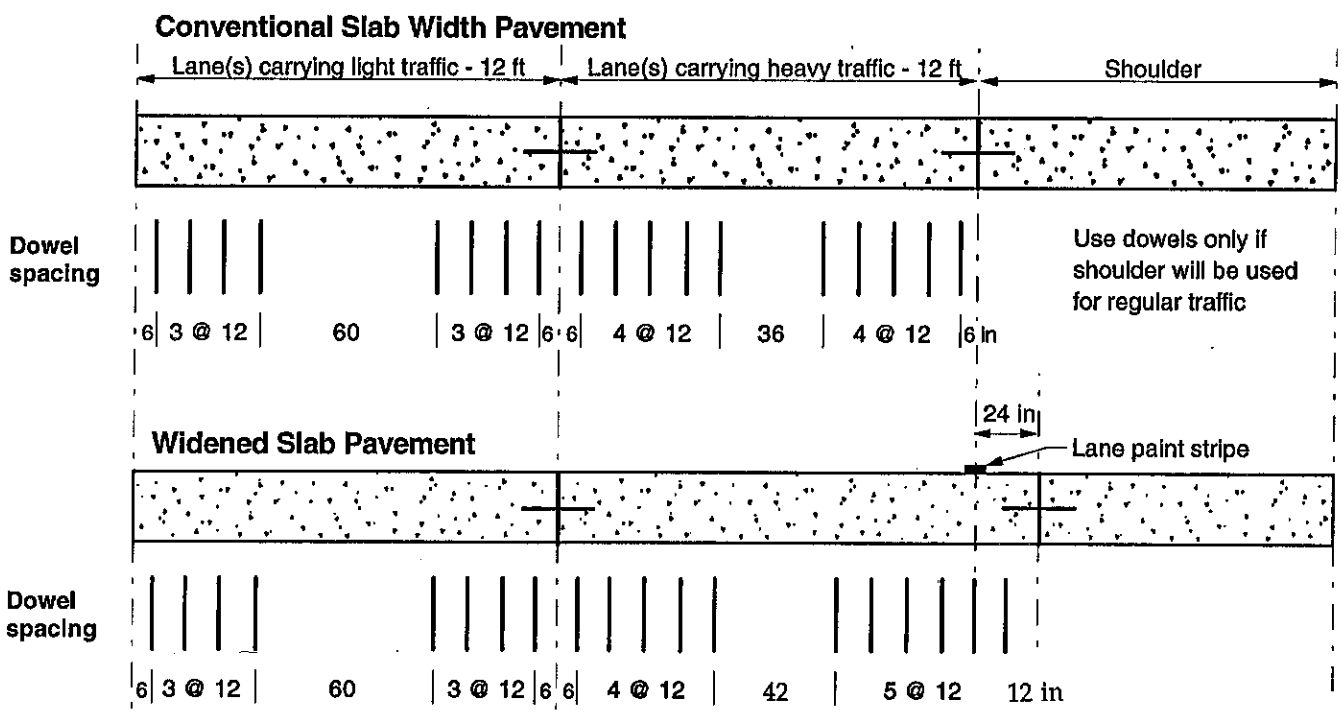


Figure 23. Recommended design for transverse contraction joints including the layout of dowel bars.

4B.4 Load Transfer Design (Dowel Bars)

Load transfer devices (dowels recommended) are placed at transverse joints to provide for the transfer of heavy axle load across the joint. This results in two benefits. First, differential deflection across the joint is reduced, which minimizes erosion and pumping and subsequent faulting of the joint. Second, tensile stress on the top of the slab near the corner is reduced, which essentially eliminates corner breaks, diagonal cracks, and perhaps even some transverse cracks (if severe warping or negative curling is present in the slab). Dowels must be of the proper diameter, length, and spacing, and must be placed properly and concrete consolidated around them to be effective. Dowels are recommended for JPCP and JRCP carrying over 6 million ESALs.

1. Recommended dowel diameters for various load and design conditions are shown in Table 20. These diameters (and corresponding 12 inch spacing and 18 inch length) are those required to limit joint faulting to the limits shown in section 2.3, based on comprehensive faulting prediction models [15].

Table 20. Recommended dowel diameter for different loading conditions.

Design traffic (million ESALs)	Recommended dowel diameter (in)
<30	1.25
30 - 90	1.5
>90 - 150	1.625

2. Dowel bars must be corrosion-resistant (i.e., epoxy coated, stainless steel coated, metallic sleeve). Research has shown that less joint spalling occurs when corrosion-resistant dowels are used [15].
3. Solid grade 40 or higher steel dowels are recommended.
4. Accurate placement of dowels and good consolidation around the dowel is important. Consolidation around the dowels is important to achieve good load transfer.
5. The recommended design for transverse joints and the layout of dowel bars for both conventional slab width and widened slab width pavements is provided in figure 23. Variable spacing is provided to place the bars only where they are really needed for heavy traffic loads.

4B.5 Longitudinal Joints And Tie Bars

Longitudinal joints are required to avoid longitudinal cracking from thermal gradients and from moisture gradients that occur through the slab, and from shrinkage of the slab restrained by the base/slab friction. The climatic region, slab thickness, base stiffness and friction, subgrade stiffness, and lane/shoulder widths all affect the potential for longitudinal cracking. Past experience has shown that longitudinal cracking will occur when longitudinal joint spacing is greater than about 15 ft for conventional slab thickness (7 to 10 in). Longitudinal joints should coincide with pavement traffic lane lines whenever possible, to improve traffic operations.

1. Sawed joints are recommended to a depth of one-third the slab thickness. They should be sawed as soon as the concrete strength is sufficient to avoid sawing raveling to minimize the problem of random cracking. The prevention of random longitudinal cracks by sawing as soon as possible must be a top priority of the construction effort, especially for treated bases. Figure 24 shows the recommended design of longitudinal joints. The earliest possible sawing of longitudinal joints is even more critical when a permeable base is present due to the increased friction between slab and base.

2. The use of plastic inserts to form the longitudinal joint is not recommended. Some States have had success with plastic inserts; however, many have had extensive longitudinal cracking because the insert did not properly form the joint. It is also very difficult to seal the joint formed by these inserts.

3. A joint sealant reservoir is not required if the joint is tied together by adequate reinforcing steel and is not a working joint. A width of a saw blade is normally adequate.

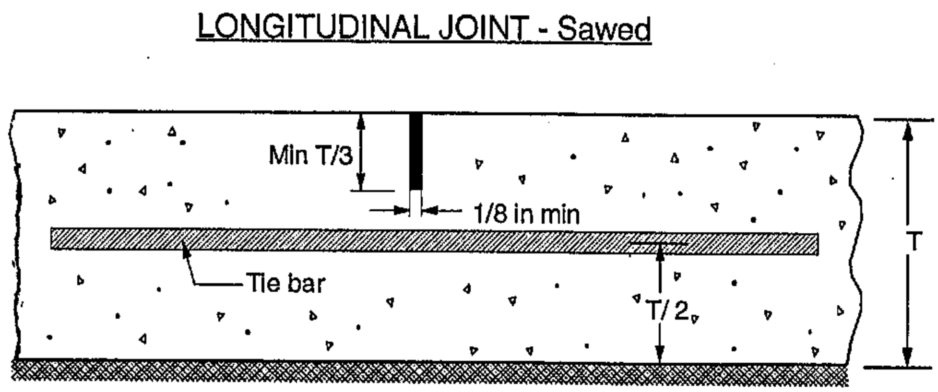


Figure 24. Recommended design of longitudinal joints.

4. Tie bars. Load transfer across longitudinal joints occurs through aggregate interlock, which can only be maintained when deformed steel tie bars of adequate diameter and spacing are used. Therefore, all longitudinal joints should be adequately tied with deformed reinforcing bars. Otherwise, the joints will open allowing water to enter and result in no load transfer.

   a) Recommended diameter and spacing for tie bars are based on the successful practices of SHAs. (Consensus group recommendation due to inadequacy of traditional computation procedure). The predominant diameter of deformed tie bar used today is ⅝ in or No. 5 bar. Grade 40 or higher steel is used. Only a few states use No. 4 bars (6 states); however, about 10 states use No. 6 bars. The spacing of the bars is predominantly 30 in, with a few SHAs using shorter (18 to 24-in) and longer (36 to 48-in) spacings.[2] There does not appear to be any research data that show that any of these designs are superior to the others, with the exception that the longitudinal joint between traffic lanes or lanes and shoulders has separated at some locations where No. 4 bars have been used. The following design is recommended for most lane-to-lane applications:

      No. 5 (0.625 in diameter) minimum deformed reinforcing bars spaced at 30 in.

   b) Tie bars should not be placed within 15 in of transverse joints. When using tie bars longer than 32 in with skewed joints, they should not be placed within 18 in of the transverse joints. The predominant length used by SHAs is 30 in.

   c) It is essential that tie bars be firmly anchored in the concrete. Tie bars should either mechanically inserted into the plastic concrete or installed as a two-part threaded tiebar and splice coupler system. It is recommended that periodic pull-out tests be conducted to ensure the tie bars are securely anchored in the concrete. See reference 20 for a recommended procedure for testing tie bars in the field.

   d) Bending of tie bars is not encouraged. Where bending is considered necessary, it is recommended that a two-part threaded tie bar and splice coupler system be used instead. If tie bars must be bent and later straightened during construction, Grade 40 steel should be used, as it better tolerates the bending. It may be necessary to reapply a corrosion-resistant coating to the tie bars after they have been straightened. When pull-out tests are performed, they should be conducted after the tie bars have been straightened.

5. For JPCP, when either cement-treated base or lean concrete bases are used it is recommended that longitudinal (and transverse) joints be formed beneath the joints in the slab. The slab can then be allowed to bond with the base course, reducing the potential for erosion between these two layers. This practice will reduce the potential for random cracking and provide for uniform cracking and opening of cracks in the JPCP slab. If the slab is bonded to a notched lean concrete base, a deeper saw-cut between 0.4T to 0.45T, where T is the thickness of the slab, is recommended; tie bars should be T/3 from the bottom of the slab.[26]

6. Keyways have often been used for construction longitudinal joints. While some keyways work well, there have been many problems with keyways over the years, particularly the spalling of the upper key beginning at the transverse joint and progressing along the joint over time. This creates a very difficult maintenance problem. Construction of keyways is quite difficult, which can also lead to failure. For these reasons, keyways are not recommended for longitudinal construction joints. The use of butt joints with tie bars is recommended for longitudinal construction joints.

7. The number of lanes/tied shoulders that can be "tied together" without causing longitudinal cracking varies with several factors, including the size and spacing of the tiebars (which limits the opening at the joint) and the friction between the slab and base. Some states limit this distance to 3 lanes/tied shoulders, however, no research data that supports this recommendation could be located.

4B.6 Expansion Joint Design

Expansion joints are recommended only at fixed structures to protect the structure (such a bridge end) from expansive pressure on hot days. The recommended expansion joint design is shown in figure 25.

1. The width of an expansion joint is typically 0.75 in or more. In some cases, it may be desirable to place two or three expansion joints in a row to protect the structure. Filler material is commonly placed 0.75 to 1 in below the slab surface to allow space for sealing material.
2. Load transfer is provided most commonly by dowel bars, which are fabricated with a cap on one end of each dowel that creates a void in the slab to accommodate the dowel as the adjacent slab closes the expansion joint.

4B.7 Joint Sealant Reservoir and Joint Sealants

Joint sealants perform two primary functions: they minimize the infiltration of water, and they minimize the intrusion of incompressibles. The FHWA technical advisory on joints provides excellent guidance. Research has shown that for both JPCP and JRCP, the type and presence of joint sealant originally installed has a significant effect on joint spalling, particularly after about 7 to 10 years [15,17]. One SHA permits a single saw cut (0.125 in width approximately) and does not place any sealant in the slot [19]. General guidelines on the use of joint sealant are provided below (these have been reviewed by several manufacturers), however, manufacturer's recommendations for specific products should be fully considered.

TRANSVERSE EXPANSION JOINT

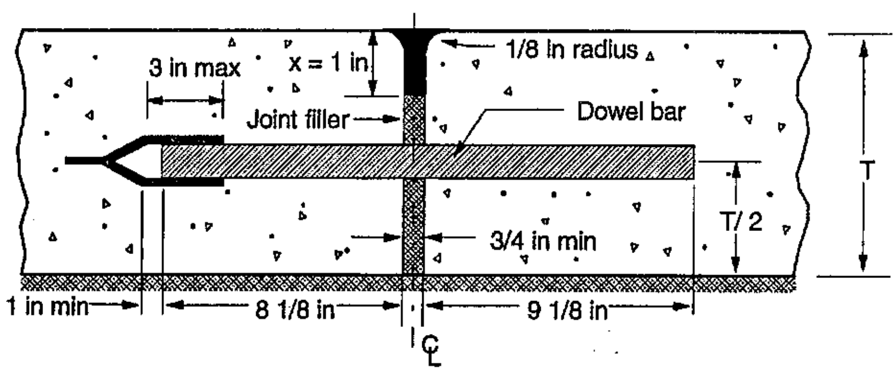


Figure 25. Recommended design for transverse expansion joints at fixed structures.

1. Joint sealant performance is affected by the design of the reservoir, joint opening, load transfer, and the sealant material. Table 21 shows a summary of three joint sealant types recommended: rubberized asphalt and low modulus rubberized asphalt, silicone sealants, and preformed compression seals. The cost and design of the joint reservoir is different for each of these sealants.

Table 21. Summary of recommended joint sealants, applicable specifications and design tensile extension.

Sealant material	Applicable specification	Design extension
Rubberized Asphalt	ASTM D1190, D3405 AASHTO M173, M301-851 Fed SS-S-164	15 to 30 percent
Low-Modulus Rubberized Asphalt	Modified ASTM D 3405	30 to 50 percent
Silicone (non-self-leveling)	ASTM D5893-96, Type NS; State specifications	30 to 50 percent
Silicone (self-leveling)	ASTM D5893-96, Type SL; State specifications	30 to 50 percent
Preformed compression seal	ASTM 2628 AASHTO M220	Compress 45 to 85 percent

2. The width of a joint and the thickness of the sealant in that joint can significantly affect the performance of the sealant. In designing the dimensions of a joint sealant and the sealant reservoir, two major items must be determined: the shape factor and the expected joint movement. Figure 26 shows a typical sealant reservoir containing sealant material and backer rod. The shape factor is the width "W" divided by the thickness "T" of the sealant. The sealant recess is designated as "R" and the joint channel depth is "D". Manufacturers' recommendations should be followed when choosing a shape factor. Typical shape factors are given in table 22.

Table 23. Recommended design width for transverse joint sealants.

Sealant type	Joint spacing	Minimum joint width (W), non-freeze region	Minimum joint width (W), freeze region
Rubberized Asphalt	< 15 ft	0.375 in	0.375 in
(20% extension maximum)	16 to 25 ft	0.50	N/A
	26 to 40 ft	0.50	N/A
Low-Modulus Asphalt	< 15 ft	0.375	0.375
(50% extension maximum)	16 to 25 ft	0.375	0.50
	26 to 40 ft	0.50	0.50
Silicone	< 15 ft	0.375	0.375
(50% ext. max)	16 to 25 ft	0.375	0.375
	26 to 40 ft	0.375	0.50
Preformed Compression	< 15 ft	0.375	0.375
(20 to 50% compression)	16 to 25 ft	0.375	0.437
	26 to 40 ft	0.50	0.50

Computations and assumptions:

Minimum joint width = 0.375 in for improved performance of asphalt and silicone seals.

Maximum joint opening = Mmax = C*L{A*T+E)

C = 0.80 aggregate base (used to compute joint widths), 0.65 treated base

L = joint spacing, in

A = thermal coefficient of expansion of concrete (5.5*10^-6/F)

T = change in temperature (installation temperature - minimum temperature)

Installation temperature = 80 F, minimum temperature non-freeze region = 20F freeze region = - 15F)

E = shrinkage coefficient of concrete (200*10^-6)

Width of the uncompressed seal = S >= Mmax / (Cmax - Cmin)

Cmax = 0.8;   Cmin = 0.2

Width of joint saw cut = W = { 1 - PC } * S

PC = percent compression of seal at installation, expressed as a decimal

S = width of uncompressed seal, in

4B.8 Reinforcement Design For JRCP

JRCP has longer joint spacing to reduce joint costs. However, longer joint spacing results in transverse cracks developing over time from a combination of load, temperature gradient, moisture gradient stresses, and concrete volume change (from moisture and temperature changes). These cracks must be held tight by reinforcing steel or they will rapidly spall and fault.

The amount of steel reinforcement required to hold these cracks tight has been calculated based on the concept of pulling the slab over the base course by the reinforcement without yielding the reinforcement. This design has often resulted in inadequate reinforcement and the failure of many transverse cracks, especially in freeze climates. There are several reasons for this failure:

- Friction between the slab and base may be more than assumed in design.
- Dowel bar corrosion causing lockup of transverse joints and thus increased tensile stress in the steel.
- Corrosion of the reinforcement in the crack after it opens up slightly to allow chlorides to infiltrate to the steel.
- If the cracks open sufficiently, the steel must also carry vertical shear forces from heavy axle loads as they travel over the crack.

Research has recently been conducted to determine the amount of needed reinforcement [15, 21, 58]. Recommendations provided in the structural design cells are based on a model developed from field data collected on many JRCP in the U.S [15]. The percent steel required to limit the number of deteriorated transverse cracks to 25 per mile was computed from the model for each of the cells in the design matrix. A minimum of 0.15 percent was selected to limit crack deterioration potential. Table 24 shows the minimum percent of deformed reinforcement recommended. This results in increased reinforcement relative to that computed using the conventional method. However, this will avoid the failure of many transverse cracks.

Deformed steel wire or deformed reinforcement bars are recommended for use in JRCP [21]. Transverse steel may be used to aid in placement of the longitudinal steel. The preferred

location of the reinforcement is above mid-depth, but with a minimum of 3 in of concrete cover from the top of the slab. The closer to the top of the slab, the tighter the resulting cracks.

Table 24. Recommended minimum percent reinforcement content for JRCP.

Slab thickness, in.	Minimum percent reinforcement **
5 - 6.5	0.15
6.5 - 7.5	0.16
7.5 - 8.5	0.17
8.5 - 9.5	0.18
9.5 - 10.5	0.19
10.5 - 11.5	0.20
11.0 - 12.5	0.21
12.0 - 13.5	0.22
13.5 - 15.0	0.23

**Required deformed reinforcement to limit the number of deteriorated transverse cracks to 25/mi or less. Results checked across all climatic zones. Slab thickness depends on traffic levels, subgrade support, and other factors.

4B.9 Reinforcement Design for CRCP

Reinforcement is placed in CRCP to hold transverse cracks very tight so that vertical shear load from heavy axles is carried by aggregate interlock. Because no transverse joints are placed in CRCP, and due to the restraint of the reinforcement, many closely spaced transverse cracks will develop. The most critical aspect of these cracks is to hold them very tight so that aggregate interlock is not lost and so that chlorides do not infiltrate to the steel. Although much literature states that a 3 to 6 ft crack spacing is optimum, other research shows that crack width is the more critical parameter in minimizing punchouts and ruptured steel. There exists many CRCP in the U.S. and Europe with higher steel percentages that have very short transverse crack spacing (i.e. < 3 ft) that exhibit no punchouts. [16,26]

recommendations on materials quality levels for various design cells defined by traffic level, subgrade, and climatic for flexible pavements. These guidelines are based on engineering judgement and must be tailored to specific local situations and materials.

Table 28. Recommended materials quality levels for various design cells to minimize erosion for rigid pavements.

Design Cells	Rigid Traffic ESALs	Subgrade	Climate	Base Material Recommendations
1-6	<3 million	All	All	Class E or D
7, 8, 9	3 - 6	All	All	Class D or C
12, 15	6 - 18	Strong	Non-freeze	Class B
12, 15	6 - 18	Strong	Freeze	Class A
10, 11, 13, 14	6 - 18	Very Soft, Weak-Fair	All	Class A
16 to 27	18 - 150	All	All	Class A

Table 29. Recommended materials quality levels for various design cells to minimize erosion for flexible pavements.

Design Cells	Flexible Traffic ESALs	Subgrade	Climate	Base Material Recommendations
1 to 8	<2 million	All	All	Class E or D
9 to 12	2 - 4	All	All	Class D or C
16, 20	4 - 12	Strong	Non-freeze	Class B
16, 20	4 - 12	Strong	Freeze	Class A
13, 14, 15, 17, 18, 19	4 - 12	Very Soft, Weak-Fair	All	Class A
21 to 36	12-90	All	All	Class A

4C.4 Subdrainage Recommendations

Conceptually, the need for improving any specific design feature (such as subdrainage) for any given pavement structure and site conditions (traffic, climate, subgrade) should be determined through a detailed performance evaluation and life-cycle cost analysis where the various alternative levels of subdrainage are compared. The alternative level with the lowest life-cycle cost that also meets the project performance criteria would logically be that recommended for construction for the given project.

The various levels of subdrainage and materials requirements listed above (i.e., Level 1: Sealing Joints and Cracks/Geometrics, Level 2: Non-erodible Materials, Level 3: Edge drains and Non-erodible Materials, Level 4: Full Subdrainage System (including a permeable drainage layer) will progressively increase the cost of construction and maintenance of the pavement, and thus they must result in a corresponding increase in life of the pavement to be cost effective. If the design engineer does not have the performance prediction models that are needed to predict the increase in life and rehabilitation costs, the following general recommendations are provided that are expected to result in the most cost-effective pavement design for most situations. However, these must be tailored to local conditions.

Table 30 provides recommendations for non-doweled JPCP, Table 31 for doweled JPCP and JRCP, and CRCP, and Table 32 for flexible pavements.

Table 30. Recommended levels of subdrainage based on site conditions for non-doweled JPCP.

Design Cells	Rigid Traffic ESALS	Subgrade	Climate	Subdrainage Recommendations
1, 2, 3	<1.5 million	All	All	Level 1
6	1.5 - 3	Strong	Dry, Wet	Level 1
4, 5	1.5 - 3	Very Soft, Weak-Fair	Dry, Wet	Level 2
7, 8, 9	3 - 6	All	Dry	Level 2
7, 8	3 - 6	Very Soft, Weak-Fair	Wet	Level 3 (treated base required)
9	3 - 6	Strong	Wet	Level 2 (treated base required)

Table 31. Recommended levels of subdrainage based on site conditions for doweled JPCP, JRCP and CRCP.

Design Cells	Rigid Traffic ESALS	Subgrade	Climate	Subdrainage Recommendations
6	1.5 - 3	Strong	Dry, Wet	Level 1
4, 5	1.5 - 3	Very Soft, Weak-Fair	Dry, Wet	Level 1
7, 8, 9	3 - 6	All	Dry	Level 1
7, 8, 9	3 - 6	All	Wet	Level 2
10, 11, 12, 13, 14, 15	6 - 18	Strong	Dry, Wet	Levels 3
10, 11, 12, 13, 14, 15	6 - 18	Very Soft, Weak-Fair	Dry, Wet	Levels 3 (treated base required), or Level 4*
16 to 27	18 - 150	All	Dry, Wet	Level 3 (treated base required), or Level 4*

*Level 4 NOT recommended for CRCP.

Table 32. Recommended levels of subdrainage based on site conditions for flexible pavements.

Design Cells	Flexible Traffic ESALS	Subgrade	Climate	Subdrainage Recommendations
1 to 4	0.5 - 1	All	All	Level 1
8	1 - 2	Strong	All	Level 2
5, 6, 7	1 - 2	Very Soft, Weak-Fair	All	Level 2
9 to 12	2 - 4	All	Non-freeze	Level 1
9 to 12	2 - 4	All	Freeze	Level 2
16, 20	4 - 12	Strong	All	Levels 3
13, 14, 15, 17, 18, 19	4 - 12	Very Soft, Weak-Fair	All	Levels 3 (treated base required), or Level 4
21 to 36	12 - 90	All	All	Level 3 (treated base required), or Level 4

Note that for heavier traffic loadings there are two main alternate subdrainage designs. At this time, the state-of-the-art is not able to distinguish between them in terms of effectiveness. However, a decision to include a level 4 permeable base must require a commitment to continued maintenance of outlets and longitudinal drain pipes or it will be ineffective.

Approach 1 - Seal out moisture (as possible) and provide non-erosive materials

Provide densely graded treated pavement materials that strongly resist softening, disintegration, or stripping in the presence of water. Limit water infiltration into the pavement section through sealing of all cracks as they occur and full width (traffic lanes and shoulders) paving. This includes dense graded hot mixed asphalt base (that has been thoroughly evaluated for stripping potential), or higher strength cement treated base or lean concrete base. Include longitudinal edge drain pipes, lateral outlet pipes, and head wall system to drain any water that seeps into the structural section.

Placement of a granular subbase beneath a dense graded treated base course is highly recommended to provide vertical seepage of excess moisture and to reduce erosion beneath the treated base course. The amount of fines in the subbase must be limited to provide for adequate vertical seepage. This is an extremely important recommendation for rigid pavements to reduce erosion beneath a treated base layer. This granular layer will also reduce the pumping of fines from the subgrade into the base course.

When the subgrade is "Very Soft," improvement of the upper portion of this subgrade through placement of a thick granular layer or stabilized material is required in the structural section, as a minimum. Section 5 - Special Subsurface Conditions, provides discussion on additional techniques and approaches that can be considered depending on the local conditions encountered.

Approach 2 - Drain moisture rapidly from pavement section

Provide permeable open-graded asphalt-treated base course beneath the lowest asphalt bound layer, a filter or separation layer, collector system (pipe edge drain), and discharge pipe and head wall system. See Section 4C.5 for design details. Locations where use of a permeable base that may cause problems include very flat terrain with a longitudinal grade of less than 1 percent, and where adequate side ditches cannot be constructed with a

fines into the permeable base. In addition, the placement of a geotextile fabric between the permeable base and granular separator layer will further restrict fines pumping into the permeable layer. Stabilization of the fine-grained subgrade or placement of a thick granular layer over the subgrade, beneath the filter layer, is also strongly recommended to reduce further the potential of excess moisture problems.

4C.5 Basic Elements of a Level 4 Subsurface Pavement Drainage System

The basic components of a fully functional Level 4 subdrainage system include the following:[27-55]

- Permeable treated base drainage layer.
- Separation layer(s).
- Collector system (pipe edge drain) (must be maintained).
- Discharge pipe and head wall system (must be maintained).

Everyone of these components must perform its function or the drainage system will fail. It is important to note that a pavement subdrainage system that includes these components is only meant to address problems that are related to water that infiltrates into the pavement from the surface. Appropriate foundation/subgrade drainage measures need to be taken during construction to mitigate against moisture-related problems that result from a high water table, seepage, capillary action, and other sources of water; particularly in cut areas. A level 4 system is not recommended for CRCP due to potential problems.

Permeable Bases. Permeable bases provide a means for rapidly draining the water that is able to get into the pavement and is an essential part of a subsurface drainage system. They involve the placement of a base of sufficient thickness and permeability above the subgrade to drain the water from the pavement layers above and prevent saturation. A thickness of 4 in is recommended and the base usually extends 1 to 3 ft beyond either edge of the pavement [27,32]. A permeable base must provide three very important functions [33]:

- The base material must be permeable enough so that the base course drains within the design time period.
- The base course must have enough stability to support the pavement construction operation, and must not cause premature distress in the surface layer.

- The base course must have enough stability to support the pavement construction operation, and must not cause premature distress in the surface layer.
- The base course must have enough stability to provide the necessary support for the pavement structural design over the entire design life.

The two types of permeable bases are untreated and treated. Asphalt or cement are the usual agents used for stabilizing the base to obtain a material that provides a stable working platform, and yet has the required permeability.

An effective permeable base should be able to drain water from the pavement within 2 hours after the end of rainfall. This can be achieved if the coefficient of permeability of the base is greater than 1,000 ft/day. However, this must be balanced with the need to provide a permeable base stable enough to withstand traffic loading during construction and normal service. Also, the materials for both treated and untreated permeable bases must be hard, durable, crushed, angular aggregates with virtually no fine or minus No. 200 sieve material [28]. Gradations will vary depending on whether the base is treated or untreated.

<u>Asphalt-Treated Permeable Base</u>
The specifications for asphalt-treated permeable bases (ATPB) vary from state to state and typically include specifications on the following [28,33]:

- asphalt cement content, grade, and permeability.
- gradation of the base.
- aggregate material quality tests.

An ATPB layer typically consist of an open-graded aggregate in which particles are restricted to the range between No. 4 and 3/4" sieves, that are mixed with enough asphalt to bind the aggregate into a stable mass. The asphalt content typically ranges between 1.5 and 2.5 percent by weight of 85 to 100 penetration grade asphalt cement [28,32]. The asphalt content functions only as a binder for the open-graded aggregate and in no way hinders the flow of water through the drainage layers. Typical gradations specified by a number of State highway agencies for asphalt-treated permeable bases (ATPB) are provided in reference 27; it also provides accompanying materials specifications relating to the asphalt cement content, permeability, aggregate, and anti-strip requirements. Adequate compaction of the base with a 5 to 10 ton steel-wheeled roller is usually achievable in one to three passes.

Cement-Treated Permeable Base

Cement-treated permeable bases are similar to their asphalt counterparts in that they include a small amount of cement added to bind the base to provide a stable material. Application rates range from 2 to 4 bags per cubic yard of base material [27]. This small amount of cement is adequate to provide a stable platform for concrete paving operations. Water contents should prevent segregation but must be adequate for the cement paste to flow to points in the base layer to promote cementing between aggregate particles [27]. Vibrating screeds and plate have been used to provide good compaction of CTPBs. Curing of the base is one aspect of CTPB construction that requires a lot of attention. Methods that have been used include covering the base with polythylene sheeting for 3 to 5 days or spraying a fine water mist on the base several times a day after it is placed. The best approach to finding out the most appropriate curing and compaction methods is to construct a test patch for evaluation [27].

Untreated Permeable Base

In comparison to the materials used for stabilized permeable bases, untreated materials contain more smaller sized aggregates to provide the aggregate interlock required for stability. This also means that the permeabilities of untreated permeable bases are much lower than those of stabilized permeable bases. Typical permeabilities range from 200 to 3,000 ft/day [32]. Just as ATPB, adequate compaction of the base can be achieve with one to three passes of a 5 to 10 ton steel-wheeled roller. Treated permeable bases are recommended for both flexible and rigid pavements.

Separator/Filter Layer. When permeable bases are used, a separator/filter layer is required between the base and the subgrade to prevent contamination of the base from fines in the subgrade. Substantial migration of fines from the subgrade will cause failure of the permeable base and significant pumping and other moisture related problems. The separator layer can act as a filtration layer, or a low permeability layer that will help direct water to the edge drain system, as well as minimize the infiltration of water from the top layers into the subgrade. The recommended separator layer is a properly graded aggregate layer. Aggregate layers have been most successful in keeping fines from infiltrating the permeable base layer. Aggregate separator/filter layers are typically 4 or more inches thick. In addition, the placement of a geotextile fabric between the permeable abase and aggregate separator layer is recommended as added insurance against pumping of fines into the permeable base. The geotextile should be 10-12 ounces per square yard minimum. A lime treated subgrade is not recommended as a separator layer, even in conjunction with a geotextile since it will likely pump up into the permeable base.

Longitudinal Edge Drains. Longitudinal edge drains, particularly used in conjunction with permeable bases, will improve the subsurface drainage of pavements [27,28,40]. Pipe edge drains that have been used include a 3- to 6-inch pipe in a trench with the appropriate backfill material. Geocomposite fin drains wrapped in geotextile are also used [40,41]. Factors that need to be taken into consideration in the design of an effective pipe edge drain are the amount of water to be discharged, the condition of the permeable base, and the amount of fines in the base and backfill material.

It is very important to ensure that an edge drain placed in a pavement with a permeable base can effectively drain water at all points along the pavement. The location of the edge drain is essential to performance. Because the pavement/shoulder joint is the primary point of entry for infiltrated water into the pavement, an edge drain that is adjacent to the joint and under the shoulder is most effective for quick subdrainage.

Recommended Cross-Sections. Recommended cross-section designs for full subdrainage systems are provided in figures 32 and 33 for flexible and rigid pavements, respectively. These recommendations provide for a good flow of water after it enters the cross section until it discharges from the lateral headwall.

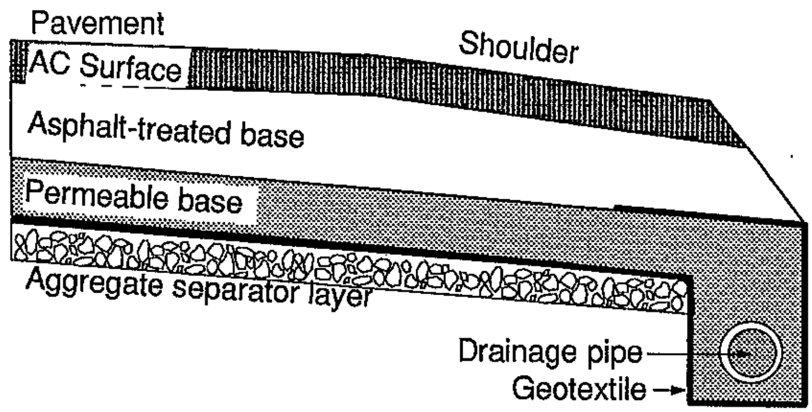


Figure 32. Recommended cross section of full subdrainage system for flexible pavement.

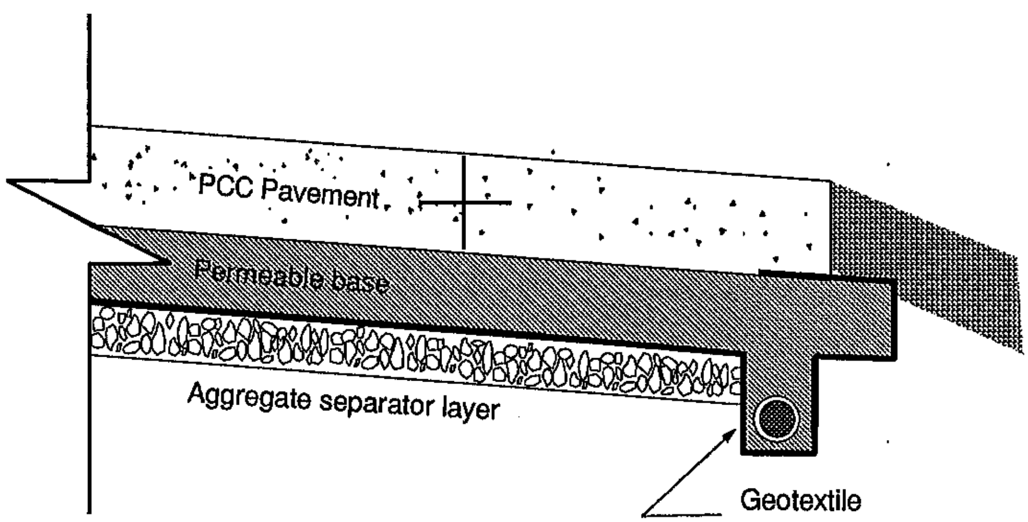


Figure 33. Recommended cross section of full subdrainage system for rigid pavement.

SECTION 5 SPECIAL SUBSURFACE CONDITIONS

Special subsurface conditions, such as swelling soils and frost-susceptible soils must be considered in pavement design. Section 5 provides guidelines on how to identify and address these special subsurface conditions. Four special subsurface conditions are included in this section of the catalog. These conditions are:

1. Collapsible or highly compressible soils
2. Expansive or swelling soils
3. Subsurface water flow and/or saturated soils
4. Frost susceptible soils

However, in all of these considerations, the provision of a uniform soil in the upper portion of the subgrade relative to textural classification, moisture, and density cannot be over emphasized. This uniformity can be achieved through subcutting and/or soil replacement, etc., along with test rolling. In addition, tapers should be provided when changing soil types.

5.1 Subsurface Investigations to Identify Special Conditions

The horizontal and vertical variations in subsurface soil types, moisture contents, densities and water table depths should be identified. Appendix B provides general requirements for subsurface investigations for pavement design. Each soil strata encountered should be characterized for its use to support pavement structures and whether the subsurface soils will impose special problems for the construction and long term performance of pavement structures. Table 33 provides a general summary of the different soil types and/or groups, as related to pavement performance and design.

Table 33. Summary of soil characteristics as a pavement material.

Major Divisions		Name	Subgrade Strength When Not Subject to Frost Action	Potential Frost Action	Compressibility and Expansion	Drainage Characteristics
Gravel and Gravelly Soils	GW	Well-graded gravels or gravel-sand mixtures, little or no fines	Excellent	None to Very Slight	Almost None	Excellent
	GP	Poorly graded gravels or gravel-sand mixtures little or no fines	Good to Excellent	None to Very Slight	Almost None	Excellent
	GM– d	Silty gravels, gravel-sand silt mixtures	Good to Excellent	Slight to Medium	Very Slight	Fair to Poor
	GM– u		Good	Slight to Medium	Slight	Poor to Practically Impervious
	CC	Clayey gravels, gravel-sand-clay mixture	Good	Slight to Medium	Slight	Poor to Practically Impervious
Sand and Sandy Soils	SW	Well-graded sands or gravelly sands, little or no fines	Good	None to Very Slight	Almost None	Excellent
	SP	Poorly graded sands or gravelly sands, little or not fines	Fair to Good	None to Very Slight	Almost None	Excellent
	SM– d	Silty sands, sand-silt mixtures	Fair to Good	Slight to High	Very Slight	Fair to Poor
	SM– u		Fair	Slight to High	Slight to Medium	Poor to Practically Impervious
	SC	Clayey sands, sand-clay mixtures	Poor to Fair	Slight to High	Slight to Medium	Poor to Practically Impervious

Table 33. Summary of soil characteristics as a pavement material (continued).

Major Divisions		Name	Subgrade Strength When Not Subject to Frost Action	Potential Frost Action	Compressibility and Expansion	Drainage Characteristics
Silts and Clays LL is Less than 50	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sand or clayey silts with slight plasticity	Poor to Fair	Medium to Very High	Slight to Medium	Fair to Poor
	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays silty clays, lean clays	Poor to Fair	Medium to High	Slight to Medium	Practically Impervious
	OL	Organic silts and organic silt-clays or low plasticity	Poor	Medium to High	Medium to High	Poor
Silts and Clays LL is Greater than 50	ME	Inorganic silts, micaceous or diatomaceous fine sand or silty soils, elastic silts	Poor	Medium to Very High	High	Fair to Poor
	CH	Inorganic clays of high plasticity, fat clays	Poor to Fair	Medium to Very High	High	Practically Impervious
	OH	Organic clays of medium to high plasticity, organic silts	Poor to Very Poor	Medium	High	Practically Impervious
Highly Organic Soils	Pt	Peal and other highly organic soils	Not Suitable	Slight	Very High	Fair to Poor

5.2 Collapsible or Highly Compressible Soils

Effect of Compressible Soils

Collapsible and/or highly compressible (very weak) soils are susceptible to large settlements and deformations with time which can have a detrimental effect on pavement performance. If these compressible soils are not properly treated, large surface depressions with random cracking can develop. The surface depressions can allow water to pond on the pavement's surface and more readily infiltrate the pavement structure compounding a severe problem. More importantly, the ponding on water will also create a safety hazard to the traveling public during wet weather.

Improvements for Compressible Soils

In order to provide an adequate foundation of the pavement structure, various techniques can be used. The selection of a particular technique is dependent upon the depth of the weak soils, and the difference between the insitu conditions and the minimum compaction and/or strength requirements to limit the amount of anticipated settlement to a permissible value that will not adversely affect pavement performance.

When constructing roadways in areas with deep deposits of highly compressible layers (very low density saturated materials), an examination of the specific soil properties to calculate the estimated settlement must be done. Under these conditions, a complete geotechnical investigation and detailed settlement analysis must be completed prior to the pavement design. When existing subgrade soils do not meet minimum compaction requirements and are susceptible to large settlements over time, consider the following alternatives:

(1) Remove and process soil to attain the approximate optimum moisture content and replace and compact.
(2) Remove and replace subgrade soil with suitable borrow or select embankment materials. All granular fill materials should be compacted to at least 95% of maximum density, as defined by AASHTO T180. Cohesive fill materials should be compacted to no less than 90%, as defined by AASHTO T99.
(3) Compact soils from the surface, to increase the dry density through dynamic compaction techniques.

(4) Consolidate deep deposits of very weak-saturated soils with large fills prior to pavement construction. After consolidation, the fills can either be left in place or removed, depending on the final elevation.

5.3 Subsurface Water Flow and Saturated Soils

Effect of Subsurface Water

It is critically important to identify any saturated soil strata, the depth to ground water, and/or subsurface water flow between soil stratas. Subsurface water is especially important to recognize and identify in the transition areas between cut and fill segments. Subsurface water, if allowed to saturate unbound base/subbase materials and subgrade soils, can significantly decrease the strength and modulus of these materials and/or soils. Significant reductions in strength can result in premature surface depressions, rutting and/or cracking. Seasonal moisture flow through selected soil stratas can also significantly magnify the effects of differential volume change in expansive soils. Cut areas are particularly critical for subsurface water.

Improvements to Minimize Effects of Subsurface Water

When saturated soils and/or subsurface water are encountered, consideration should be given to the following alternatives for improving the foundation or supporting subgrade.

1. For saturated soils near the surface, dry and/or strengthen the wet soils through the use of mechanical stabilization techniques to provide a construction platform for the pavement structure (See Section 5.6).
2. Remove and replace the saturated soils with select borrow materials or soils.
3. Place and properly compact thick fills or embankments to increase the elevation of the subgrade, or in other words, increase the thickness (or distance) between the saturated soils or water table depth and pavement structure.
4. Consideration should also be given to the use of subgrade drains whenever the following conditions exist:

    (a) High ground-water levels which may reduce subgrade stability and provide a source of water for frost action.

    (b) In subgrade soils of silts and very fine sands which may become quick or spongy when saturated.

(c) Consider intercepting drains where water seeps from underlying water-bearing strata or from subgrades in cut areas.

Use subsurface drains (perforated collector pipes and filters) in lieu of deep ditches for collecting and transporting ground water. For typical subgrade drain installation, see Section 4C.

5.4 Swelling Soils

Effects of Swelling Soils

Swelling or expansive soils are susceptible to volume change (shrink and swell) with seasonal fluctuations in moisture content. The magnitude of this volume change is dependent on the type of soil (shrink-swell potential) and its change in moisture content. A loss of moisture will cause the soil to shrink, while an increase in moisture will cause it to expand or swell. This volume change of clay type soils can result in longitudinal cracks near the pavement's edge and significant surface roughness (varying swells and depressions) along the pavement's length.

Expansive soils are a very significant problem for pavement design in many parts of the U.S., and are responsible for the application of premature maintenance and rehabilitation activities on many miles of roadway each year. Expansive soils are especially a problem when deep cuts are made in a dense (over-consolidated) clay type soil.

When constructing roadways and areas with thick-highly expansive clay soils, laboratory tests should be conducted to determine the shrink-swell potential of the soil, and to estimate the potential volume change after pavement construction. Under these conditions (especially if deep cuts are required), a complete geotechnical and laboratory investigation and detailed volume change analysis should be completed prior to the pavement design.

Identification of Expansive Soils

Techniques for identifying potentially expansive soils are given in the following documents. [22, 23, 24]

1. "An Evaluation of Expedient Methodology for Identification of Potentially Expansive Soils", Report No. FHWA-RD-77-94, Federal Highway Administration, Washington, D.C., June 1977 (D.R. Snethen, L.D. Johnson and D. M. Patrick).
2. "Design and Construction of Airport Pavements on Expansive Soils", Report No. FAA-RD-76-66, Federal Aviation Administration, U.S. Department of Transportation, Washington, D.C., June 1976 (R.G. McKeen).

Figure 34 illustrates a selection process used by the Federal Aviation Administration for identification of expansive soils. Although test procedures can be used to measure the shrink-swell potential of soils, experience plays an important role in identifying those conditions requiring special treatments.

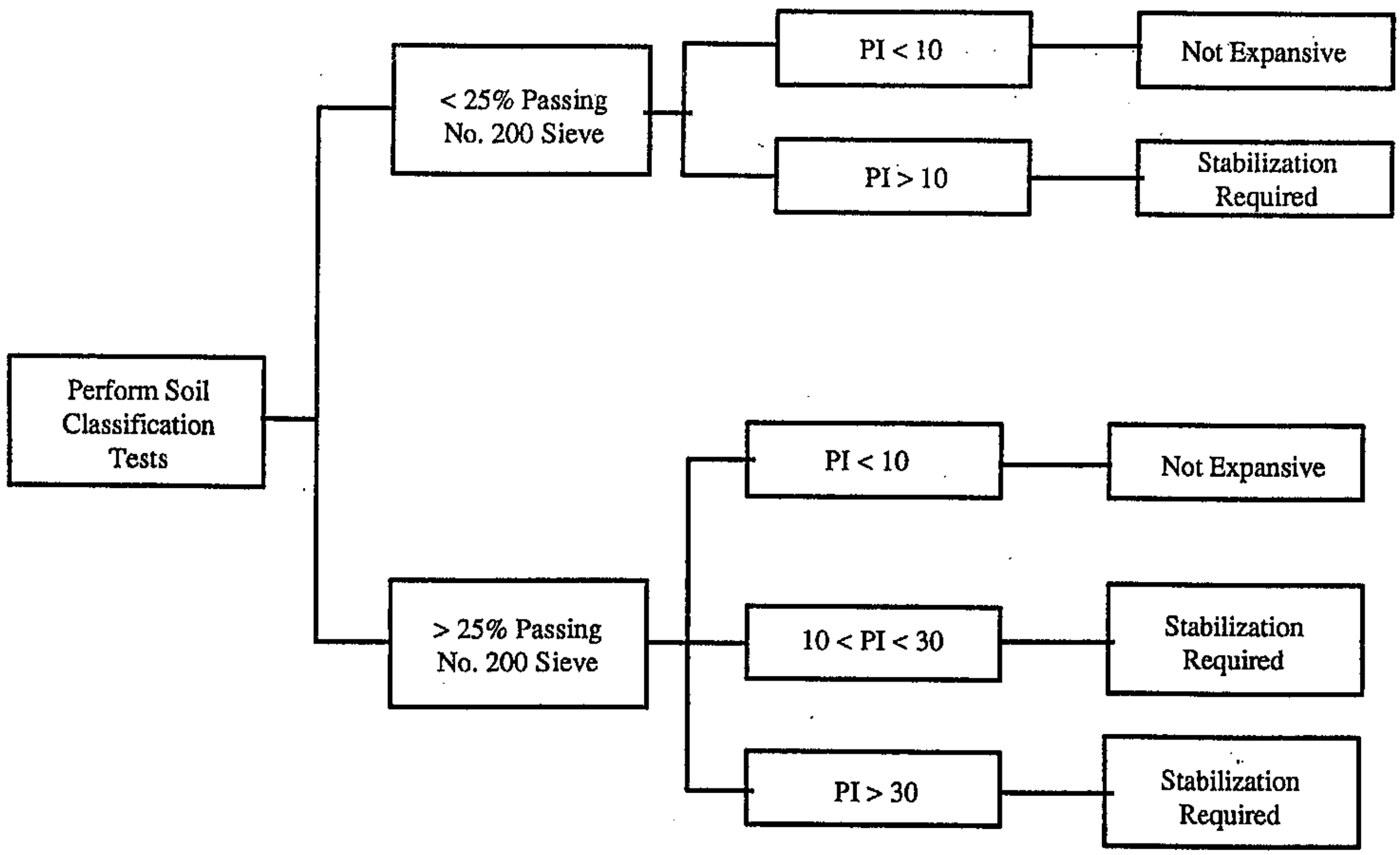


Figure 34. General flow diagram for determining if a soil can be stabilized to reduce the swelling potential.

Improvements for Expansive Soils

When expansive soils are encountered along a roadway project in environments and areas where significant moisture fluctuations in the subgrade are expected, consideration should be given to the following alternatives to minimize future volume change potential of the expansive soil.

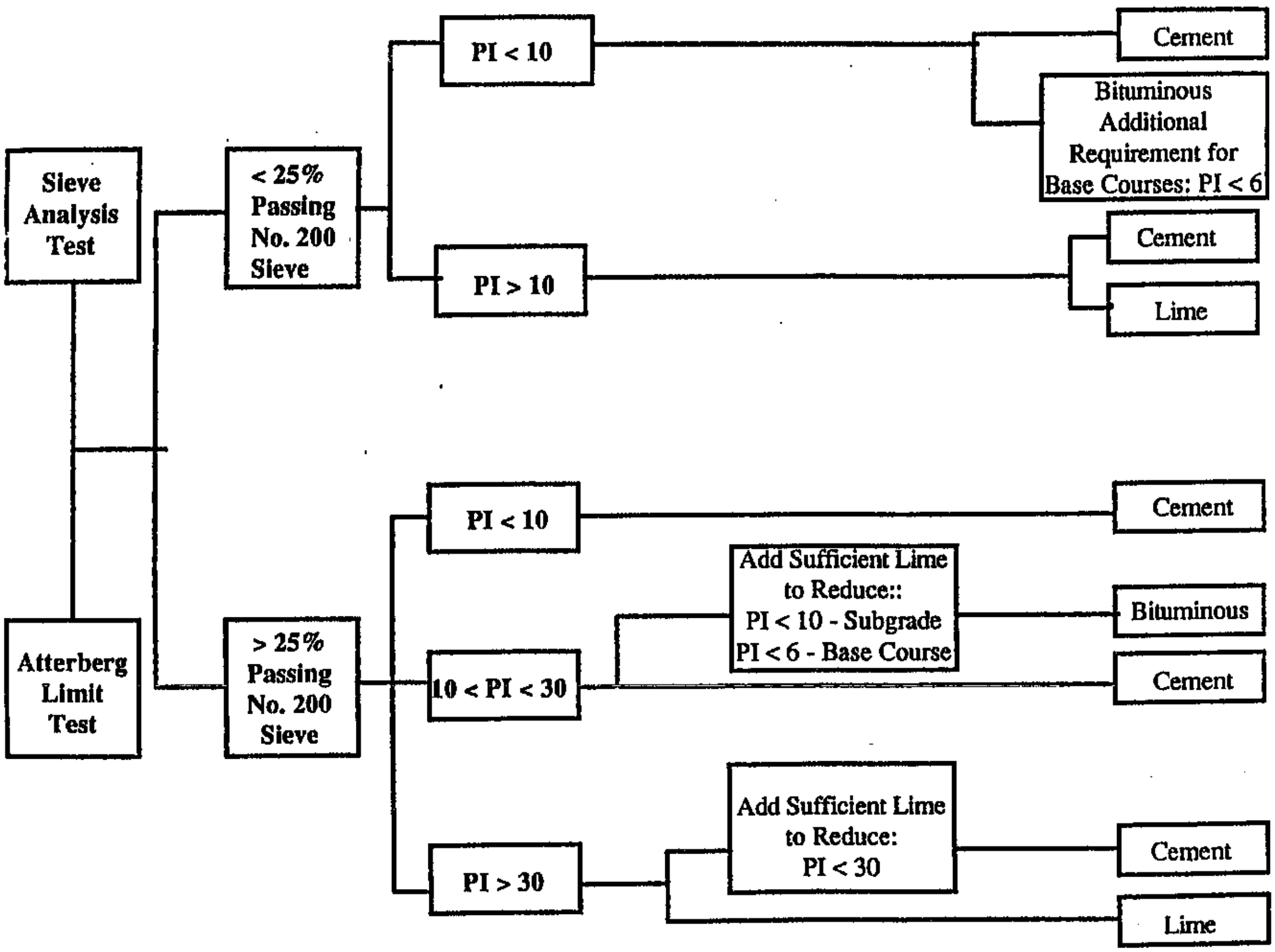


Figure 35. Flow diagram to determine the type of stabilizer for a specific soil condition.

Improvements for Expansive Soils

When expansive soils are encountered along a roadway project in environments and areas where significant moisture fluctuations in the subgrade are expected, consideration should be given to the following alternatives to minimize future volume change potential of the expansive soil.

1. For relatively thin layers of expansive clays near the surface, remove and replace the expansive soil with select borrow materials.
2. Extend the width of the subsurface pavement layers to reduce the loss of subgrade moisture along the pavement's edge.
3. Scarify, stabilize and recompact the upper portion of the expansive clay subgrade. Lime or cement stabilization is an accepted method for controlling the swelling of soils. Stabilization as used here refers to the treatment of a soil with such agents as bitumen, portland cement, slaked or hydrated lime, and fly ash to limit its volume change characteristics. This sometimes also substantially increases the strength of the treated material. The logic pattern contained in Figure 35 can then be used to select a suitable soil stabilizer.
4. In areas with deep cuts in dense, over consolidated expansive clay soils, complete the excavation of the surface soils to the proper elevation and allow the subsurface soils to rebound prior to placing the pavement layers.

5.5 Frost-Susceptible Soils

Effects of Frost Action

Frost action can cause differential heaving, surface roughness and cracking, blocked drainage, and a reduction in bearing capacity during thaw periods. These effects range from slight to severe, depending on types and uniformity of subsoil and the availability of water. Pavement design for frost action often determines the required overall thickness of flexible pavements and the need for additional select material beneath both rigid and flexible pavements.

***Frost Heaving*.** Surface heaving results from the growth of ice lenses in the pavement components or subgrade. Whether heave is uniform or nonuniform depends upon the uniformity of moisture content, soil characteristics, the depth of fill, and the depth to ground water. Uniform heave is generally not troublesome, but nonuniform heave can result in serious irregularities in the surface of flexible pavements and cracking in rigid pavements. Differential heave is usually the result of variations in subgrade soils, soil moisture and transitions from cut to fill with high ground water level.

Formation of Ice Lenses. Water tends to move toward the cold regions of the pavement, where it freezes in the form of lenses. The lenses grow by the attraction of water supplied from: (1) underlying water table, (2) infiltration from above, (3) lateral flow, especially from cracks, joints, and shoulder areas, or (4) water held within voids of fine-grained soils. To have serious formation of ice lenses three conditions must exist:

(1) Soil must be frost susceptible;
(2) Freezing temperatures must penetrate soil;
(3) A source of water must be available.

Thawing and Reduction in Strength. During thawing periods, the upper ice lenses melt, releasing water which moves into the base course. If the subsurface drains are blocked with ice or if adequate drainage has not been provided, the base course can become saturated and weakened. Traffic during this period causes high stresses in the subgrade, resulting in excess pore pressures and reduced strength.

Identification of Frost Susceptible Soils and Conditions

The potential for ice segregation in a soil under specified freezing conditions and, in the presence of available water, is its frost susceptibility. Some soils have a high capillary rate and are not cohesive, thus assisting passage of water to the ice lenses. A heavy formation of ice takes place at each successive level as the freezing temperature penetrates deeper into the ground, resulting in severe frost heave. Frost-susceptible soils have been classified into four general groups: F1, F2, F3 and F4, listed approximately in the order of increasing susceptibility to frost heaving (See Table 34). Little or no frost action is likely to occur in sands, gravels, crushed rock, cinders and similar granular materials, when clean and free draining, under normal freezing conditions. The large voids permit water to freeze in place without segregation into ice lenses. Conversely, silts are highly frost-susceptible. The combination of relatively small voids, high capillarity, and relatively good permeability of these soils accounts for this characteristic.

Table 34. Frost susceptibility classification of soils.

Frost Group	Degree of Frost Susceptibility	Type of Soil	Percentage Finer than 0.02 mm by Weight	Typical Soil Classification
F1	Negligible to low	Gravelly soil	3-10	GO, GP, GO-GM, GP-GM
F2	Low to medium	Gravelly soils	10-20	GM, GO-GM, GP-GM
		Sands	3-15	SW, SP, SM, SW-SM, SP-SM
F3	High	Gravelly soils	Greater than 20	GM-GC
		Sands, except very fine silty sands	Greater than 15	SM, SC
		Clays PI>12	---	CL, CH
F4	Very high	All silts	---	ML-MH
		Very fine silty sands	Greater than 15	SM
		Clays, PI<12	---	CL, CL-ML
		Varved clays and other fine grained, banded sediments	---	CL, ML, SM, CH

Clays are cohesive and, although their potential capillarity is high, their capillarity rate is low. Although frost heaving can occur in clay soils, it is not as severe as for silts, since the impervious nature of the clays makes passage of water slow. The supporting capacity of clays may be reduced greatly during thaws, although significant heave has not occurred. Thawing usually takes place from the top downward, leading to very high moisture contents in the upper strata.

A ground water level within five feet of proposed subgrade elevation is an indication that sufficient water will exist for ice lense formation. However, homogeneous clay subgrade soils contain sufficient moisture for ice formation, even with depth to ground water in excess of ten feet.

Unsealed joints and cracks in the pavement surface and poorly drained pavement and shoulder surfaces are common sources of trapped water. Special attention should be given to these potential sources of water, and provide joint details and grades to minimize their influence.

Improvements for Frost Susceptible Soils

When frost susceptible soils are encountered, consideration should be given to the following alternatives for improving the foundation or supporting subgrade.

1. Remove and replace the frost susceptible soil (Groups F3 and F4) with select borrow materials that are nonfrost susceptible to the depth of expected frost penetration.
2. Place and compact select borrow materials that are nonfrost susceptible to a thickness or depth to prevent subgrade freezing for frost susceptible soil Groups F2, F3, and F4.
3. Removal of isolated pockets of frost-susceptible soils to eliminate abrupt changes in subgrade conditions.
4. Increase the pavement structural layer thicknesses to account for a strength and stiffness reduction of the subgrade soils during spring-thaw for frost susceptible soils Groups F1, F2 and F3.

Pavement Design Considerations for Frost

The design freezing index is the basic value for measuring temperature effects. It is proportional to the magnitude and duration of subfreezing temperatures during the winter season. For pavement design, use the freezing index for the coldest year in a 10-year cycle or the average of the three coldest winters in the last 30 years on record. Figure 36 shows freezing index values for the continental United States. However, contact local public utility companies to confirm depth of frost penetration.

Design to Prevent Frost Penetration into Subgrade. This method essentially eliminates surface deformation and thaw problems resulting from formation of ice lenses in the subgrade, by providing nonfrost-susceptible base and subbase courses of sufficient thickness to prevent the underlying soils from freezing.

This method should be used only in exceptionally difficult situations, when soil and moisture conditions are extremely variable over the area, where the subgrade soil is F3 or F4, and where limited differential heave can present severe operational problems.

Determine the design freezing index and depth of frost penetration from Figures 36 and 37, respectively. Adjust this by reliable local experience, when available. Make overall pavement thickness, including base, subbase and any additional select embankment or material courses, equal to the depth of frost penetration. The additional depth of material required to prevent subgrade freezing must consist of a nonfrost-susceptible material.

Design for Limited Subgrade Frost Penetration. This method should not be used with the pavement cross-sections included in this catalog, because it requires adjustments to the individual layer thicknesses.

This method determines the depth of frost penetration from Figures 36 and 37. From this frost depth, the proposed thickness of asphalt concrete and other layers are adjusted to account for the increase in damage due to a weakening of the soils during the spring-thaw period. When designing for a limited subgrade protection, a detailed analysis is required for adjusting the layer thicknesses.

Base and subbase courses in areas subjected to frost action must consist of nonfrost-susceptible materials. A conservative general requirement for such materials is that they have less than 8% by weight smaller than the No. 200 sieve. In some cases, laboratory freezing tests are desirable to determine frost susceptibility of economically available materials which do not meet this general requirement. Provide base course drainage according to the requirements of Section 4.C.

When designing pavements by the limited frost penetration method, the bottom four to six inches of base should have the proper gradation to act as a filter between base and subgrade. Sand, gravelly sand, screenings, or similar materials prevent infiltration of the frost-susceptible subgrade into the overlying courses during and following the frost melting period.

5.6 Subgrade Improvement by Stabilization

In certain instances, marginal subgrade soils are stabilized to improve their strength and stiffness characteristics. Native subgrade and lower quality borrow embankment materials can be improved with the use of a cement, bitumen, or lime stabilizing agent. For stabilization or modification of cohesive subgrade soils, hydrated lime is the most widely used. Lime is applicable in clay soils (CH, CL) and in granular soils containing clay binder (GC, SC), while portland cement is more commonly used in nonplastic soils. Lime reduces the Plasticity Index (PI) and renders a clay soil less sensitive to moisture changes. Consider the use of lime whenever the PI of the soil is greater than 10.

a. **Lime Treatment**. Lime treatment or modification consists of the application of from one to three percent hydrated lime to aid drying of the soil and permit compaction. As such, it is useful in the construction of a "working platform" to expedite construction. Lime modification may also be considered to condition a soil for follow-on stabilization with cement or bitumen. Lime treatment of subgrade soils is intended to expedite construction, and no reduction in the required pavement thickness should be made.

b. **Lime or Cement Stabilization**. Lime and/or cement stabilization of very soft to weak soils is normally used to improve the material, or layer on which the pavement base and/or subbase layers can be property constructed and compacted. When used, these treated soils should be allowed to cure a minimum of seven days prior to any further pavement materials/layers are placed.

   For lime stabilization of clay (or highly plastic) soils, the lime content should be from 3% to 8% of the dry weight of the soil, and the cured mass should have an unconfined compressive strength of at least 50 psi within 28 days. The optimum lime content should be determined with the use of unconfined compression and Atterburg Limits tests on laboratory lime-soil mixtures molded at varying percentages of lime. The lime-stabilized subgrade layer should be compacted to a minimum density of 95%, as defined by AASHTO T99.

   For cement stabilization of granular and/or nonplastic soils, the cement content should be from 3 to 10% of the dry weight of the soil, and the cured material should have an unconfined compressive strength of at least 150 psi within seven days. The portland cement used should meet the minimum requirements of AASHTO M-85. The cement stabilized subgrade should

be compacted to a minimum density of 95% as defined by AASHTO M134. Only fine grained soils can be effectively treated with lime for marginal strength improvement. Lime has been found most effective with clay soils containing montmorillonite, illite and kaolinite. Lime-fly ash treatment is applicable to a broader range of soil types because its cementing action is less dependent on fines contained within the soil.

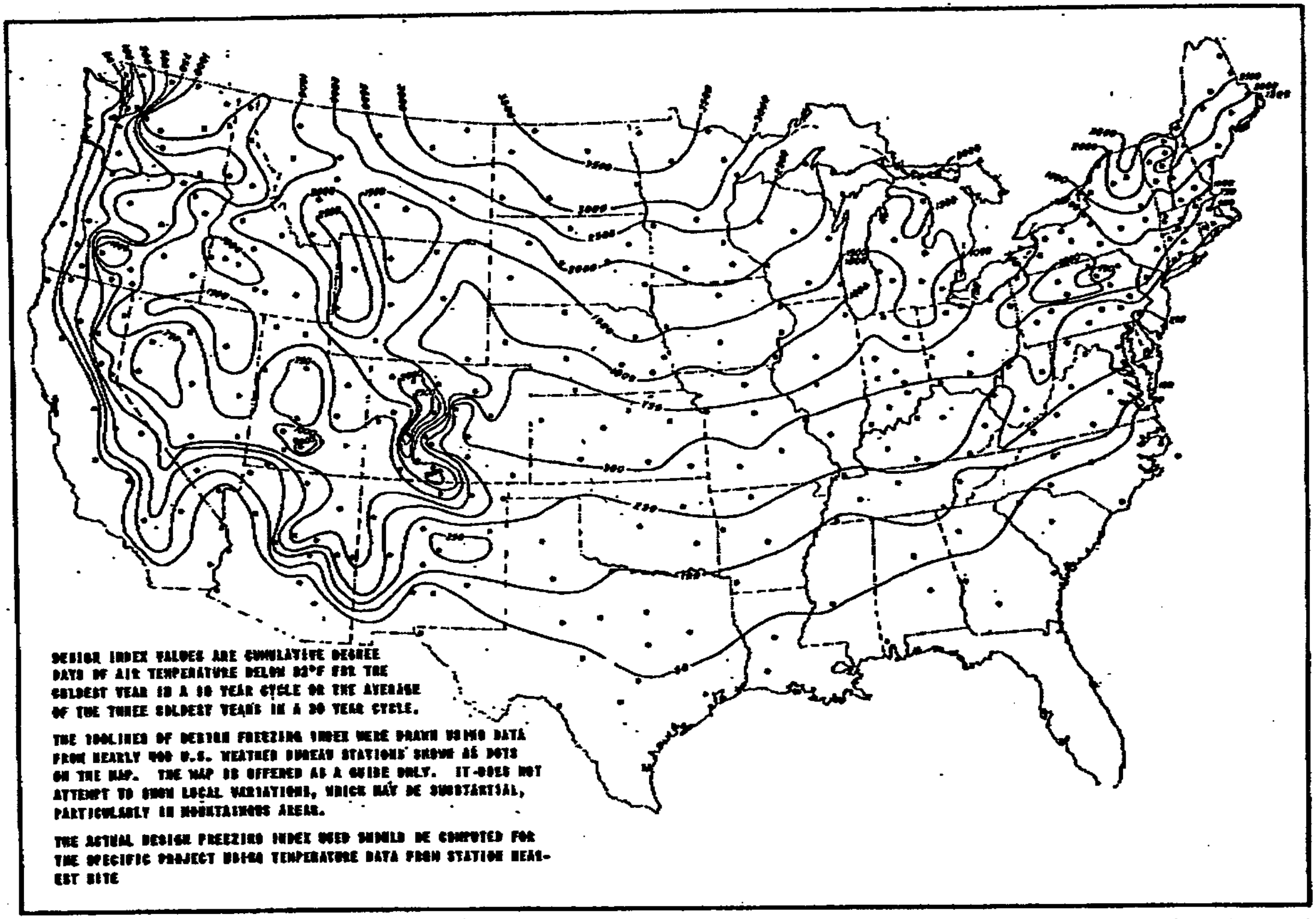
Lime treatment of clay soils can convert the material from one that shows negligible to moderate frost heave to one that is highly susceptible to frost heave. The treated material acts more like a silt than a clay. This adverse effect can be caused by insufficient curing time before freezing occurs. Hence, an adequate curing period is critical to the performance of these materials. The major durability problem associated with lime soil mixtures is resistance to cyclic freeze and thaw action.

Soils classified as CH, CL, MH, ML, SC and GC, with a plasticity index greater than 12, and with at least 10% passing the No. 40 sieve, are potentially suitable for stabilization with lime. Hydrated lime, in powder form or mixed with water as a slurry, is normally used in stabilization. To determine the design lime content for a subgrade soil, the following steps are suggested:

1. Determine the initial design lime content by mixing varying amounts of lime with the soil in water and measuring the pH levels in one hour intervals. Select the lowest lie mixture level for which a pH of 12.4 occurs as the initial design lime content.
2. Prepare specimens at the initial design lime content and at about 2% and 4% lime above that from Step 1 and cure specimens for 28 days at 73ºF (23ºC).
3. Determine the unconfined compressive strength for all cured specimens. Select as the construction design lime content the minimum percent required to achieve a compressive strength of 150 psi (1.03 Mpa).
4. Add one half to one percent additional lime in the lower percentage ranges to compensate for problems associated with non-uniform mixing during construction.

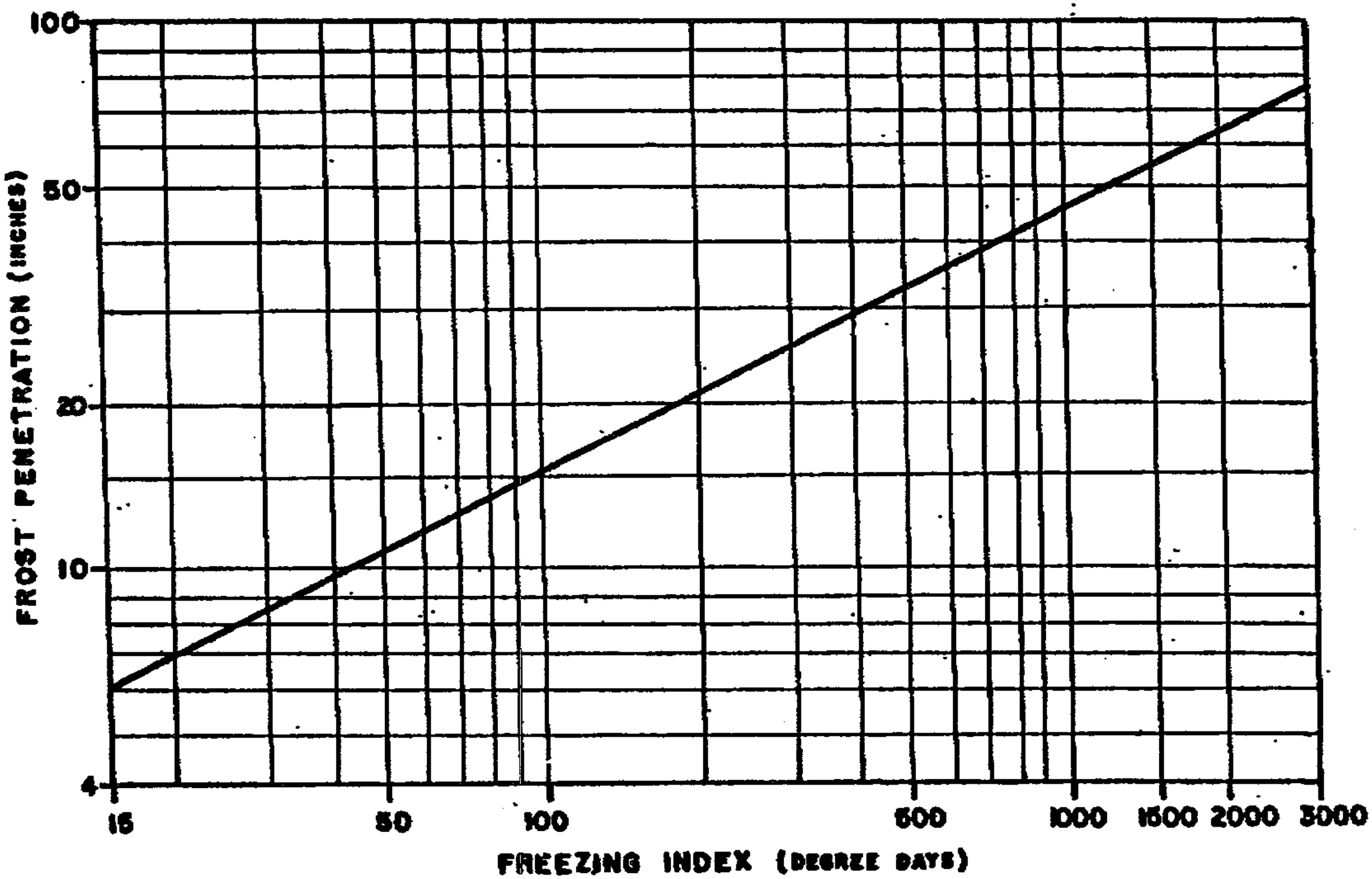
Portland cement is widely used for treating low plasticity clays, sandy and granular materials to improve their strength and stiffness characteristics. At low cement contents, the product is generally termed *cement-modified soil*. These modified soils exhibit additional improvements in such properties as plasticity, expansive characteristics, and frost susceptibility. Relatively small amounts of portland cement can be used to reduce the plasticity index and swell characteristics of many soils. For soils to be stabilized with cement, property mixing requires that the soil have

a plasticity index of less than 20% and a minimum of 45% passing the No. 40 sieve. However, heavier clays that have been treated with lime or fly ash are sometimes suitable for subsequent treatment with portland cement.



Extracted from: "Soils and Geology - Pavement Design for Frost Conditions", TM5-818-2, Department of the Army Technical Manual, Headquarters, Department of the Army, July 1965.

Figure 36. Distribution of design freezing index values in continental United States.



Extracted from: "Soils and Geology - Pavement Design for Frost Conditions", TM 5-818-2, Department of the Army Technical Manual, Headquarters, Department of the Army, July 1965.

Figure 37. Empirical relationship between freezing index and frost penetration beneath snow-free pavement surfaces.

REFERENCES

1. Darter, M. I., H. Von Quintus, E. B. Owusu-Antwi, and Y. J. Jiang, "Systems For Design Of Highway Pavements," Final Report, NCHRP Project 1-32, Transportation Research Board, 1997.
2. Jiang, Y. J., B. Killingsworth, M. I. Darter, H. Von Quintus, and E. B. Owusu-Antwi, "Catalog of Current State Pavement Design Features," Interim Report, NCHRP Project 1-32, Transportation Research Board, February 1996.
3. American Association of State Highway Officials, *AASHTO Guide for design of Pavement Structures*, Washington, D.C., 1986/1993.
4. Hall, K.T., M.I. Darter, T.E. Hoerner, and L. Khazanovich, "LTPP Data Analysis--Phase I: Validation of Guidelines for k Value Selection and Concrete Pavement Performance Prediction," Technical Report FHWA-RD-96-198, 1997.
5. Daleiden, J.F., J.B. Brent, B. Killingsworth, E. Owusu-Antwi, M.I. Darter, and R. Ahmad, *Evaluation of the AASHTO Design Equations and Recommended Improvements*, Strategic Highway Research Program, National Research Council, Washington, DC, 1994.
6. Carpenter, S.H., M.I. Darter, B.J. Dempsey, and S. Herrin, *A Pavement Moisture Accelerated Distress (MAD) Identification System*, Vol 1, FHWA/RD-81/079, Federal Highway Administration, Washington, DC, 1980.
7. Finn, F.N., C. Saraf, R. Kulkarni, K. Nair, W. Smith, and A. Abdullah, "Development of Pavement Structural Subsystems," Final Report, NCHRP Project 1-10B, National Cooperative Highway Research Program, Highway Research Board, February 1977.
8. Treybig, H.J., B.F. McCullough, P. Smith, and H. Von Quintus, "Overlay Design and Reflection Cracking Analysis for Rigid Pavements, Volume 1, Development of New Design Criteria," Final Report No. FHWA-RD-77-66, Federal Highway Administration, August 1977.
9. Barker, W.R. and W.N. Brabston, "Development of a Structural Design Procedure for Flexible Airport Pavements," FFA Report No. FAA-RD-74-199, U.S. Army Engineer Waterways Experiment Station, Federal Aviation Administration, September 1975.

10. Lister, N.W. and C.K. Kennedy, "A System for the Prediction of Pavement Life and Design of Pavement Strengthening," Volume 1, Fourth International Conference Structural Design and Asphalt Pavements, The University of Michigan, August 1979.

11. Lottman, R.P., "Predicting Moisture-Induced Damage to Asphaltic Concrete," NCHRP Report No. 192, National Cooperative Highway Research Program, Transportation Research Board, 1978.

12. The Asphalt Institute, "Mix Design Methods for Asphalt Concrete and Other Hot Mixtures," Manual Series No. 2 (MS-2), College Park, Maryland, March 1979.

13. "Skid Resistance," NCHRP Synthesis of Highway Practice No. 14, National Cooperative Highway Research Program, Highway Research Board, 1972.

14. Daleiden, J.F., J.B. Brent, B. Killingsworth, E. Owusu-Antwi, M.I. Darter, and R. Ahmad, *Evaluation of the AASHTO Design Equations and Recommended Improvements*, Strategic Highway Research Program, National Research Council, Washington, DC, 1994.

15. Yu, H. T., M. I. Darter, K. D. Smith, J. Jiang, and L. Khazanovich, *Performance of Concrete Pavements, Vol III—Improving Concrete Pavement Performance*, Report No. FHWA-RD-95-111 (Draft), Federal Highway Administration, Washington, D.C., 1996.

16. Lee, Y.H. and Darter, M.I., *Development of Pavement Prediction Models*, Research Report 529-2, Illinois Department of Transportation, July 1994.

17. Smith, K.D., A.L. Mueller, M.I. Darter, and D.G. Peshkin, *Performance of Jointed Concrete Pavements, Vol II - Evaluation and Modification of Concrete Pavement Design and Analysis Models*, Report FHWA-RD-89-137, Washington, D. C., July 1990.

18. Darter, M.I., K.T. Hall, and C.M. Kuo, *Support Under Portland Cement Concrete Pavements*, Report 372, TRB, National Research Council, Washington, D.C., 1995.

19. Shober, S.F., and T.S. Rutkowski, "The Effect of PCC Joint Sealing on Total Pavement Performance," 4th ACI World Congress on Joint Sealing and Bearing Systems for Concrete Structures.

20. FHWA, *Pavement Notebook for FHWA Engineers*, Publication No. FHWA-ED-90-016, Washington D.C., September, 1990.

21. Snyder, M.B., *Effects of Reinforcement Design and Foundation Stiffness on the Deterioration of Transverse Cracks in JRCP*, Proceedings: 3rd International Workshop on the Design and Evaluation of Concrete Pavements, September, 1994, Krumbach, Austria. (Published by Centre for Research and Contract Standardization in Civil and Traffic Engineering, The Netherlands).

22. Snethen, D.R., L.D. Johnson, and D.M. Patrick, "An Evaluation of Expedient Methodology for Identification of Potentially Expansive Soils," Report No. FHWA-RD-77-4, Federal Highway Administration, June 1977.

23. Snethen, O.R., L.D. Johnson, and D.M. Patrick, "An Investigation of the Natural Microscale Mechanism that Cause Volume change in Expansive Clays," Report No. FHWA-RD-77-75, Federal Highway Administration, January 1977.

24. McKeen, R.G., "Design and Construction of Airport Pavements on Expansive Soils," Report No. FAA-RD-76-66, Federal Aviation Administration, U.S. Department of Transportation, June 1976.

25. Wisconsin DOT, 1985 Wisconsin Interstate Pavement Rehabilitation Study.

26. Darter, M.I., "Report on the 1992 U.S. Tour of European Concrete Highways," Publication No. FHWA-SA-93-012, Federal Highway Administration, 1993.

27. FHWA, *Drainable Pavement Systems*, FHWA-SA-92-008, Washington, D.C. 1992.

28. FHWA, Technical Guide Paper on Subsurface Pavement Drainage, Technical Paper 90-01, Office of Engineering, Pavement Division, October 1990.

29. Ridgeway, H.H., Pavement Subsurface Drainage Systems, NCHRP Synthesis of Highway Practice 96, Transportation Research Board, Washington, D.C.

30. Moulton, L.K., Highway Subdrainage Design, Report FHWA-TS-80-224, Federal Highway Administration, 1980.

31. Cedergren, H.R., J.A. Arman, and K.H. O'Brein, *Development of Guidelines for the Design of Subsurface Drainage Systems for Highway Pavement Structural Sections*, Report FHWA-RD-73-14, Federal Highway Administration, Washington, D.C., 1973.

32. Mathis, D.M., "Permeable Base Design and Construction," Proceedings: Fourth International Conference On Concrete Pavement Design and Rehabilitation, 1993.

33. Forsyth, R.A., *Asphalt Treated Permeable Material—Its Evolution and Application*, QIP 117, 1994.

34. Dempsey, B.J., S.H. Carpenter, and Darter, *Improving Sudrainage and Shoulders of Existing Pavements—State of the Art*, FHWA Report FHWA/RD-81/077, Washington, DC, 1982.

35. Barenberg, E.J. and D. Brown, *Modeling Effects of Moisture and Drainage of NJDOT Flexible Pavement Systems*, New Jersey Department of Transportation, New Jersey, 1981.

36. Forsyth, R.A., G.K. Wells, and J.H. Woodstrom, "Economic Impact of Pavement Subsurface Drainage," *Transportation Research Record 1121*, Transportation Research Board, Washington, DC, 1987.

37. Cedergren, H.R, "Why All Important Pavements Should be Well Drained," *Transportation Research Record 1188*, Transportation Research Board, Washington, DC, 1988.

38. ERES Consultants, Inc., *Performance of Subsurface Pavement Performance*, NCHRP Project 1-34 Interim Report, Transportation Research Board, Washington, DC, 1996.

39. Kazmierowski, T.J., A. Bradbury, and J. Hajek, "Field Evaluation of Various Types of Open-Graded Drainage Layers," *Transportation Research Record 1440*, Transportation Research Board, Washington, DC, 1994.

40. Koerner, R.M., G.R. Koerner, A.K. Fahim, and R.F. Wilson-Fahmy, *Long-Term Performance of Geosynthetics in Drainage Applications*, NCHRP Report 367, Transportation Research Board, Washington, DC, 1994.

41. Allen, D.L. and J. Fleckenstein, "Evaluation and Performance of Geocomposite Edge drains in Kentucky," *Transportation Research Record 1329*, Transportation Research Board, Washington, DC, 1991.

42. Wells, G.K., *Evaluation of Edge Drain Performance*, Report FHWA/CA/TL-85/15, California Department of Transportation Sacramento, CA, 1985.

43. Wells, G.K., "Improving Pavement Performance," *Virginia Pavement Drainage Workshop*, Virginia Department of Transportation, Williamsburgh,.VA, 1990.

44. Wells, G.K., *Evaluation of Edge Drain Performance*, Report FHWA/CA/TL-85/15, California Department of Transportation Sacramento, CA, 1985.

45. Wells, G.K. "California's Experience with Drained PCC Pavements, *Western States Drainable PCC Pavement Workshop—Summary Report*, FHWA-SA-94-045, Federal Highway Administration, Washington, DC, 1993.

46. Smith, K.D., M.J. Wade, D.G. Peshkin, L. Khazanovich, H.T. Yu, and M.I. Darter, *Performance of Concrete Pavements, Volume II—Evaluation of Inservice Concrete Pavements*, Draft Final Report FHWA-RD-95-110, Federal Highway Administration, Washington, DC, 1996.

48. Smith, K.D., H.T. Yu, and M.I. Darter, "A Performance Evaluation of PCC Pavements Constructed on Permeable Bases." *Western States Drainable PCC Pavement Workshop—Summary Report*, FHWA-SA-94-045, Federal Highway Administration, Washington, DC, 1993.

49. Cancela, M.D., J.R. Graciani and J.J. Vaquero, "Performance of Concrete Pavement Drainage Systems in Spain," Proceedings, 7th International Symposium on Concrete Roads, Vienna, Austria, 1994.

50. Fehsenfeld, F.M. and A.J. Kriech, "Construction Experience of Drainage Pavements," *Virginia Pavement Drainage Workshop*, Virginia Department of Transportation, Williamsburgh, VA, 1990.

51. Baldwin, J., "West Virginia Free Drainage Pavement System," *Virginia Pavement Drainage Workshop*, Virginia Department of Transportation, Williamsburgh, VA, 1990.

52. Mottola, V., "New Jersey's Internally Drainable Pavements," *Virginia Pavement Drainage Workshop*, Virginia Department of Transportation, Williamsburgh, VA, 1990.

53. Christory, J.P., "Assessment of PIARC Recommendations on the Combating of Pumping in Concrete Pavements," Proceedings of the Second International Workshop on the Design and the Evaluation of Concrete Pavements, Siguenza, Spain, 1990.

54. PIARC Technical Committee on Concrete Roads, "Combating Concrete Pavement Slab Pumping," 1987.

55. Ray, M. And J.P. Christory, "Combating Concrete Pavement Slab Pumping State of the Art and Recommendations," Proceedings of the Fourth International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, West Lafayette, Indiana, 1989.

56. Von Quintus, H.L., and B. Killingsworth, "Analysis Relating to Pavement Material Characterizations and their Effects on Pavement Performance," Draft Report, Contract No. DTFH61-95-C-00029, Federal Highway Administration, August 1996.

57. McGhee, K. H., "Design, Construction, and Maintenance of PCC Pavement Joints," NCHRP Synthesis 211, Transportation Research Board, 1995.

58. Darter, M.I., J.M. Becker, M.B. Snyder, and R.E. Smith, "PCC Pavement Evaluation System - COPES," NCHRP Report 277, Transportation Research Board, 1985.

59. Dhamrait, J.S., and R.K. Taylor, "Behavior of Experimental CRCP in Illinois," Report FHWA-IL-PR-BL, Illinois DOT, 1979.

GLOSSARY OF TERMS

Aggregate Base (AB) - A base course consisting of compacted mineral aggregates. Also, granular base (GB).

Aggregate Subbase (ASB) - A subbase course consisting of compacted mineral aggregates. Also, granular subbase.

Asphalt Concrete (AC) - A controlled mixture of asphalt cement and graded aggregate compacted to a dense mass. Also, hot-mixed asphalt (HMA), hot mixed asphalt concrete (HMAC), bituminous concrete (BC), plant mix (PM).

Asphalt Concrete Base (ACB) - Asphalt concrete used as a base course. Also, asphalt base course (ABC), asphalt stabilized base - hot-mixed (ASB-HM), asphalt treated base (ATB), bituminous aggregate base, bituminous concrete base (BCB), bituminous base (BB), hot-mixed asphalt base (HMAB).

Asphalt Concrete Pavement (ACP) - A pavement structure, placed above a subgrade or improved subgrade and consisting of one or more courses of asphalt concrete or a combination of asphalt concrete and stabilized or unstabilized aggregate courses.

Asphalt Concrete Surface (ACS) - Asphalt concrete used as a surface course. Also, dense-graded asphalt concrete (DGAC).

Asphalt Treated Permeable Base (ATPB) - A permeable base containing a small percentage of asphalt cement to enhance stability. Also, asphalt treated open-graded base (ATOGB), asphalt treated base - permeable (ATB-Perm).

Base - The layer or layers of specified or select material of designed thickness placed on a subbase or subgrade to support a surface course. For Portland cement concrete pavements, the layer just beneath the concrete slab.

Bituminous Sand - Asphalt concrete containing sand as the mineral aggregate component.

Cement-Treated Base (CTB) - A base course consisting of mineral aggregates blended in place or through a pugmill with a small percentage of portland cement to provide cementitious properties and strengthening. Also, aggregate cement, cement stabilized graded aggregate (CSGA), cement stabilized base (CSB).

Cement Treated Open-Graded Base (CTOGB) - An open-graded aggregate base treated with portland cement to provide enhanced base strength and reduce erosion potential. Also, cement-treated permeable base (CTPB).

Continuously Reinforced Concrete Pavement (CRCP) - Portland cement concrete pavement containing continuous longitudinal steel reinforcement. Joints exist only at construction joints and on-grade structures.

Crushed Stone Base - A base course of designed thickness and constructed of graded and mechanically crushed mineral aggregate compacted above a subbase course or subgrade. Also, aggregate base (AB), graded aggregate base (GAB), crushed aggregate (CA).

Crushed Stone Subbase - A subbase course of designed thickness and constructed of graded and mechanically crushed mineral aggregate compacted above a subgrade.

Dense-Graded Aggregate (DGA) - A mechanically crushed aggregate having a particle size distribution such that when it is compacted, the resulting voids between the aggregate particles, expressed as a percentage of the total space occupied by the material, are relatively small.

Dowel Bar - Cylindrical solid steel bars used at transverse joints to improve load transfer across the joint, of varying diameter and spacing.

Drainable Granular Subbase - A subbase constructed of compacted and crushed open-graded aggregate.

Flexible Pavement - A pavement structure which maintains intimate contact with and distributes loads to the subgrade and depends on aggregate interlock, particle friction, and cohesion for stability.

Gravel Base - A base course constructed of compacted gravel. May or may not be graded and/or crushed.

Gravel Subbase - A subbase course constructed of compacted gravel. May or may not be graded and/or crushed.

Gravel Subgrade - A subgrade where a natural gravel has been used as the roadbed surface or where the native soil has been blended with a gravel additive.

Gravel - Coarse aggregate resulting from natural disintegration and abrasion of rock or processing of weakly bound conglomerate.

Jointed Plain Concrete Pavement (JPCP) - Jointed portland cement concrete pavement containing no distributed steel to control random cracking, may or may not contain joint load transfer devices.

Jointed Reinforced Concrete Pavement (JRCP) - Jointed portland cement concrete paving containing distributed steel reinforcement to control random cracking and usually containing joint load transfer devices.

Lean Concrete Base (LCB) - A base course constructed of mineral aggregates plant mixed with a sufficient quantity of portland cement to provide a strong platform for additional pavement layers.

Lime-Treated Subgrade - A prepared and mechanically compacted mixture of hydrated lime, water and soil supporting the pavement system.

Lime-Flyash Base (LFB or LFA) - A blend of mineral aggregate, lime, flyash and water, combined in proper proportions and producing a dense mass when compacted.

Open-Graded Aggregate Base (OGAB) - A crushed mineral aggregate base having a particle size distribution such that when compacted the interstices will provide enhanced drainage properties. Also, granular drainable layer, untreated permeable base (UPB).

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

Permeable Base (PB) - A base course constructed of treated or untreated open-graded aggregate. Also, free draining base.

Portland Cement Concrete Pavement (PCC) - A pavement structure that consists of a PCC slab as the top layer and usually including a base and a subbase layer.

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.

Soil Aggregate - Natural or prepared mixtures consisting predominantly of stone, gravel or sand which contain a significant amount of minus 75-μm (No. 200) silt-clay material.

Soil Cement - A mechanically compacted mixture of soil, portland cement and water, used as a layer in a pavement system to reinforce and protect the subgrade or subbase. Also, cement-treated subgrade (CTS).

Stabilized Granular Base - A base course with an unspecified stabilizing material, usually asphalt cement or portland cement.

Stabilized Permeable Base - A permeable base with an unspecified stabilizing material, usually asphalt cement or portland cement. Also, bound drainable base.

Subbase - The layer or layers of specified or selected materials of designed thickness placed on a subgrade to support a base course. For Portland cement concrete pavements, the layer between the base course and the subgrade.

Subgrade, Improved - Any course or courses of select or improved materials between the subgrade soil and the pavement structure.

Surface Course - One or more layers of a pavement structure designed to accommodate the traffic load, the top layer of which resists skidding, traffic abrasion and the disintegrating effects of climate.

Tiebar - Deformed steel reinforcing bar placed across longitudinal joints to hold them tightly together.

Appendix A

Traffic Input Details

Definition Of Traffic Input

The traffic input is the 18-kip Equivalent Single-Axle Loads (ESALs) as presented in the AASHTO Design Guide [3] and as developed at the AASHO Road Test. The specific input is the total ESALs that are expected to accumulate during the design life of the heaviest trafficked lane.

Methods Of Estimation

Methods available for estimating the number of 18-kip ESALs over the design period for the highway vary in complexity and thus in accuracy. The method provided in this appendix is relatively simplistic and easy to use and will assist the designer in obtaining an approximate value of total design ESALs over the design period. More complex procedures that utilize axle load distributions and vehicle classifications are readily available as described in appendix D of the 1993 AASHTO Design Guide.[3]

Overall Accuracy In Prediction of ESALs

Overall accuracy in prediction of total ESALs over a design period can be related to the following to major items:

- Estimates of traffic data for the initial year. Obviously, the more site specific the volume and weight data is measured, the more accurate the initial values.
- Estimates of future growth in truck volumes and weights over the design period.

Past experience has shown that generally the total ESALs have been underestimated, especially on major rural and urban highways. Changes in axle weight distributions and configuration of axles are perhaps the most difficult to estimate over a long design period due to uncertainty in legislative and economic conditions. The overall error in predicting total ESALs over say a 20 year period could easily be as great as 200 percent or as little as 25 percent if done with great care.

Inputs Required

The following traffic inputs are required: initial ADT, initial proportion of truck of ADT, directional proportion of trucks, lane distribution of trucks, growth rate of trucks, design period, and mean truck equivalency factor.

Initial Average Daily Traffic (ADT). This annual average daily traffic is two directional (as is usually provided from traffic statistics) and includes all vehicles in the traffic stream during the first year of pavement life.

Initial Proportion of Trucks in ADT. The proportion of trucks is simply the number of trucks expressed as proportion of the ADT. This value ranges from as low as 0.05 (5 percent) to as high as 0.5 (50 percent).

Truck Directional Distribution Factor. This factor is used to quantify differences in the overall direction of trucks, if any. Generally, this value is 0.5 since the ADT is given in two directions and the number of trucks in each direction is the same over the long term.

Truck Lane Distribution Factor. This factor accounts for the lateral distribution of truck traffic across lanes in one direction. For two lane, two way highways, this factor is almost always 1.0 since all truck traffic in one direction must use the same lane. For multiple lanes in one direction, it depends on ADT and other geometric conditions. A site specific determination is far more accurate than the typical values shown in Table A-1.

Table A-1. Recommended truck design lane distribution factors. [58]

One-Way ADT	2-lanes (One Direction)		2+ Lanes (One Direction)		
	Inner	Outer	Inner*	Center	Outer
2,000	0.06**	0.94	0.06	0.12	0.82
4,000	0.12	0.88	0.06	0.18	0.76
6,000	0.15	0.85	0.07	0.21	0.72
8,000	0.18	0.82	0.07	0.23	0.70
10,000	0.19	0.81	0.07	0.28	0.68
15,000	0.23	0.77	0.07	0.28	0.65
20,000	0.25	0.75	0.07	0.30	0.63
25,000	0.27	0.73	0.07	0.32	0.61
30,000	0.28	0.72	0.08	0.33	0.59
35,000	0.30	0.70	0.08	0.34	0.58
40,000	0.31	0.69	0.08	0.35	0.57
50,000	0.33	0.67	0.08	0.37	0.55
60,000	0.31	0.66	0.08	0.39	0.53
70,000	-	-	0.08	0.40	0.52
80,000	-	-	0.08	0.41	0.51
100,000	-	-	0.09	0.42	0.49

* Combined inner one or more lanes.

** Proportion of all trucks in one direction (note that the proportion of trucks in one direction sums to 1.0).

Growth Rate Of Trucks . This factor is a convenient way to convert the total number of trucks in the first year of the design period to total trucks over the design period. Traffic growth is usually expressed as an annual compound growth rate. Growth rates of trucks varies widely form one highway to the next and past historical data is an important source of information. Typical compound growth rates have ranged between 1 and 10 percent. The Growth Factor is computed as follows:

$$GF = [(1 + r)^n - 1] / r \quad \text{(A-1)}$$

where r = annual growth rate (a proportion)
n = design period, years

Table A-2 provides the GF computed for a range of inputs.

Table A-2. Growth factors for traffic.

	Annual Growth Rate, Percent (r)							
Analysis Period Years (n)	No Growth	2	4	5	6	7	8	10
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	2.0	2.02	2.04	2.05	2.06	2.07	2.08	2.1
3	3.0	3.06	3.12	3.15	3.18	3.21	3.25	3.31
4	4.0	4.12	4.25	4.31	4.37	4.44	4.51	4.64
5	5.0	5.20	5.42	5.53	5.64	5.75	5.87	6.11
6	6.0	6.31	6.63	6.8	6.98	7.15	7.34	7.72
7	7.0	7.43	7.90	8.14	8.39	8.65	8.92	9.49
8	8.0	8.58	9.21	9.55	9.90	10.26	10.64	11.44
9	9.0	9.75	10.58	11.03	11.49	11.98	12.49	13.58
10	10.0	10.95	12.01	12.58	13.18	13.82	14.49	15.94
11	11.0	12.17	13.49	14.21	14.97	15.78	16.65	18.53
12	12.0	13.41	15.03	15.92	16.87	17.89	18.98	21.38
13	13.0	14.68	16.63	17.71	18.88	20.14	21.50	24.52
14	14.0	15.97	18.29	19.16	21.01	22.55	24.21	27.97
15	15.0	17.29	20.02	21.58	23.28	25.13	27.15	31.77
16	16.0	18.64	21.82	23.66	25.67	27.89	30.32	35.95
17	17.0	20.01	23.70	25.84	28.21	30.84	33.75	40.55
18	18.0	21.41	25.65	28.13	30.91	34.00	37.45	45.60
19	19.0	22.84	27.67	30.54	33.76	37.38	41.45	51.16
20	20.0	24.3	29.78	33.09	36.79	41.00	45.76	57.28
25	25.0	32.03	41.65	47.73	54.86	63.25	73.11	98.35
30	30.0	40.57	56.08	66.44	79.06	94.46	113.28	164.49
35	35.0	49.99	73.65	90.32	111.43	138.24	172.32	271.02

When the GF is multiplied by the initial trucks/year the total trucks over the design period is obtained. For example, if the initial trucks/year = 1,000, r = 0.05, n = 20,
Total trucks/20 years = 33.06 * 1,000 = 33,060

Mean Truck Equivalency Factors. The mean truck equivalence factor for all trucks is dependent upon the type of pavement structure (flexible or rigid), the types of trucks which are expected to use the highway class, their axle weight distribution, and the terminal serviceability design criteria.

The mean truck equivalence factor also varies over time as it has shown a steady increase over the years for most highways ranging from 1 to over 10 percent per year.

An agency should ideally measure the current axle load distribution of single, tandem, and tridems for each truck classifications desired and then use this data to compute a current mean ESAL/truck for each classification using both flexible and rigid pavement equivalency factors. The current mean truck factor for any mix of trucks can then be computed from this data. The current value should then be increased to the mean value expected over the design period.

Table A-3 has been prepared to illustrate some typical current truck equivalency factors for different highway classifications. These should not be used for design, as they must be determined from data obtained by the agency for their highways. Again, site specific data is considered as extremely important to even coming with 50 percent of the actual total ESALs for a given highway.

Often, truck weights are different in two directions and thus site specific determination would measure this difference and each direction would have different mean ESALS/truck and be designed with different levels of ESALs. These values also vary considerably from state to state and from highway to highway within a state. The mean truck equivalency factors are also time dependent, as they often increase over time for a given project.

Table A-3. 18-kip mean truck equivalency factors examples as a function of highway classification (data only valid for early 1990's).

Highway Classification	Flexible ESALs	Rigid ESALs
Secondary	0.2 - 0.5	0.3 - 0.75
Primary	0.5 - 1.0	0.75 - 1.5
Interstate	0.75 - 2.0	1.0 - 3.0

Total ESALs Over Design Period

Although the above description implies that an accurate value of the current mean truck equivalency can be obtained, this value is generally estimated from weight data from several weight stations located throughout a state and is not site specific. There exists substantial site to site variation in vehicle types and weights, even for similar highway classifications. Thus, use of a current mean ESAL/truck is very approximate when applied to any given site. This value then needs to be adjusted for any anticipated growth over the design period.

Given a reasonable mean truck equivalency factor over the design period, the following equation can be used to estimate the total number of 18-kip ESALs for the design lane over the design period, Total ESALs.

$$\text{Total ESALs} = (\text{ADT})(\text{PTRUCK})(\text{TLDF})(\text{TDDF})(\text{GF})(\text{TEF}) \qquad \text{(A-2)}$$

where:

ADT	=	Average daily traffic (two-directional, all vehicles)
PTRUCK	=	Proportion of truck traffic within ADT (varies from 0.05 to 0.5)
TLDF	=	Truck (Design) Lane Distribution Factor over the design period (varies from 0.5 to 1.0, See Table A-1)
TDDF	=	Truck Directional Distribution Factor (typically 0.5)
GF	=	Growth Factor over design period (see Equation A-1 or Table A-2)
TEF	=	Mean Truck Equivalency Factor (See Table A-3, as an example)

Improved Approach

A procedure to make this approach much more accurate is to compute a mean ESAL/truck for each of the FHWA truck classifications for several weigh-in-motion sites on the same highway classification. Thus, there would be a mean ESAL/truck for each truck classification. This makes it possible to use these mean ESAL/truck factors along with vehicle classifications at a given site to much more accurately estimate current total ESALs by bringing in site specific vehicle classification data. This approach is highly recommended over the use of a single truck equivalency factor.

APPENDIX B

Subgrade Input Details

Appendix B provides procedures that are recommended for determining the design parameters of the subgrade soils for use in pavement design. Appendix B is subdivided into three basic parts. The first part is a description of typical subsurface characterization methods employed for pavement design (i.e., subsurface exploration, selection of boring location and depth to identify the supporting subgrade layers, and recovering samples of subgrade soils for identification and classification). The second part of Appendix B is devoted toward determining the design resilient modulus of the subgrade soils for use in flexible pavement design, and the third part for determining the elastic k-value of the subgrade supporting soils for use in rigid pavement design.

B.1 Subsurface Characterization for Pavement Design

Subsurface Exploration

The subsurface investigation should be sufficiently detailed to define the depth, thickness, and areal extent of all major soil and rock strata that will be affected by construction. Disturbed and undisturbed samples of the subsurface materials must be obtained for laboratory analyses (and/or tested in the field) to determine their engineering properties. The extent of the program depends on the nature of both the project and the site specific subsurface conditions. The standard penetration and dynamic cone penetrometer tests can be used to determine the in situ strength characteristics of subsurface soils.

Procedures for the exploration of pavement sites cannot be reduced to a single guideline to fit all existing conditions. To acquire reliable engineering data, each job site must be explored and analyzed according to its subsurface conditions. The engineer in charge of the subsurface exploration must furnish complete data in order that an impartial and thorough study of practical pavement thickness designs can be made. Suggested steps which can be followed are listed below:

1. Make a complete and thorough investigation of the topographic and subsurface conditions.

2. Conduct exploratory borings at a spacing and depth prescribed by the engineer. The spacing and depth of these borings are dependent on the variability of the existing soil conditions, both vertically and horizontally. These borings should also be used to determine the water table depth. Take sufficient and appropriate auger, split tube, or undisturbed samples of all representative subsoil layers. Prepare boring logs and soil profiles.

3. Classify all soils using the AASHTO (or Unified) soil classification system. Table B-1 relates the Unified soil classification of a material to the relative value of a material for use in a pavement structure. The modified Proctor moisture-density test should be used to determine the compaction characteristics for soil and untreated pavement materials. The degree of compaction required for the in-place density should be expressed as a percentage of the maximum density from the modified Proctor test.

4. Examine the boring logs, soil profiles, and classification tests and select representative soil layers for laboratory testing. Determine the insitu resilient modulus for each major soil type encountered for flexible pavement design or the elastic K-value for rigid pavement design.

5. Use the soil profile along the roadway alignment to relate resilient modulus to each type of subgrade soil encountered. Select a design subgrade resilient modulus that is representative of each boring. For design purposes, it is recommended that the weakest subgrade layer be selected as the design resilient modulus, unless the material is removed, improved or stabilized.

Boring Location and Depth

Regardless of the type of project, the borings should be spaced to establish in reasonable detail the stratigraphy of the subsurface materials. Borings should also be located to obtain a basic knowledge of the engineering properties of the overburden and bedrock formations that will be affected by or will have an effect upon the proposed pavement structure, and to locate and determine the quality and approximate quantity of construction materials, if required.

Appendix C

Determination Of Climate Imputs

An important and complex site condition that affects pavement performance is climate. This is especially true in the United States, which is a large country that encompasses a very wide range of climates. This section documents the considerations of the climatic factors used in the catalog.

<u>Selection of Climatic Variable to Characterize Site Condition</u>
Environmental conditions have significant effects on highway pavements. The two most important climatic factors are precipitation and temperature. Excess water in pavement structures can cause pumping, erosion of certain materials, stripping of asphalt, and other serious problems. Also, excess moisture in the subgrade can decrease the strength of the subgrade soil greatly increasing stresses and strains in the pavement. These lead to increased rutting and fatigue cracking of AC pavements, faulting of joints, loss of support and cracking of PCC pavements. The temperature effects on the pavement structure mainly include low temperature damage such as transverse cracking and frost heave; freeze-thaw cycling of pavement materials, causing durability problems; high temperature effects, which can cause rutting and block cracking from shrinkage; and temperature variation during a day, which can cause curling of the PCC slabs.

To select the variables for characterization of the effects of climate and the corresponding levels to be used in the factorial matrix, several pavement studies involving climatic effects on pavements were reviewed. These studies include the Long-Term Pavement Performance (LTPP) study [C-1], the Moisture Accelerated Distress (MAD) identification study [C-2], and pavement design practices of several State highway agencies. [C-3]

The potential climatic variables that were initially identified for use in characterizing moisture conditions include the following:

- Annual or monthly precipitation, inch.
- Thornthwaite Moisture Index.
- Days of precipitation greater than 0.01 inch.

The variables initially selected to characterize temperature conditions include the following:

- Freezing Index, degree-days below freezing.
- Average annual air temperature, °F.
- Average annual temperature range, °F.
- Number and length of freeze-thaw cycles.
- Average daily high temperature during the month of construction, °F.
- Average low temperature for the coldest month of the pavement life, °F.
- Average annual frost depth, inch.
- Concentration of summer thermal efficiency (CSTE).

Definitions and Contour Maps of Climatic Variables

To give a quick reference for the climatic conditions of a specific site, contour maps of several key climatic variables are provided in this section. Distribution maps of the normal annual precipitation and annual temperature are obtained from the National Climatic Data Center. [C-4] The normal climate is defined as the statistical average over a time period usually consisting of three decades. The values are statistically determined and cannot be recreated solely from the original records. The contour maps are created by temperature data from more than 4,000 stations and precipitation data from more than 6,000 stations. Figure C-1 is the annual 1961-1990 normal precipitation map of the U.S., and figure C-2 provides the distribution of the number of the days with precipitation of 0.01 in or more. Figure C-3 is a map of the annual 1961-90 normal temperature map of the U.S.

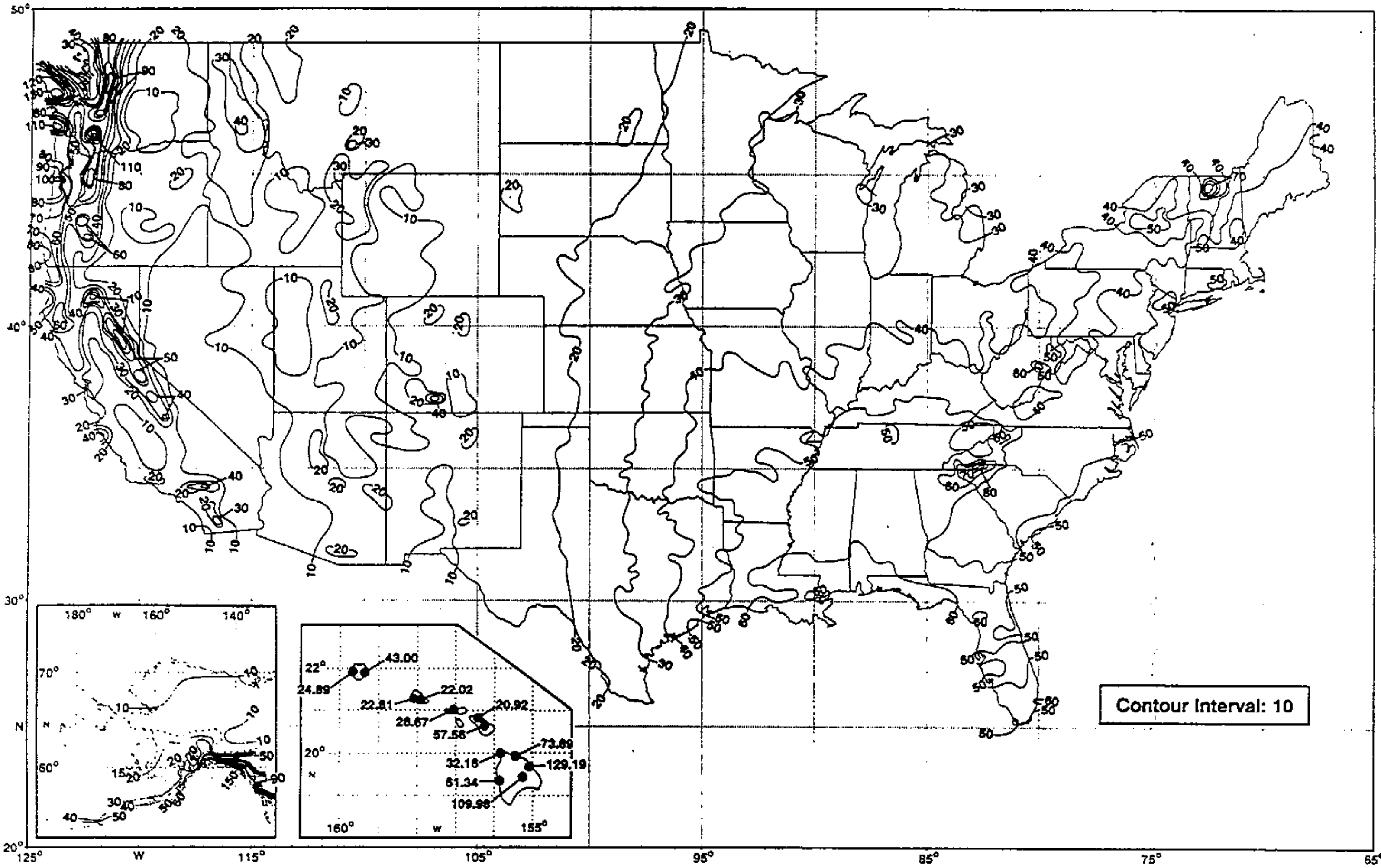


Figure C-1. Mean annual precipitation, inches, based on normal period 1961-1990.

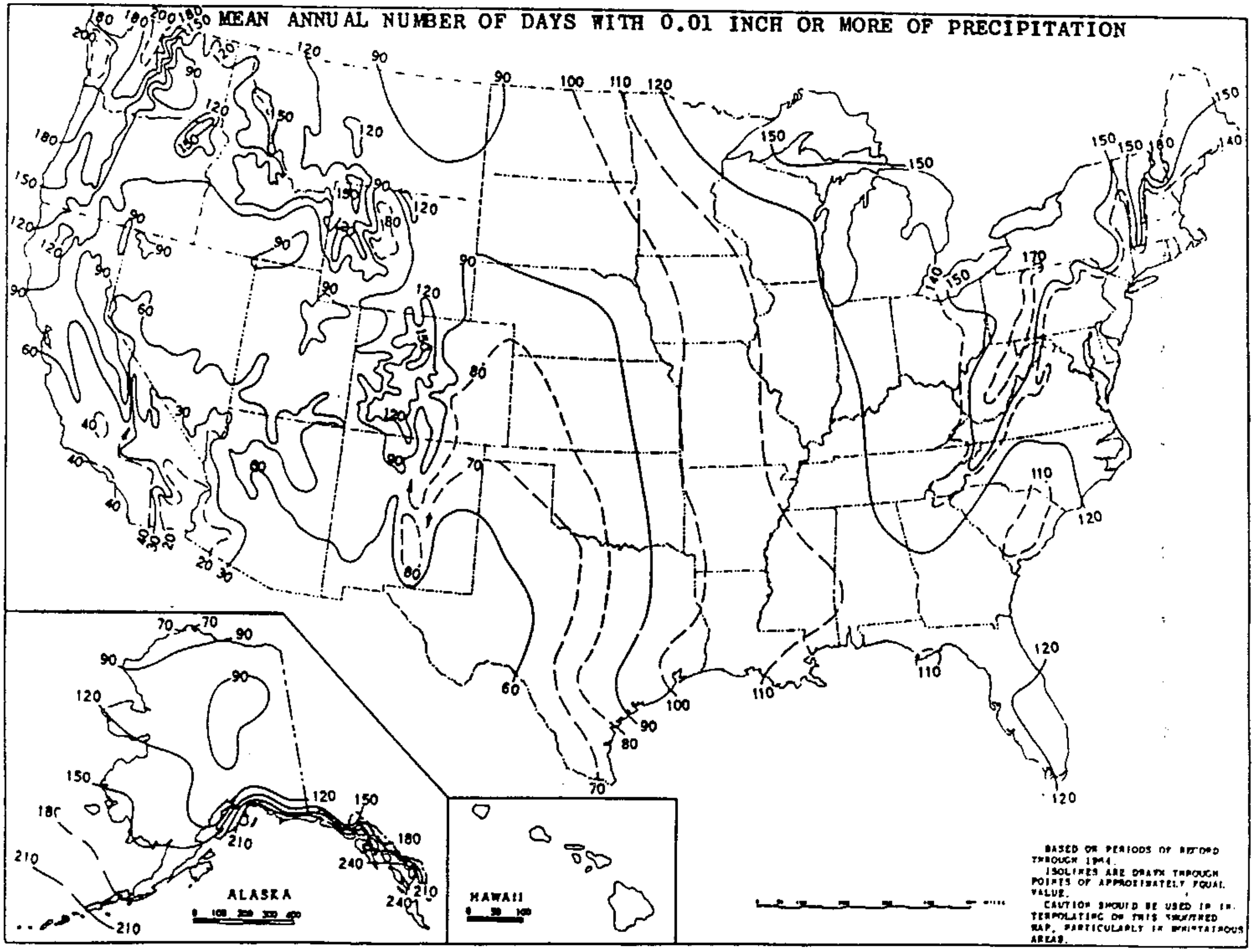


Figure C-2. Mean annual number of days with 0.01 inch or more precipitation, based on data through 1964.

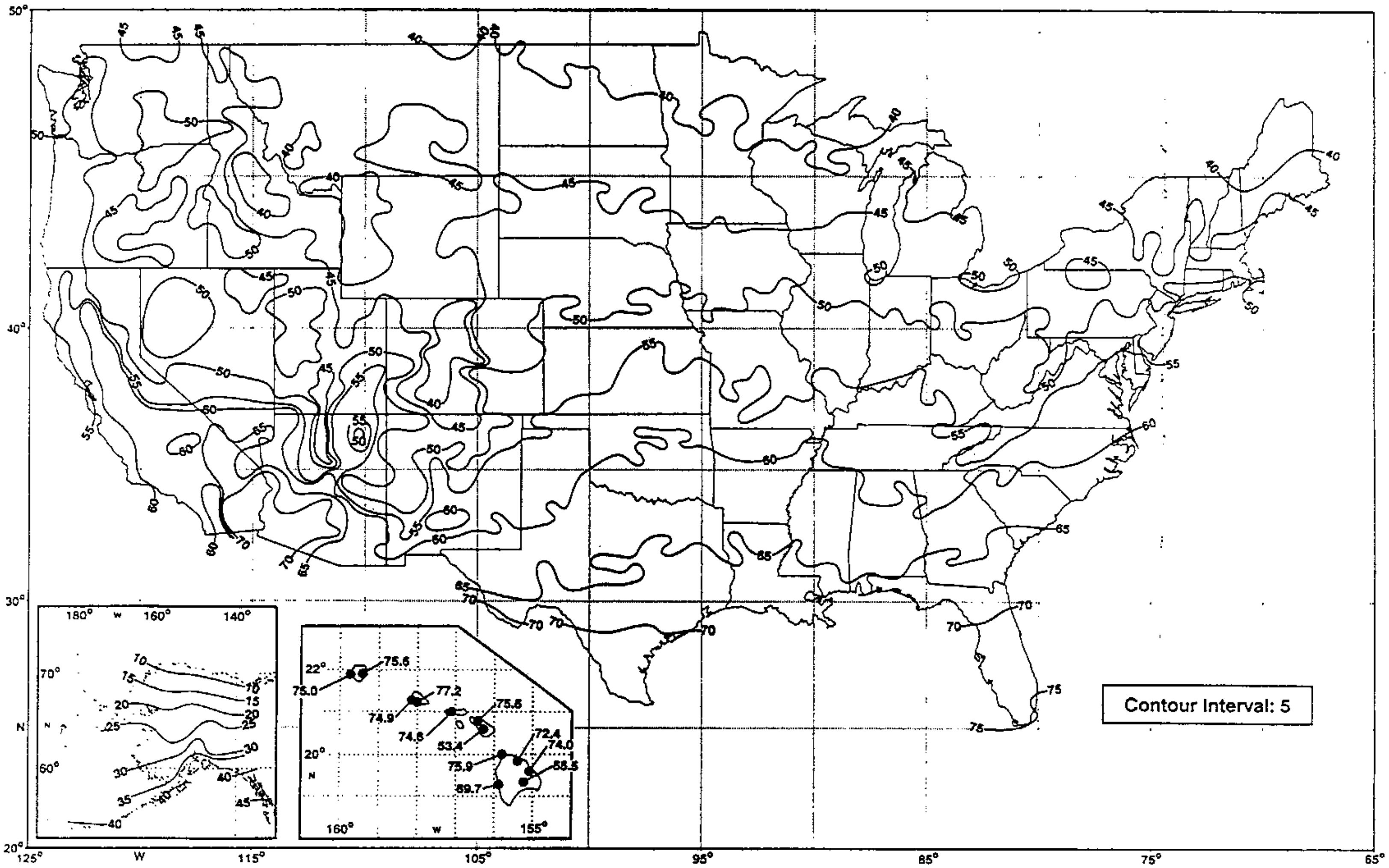


Figure C-3. Mean annual air temperature, °F, based on normal period 1961-1990.

Freezing Index is defined by the Corps of Engineers as the cumulative number of degree-days below the freezing point occurring during any freezing season. [C-5] The following equation can be used to calculate air freezing index:

$$FI = \sum^{N} (32-T)$$

where:

T = Mean air temperature of the day that goes below freezing.

N = Number of days during the year when minimum temperature falls below 32 °F.

Mean freezing index is based on the mean air temperatures and is averaged over a minimum of 10 years and preferably 30 years. Figure C-4 shows a contour map of the mean freezing index in the United States, generated by the Corps of Engineers using 361 National Weather Service stations. [C-5]

A freeze-thaw cycle is defined by Hershfield [C-6] as an occurrence of air temperature crossing the freezing point during a calendar day. The number of days on which a freeze-thaw cycle happens is the variable of interest. It is an indication of the temperature variation about 32 °F, and it can be calculated from daily maximum and minimum temperature. Hershfield used about 1,300 weather station data to generate a contour map of the United States with isolines of the number of the days with freeze thaw cycles, as shown in figure C-5.

Some indirect measurement of moisture and temperature used in pavement studies are also examined. Annual temperature range is defined as the difference between the maximum July temperature and the minimum January temperature. Thornthwaite developed a moisture index to represent the moisture adequacy of the soil. [C-7] It is a comparison of precipitation and potential evapotranspiration. He also introduced a variable called concentration of summer thermal efficiency (CSTE), which indicates the relative amount of energy reaching the pavement in the summer months as compared to the rest of the year. Figures C-6 and C-7 are the contour maps of the moisture index and the concentration of summer thermal efficiency, respectively, reproduced after Thornthwaite. [C-7]

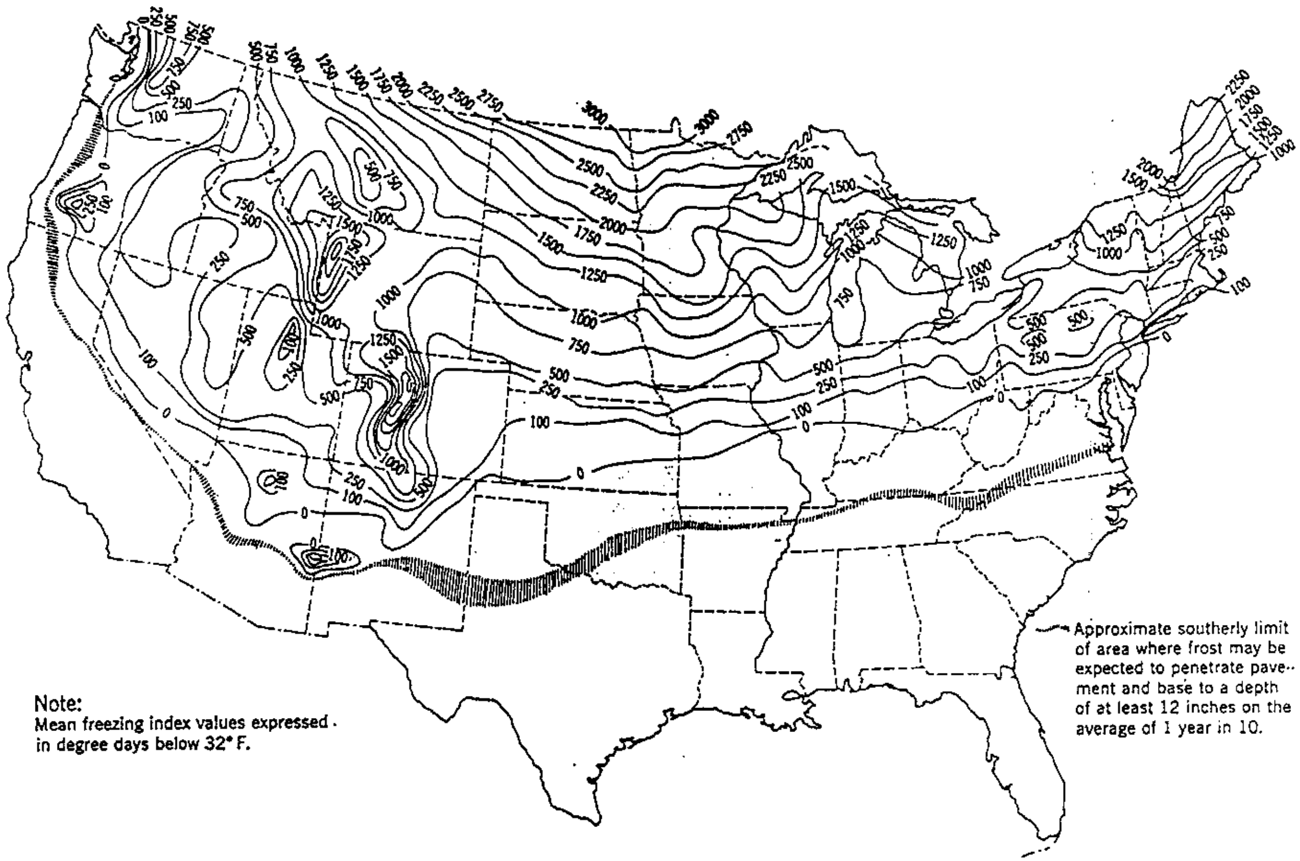


Figure C-4. Mean Freezing Index values in the United States, °F-days.

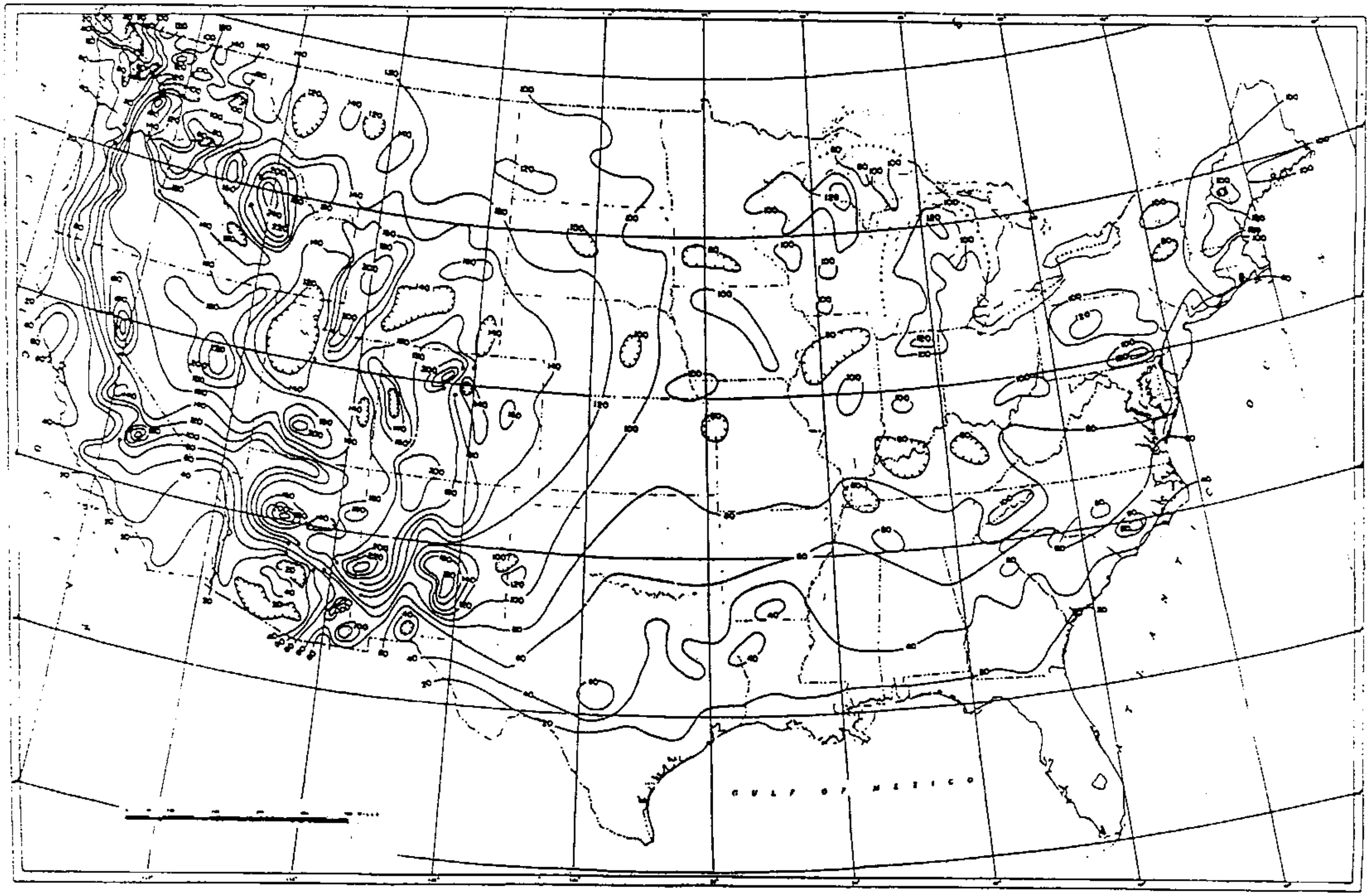


Figure C-5. Mean annual frequency of freeze-thaw cycles, days.

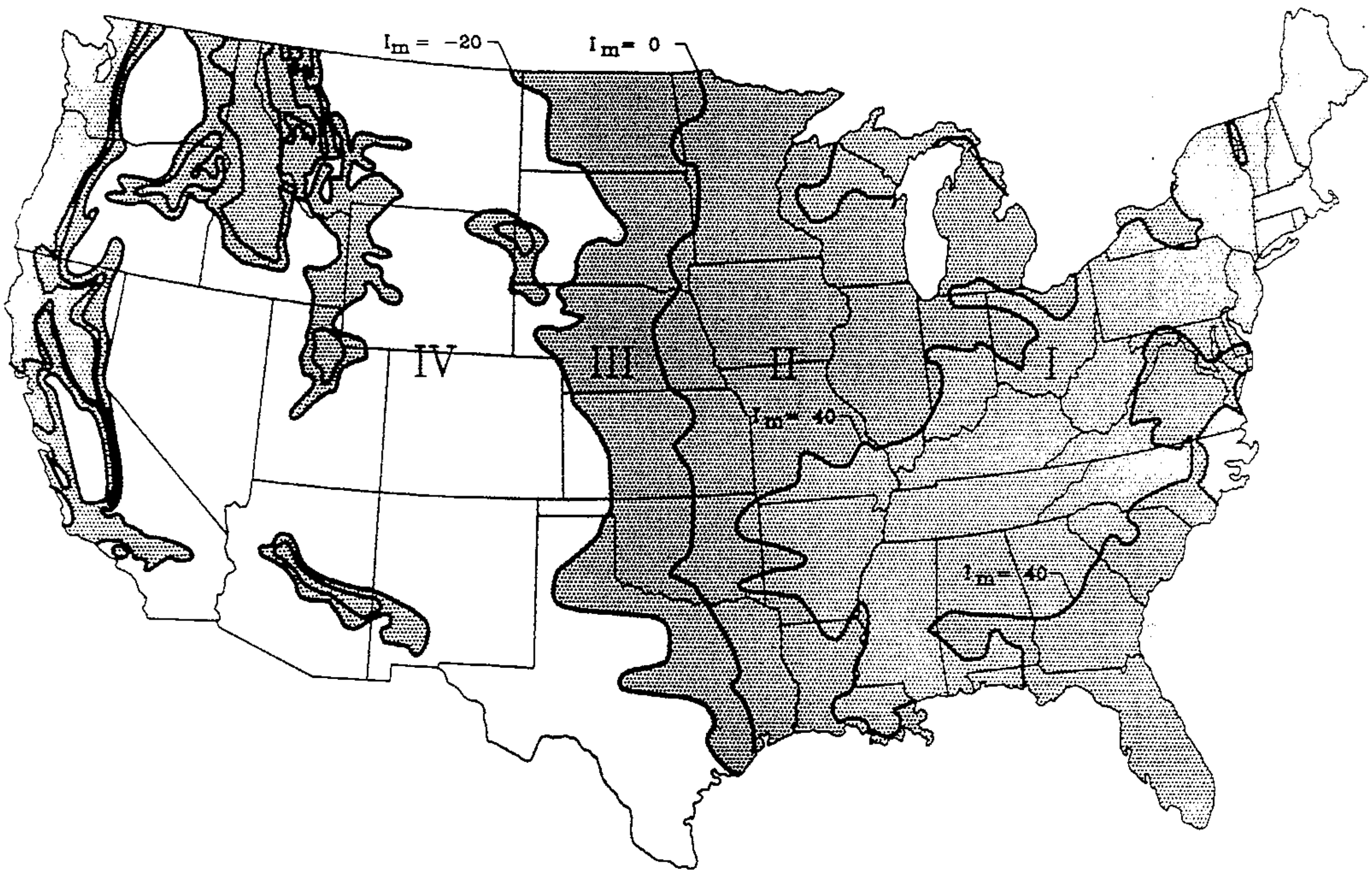


Figure C-6. Distribution of Thornthwaite Moisture Index in the United States, after Thornthwaite.

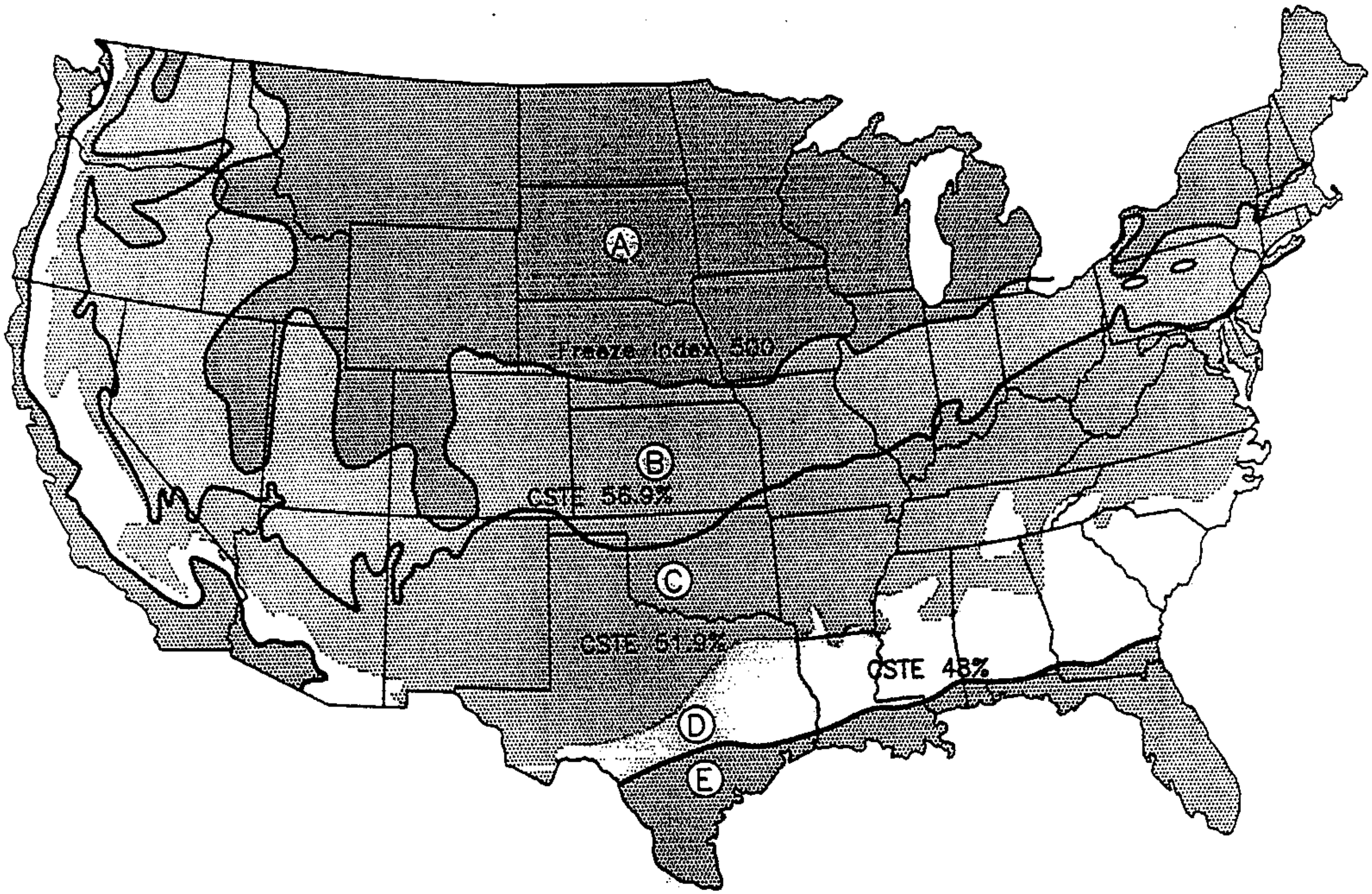


Figure C-7. Distribution of the concentration of summer thermal efficiency in the United States, after Thornthwaite.

Correlation of the Climatic Variables

Climatic data of different climatic variables are collected and compared to show their relationship to each other. The main data are taken from an FHWA pavement performance study database [C-8], including most of the temperature and precipitation data. Additional climatic data from different sites in the United States are obtained through the publications of the National Climatic Date Center of National Oceanic and Atmospheric Administration (NOAA) and published climatic maps. Some indirect variables, such as annual temperature range, Thornthwaite moisture index, and concentration of summer thermal efficiency, are calculated from other available climatic variables.

Figures C-8 and C-9 show the climatic data from 50 weather stations across the United States. As shown in the graphs, the variables characterizing moisture and the variable representing temperature are highly correlated to each other.

Table C-1 provides a correlation matrix of moisture variable data from 50 weather stations across the U.S. As shown in the table, the moisture-related climatic variables are highly correlated. Therefore, it is reasonable to use only one variable (such as annual precipitation) to characterize the moisture-related climatic condition in certain area. A correlation matrix of the temperature variables is shown in table C-2. Again, the correlation coefficients of all the temperature-related climatic variables are high (greater or equal to 0.60). It is sufficient to use either annual mean temperature or freezing index to characterize temperature for an area.

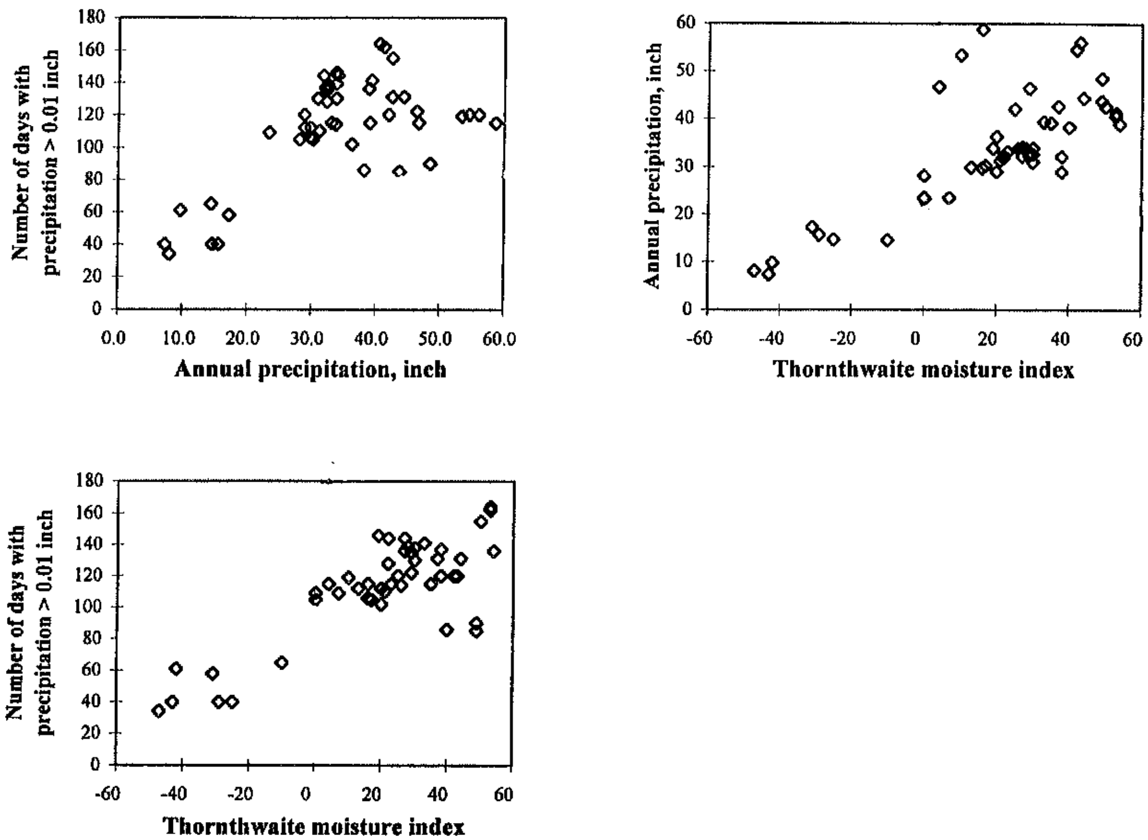


Figure C-8. Two-dimensional plots of selected moisture-related variables.

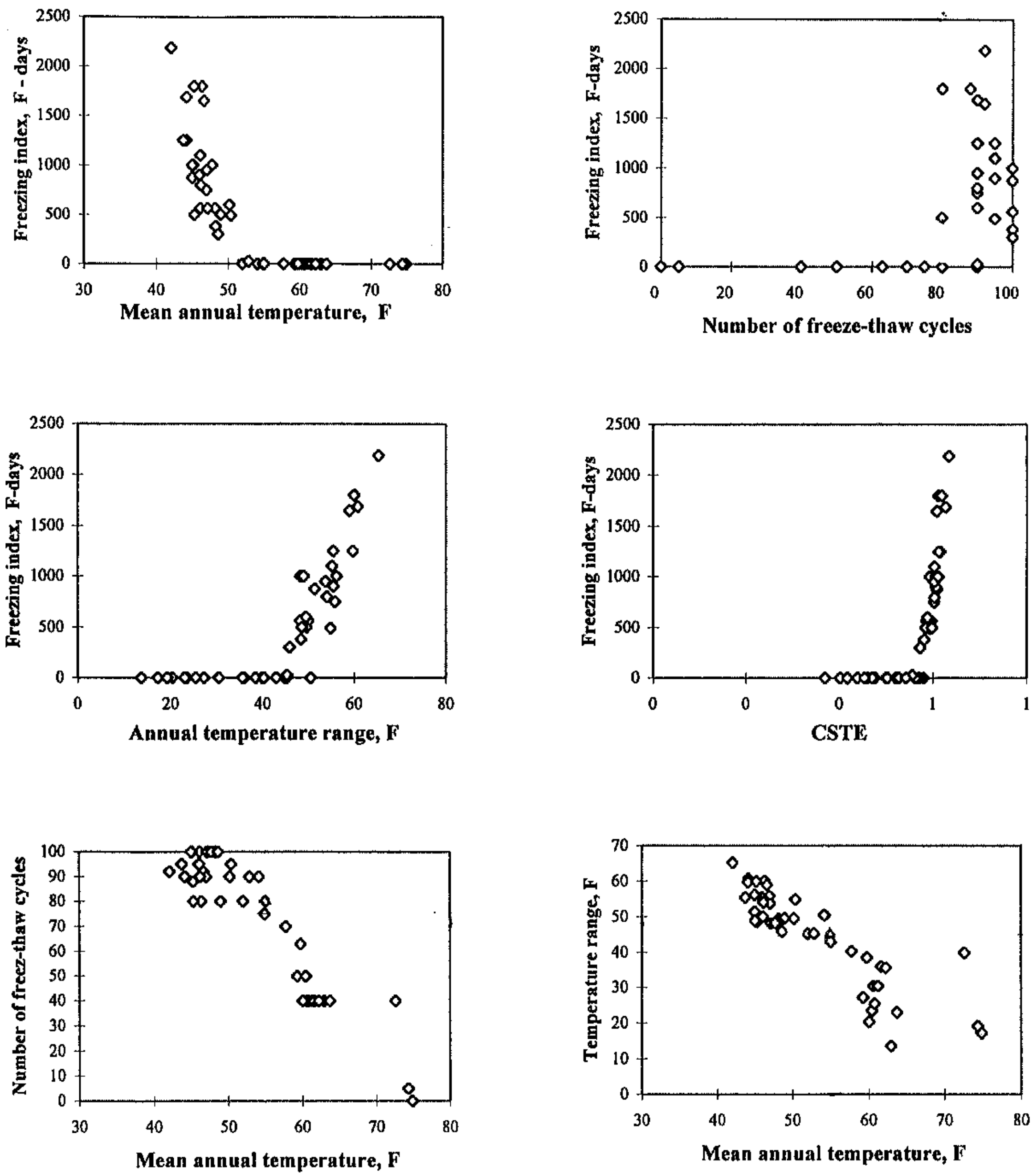


Figure C-9. Two-dimensional plots of selected temperature-related variables.

Table C-1. Correlation coefficient matrix of the moisture related climatic variables.

	Mean annual precipitation	Mean no. of days w/ precipitation > 0.01 in	Thornthwaite Moisture Index
Mean Annual Precipitation	1	0.64	0.78
Mean No. of Days w/ Precipitation > 0.01 in	0.64	1	0.81
Thornthwaite Moisture Index	0.78	0.81	1

Table C-2. Correlation coefficient matrix of the temperature related climatic variables.

	Mean annual temp.	Mean Freezing Index	Temp range	No. of F-T cycles/year	Thornthwaite CSTE
Mean Annual Temp.	1	-0.75	-0.89	-0.94	-0.88
Mean Freezing Index	-0.75	1	0.80	0.60	0.72
Temp Range	-0.89	0.80	1	0.88	0.98
No. of F-T Cycles/year	-0.94	0.60	0.88	1	0.90
Thornthwaite CSTE	-0.88	0.72	0.98	0.90	1

More typical climatic data were obtained from NOAA data and information service. Figure C-10 provides several plots of some of the climatic variables using 250 weather station data from NOAA. Again, the climatic variables are found to be highly correlated.

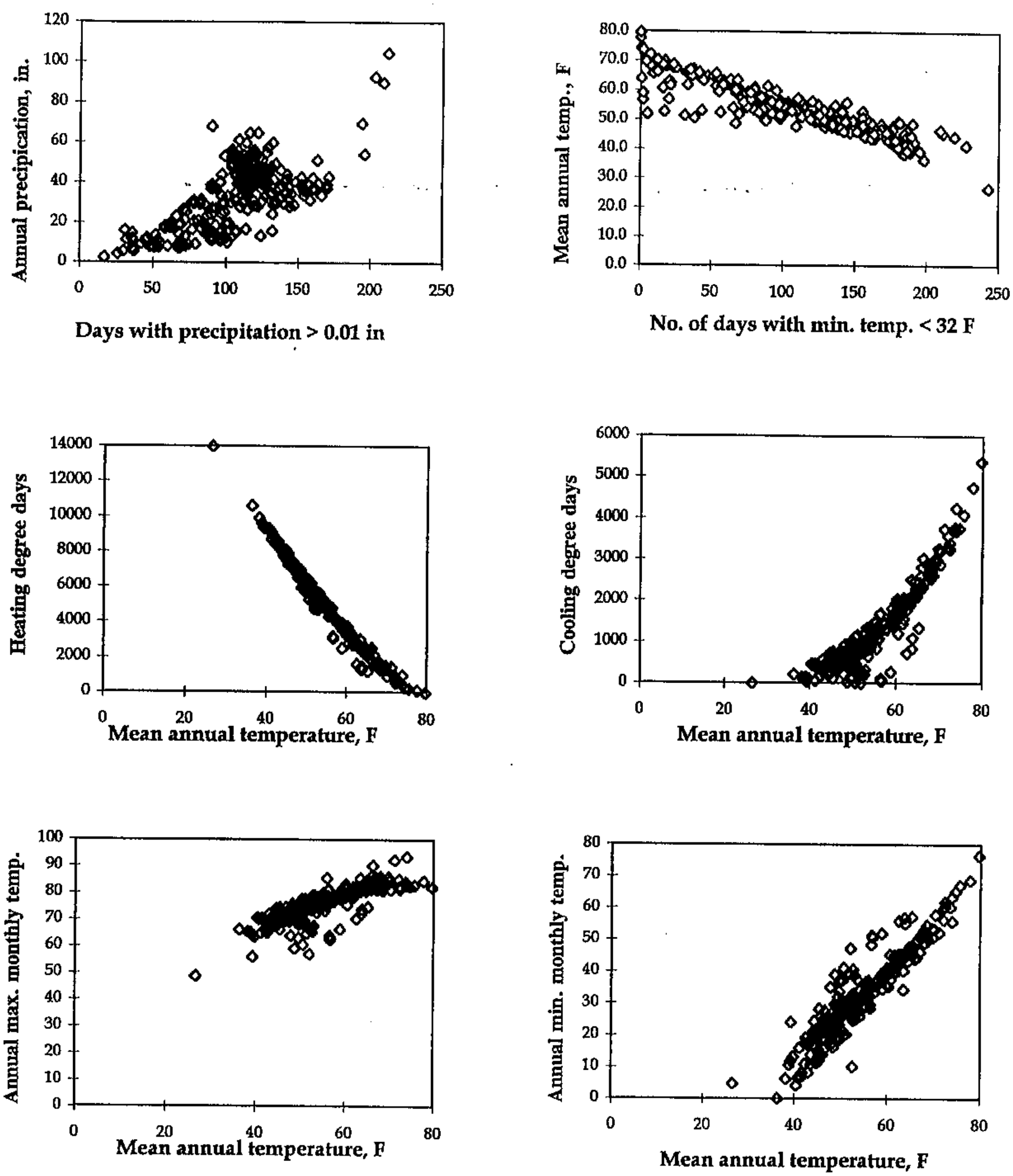


Figure C-10. Two-dimensional plots of typical climatic variables from NOAA data.

Selection of the LTPP Climatic Zones

An evaluation of the information obtained indicates that many temperature-related variables are strongly correlated; similarly, many moisture-related variable are correlated. Therefore, it is possible to select a few key temperature and moisture variables that can be considered together to characterize a general project site. Furthermore, the information obtained from the States indicates that few SHAs consider climate variation across their State as a direct input to their pavement thickness design procedure. Climatic effects are often adjusted through drainage design, material requirements, or the provision of nonfrost susceptible layers, rather than through pavement structural design. A few of the larger States do vary pavement design with temperature and moisture conditions. In view of this, the four LTPP climatic zones are selected to characterize climatic effects. These four climatic zones, shown in figure C-11, [C-1] define the site climatic conditions for the factorial matrix. Typical climatic variables for the four climatic zones are given in table C-3.

Table C-3. Typical climatic factor levels for the LTPP climatic zones.

Climatic zone	Climatic variable			
	Mean freezing index	Mean monthly temp, °C	Temp. range, °C[a]	Mean annual precip., mm
Wet-freeze	200 to 1,000	11	28	850
Dry-freeze	200 to 1,000	7	21	380
Wet-nonfreeze	0	19	17	1240
Dry-nonfreeze	0	19	20	420

[a]*Note:* Difference between mean maximum monthly July temperature and mean minimum monthly January temperature.

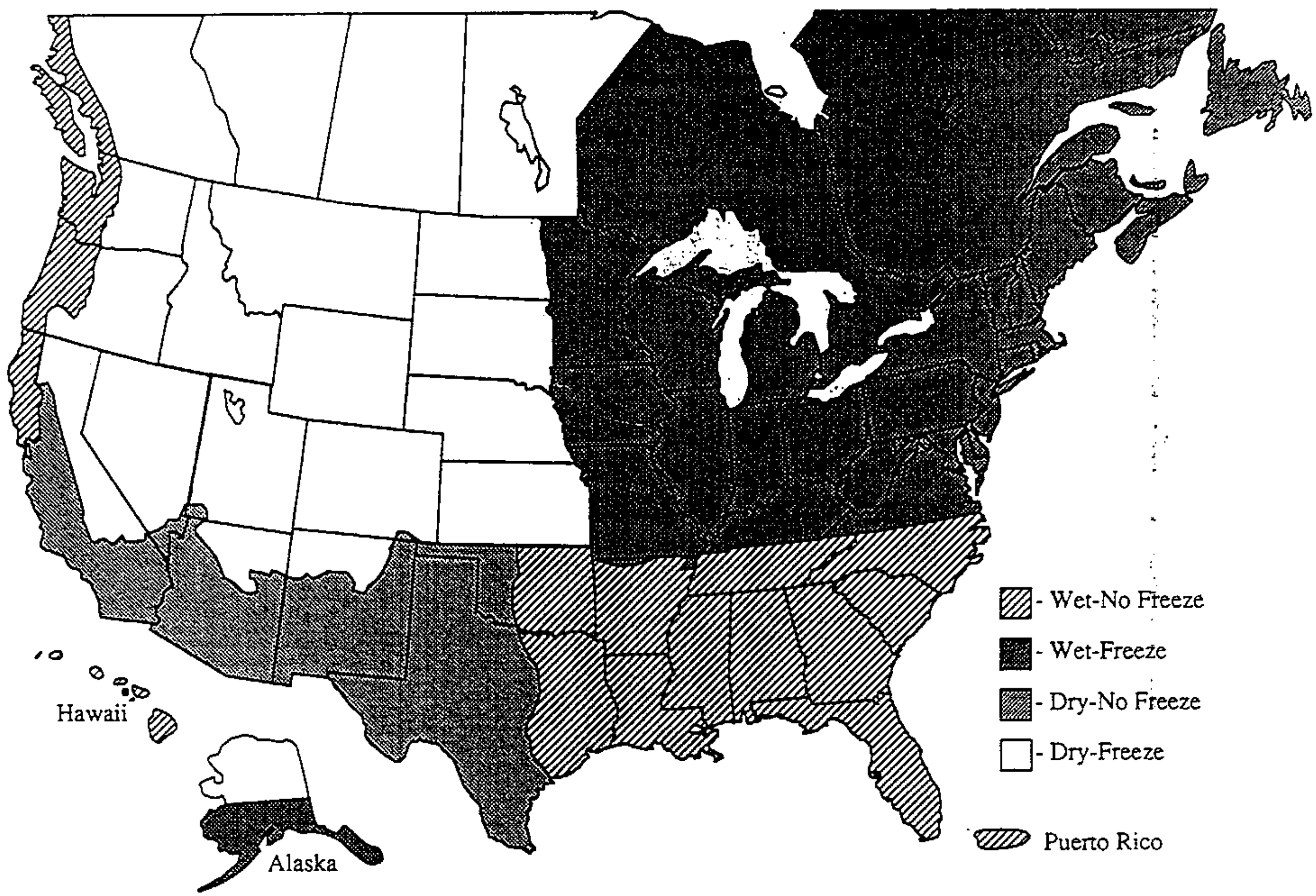


Figure C-11. SHRP/LTPP climatic zones.

Determination of a Specific Site's Climatic Zone

LTPP climatic zones can be defined approximately by mean annual precipitation (PRECIP) and mean freezing index (FI). [C-1] Table C-4 gives an approximate boundary to determine climatic zone of a specific site using precipitation and freezing index.

Table C-4. Approximate boundary for LTPP climatic zones.

Climatic zone	Approximate definition
Wet-freeze	FI >150, PRECIP >20 in
Dry-freeze	FI>150 F-Days, PRECIP<20 in
Wet-nonfreeze	FI<150 F-Days, PRECIP>20 in
Dry-nonfreeze	FI<150 F-Days, PRECIP<20 in

Because of the strong correlation of the climatic variables, any one of the following approximate boundary values in table C-5 can be used to determine the LTPP climatic zone of a specific pavement site.

Table C-5. Determination of the LTPP climatic zones.

Climatic zone	Approximate climatic zone boundaries
Wet	• Annual precipitation > 20 in, or • Number of days with precipitation > 0.01 in greater than 100 days, or • Thornthwaite moisture index > 0.
Dry	• Annual precipitation < 20 in, or • Number of days with precipitation > 0.01 in less than 100 days, or • Thornthwaite moisture index < 0.
Nonfreeze	• Freezing index <150 °F-Days, or • Annual mean temperature > 55 °F, or • Number of air freeze-thaw cycles < 80
Freeze	• Freezing index >150 °F-Days, or • Annual mean temperature < 55 °F, or • Number of air freeze-thaw cycles > 80

References

C-1. Long-Term Pavement Performance Program Guide, Federal Highway Administration, Washington, DC, 1993.

C-2. Carpenter, S. H., M. I. Darter, B. J. Dempsey, and S. Herrin, *A Pavement Moisture Accelerated Distress (MAD) Identification System*, Vol 1, FHWA/RD-81/079, Federal Highway Administration, Washington, DC, 1980.

C-3. ERES Consultants, Inc., *Catalog of Current State Pavement Design Features*, Draft Interim Report, NCHRP Project 1-32, Transportation Research Board, February 1996 (under review).

C-4. Owenby, J., R. Heim Jr., M. Burgin, and D. Ezell, National Oceanic and Atmospheric Administration, *Maps of Annual 1961-90 Normal Temperature, Precipitation, and Degree Days, Climatography of the United States No. 81 - Supplement No. 3,* Environmental Data and Information Service, National Climatic Center, Asheville, North Carolina, 1992.

C-5. Corps of Engineers, *Pavement Design for Frost conditions*, Engineering Manual EM 1110-1-306, U. S. Army, 1962.

C-6. Hershfield, D. M., *The Frequency of Freeze-Thaw Cycles*, Journal of Applied Meteorology, Vol. 113, No. 3, April 1974.

C-7. Thornthwaite, C.W., *An Approach Towards a Rational Classification of Climate,* Geographical Review, Vol. 38, 1, 1948, pp. 55-74.

C-8. ERES Consultants, Inc., *Performance of Concrete Pavements, Vol III—Improving Concrete Pavement Performance*, Draft Report, FHWA, Washington, D.C., 1996.

C-9. American Association of State Highway and Transportation Officials, *AASHTO Guide for Design of Pavement Structures, 1993*, Washington, D.C.

Appendix D

Design Examples Using Catalog Recommendations

Flexible Pavement Design

Step 1 - General project description

Conversion of two lane highway into four lane highway by construction of two additional lanes that will carry one directional traffic

Primary highway, two lanes in one direction

Crowned cross-section with 12 ft lanes and 6 ft shoulders on each side

Design period = 20 years

Climatic data: Freezing Index = 500, Annual Precipitation = 40 in

Step 2 - Determine site condition input for traffic (Appendix A)

ADT (initial) = 10,000 two-directions

Mean percent trucks = 10.0

Lane distribution factor (trucks) = 0.87

Directional distribution factor (trucks) = 0.5 (same number in each direction)

Future growth of trucks = 5 percent per year, compounded

$$GF = [\ (1 + 0.05)^{20} - 1\ ] / 0.05 = 33.06$$

Mean truck equivalency factor over 20 years (flexible ESAL/truck) = 1.1

Total ESALs = 10,000 * 0.1 * 365 * 0.87 * 0.5 * 1.1 * 33.06 = 5,774,012 outer lane, one direction.

Step 3 - Determine site condition input for subgrade (Appendix B)

Natural subgrade soil = silty clay

Resilient modulus backcalculated form FWD deflection data from existing pavement.

Mean backcalculated resilient modulus = 15,000 psi

Mean adjusted resilient modulus = 15,000 * 0.35 = 5250 psi

Seasonal adjustment required as shown in table D-1.

Table D-1. Calculation of seasonally adjusted effective resilient modulus for subgrade.

Season	No. of Months	In Situ Resilient Modulus, psi	Damage Ratio	Seasonal Damage Ratio
Summer	3	5,000	0.40	1.20
Fall	3	6,000	0.30	0.90
Winter	3	10,000	0.06	0.18
Spring Thaw	1	2,000	2.60	2.60
Spring	2	3,500	0.70	1.40
Total	12			6.28

Average Damage Ratio = 6.28 / 12 = 0.52

Effective Resilient Modulus = 4,000 psi (Figure B-3 in Apendix B)

Step 4 - Determination of subgrade preparation/improvement needed (Part 4A, Part 5)
The seasonally adjusted resilient modulus falls into the "Very Soft" class. Subgrade "improvement" is strongly recommended for this class of soil to provide a good construction platform and a more uniform support condition. Since soil was found to be reactive with hydrated lime, the top 12 in of the subgrade will be stabilized and compacted prior to construction of the pavement layers.

Step 5 - Determine site condition input for climate (Appendix C)
Pavement is located in a wet-freeze area of the United States. The freezing index = 500 degree days below freezing, average annual precipitation = 40 in.

Step 6 - Determination of recommended alternative flexible pavement types (Part 4A)
Cell 13: 4-8 million ESALs and Subgrade seasonally adjusted resilient modulus = 4,000 psi.

Alternative 1: HMAC Surface/Binder over Conventional Unbound Granular Base

Alternative 2: HMAC Surface/Binder over Asphalt Treated Base

Step 7 - Determination of material requirements (Part 4A)
Asphalt cement binder: AC-20 viscosity grade, or 60-70 penetration grade (Part 4A.4)

HMAC surface and binder, crushed stone aggregate base, asphalt treated base, granular subbase (Part 4A.3)

Improved subgrade (Part 4A, Part 5)

Step 8 - Recommended design features for "Conventional Unbound Granular Base"(Part 4A - Cell 13)

HMAC Surface and Binder	=	7 - 8 in
Crushed Stone Aggregate Base	=	10 in
Crushed Stone Subbase	=	13 - 14 in
Improved Subgrade	=	12 in hydrated lime stabilized

Step 9 - Recommended design features for "Asphalt Treated Base" (Part 4A - Cell 13)

HMAC Surface and Binder	=	5.5 - 6.5 in
Asphalt Treated Aggregate Base	=	8 in (plant mixed)
Granular (Pit Run Gravel Subbase)	=	14 in
Improved Subgrade	=	12 in hydrated lime stabilized

Step 10 - Subdrainage recommendations (Part 4C, Table 31)

Table 31 recommends Level 3 subdrainage (requiring a treated base) or Level 4-Full subdrainage system for Design Cell 13. One option would be the asphalt treated base section with edge drains. Another option would be to design a full subdrainage design that includes a permeable asphalt treated layer just beneath the asphalt treated base course.

Step 11 - Cross-Section Of Pavement

The cross section shown in Figure 8 is appropriate for this project.

Rigid Pavement Design

Step 1 - General project description

Reconstruction of rural freeway pavement

Interstate highway, two lanes in one direction.

Uniform cross-section with 14 ft widened outer slab and 10 ft outer shoulder (2 ft widened lane plus 8 ft shoulder).

Design period = 20 years.

Step 2 - Determine site condition input for traffic(Appendix A)

ADT (current) = 20,000 two-directions.

Percent trucks = 6.0

Lane distribution factor of trucks = 0.81

Directional distribution factor of trucks = 0.5 (same number in each direction)

Future growth of trucks = 6 percent per year, compounded

$GF = [(1 + 0.06)^{20} - 1] / 0.06 = 36.79$

Mean truck equivalency factor over 20 years (rigid ESAL/truck) = 2.0

Total ESALs = 20,000 * 0.06 * 365 * 0.81 * 0.5 * 2 * 36.79 = 13.1 million, outer lane, one direction.

Step 3 - Determine site condition input for subgrade (Appendix B)

Natural subgrade soil = silty clay

Elastic k-values backcalculated form FWD deflection data from existing pavement from different seasons are shown in Table D-2. The effective k-value is then calculated from those values using the procedure provided in appendix B.

Table D-2. Determination of seasonally adjusted effective subgrade k-value.

Seasons (3 months each)	Backcalculated Dynamic k-value (psi/in)	Static k-value (psi/in)	W18 (millions)	Relative Damage (1/W18)
Spring	154	77	12.75	0.0784
Summer	196	98	13.15	0.0760
Fall	222	111	13.37	0.0748
Winter	336	164	14.20	0.0704
			Mean damage	0.0749
			W18	13.3 million
			Effective k-value	110 psi/in

Step 4 - Determination of subgrade preparation/improvement needed (Part 4B, Part 5)

The seasonally adjusted subgrade k-value falls into the "Weak-fair" class. Subgrade "improvement" is strongly recommended for this class of soil to provide a good construction platform and a more uniform support condition.

Step 5 - Determine site condition input for climate (Appendix C)

Freezing index = 500 degree days below freezing

Average annual precipitation = 33 in

The project site is located in a wet-freeze area.

Step 6 - Determination of recommended alternative rigid pavement types (Part 4B.2)

Cell 14: Traffic (13.1 million ESALs) and Subgrade Weak-Fair (effective k-value = 110 psi/in)

Edge Support: Type 1 - Widened Lane

Base type selected: Lean concrete base

Feasible alternatives selected: JPCP with Dowels

CRCP

Step 7 - Determination of material requirements (Part 4B.2, 4B.11, 4C Table 28)

Portland cement concrete: 650 psi mean flexural strength of third-point loading at 28 days

Lean concrete base: Class A base is recommended, e.g. lean concrete with 7-8% cement

Improved subgrade: 12 in of granular material

Step 8 - Recommended design features for "JPCP with Dowels" (Part 4B)

Doweled JPCP Slab	=	9.5-10.5 in (Widened slab - 2 ft)
Lean Concrete Base	=	4-6 in
Improved Subgrade	=	12 in aggregate
Transverse joint spacing	=	17-19 ft
Dowel bar design	=	1.25 in diameter corrosion-resistant dowel bars spaced at 12 in
Tie bar design	=	No. 5 (0.625 in diameter) deformed bars spaced at 30 in
Transverse joint seal	=	Preformed neoprene compression seal. See table 23, Figure 29.
Longitudinal joint seal	=	See Figure 24.

Step 9 - Recommended design features for "CRCP" (Part 4B)

CRCP Slab	=	9.5-10.5 in (Widened slab - 2 ft)
Lean Concrete Base	=	4-6 in
Improved Subgrade	=	12 in aggregate
Reinforcement content	=	0.70% (No. 6 deformed bar)
Tie bar design	=	No. 5 (0.625 in diameter) deformed bars spaced at 30 in

Step 10 - Subdrainage recommendations (Part 4C)

Table 31 in Part 4C recommends either Level 3 or Level 4 drainage design for Design Cell 14. Level 3 requires a treated base such as the lean concrete proposed for this project with edge drains.

Step 11 - Cross Section (Part 4B.1)

The cross section provided in Figure 18 is appropriate for this project.

Appendix E

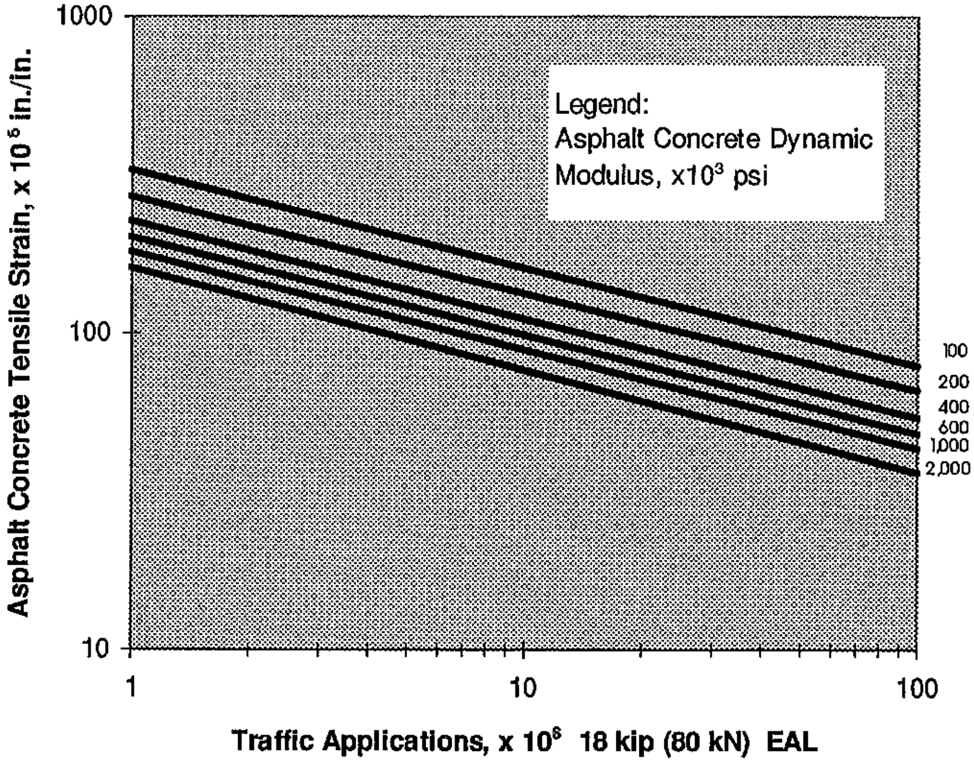
Mechanistic-Empirical Models and Criteria Used to Check Flexible Pavement Designs

Appendix E presents the additional criteria that were used to check and adjust the layer thicknesses that were determined using the 1993 AASHTO Design Guide and material assumptions.

Smoothness. Most SHAs use the AASHTO Design Guide, which utilizes the present serviceability index (basically a measure of pavement smoothness) for its performance criteria. Thus, smoothness was used as the initial performance indicator in establishing the layer thickness requirements for the asphalt concrete-surfaced pavements. These thicknesses were then adjusted if needed to satisfy the other criteria discussed below.

Fatigue Cracking. The structural thickness requirements for asphalt concrete-surfaced pavements were based on limiting tensile strain or tensile stresses at the bottom of the surface or treated base layers. [E-2,E-3] Tensile strain at the bottom of the asphalt concrete surface or asphalt treated base layer was used for the conventional flexible and full-depth pavement cross sections; while tensile stress at the bottom of the cement treated base layer was used for the composite cross section. Those relationships relating stress or strain and allowable number of load applications for a given material strength and performance that were used for the catalog are shown in Figures E-1, E-2 and E-3.

Rutting. Rutting from supporting layers or mechanical distortion was selected as one of the limiting criteria for both the flexible and composite pavement structures. Field studies have shown that certain levels of permissible subgrade vertical compressive strains are related to performance or surface rutting.[E-4] This criterion is to ensure that there is sufficient cover over the supporting subgrade soils, assuming that the other pavement layers are designed and constructed such that minimal deformations will occur in each layer. The relationship used to develop the thickness requirements for the pavement structures is shown in Figure E-4.



$$Log\ N = 15.947 - 3.291\ Log(\epsilon_t/10^{-6}) - 0.854\ Log(E^*/10^3)$$

where: ϵ_t = Tensile strain at the bottom of the asphalt concrete surface and/or base layer

E^* = Complex modulus, psi

Figure E-1 Limiting criteria for tensile strain at bottom of AC. [E-1]

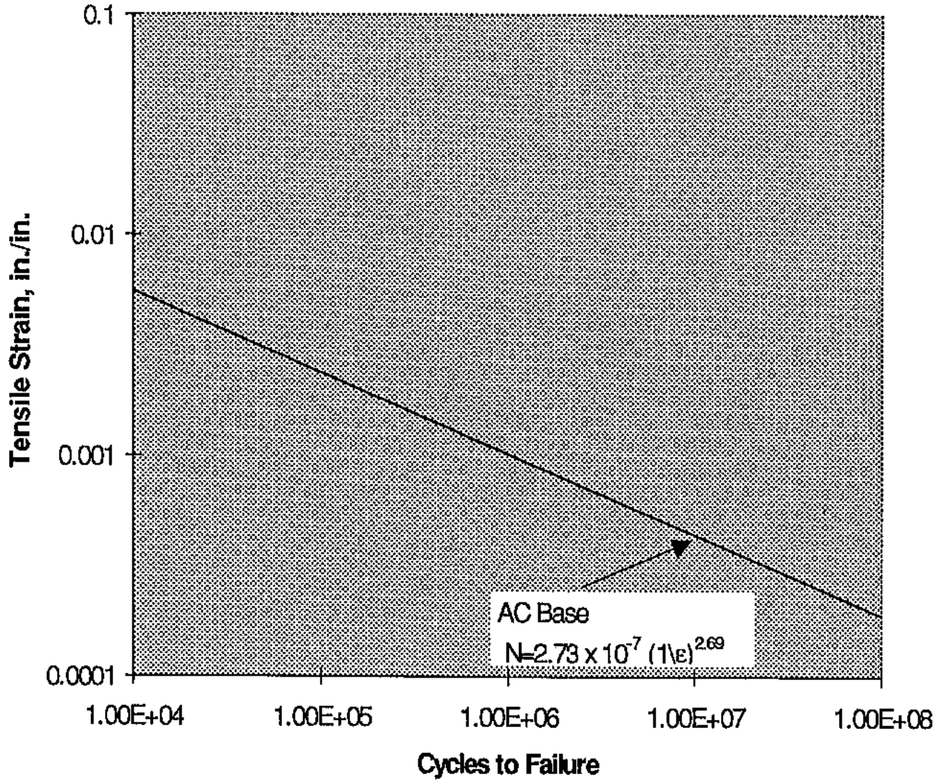


Figure E-2 Limiting criteria for tensile strain at bottom of AC treated base. [E-3]

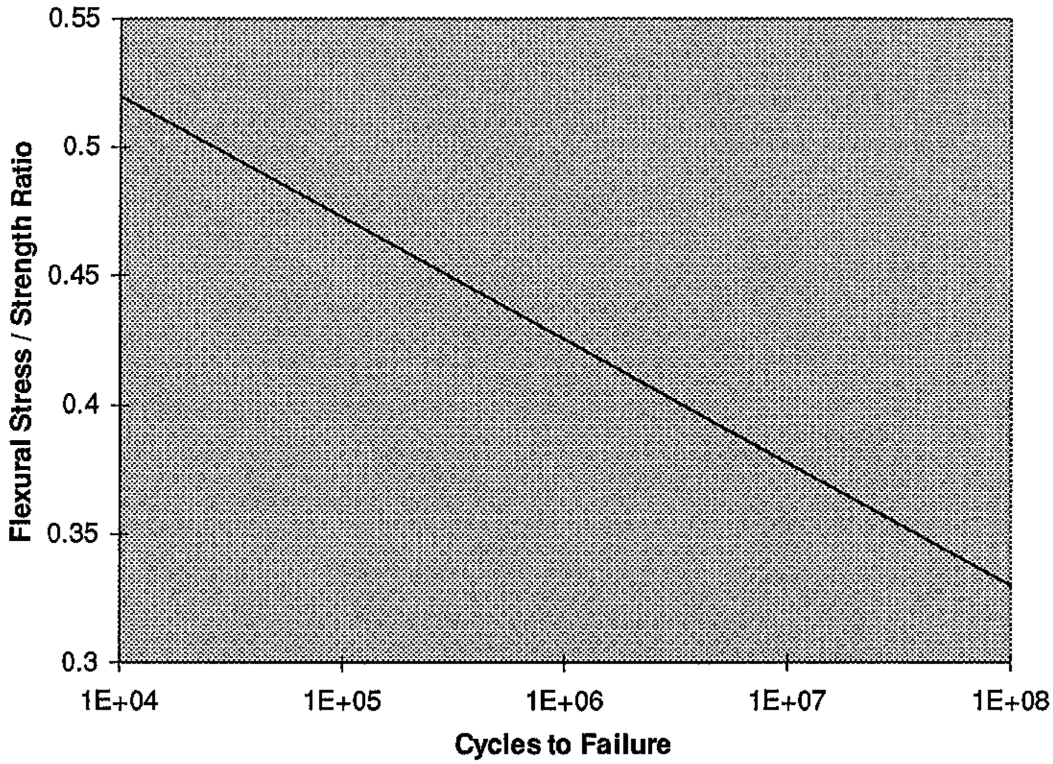
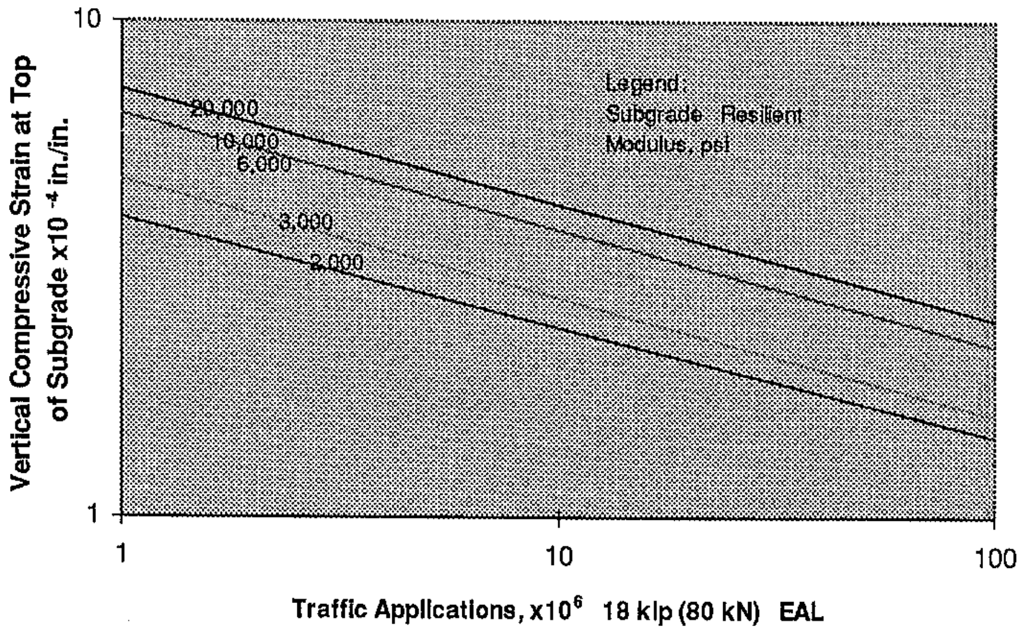


Figure E-3. Relationship between stress/strength ratio and cycles to failure for cement-treated aggregate base. [E-3]



$$\text{Log } N = 0.955 (\text{Log } M_R) - 4.082 (\text{Log } \epsilon_v) - 10.90$$

where:

M_R	=	Resilient modulus, psi
ϵ_v	=	Vertical compressive strain at the top of the subgrade
N	=	Allowable or permissible number of equivalent load repetitions

Figure E-4. Limiting criteria for vertical compressive strain at top of subgrade. [E-4]

REFERENCES

E-1 Finn, F.N., C. Saraf, R. Kulkarni, K. Nair, W. Smith, and A. Abdullah, "Development of Pavement Structural Subsystems, "Final Report, NCHRP Project 1-10B, national Cooperative Highway Research Program, Highway Research Board, February 1977.

E-2 Kallas, B.F. and V.P. Pazinanskas, "Flexural Fatigue Tests on Asphalt Paving Mixtures", ASTM STP 508, American Society for Testing and Materials, July 1971 (pp. 47-66).

E-3 Treybig, H.J., B.F. McCullough, P. Smith, and H. Von Quintus, "Overlay Design and Reflection Cracking Analysis for Rigid Pavements, Volume 1, Development of New Design Criteria", Final Report No. FHWA-RD-77-66, Federal Highway Administration, August 1977.

E-4 Barker, W.R. and W.N. Brabston, "Development of a Structural Design Procedure for Flexible Airport Pavements", FFA Report No. FAA-RD-74-199, U.S. Army Engineer Waterways Experiment Station, Federal Aviation Administration, September 1975.

Appendix F

Mechanistic-Empirical Models and Criteria Used to Check Rigid Pavement Designs

Introduction

This appendix describes the performance prediction models used for the design checks of rigid pavements. Pavement performance prediction models are mathematical relationships that predict the development of a key performance indicator (e.g., cracking, faulting) based on design, traffic, and climatic inputs. These models can be mechanistic-based, in which basic pavement responses (stresses, strains, deflections) are calibrated with field observations of pavement performance, or empirically based, in which a statistical regression model is developed solely on the observed performance of the pavement.

Performance prediction models presented in this appendix include:

- Doweled JPCP joint faulting.[F-1]
- Non-doweled JPCP joint faulting.[F-1]
- JPCP slab cracking.[F-1]
- JRCP crack deterioration. [F-1]
- CRCP localized failure.[F-2]
- PCCP terminal serviceability index (smoothness) model.[F-3]

Joint Faulting Model for Doweled Jointed Concrete Pavements

Several PCCP models that are used for design checks of this catalog were developed under an FHWA project on pavement performance,[F-1] called RPPR from here on. The models include doweled JPCP joint faulting, JPCP slab cracking, non-doweled JPCP joint faulting mode, and JRCP crack deterioration model. A total of 304 concrete pavement sections were used to develop RPPR models. The concrete pavement sections evaluated under RPPR represent a variety of designs that are located throughout the United States, and Canada. A variety of design features (i.e., slab thickness, joint spacing, load transfer, and so on) are present on these pavement sections. These sections also vary considerably in age and in cumulative traffic loadings (expressed in terms of 18-kip equivalent single-axle load [ESAL] applications) that they have sustained.

Transverse joint faulting is a major distress of jointed concrete pavements. Transverse joint faulting is the difference in elevation between abutting slab faces and is primarily the result of a combination of heavy axle loads, free moisture beneath the pavement, and pumping of the supporting base or subbase material from beneath the slab. The RPPR transverse joint faulting model for the jointed concrete pavements (both JPCP and JRCP) with dowel bars is as follows:

$$\begin{aligned} FaultD = {} & CESAL^{0.25} * [0.0628 - 0.0628 * C_d + 0.3673 * 10^{-8} * Bstress^2 \\ & + 0.4116 * 10^{-5} * Jtspace^2 + 0.7466 * 10^{-9} * FI^2 * Precip^{0.5} \\ & - 0.009503 * Basetype - 0.01917 * Widenlane + 0.0009217 * Age] \end{aligned} \tag{F-1}$$

where:

CESAL	=	Cumulative 18-kip (80-kN) equivalent single axle loads, millions.
Bstress	=	Maximum dowel/concrete bearing stress, lb/in^2.
Jtspace	=	Mean transverse joint spacing, ft.
Basetype	=	Base type (0 = nonstabilized base; 1 = stabilized base).
Widenlane	=	Widened lane (0 = not widened, 1 = widened).
C_d	=	Modified AASHTO drainage coefficient, calculated from data base information.
FI	=	Mean annual freezing index, degree-days.
Precip	=	Mean annual precipitation, in.
Age	=	Pavement age, years.

The modified Friberg analysis was used to calculate the maximum bearing stress exerted by the dowels on the surrounding concrete (Bstress, lb/in^2): [F-5,F-6]

$$Bstress = K * \delta_o \tag{F-2}$$

where:

K	=	Modulus of dowel support, fixed at 1.5*10^6 lb/in^2/in (4.07*10^8 kN/m^2/m).
δ_o	=	Deflection of the dowel at the face of the joint, in
	=	$P_t (2 + \beta z) / 4\beta^3 E_s I$

in which

P_t = Shear force acting on dowel, fixed at 9000 lb (40-kN).
z = Width of joint opening, in.
E_s = Modulus of elasticity of dowel bar, fixed at $2.9*10^7$ lb/in^2 ($2.0*10^5$) MPa.
I = Moment of inertia of dowel bar cross-section, in^4.
= $0.25 * \pi * (d/2)^4$ for dowel diameter d in inches.
β = Relative stiffness of the dowel concrete system, 1/in.
= $[(Kd) / (4E_sI)]^{0.25}$.

The analysis assumes a 9000-lb (40-kN) wheel load placed at the corner, which will produce the maximum stress in the outermost dowel bar. Only dowel bars within a distance of 1.0*ℓ from the center of the load are considered to be active, where ℓ is the radius of relative stiffness, defined as:

$$\ell = \left[\frac{Eh^3}{12k(1 - \mu^2)}\right]^{0.25} \qquad \text{(F-3)}$$

where:

E = Concrete modulus of elasticity, lb/in^2.
h = Slab thickness, in.
k = Effective modulus of subgrade reaction, lb/in^2/in.
μ = Poisson's ratio, fixed at 0.15.

The modified Friberg analysis is based on the assumption that 45 percent of the *load* (not the stress) is transferred across the joint.

The drainage coefficient, C_d, is based on the AASHTO drainage coefficient introduced in the AASHTO rigid pavement design procedure in 1986. [F-7] This factor is a reflection of the pavement's ability to drain excessive moisture from within the structure, as well as the pavement's potential for being exposed to near saturated conditions. Although the drainage coefficient represents a major part of the AASHTO design procedure, little guidance is presented for its selection. A rational procedure is presented in reference 8, which was also used in this study to develop drainage coefficients. Using that information, a simplified matrix

was developed for the selection of drainage coefficients based on key climatic and pavement design information. This matrix is presented in table F-1.

Table F-1. Simplified design matrix for the selection of the overall drainage coefficient, C_d.

Edge Drains	Precip. Level	Fine-Grained Subgrade		Coarse-Grained Subgrade	
		Nonpermeable Base	Permeable Base	Nonpermeable Base	Permeable Base
No	Wet	0.70–0.90	0.85–0.95	0.75–0.95	0.90–1.00
	Dry	0.90–1.10	0.95–1.05	0.90–1.15	1.00–1.10
Yes	Wet	0.75–0.95	1.00–1.10	0.90–1.10	1.05–1.15
	Dry	0.95–1.15	1.10–1.20	1.10–1.20	1.15–1.20

Notes:

1. Fine subgrade = A-1 through A-3 classes,
   Coarse subgrade = A-4 through A-7 classes.
2. Permeable Base = k = 1000 ft/day (305 m/day) or Cu ≤ 6.
3. Wet climate = Precipitation > 25 in/year (635 mm/year);
   Dry climate = Precipitation ≤ 25 in/year (635 mm/year).
4. Select mid-point of range and use other drainage features (adequacy of cross slopes, depth of ditches, presence of daylighting, relative drainability of base course, bathtub design, etc.) to adjust upward or downward.

Joint Faulting Model for Nondoweled Jointed Concrete Pavements

The selected joint faulting model for nondoweled JPCP is also from RPPR study.[F-1] In nondoweled transverse joints, load transfer is accomplished through aggregate interlock of the abutting joint faces. However, under heavy traffic loadings and under certain environmental conditions, aggregate interlock can become ineffective, leading to pumping and faulting. The RPPR model selected for transverse nondoweled joint faulting is as follows:

$$\begin{aligned} FaultND = {} & CESAL^{0.25} * [0.2347 - 0.1516 * C_d - 0.000250 * \frac{Slabthick^2}{Jtspace^{0.25}} \\ & - 0.0115 * Basetype + 0.7784 * 10^{-7} * FI^{1.5} * Precip^{0.25} \\ & - 0.002478 * Days90^{0.5} - 0.0415 * Widenlane] \end{aligned} \qquad \text{(F-4)}$$

where:

CESAL	=	cumulative 18-kip (80-kN) equivalent single axle loads, millions.
Jtspace	=	Mean transverse joint spacing, ft.
Slabthick	=	PCC slab thickness, in.
Basetype	=	Base type (0 = nonstabilized base; 1 = stabilized base).
Widenlane	=	Widened lane (0 = not widened, 1 = widened).
C_d	=	Modified AASHTO drainage coefficient, calculated from data base information.
FI	=	Widened lane (0 = not widened, 1 = widened).
Precip	=	Mean annual precipitation, in.

Transverse Cracking Model for JPCP

RPPR's JPCP transverse cracking model is used to check if the selected designs satisfy the slab cracking criterion. Transverse cracking in concrete pavements can occur as a result of either very high stresses in the slabs or fatigue failure. The high stress levels are usually caused by the combined effects of the restraint forces, thermal curling, moisture warping, and traffic loads. Fatigue cracking is a key measure of concrete pavement performance for JPCP and is a critical item for consideration in the design of concrete pavements.

The transverse cracking model developed by RPPR is based on field observations on 303 in service concrete pavements all over the country plus a few sections in Canada in 1987 and 1992. Total of 465 data points were used to develop the model. The model is given as follows:

$$percent\ cracking = \frac{100}{1 + 1.41FD^{1.66}} \qquad \text{(F-5)}$$

where:

FD = Accumulated fatigue damage ($\Sigma n/N$).

Several steps need to be taken to calculate the predicted percent cracking of a pavement section:

- Stress calculation at the critical damage location
- Fatigue damage determination using a reliable fatigue damage model

Stress Calculation

The stress of interest in a fatigue analysis is the maximum tensile stress at the critical damage location. To perform the analysis, the critical damage location must first be determined, and then the combined stress at that location determined considering all factors that significantly affect stresses. In general, the critical damage location is the location in the slab where the maximum stress occurs. The factors that cause stresses in pavement slabs include traffic loads, temperature gradients, moisture gradients, and various factors that cause uniform expansion or contraction of PCC, such as uniform temperature changes and drying shrinkage. In JPCP, because of short joint spacing, the stresses due to the uniform expansion or contraction of PCC are not significant. Therefore, the stress calculation for fatigue analysis involves determining the combined stress due to the traffic loads and slab curling (or warping) at the critical damage location.

Critical Damage Location

In this project, the fatigue analysis was conducted assuming that the transverse cracks observed on JPCP are results of fatigue failures initiating at the slab bottom (bottom-up failure). This assumption is accurate if the pavement slabs are flat when the temperature gradient is zero. The critical damage location for this mode of failure is:

- For normal-width (12 ft [3.7 m]) sections, bottom of longitudinal edge, half-way between the two transverse joints that borders the slab.
- For widened lane sections (≥ 12 ft [3.7 m] wide), bottom of the wheel path, also at the midslab location.

The cracking model developed under this project is based on the fatigue damage determined for the edge loading condition. The stresses for this analysis were determined using the regression equations developed under NCHRP Project 1-26.[F-9] These equations are based on the results given by the finite element program ILLI-SLAB, and they provide an accurate and efficient means of determining the combined stress due to axle loads and slab curling under the edge loading condition. The stress calculation procedures are described in the next section.

Load Stress

The NCHRP 1-26 equations utilize Westergaard's edge stress equation for a circular load and various adjustment factors to reproduce the results given by the ILLI-SLAB finite element program. The NCHRP 1-26 equation for the load stress has the following form:

$$\sigma_{load} = f1 * f2 * f3 * f4 * \sigma_e \tag{F-6}$$

where:

- σ_{load} = Load stress, lbf/in^2.
- f1, f2, f3, f4 = Adjustment factors for slab size, stabilized base, widened lane, and tied concrete shoulder.
- σ_e = Stress obtained using Westergaard's edge load equation for circular loads, lbf/in^2.

The equivalent single-axle radius (ESAR) concept is used to handle multiple wheel loads, and adjustments are made to account for the slab size effect, widened traffic lane, tied concrete shoulder, and the presence of a stabilized base. The ESAR is the equivalent single wheel radius of a multiple wheel load that will produce the same stress intensity at the critical location. The application of the ESAR concept allows the use of a closed form solution to determine the maximum stress under a multiple wheel load.

The edge load stress is calculated using the equation given in Westergaard's 1948 paper for circular load given below, substituting the radius of the applied load with the equivalent single axle radius: [F-10]

$$\sigma_e = \frac{3(1+\mu)P}{\pi(3+\mu)h^2}\left[\ln\frac{Eh^3}{100ka^4} + 1.84 - \frac{4\mu}{3} + \frac{1-\mu}{2} + 1.18(1+2\mu)\frac{a}{\ell}\right] \tag{F-7}$$

where:

- P = Total applied load, lbf.
- μ = Poisson's ratio.
- E = Modulus of elasticity of PCC, lbf/in^2.
- h = Slab thickness, in.
- k = Modulus of subgrade reaction, $lbf/in^2/in$.
- a = Radius of the applied load, in.
- ℓ = Radius of relative stiffness, in, defined as follows:

$$\ell = \left[\frac{Eh^3}{12(1 - \mu^2)k} \right]^{0.25} \tag{F-8}$$

where:

E = Modulus of elasticity of PCC, lbf/in^2.
h = Slab thickness, in.
μ = Poisson's ratio.
k = Modulus of subgrade reaction, $lbf/in^2/in$.

Please note that the k-value used here is the backcalculated dynamic k, which can be taken as twice the staic k obtained by laboratory testing. The PCC modulus of rupture and Epcc are long-term values. The long-term concrete strength is typically about 10 percent greater than the 28-day strength.

The equivalent single-axle radius for the dual wheel load is obtained using the following equation:

$$\frac{a_{eq}}{a} = 0.909 + 0.339485\frac{S}{a} + 0.103946\frac{a}{\ell} - 0.017881\left(\frac{S}{a}\right)^2 - 0.045229\left(\frac{S}{a}\right)^2\frac{a}{\ell} + 0.000436\left(\frac{S}{a}\right)^3 - 0.301805\frac{S}{a}\left(\frac{a}{\ell}\right)^3 + 0.034664\left(\frac{S}{\ell}\right)^2 + 0.001\left(\frac{S}{a}\right)^3\frac{a}{\ell} \tag{F-9}$$

Limits: $0 \le S/a \le 20$
$0 \le a/\ell \le 0.5$

where:

a_{eq} = Equivalent single axle radius of dual wheels, in.
a = Radius of the applied load, in.
S = Dual wheel spacing, in.
ℓ = Radius of relative stiffness, in.

In the NCHRP 1-26 procedure, the load stress is determined by applying various adjustment factors to the edge stress calculated using Westergaard's equation (equation F-6). The adjustments are made for the slab size effect, widened lane, tied concrete shoulder, and

stabilized base. Regression equations are provided for determining each of these factors, but only the factor for widened lane was used in this model for the following reasons:

- The adjustment factor for the slab size effect was not used, because the ILLI-SLAB analysis performed to validate all procedures used in this project showed that the use of this factor could result in overcompensation for the slab size effect. This factor was originally introduced because the load stress in short slabs can be significantly less than that in an infinite slab assumed in the Westergaard solution. The stresses are lower in short slabs because some of the load on short slab is carried by the rigid body motion of the slab (i.e., slabs sinking into the subgrade). If this rigid body motion is prevented, by the adjacent slabs for example, the stresses in short slabs can be even higher than that in infinite slabs. The analysis has shown that the response of multiple slab system with even a moderate load transfer efficiency at the transverse joints closely approximate that of an infinitely long slab. For highway pavements, this factor is significant only for very short slabs (12 ft [3.7 m] or less), even if the slabs have very poor load transfer efficiency.

- The effects of tied concrete shoulder were treated by directly considering the stress load transfer efficiency (LTE). The stress LTE was determined from deflection LTE using the following regression equation:

$$Log_{10}(LTE_\sigma) = 0.064787 + 0.0047221 LTE_\Delta + 0.00089586 LTE_\Delta^2 - 0.16478x10^{-4} LTE_\Delta^3 + 0.89222x10^{-7} LTE_\Delta^4 \quad \text{(F-10)}$$

where:

LTE_σ = Stress LTE, percent.
LTE_Δ = Deflection LTE, percent.

For sections provided with tied concrete shoulder or other forms of edge support (such as adjacent lane or tied curb and gutter), the load stress was multiplied by the following factor to account for the edge support:

$$f_{LTE} = \frac{100}{100 + LTE_\sigma} \quad \text{(F-11)}$$

where:

f_{ES} = Adjustment factor for edge support.
= 1.0 if no edge support.
LTE_σ = Stress LTE, percent.

- The effects of stabilized bases were considered directly using the effective slab thickness. The effective slab thickness was determined from FWD testing results, and it represents the equivalent thickness of a single concrete layer that would give the same structural response as the actual pavement structure (slab and base). The procedure used to determine the effective slab thickness is described in chapter 4 of volume II. The effective slab thickness as determined in this project accounts for the structural contribution of all pavement layers and any interaction between layers. On those section where the effective slab thickness was used, the following equation was used to determine the maximum tensile stress at the bottom of the pavement slab:

$$f_{SB} = \frac{2\ (h - x)}{h_e} \qquad \text{(F-12)}$$

where:

f_{SB} = Adjustment factor for stabilized base.
= 1.0 if $h_e = h$.
h = Actual slab thickness, in.
h_e = Effective slab thickness, in.
x = neutral axis location:

$$x = \frac{\frac{h_1^{\,2}}{2} + \frac{E_2}{E_1} h_2 \left(h_1 + \frac{h_2}{2} \right)}{h_1 + \frac{E_2}{E_1} h_2} \qquad \text{(F-13)}$$

where:

h_1 = Slab thickness, in.

h_2 = Base thickness, in.
E_1 = Concrete modulus of elasticity, lbf/in^2.
E_2 = Base modulus of elasticity, lbf/in^2.

Unlike other adjustment factors, f_{SB} is applied to the combined stress, because this factor is an adjustment for the slab thickness.

On widened lane sections, the critical location for fatigue damage is the bottom of slab, directly under the wheel path. Studies have shown that the slabs are almost never loaded at the outer edge on widened lane sections Therefore, the following adjustment factor was used to obtain the maximum stress directly under the wheel load:

$$f_{WL} = 0.454147 + \frac{0.013211}{D/\ell} + 0.386201\frac{a}{D} - 0.24565\left(\frac{a}{D}\right)^2 + 0.053891\left(\frac{a}{D}\right)^3 \qquad \text{(F-14)}$$

where:

f_{WL} = Adjustment factor for widen lane.
= 1.0 if standard-width lane.
a = Radius of loaded area, in.
D = Mean wheel location, inches from outer edge.
ℓ = Radius of relative stiffness, in.

The load stress can now be determined using the following equation:

$$\sigma_{Load} = f_{ES}\, f_{WL}\, \sigma_e \qquad \text{(F-15)}$$

where:

σ_{Load} = Load stress, lbf/in^2.
f_{ES} = Adjustment factor for edge support (equation F-14).
f_{WL} = Adjustment factor for widened lane (equation F-17).
σ_e = Westergaard's edge stress (equation F-10), lbf/in^2.

Curling Stress

The curling stress is determined using the following equation and then combined with the load stress using a regression coefficient in the NCHRP 1-26 procedure:

$$\sigma_c = \frac{CE\ \alpha_T\ \Delta T}{2} \tag{F-16}$$

where:

- σ_c = Curling stress, lbf/in².
- C = Curling stress coefficient.
- E = Concrete modulus of elasticity, lbf/in².
- α_T = Concrete coefficient of thermal expansion (5.5×10^{-6}).
- ΔT = Temperature difference between the top and bottom of the slab, °F.

This equation was developed by Westergaard, and Bradbury developed the coefficients for solving this equation.[F-11] For maximum stress at the longitudinal edge, the curling stress coefficient is given by the following equation:

$$C = 1 - \frac{2\ \cos\lambda\ \cosh\lambda}{2\ \sin\lambda\ \sinh\lambda}\ (\tan\lambda + \tanh\lambda) \tag{F-17}$$

where:

$$\lambda = \frac{L}{\ell\ \sqrt{8}} \tag{F-18}$$

- L = Slab length, in.
- ℓ = Radius of relative stiffness, in.

Combined Stress

The combined stress due to load and curling is obtained using the following equation:

$$\sigma_{combined} = f_{SB}(\sigma_{load} + R * \sigma_{curl}) \tag{F-19}$$

where:

$\sigma_{combined}$	=	Combined edge stress, lbf/in².
f_{SB}	=	Adjustment factor for stabilized base.
σ_{load}	=	Load stress, psi.
R	=	Regression coefficient.
σ_{curl}	=	Curling stress, lbf/in².

The regression coefficient R is determined using the following equation:

$$
\begin{aligned}
R = {} & 1.062 - 0.015757 dT - 0.0000876 k - 1.068\frac{L}{\ell} + 0.387317 dT\frac{L}{\ell} \\
& + 1.17x10^{-11}E\,dTk - 1.81x10^{-12}E\,dT^2k - 1.051x10^{-9}E\left(\frac{L}{\ell}\right)^2 kdT \\
& + 1.84x10^{-11}E\,dT^2\frac{L}{\ell}k - 1.7487\left(\frac{L}{\ell}\right)^2 dT + 0.000034351 dT^3 \\
& + 86.97\left(\frac{L}{\ell}\right)^3 - 0.00816396 dT^2\frac{L}{\ell}
\end{aligned} \qquad \text{(F-20)}
$$

where:

dT	=	$\alpha \Delta T \times 10^5$.
α	=	PCC coefficient of thermal expansion, ε/°F.
ΔT	=	Temperature difference through the slab, °F.
k	=	Subgrade modulus of reaction, lbf/in²/in.
L	=	Slab length, in.
ℓ	=	Radius of relative stiffness, in (equation F-11).
E	=	Modulus of elasticity of PCC, lbf/in².

The coefficient R is needed because the load and curling stresses are not directly additive. Curling causes various parts of the slab to lift off of the base, invalidating the full contact assumption made in the load stress calculation. The regression coefficient R provides the necessary adjustment to the curling stress to give the correct combined stress.

Further refinements were made to the calculated damage considering a more refined pass-to-coverage ratio, and consideration of moisture gradient and residual temperature gradients.

Pass To Coverage

The effects of the lateral traffic wander was given a more rigorous statistical treatment in this study. Assuming that the lateral wander of traffic is normally distributed, the probable lateral distribution of the traffic wheels was determined. Then, considering the contribution to the fatigue damage at the critical location (longitudinal edge for all normal-width sections) by traffic passing through any point and the probability that the traffic will pass through that point, the pass to coverage (p/c) ratio was determined.

The p/c is simply the ratio that gives the number of traffic passes needed to produce the same amount of fatigue damage at the critical location as one pass that causes the critical loading condition (i.e., edge loading condition). The number of fatigue loading cycles (or coverage) that the applied traffic causes is the number traffic passes divided by p/c. For example, if the p/c is 100, this means that it takes 100 traffic passes to cause the same amount of damage as 1 load placed directly at the edge.

The p/c as described here may be expressed mathematically as follows:

$$p/c = \frac{FD_{Dii}}{\sum_j P(COV_{Dj}) * FD_{Dij}} \tag{F-21}$$

where:

FD_{Dii} = Fatigue damage at location D_i due to the load at D_i.
$P(COV_{Dj})$ = Probability that the load will pass through location D_j.
FD_{Dij} = Fatigue damage at location D_i due to the load at D_j.

The p/c is commonly taken as a percentage of traffic that passes close to the pavement edge. In this approach, the traffic passing within a certain distance of the outer edge is assumed to cause one edge loading application. In this project, the concept "fatigue damage per pass" (FD/Pass) was introduced to more precisely determine the amount of fatigue damage cause by passing traffic.

The fatigue damage caused by the traffic at any point on a pavement slab may be determined using FD/Pass. The FD/Pass may be defined as follows:

$$FD_{Di}/Pass = \sum_j P(COV_{Dj}) * FD_{Dij} \tag{F-22}$$

where:

$FD_{Di}/Pass$	=	Fatigue damage per pass at the damage location D_i.
$P(COV_{Dj})$	=	Probability that the load will pass through location D_j.
FD_{Dij}	=	Fatigue damage at location D_i due to the load at D_j.

The FD/Pass as defined above, represents the probablistic amount of damage caused at the damage location Di due to the applied traffic. It is important to note that FD/Pass is determined for a specific point on the pavement. To determine FD/Pass, the stress at the location of interest due to the loads placed at all relevant locations must be determined.

For fatigue analysis of JPCP, the most relevant location of interest is the longitudinal edge. Once the FD/Pass is determined, this number can be converted to p/c to show the number of equivalent load cycles (edge load applications) produced by the applied traffic. Taking fatigue damage as 1/N, equation F-22 can be used to determine p/c based on FD/Pass. Rewriting equation F-21,

$$p/c_{Di} = \frac{\frac{1}{N_{Dii}}}{\sum_j P\ (COV_{Dj})\ *\ \frac{1}{N_{Dij}}} \tag{F-23}$$

where:

p/c_{Di}	=	p/c at location D_i.
N_{dii}	=	Allowable number of load applications based on stress at location D_i due to the load placed at D_i.
$P(COV_{Dj})$	=	Probability that the load will pass through location D_j.
N_{dij}	=	Allowable number of load application based on stress at location D_i due to the load at D_j.

The traffic is assumed to be normally distributed. The subscript on p/c above denotes that the p/c determined above converts the traffic placed on the pavement to the equivalent number of

load applications by the loads placed directly at D_i for fatigue damage at D_i. Equation F-23 reduces to the following:

$$p/c_{Di} = \frac{1}{\sum_j P(COV_{Dj}) * \frac{N_{Dii}}{N_{Dij}}} \qquad \text{(F-24)}$$

The p/c as defined in equation F-24 involves a considerable amount of analysis; however, since it is a measure of relative damage caused by the loads placed at various locations, it is not very sensitive to the pavement structure. Therefore, p/c determined for the average case may be used. The p/c is, however, affected by several factors, including the following:

- Mean wheel location.
- Standard deviation of traffic wander.
- Stress level.

The mean wheel location and standard deviation of traffic is somewhat variable, and both of these factors have a significant effect on p/c. In this project the figures reported in reference 12 were used:

- Average wheel location = 22 in from pavement edge.
- Standard deviation = 8.4 in.

These results are based on 1,300 observations. The average wheel location on widened lane sections were about 2 in closer to the paint stripe; however, since the critical damage location on widened lane sections is directly under the wheel path, the p/c is close to 1.0 (i.e., almost every wheel passes through the critical location).

The following regression equation was developed for p/c and used in the analysis:

$$p/c = 395.1 - 924.8SR + 1047.26SR^2 - 456.73SR^3 \qquad \text{(F-25)}$$

where:

SR = Stress-to-strength ratio (σ/MR).

Consideration of Moisture and Residual Temperature Gradients

In this project, the cumulative effects of curling (or warping) caused by all factors other than temperature gradients were addressed by shifting the temperature gradients determined for each pavement section. The actual magnitude of the effective residual curling is unknown. However, using the same logic used to make the thickness adjustments, the consistency within the data set could be used as the guide to make relative adjustments. Again, consistent adjustments were made for all data points within an actual pavement section, and the reasonableness of the results was used as the guide in making these adjustments. The average values for the four climatic zones are as follows:

- DF — 11 °F
- DNF — 11.5 °F
- WF — 8 °F
- WNF— 8.5 °F

The above values should be subtracted from the actual temperature gradients when using the cracking model.

Fatigue Damage Determination

The fatigue damage was determined using the linear damage accumulation approach proposed by Miner: [F-13]

$$FD = \sum \frac{n}{N} \qquad \text{(F-26)}$$

where:

FD = Fatigue Damage

n = number of applied 18-kip (80-kN) single axle loads

N = number of allowable 18-kip (80-kN) single axle loads

The model developed from Corps of Engineers (COE) data from 51 full-scale field sections was selected to calculate the allowable load applications. The edge load stress was calculated using H-51 program (computerized Pickett and Ray charts) and multiplied by 0.75 to account for the edge support in the sections.[F-14]

$$\log N = 2.13\ SR^{-1.2} \qquad \text{(F-27)}$$

where:

N = Number of allowable load applications.
SR = Stress to strength ratio (σ/MR).
σ = Critical tensile stress, lbf/in^2.
MR = PCC modulus of rupture, lbf/in^2.

This model was originally developed for airfield pavements, but has shown good results in various other applications.

Crack Deterioration Model for JRCP

Low-severity transverse cracks are a normal occurrence in JRCP. These cracks are expected to develop as the slab responds to drying shrinkage, thermal curling, and thermal contractions. Reinforcement is placed in JRCP to hold the cracks tight and prevent deterioration. However, repeated heavy load applications, environmental effects, and inadequate steel design can result in the cracks breaking down and deteriorating. Medium- and high- severity transverse cracks in JRCP cause localized failures, increased roughness, user discomfort, and trigger the need for rehabilitation. The RPPR model used for the catalog design check is given below:

$$\begin{aligned} CRACKJR = {} & AGE^{2.5} * [6.88 * 10^{-5} * FI/THICK \\ & + (0.116 - 0.073\ BASE) * CESAL * \left(1 - e^{-0.032 * MI}\right) \\ & * e^{(7.55188 - Epcc - 66.5\ PERSTEEL + 5\ PERSTEEL * Epcc)}] \end{aligned} \qquad \text{(F-28)}$$

where:

CRACKJR = number of transverse cracks (medium- and high- severity)/mi.
CESAL = cumulative 18-kip (80-kN) ESALs in traffic lane, millions.
PERSTEEL = percentage of steel (longitudinal reinforcement).
Epcc = mean backcalculated modulus of elasticity of concrete million lb/in^2.
THICK = PCC slab thickness, in.
MI = Thornthwaite moisture index.
BASE = 0, if nonstabilized base exists.
= 1, if stabilized base exists.
FI = Freezing Index, degree days below freezing.

CRCP Localized Failure Model

The CRCP local failure model developed under project IHR-529 of Illinois Cooperative Highway Research Program was selected for the design check of the catalog.[F-2] Total 408 data points were used for the development of the model and the model for predicting the number of CRCP failures on a per mile basis is given as follows:

$$\begin{aligned}\log_e(FAIL) &= 6.8004 - 0.0334 * PAVTHK^2 - 6.5858 * PSTEEL \\ &+ 1.2875 * \log_e(CESAL) - 1.1408 * BAM - 0.9367 * CAM \\ &- 0.8908 * GRAN - 0.1258 * CHAIRS\end{aligned} \qquad \text{(F-29)}$$

where:

FAIL	=	total number of failures in the outer lane, #/mile
THICK	=	CRCP slab thickness, in.
PSTEEL	=	longitudinal reinforcement, percent
CESAL	=	cumulative ESALs, millions
BAM	=	1 if subbase material is bituminous-aggregate mixture, 0 otherwise
CAM	=	1 if subbase material is cement-aggregate mixture, 0 otherwise
GRAN	=	1 if subbase material is granular, 0 otherwise
CHAIRS	=	1 if chairs used for reinforcement placement, 0 if tubes used

PCCP Terminal Serviceability Index (Smoothness) Model

A comprehensive evaluation and revision of the AASHO Road Test and the resulting concrete pavement design models were conducted under NCHRP project 1-30. [F-3,F-4] As a result of this study, an improved terminal serviceability index performance model was developed using both empirical and mechanistic modeling techniques plus the three dimensional finite element models. This model is selected to conduct the design checks on the terminal serviceability index (2.5) requirement. The following steps can be taken to preform the computation.

The rigid pavement design equation for 50 percent reliability is given below:

$$\log W' = \log W + \left(5.065 - 0.03295\, P2^{2.4}\right)\left[\log\left(\frac{(S'_c)'}{\sigma_t'}\right) - \log\left(\frac{690}{\sigma_t}\right)\right] \qquad \text{(F-30)}$$

where W' = number of 18-kip [80-kN] ESALs estimated for design traffic lane

$$F = 1.00 + \frac{3.63\ (L1 + L2)^{5.2}}{(D + 1)^{8.46}\ L2^{3.52}} \qquad \text{(F-32)}$$

$$\log R = 5.85 + 7.35 \log (D + 1) - 4.62 \log (L1 + L2) + 3.28 \log L2 \qquad \text{(F-33)}$$

$$G = \log \left(\frac{P1 - P2}{P1 - 1.5} \right) \qquad \text{(F-34)}$$

W = number of 18-kip [80-kN] ESALs computed from the equation below:

$$\log W = \log R + \frac{G}{F} \qquad \text{(F-31)}$$

D = concrete slab thickness, inches

L1 = load on a single or tandem axle, kips

L2 = axle code, 1 for single axle, 2 for tandem axle

P1 = initial serviceability index

P2 = terminal serviceability index

$(S'_o)'$ = mean 28-day, third-point loading flexural strength, psi (690 psi [4754 kPa] for AASHO Road Test)

σ_t = midslab tensile stress due to load and temperature with AASHO Road Test constants

σ_t' = midslab tensile stress due to load and temperature with inputs for new pavement design

$$\sigma_t = \sigma_l\, E\, F \left[\, 1.0 + 10^{(\log b)}\, TD \,\right] \qquad \text{(F-35)}$$

σ_l = midslab tensile stress due to load only, which

$$\sigma_t = \frac{18{,}000}{D^2}\left\{4.227 - 2.381\left(\frac{180}{\ell}\right)^{0.2} - 0.0015\left[\frac{E_b\,H_b}{1.4\,k}\right]^{0.5} - 0.155\left[H_b\left(\frac{E_b}{E_c}\right)^{0.75}\right]^{0.5}\right\} \quad \text{(F-36)}$$

E_c = modulus of elasticity of concrete slab, psi (4,200,000 psi [28,940 MPa] for AASHO Road Test)

E_b = modulus of elasticity of base, psi (25,000 psi [172 MPa] for AASHO Road Test)

H_b = thickness of base, inches (6 in [152 mm] for AASHO Road Test)

$$\ell = \sqrt[4]{\frac{E_c\,D^3}{12\,(1 - \mu^2)\,k}} \quad \text{(F-37)}$$

k = effective elastic modulus of subgrade support, psi/in (110 psi/in [29.92 kPa/mm] for AASHO Road Test)

μ = Poisson's ratio for concrete (0.20 for AASHO Road Test)

E = edge support adjustment factor (1.00 for AASHO Road Test)
= 1.00 for conventional 12-ft-wide [3.66-m-wide] traffic lane
= 0.94 for conventional 12-ft-wide [3.66-m-wide] traffic lane plus tied concrete shoulder
= 0.92 for 2-ft [0.6-m] widened slab with conventional 12-ft [3.66-m] lane width

F = ratio between slab stress at a given coefficient of friction (f) between the slab and base and slab stress at full friction, given as:

$$F = 1.177 - 4.3 * 10^{-8}\,D\,E_b - 0.01155542\,D + 6.27 * 10^{-7}\,E_b - 0.000315\,f \quad \text{(F-38)}$$

f = friction coefficient between slab and base (see table F-2)

Table F-2. Modulus of elasticity and coefficient of friction for various base types.

Base Type or Interface Treatment	Modulus of Elasticity (psi)	Peak Friction Coefficient low	mean	high
Fine-grained soil	3,000 - 40,000	0.5	1.3	2.0
Sand	10,000 - 25,000	0.5	0.8	1.0
Aggregate	15,000 - 45,000	0.7	1.4	2.0
Polyethylene sheeting		0.5	0.6	1.0
Lime-stabilized clay	20,000 - 70,000	3.0		5.3
Cement-treated gravel	(500 + CS) * 1000	8.0	34	63
Asphalt-treated gravel	300,000 - 600,000	3.7	5.8	10
Lean concrete without curing compound	(500 + CS) * 1000		> 36	
Lean concrete with single or double wax curing compound	(500 + CS) * 1000	3.5		4.5

Notes: CS = compressive strength, psi

Low, mean, and high measured peak coefficients of friction summarized from various references are shown above.

1 psi = 6.89 kPa

$$\log b = -1.944 + 2.279 \frac{D}{\ell} + 0.0917 \frac{L}{\ell} - 433{,}080 \frac{D^2}{k\,\ell^4}$$

$$+ \left(\frac{0.0614}{\ell} \right) * \left(\frac{E_b\, H_b^{\,1.5}}{1.4\, k} \right)^{0.5} - 438.642 \frac{D^2}{k\,\ell^2} - 498{,}240 \frac{D^3 L}{k\,\ell^6} \qquad \text{(F-39)}$$

L = joint spacing, inches (180 in [4572 mm] for AASHO Road Test)

TD = effective positive temperature differential, top of slab minus bottom of slab, °F

$$\text{ective positive } TD = 0.962 - \frac{52.181}{D} + 0.341\ WI.$$

$$+ 0.184\ TEMP - 0.00836\ PRECIP \qquad \text{(F-40)}$$

D = slab thickness, inches

WIND = mean annual wind speed, mph

TEMP	=	mean annual temperature, °F
PRECIP	=	mean annual precipitation, inches

The W_{18R} for any level of design reliability and overall standard deviation is computed as follows:

$$W_{18R} = 10^{(\log W_{18} + Z S_o)} \tag{F-41}$$

where:

W_{18R}	=	design 18-kip [80 kN] ESALs for a specified level of design reliability R
W_{18}	=	estimated 18-kip [80 kN] ESALs over the design period in the design lane
Z	=	standard deviate from normal distribution table for given level of reliability (e.g., 1.28 for R = 90 percent)
S_o	=	overall standard deviation

References

F-1. Yu, H.T., M.I. Darter, K.D. Smith, Y.J. Jiang, and L. Khazanovich, *Performance of Jointed Concrete Pavements, Volume III: Improving Concrete Pavement Performance*, Final report, DTFH61-91-C-0053, Federal Highway Administration, Washington, DC, August, 1996.

F-2. Lee, Y.H. and M.I. Darter, *Development of Pavement Prediction Models*, Interim report, 1990-1993, FHWA-IL-UI-250, Illinois Department of Transportation, 1993.

F-3. Darter, M.I., K.T. Hall, and C.M. Kuo, *Support Under Concrete Pavements*, NCHRP Report No. 372, Transportation Research Board, 1994.

F-4. Darter, M.I., K.T. Hall, and C.M. Kuo, *Support Under Concrete Pavements*, NCHRP Project 1-30, Appendix to Final Report, 1994.

F-5. Heinrichs, K.W., M.J. Liu, M.I. Darter, S.H. Carpenter, and A.M. Ioannides, *Rigid Pavement Analysis and Design*, FHWA-RD-88-068, Federal Highway Administration, Washington, DC, 1989.

F-6. Friberg, B.F., *Design of Dowels in Transverse Joints of Concrete Pavements*, *Transactions*, American Society of Civil Engineers, Vol. 105, 1940.

F-7. *AASHTO Guide for Design of Pavement Structures*, American Association of Highway and Transportation Officials, Washington, DC, 1986.

F-8. Smith, K.D., D.G. Peshkin, M.I. Darter, A.L. Mueller, and S.H. Carpenter, *Performance of Jointed Concrete Pavements, Volume V: Appendix B—Data Collection and Analysis Procedures*, FHWA-RD-89-140, Federal Highway Administration, Washington, DC, March 1990.

F-9. Salsilli, R.A., E.J. Barenberg, and M.I. Darter, *Calibrated Mechanistic Design Procedure to Prevent Transverse Cracking of Jointed Plain Concrete Pavements*, *Proceedings of the 5th International Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, 1993.

F-10. Armaghani, J.M., T.J. Larsen, and L.L. Smith, *Temperature Response of Concrete Pavements*, Transportation Research Record 1121, Transportation Research Board, Washington, DC, 1987.

F-11. Darter, M.I., *A Comparison Between Corps of Engineers and ERES Consultants, Inc. Rigid Pavement Design Procedures*, Technical Report Prepared for the United States Air Force SAC, Urbana, IL, 1988.

F-12. Seiler, W.J., *Expedient Stress Analysis of Jointed Concrete Pavement Loaded by Aircraft with Multiwheel Gear, Transportation Research Record 1370*, Transportation Research Board, Washington, DC, 1993.

F-13. Treybig, H.J., B.F. McCullough, P. Smith, and H. Von Quintus, *Overlay Design and Reflection Cracking Analysis for Rigid Pavements*, Federal Highway Administration, Washington, DC, 1977.

F-14. Benekohal, R.F., K.T. Hall, and H.W. Miller, *Effects of Lane Widening on Lateral Distribution of Truck Wheels, Transportation Research Record 1286*, Transportation Research Board, Washington, DC, 1990.

Appendix G

Notes On Recommended Design Features

Basis Of The Catalog Recommendations

The catalog recommendations are based on many sources, however, the most significant source was the recommendations achieved by consensus of a large resource group of pavement design experts from Federal, state, industry, consulting, and academia. A list of those involved is provided in this Appendix. The resource group met for an entire week and debated and revised many proposed recommendations until a consensus was reached. (See Reference 1, Appendix A for minutes of the meeting.) Additional information on the consensus procedures are given in this appendix G.

Contributions were also made by the NCHRP Project 1-32 panel based on reviews of the documents. In addition, use was made of current SHA design practices, FHWA design manuals, the 1993 *AASHTO Guide for Design of Pavement Structures*, and mechanistic-empirical performance models that were used to limit the occurrence of key distress types for flexible and rigid pavements and adjusted as needed to limit key distress types within specified performance criteria.

Consensus Group Meeting

NCHRP project 1-32 consensus meeting on pavement design features was held in Chicago from 1 pm on January 22 to noon on January 26, 1996. The objective of this meeting was to reach consensus on key pavement design site conditions and design features recommended for inclusion in the pavement design catalog. Participants were sent a copy of the draft design catalog prior to the meeting for review. A copy of the meeting agenda is provided in the appendix. A brief summary of workshop activities is as follows.

Monday afternoon: introductions, objectives of NCHRP Project 1-32 and of this meeting, overview of the draft catalog, European experience presentation, consensus building process, and an open discussion on the catalog development.

Tuesday: more discussion on catalog development, the entire group discussed and took consensus ballots on some general issues concerning both flexible and rigid pavements including site conditions, the pavement design process, and general design criteria (e.g. design reliability).

Wednesday: the group was split into a flexible pavement group and a rigid pavement group. Each group discussed, built consensus on pavement design features and took ballots on many recommendations.

Thursday morning: the entire group met to summarize each group's activities and discuss the progress of the consensus building on the previous day. Then the group discussed and took ballots on the initial and terminal serviceability to be used in the catalog. After that, the group broke into the same two groups again to continue discussions and balloting on pavement design feature recommendations. The flexible pavement group finished at noon, so some members joined the rigid pavement group in the discussion and consensus building on PCC pavement design features during the afternoon.

Friday morning: the entire group again summarized Thursday's progress. A presentation was made on the knowledge-based expert system (KBES) development plan, and the group had a discussion on the usage, development, and implementation of the KBES. After that, terminal serviceability and slab on grade option for PCC pavement design were further discussed and balloted. In conclusion, the entire group had an open discussion on the future development and other general aspects of the catalog.

The consensus building process included the following steps for each design recommendation.

First, a member of the research team briefly presented a specific design recommendation (i.e., subgrade treatment, design reliability).

Second, the consensus group freely discussed the recommendation.

Third, if it was apparent that most members agreed with the recommendation, a consensus ballot was completed by each member (see appendix for consensus ballots).

Fourth, the ballot results were entered into a personal computer (Excel spreadsheet) and a frequency distribution was projected onto a screen for all to see.

Fifth, if a consensus was reached (meaning no one disagreed with the recommendation), the group moved on to the next recommendation.

Sixth, if one or more participants disagreed as indicated by a 40 or lower rating, their

reason was read to the group (anyone who disagreed had to write the reason on the ballot), and additional discussion was held until either a consensus was achieved or it became apparent that it was impossible to achieve a consensus at the time.

Nearly always, the further discussion resulted in either a modification of the recommendation, or the attachment of notes to the recommendation indicating the concerns of the consensus group. When agreement could not be reached, the recommendation was brought up at a later time and discussed and re-balloted, which usually resulted in a consensus at that time. A summary of all ballots for each recommendation voted, histograms of the voting results, and all comments provided by the resource group members are given in the appendix.

Overall, the consensus meeting was very successful and a consensus was reached on almost all the issues, often after various revisions were made. A virtual wealth of knowledge and experience existed in the consensus group and many good ideas were brought out in the discussions. The group generally appeared to have a positive feeling about the achievements of the consensus group meeting.

Catalog Recommendations

Many of the recommendations in the catalog originated from the discussions with the consensus groups. For example, all of the inputs to the 1993 AASHTO Design Guide that was used to obtain the initial structural designs were debated and agreed to by the consensus group. Most of the numerical recommendations emanating from the consensus group are indicated by an asterisk (*). Additional recommendations included in the catalog were obtained from the sources indicated above (State practice, FHWA manuals, checks with mechanistic and empirical performance models, and various research findings and training manuals listed in the reference list) plus many suggestions from the NCHRP Project 1-32 panel.

Many thanks are given to the resource group that consists of the following individuals/ agencies: Sohila Bemanian (Nevada DOT), Ray Brown (Auburn University), Bill Cape (James Cape & Sons Company), Max Grogg (Federal Highway Administration), Wouter Gulden (Georgia DOT), Marlin Knutson (American Concrete Pavement Association), Roger Larson (Federal Highway Administration), David Lippert (Illinois DOT), James Mack (American Concrete Pavement Association), Dick Moore (Parsons-Brinkerhoff), Mark McDaniels (Texas DOT), Dave Newcomb (University of Minnesota), Linda Pierce (Washington DOT), Chuck Van Dusen (Consultant), Duane Young (Minnesota DOT), and Jim Brown (Consultant), Prof. Lorenzo Domenichini, and Francesca La Torre (Italy).

Appendix H Prototype KBES And User's Guide

A key task of NCHRP project 1-32 is to develop a prototype Knowledge-Based Expert System (KBES) to supplement the *Catalog of Recommended Pavement Design Features*. This appendix documents the development and overview of the prototype KBES, called Designer, and presents its user's guide. The software development will be described first, followed by an overview of the prototype KBES, and a discussion on the use of the KBES. The user's guide is presented after that.

SOFTWARE DEVELOPMENT

A prototype microcomputer-oriented, KBES for selecting pavement design features is developed under this study. The inference engine of the KBES uses the expert system shell, CLIPS 6.04. CLIPS is an acronym for C Language Integrated Production System. It was developed by the Software Technology Branch of the National Aeronautics and Space Administrations (NASA). CLIPS is disseminated under the sponsorship of NASA by the Computer Software Management and Information Center (COSMIC) in the interest of information exchange. There is no royalty required to use and further develop the KBES using CLIPS. CLIPS 6.04 is written in C-language for interactive execution on IBM PC compatible computers running MS-DOS v5.0 or higher and MS Windows v3.x.

Features of CLIPS include a conventional rule-based expert system, procedural programming ability, and CLIPS object-oriented programming capability. All these features are utilized in developing the prototype KBES. The rule-based expert system part is used frequently in the KBES whenever there is any reasoning or pattern matching involved. The procedural and object-oriented programming languages make the pattern matching of the pavement conditions to the catalog factorial cells very easy and efficient.

The prototype KBES is a Windows 3.11 program with standard user friendly Windows graphic user interface. Microsoft Windows programing language, Visual Basic (VB) 4.0, was used to develop a friendly user interface. The core part of the prototype KBES is programmed using CLIPS. It can be executed on any IBM PC compatible 486 computer with at least 4Mb RAM and Windows 3.11 or higher.

The prototype KBES program architecture is a standard modular design and is very flexible and easy to modify. The link between the VB interface and CLIPS programs is dynamic in the sense that the inferences and screen framework are completely separated. All the logical inference, derivations, and technical contents are provided in CLIPS code. CLIPS also

provides all the necessary outputs and screen display instructions to VB. Therefore, the prototype KBES is easy to modify and enhance in the future.

OVERVIEW OF THE PROTOTYPE KBES

The prototype KBES developed in this project includes three main parts:

- Input assistant to provide interactive guidance to the designer in obtaining design inputs for the catalog site conditions and other inputs;
- Database searching and presentation to access a project database which represents the paper catalog, to quickly and efficiently identify feasible design alternatives for a given set of site and design conditions;
- Evaluate assistant to provide interactive guidance to the designer in evaluating the advantages and disadvantages of the various design alternatives and explanations about various design features.

This section describes in detail each of the above modules.

Input Assistant

The input assistant for the site conditions and other design inputs is well developed in the prototype KBES. This module guides the users through inputting values to determine the pavement site conditions. This includes the following three modules:

- Climatic zone determination
- Subgrade class determination
- Traffic input

Under each module, users have the choice of either input the site condition categories directly, based on their engineering knowledge, or use a more detailed screen (figures 4, 5, and 6) under each category to input one of the parameters with known value. For example, subgrade stiffness is characterized by weak, medium, or strong levels in the printed catalog. What the designer may actually know about the subgrade might be its descriptive name, its AASHTO classification, its CBR, its R-value, or some other parameter value. Guidance is provided in the program to map the parameter value known to the classification levels used in the catalog. The same is true for many other inputs to determine climatic zone. On paper, this type of guidance may become very voluminous. The prototype KBES can quickly transform the designer's input data into appropriate design cells for use in searching the catalog for feasible designs. Figures 1 through 6 show the screens used in this module.

Catalog Searching and Presentation

The printed catalog is well included in the program database and an on-line technical help file. Once the pavement site conditions are determined, viable pavement design alternatives are efficiently matched to the catalog factorial cells using CLIPS. The user can then select the interested pavement design alternative and review the recommended design features associated. This reduces time which is otherwise required to manually search through the printed catalog to locate the cells which correspond to the appropriate pavement site condition levels for a given design situation for several pavement types. The manual search time will increase accordingly, as will the risk of error in selecting which portions of the catalog to search and which cells to select. Here too, the KBES is very valuable in conducting a quick and efficient search for feasible design alternatives with less chance of error. Figures 7 through 10 show the screens of the catalog searching and presentation part.

Evaluation Assistant

It is rare that a set of design inputs leads to only one feasible design. In most cases three or more feasible design alternatives may be identified which satisfy the design criteria. The designer then has the responsibility of comparing the design alternatives, assessing the advantages and disadvantages of each, and selecting a preferred alternative. Many factors may enter into this evaluation process, including predicted performance, expected distress types, materials durability, construction feasibility, initial and life-cycle costs, future maintenance requirements, track record of the design alternative in similar site conditions, etc. A fully developed KBES could be very valuable in offering insights on these factors as they pertain to the specific design alternatives being considered, as well as guiding the designer interactively through an evaluation process which systematically considers the evaluation factors judged to be significant and relevant. Of course the selection of a preferred alternative always rests with the designer. The KBES serves only to offer knowledgeable insight and facilitate a systematic evaluation of the alternatives.

In the prototype KBES, it is demonstrated through mock-ups that performance models of the key pavement distresses can be used to predict the future performance of the pavement design alternative selected. A few synoptic tables of the States' current pavement designs and practices are also included to illustrate how States' design practices can be presented to the designers for their reference. Example performance models are used to predict the performance of the pavement over time and traffic. Some synoptic tables of the current States' pavement practice are also provided for the users to look at the design features that are being used by the States.

In developing a fully operational KBES, these capabilities need to be implemented fully for all the cells, prediction models, and design alternatives. Furthermore, ideas of linking the program with the LTPP performance data base, States' PMS data base, and other key studies' performance data base can also be implemented in the next phase of the KBES development. New research products, new expertise acquired, and state-of-the-art technologies can also be incorporated into the KBES in the future. For example, Super-Pave's binder grade selection scheme can be included in a future KBES. Figures 11 through 14 illustrate the implementation of this module.

Usefulness and Limitation of the Prototype KBES

The KBES can help the designer in several ways to realize the full potential of the catalog. Using the KBES, the designer is more likely to obtain proper design inputs and to consider all the feasible options for a given set of design inputs. The KBES can quickly identify the complete set of feasible design alternatives, whereas using the paper catalog only, the designer may not do a complete search and may thus miss some feasible alternatives. On paper, the designer may become accustomed to using only certain portions of the catalog pertaining to pavement types and design options. The KBES can also quickly screen out infeasible or ill-advised options.

A fully developed KBES companion to the pavement design catalog adds value to the catalog in several ways:

- Increased speed and efficiency,
- Guidance on obtaining inputs for site conditions (traffic, subgrade, climate)
- Guidance to the designer in searching for solutions,
- Explaining the logic of "best practice" recommendations,
- Coordinating decisions about many different design features,
- Making the catalog more dynamic and easier to update,
- Enhanced value as a teaching and training tool,
- Increased consistency in considering all feasible options and screening out infeasible options, and
- Evaluate the selected pavement design features.

Most important, the KBES enhances the effectiveness, the implementability, and the adaptability of the catalog, all important factors in the catalog's success.

The KBES will help to accomplish the catalog's goals and will help the user make better pavement design decisions, more rapidly and more efficiently than before. One of the goals of

the catalog is to put pavement design expertise in the hands of novice engineers in a format which permits them to apply that expertise appropriately. This is an ideal application for a KBES. The computerized KBES is highly adaptable, as the knowledge base (made up of the input guidance rules, catalog relational database, and alternative evaluation rules) is developed and expanded over time. Indeed, the typical program structure of a rule-based expert system is not rigid and is well suited to later additions and modifications. If implementability is defined as the likelihood of the tool actually being put into routine use in State highway agencies, then the implementability of the KBES is believed to be as great as, if not greater than, that of the paper catalog.

The supplemental KBES will be a very powerful tool when fully developed. However, what we developed in this project is only a prototype KBES. The prototype KBES includes most of the current printed catalog. All the structural designs in each factorial design cell and key design features are included in the program. The prototype KBES is a very useful tool for knowledgeable users as it is now. It can be used to obtain the recommended design features for all the site condition cells included in the printed catalog. These recommended features and structural design ranges can then be used to compare and check the pavement design the user has selected. However, the prototype KBES needs to be improved in many ways before it can be used as an operational software product.

Prototype Knowledge Based Expert System for Pavement Design

USER'S GUIDE

Y. Jane Jiang
ERES Consultants, Inc.
9030 Red Branch Road, Suite 210
Columbia, MD 21045
410/997-6181

Robert Wiseman
Brent Rauhut Engineering, Inc.
8240 MoPac Expressway, Suite 220
Austin, TX 78759
512/346-0870

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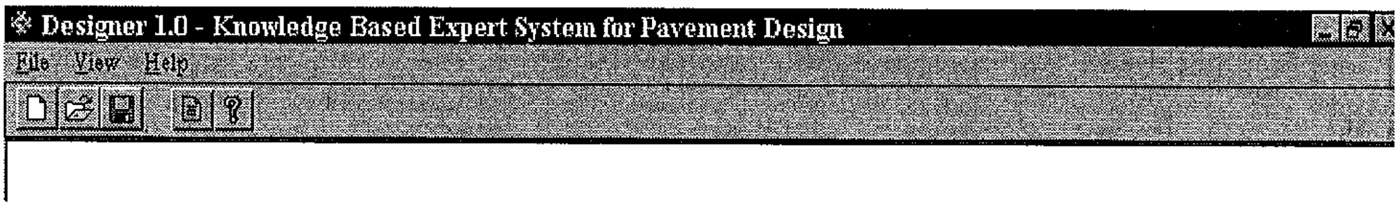
WEXTECH

WexTech Systems, Inc.
310 Madison Avenue, Suite 905
New York, NY 10017
1-800-WEXTECH
(212) 949-9595
Fax: (212) 949-4007

Contents

Chapter 1 Program overview

Getting Started



Minimum System requirements-

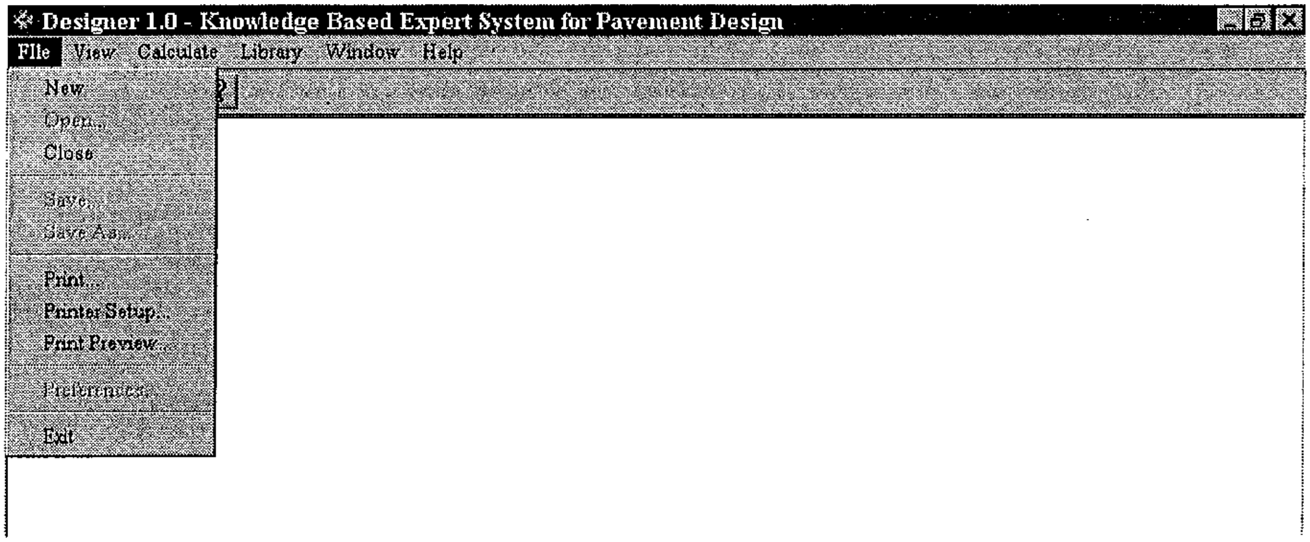
Computer with 4 megs ram running DOS/Windows.

To install insert disk one in the drive and select File Run from Program Manager and follow the instructions that follow.

Quick Start-

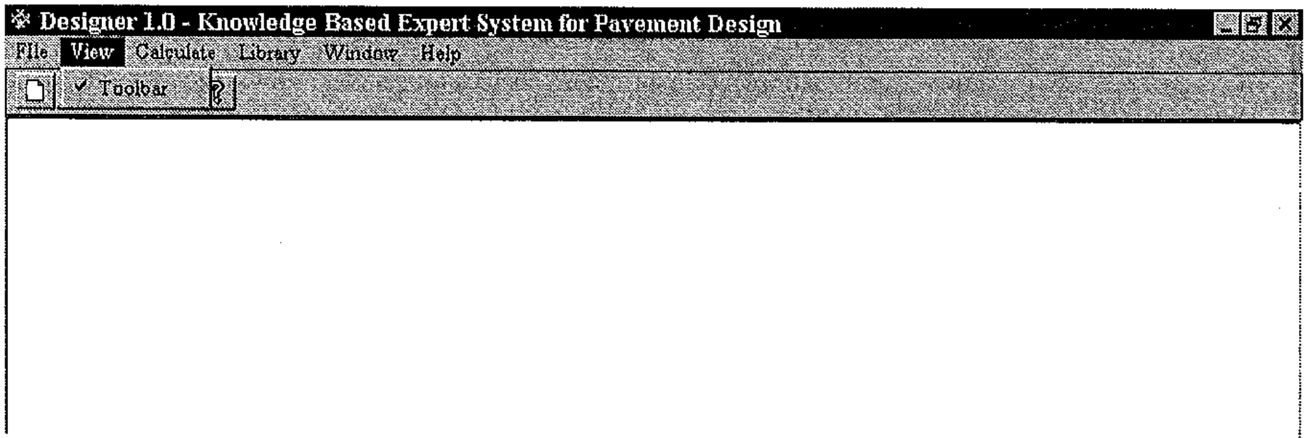
Select File and New from the menu. Select flexible or rigid pavement type. After hitting okay the pavement design windows comes up. Select the climate, subgrade, and traffic then hit Alternatives button. The Catalog Design Alternatives window will fill with data from which you can select. After making a selection hit the Design button and you are on your way.......

File Menu



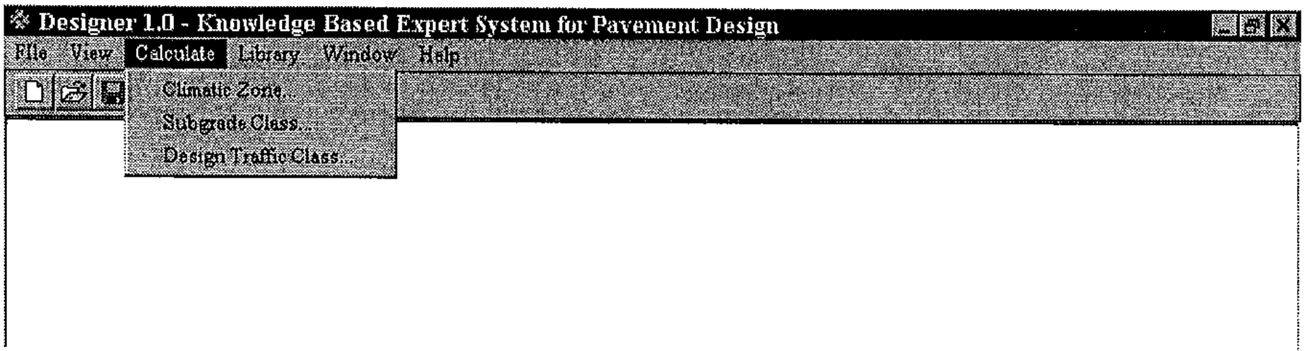
New-	Allows the user to create a new design option for either AC or PCC pavements.
Open-	Opens an existing design.
Close-	Closes the current design.
Save/Save as-	Saves the current design. 'Save as' allows the user to change the name of the design database currently being worked on.
Print-	Design: Prints a summary report of the chosen design alternative. Feature: Not implemented. Library: Not implemented.
Printer setup-	Allows the user to select the various printer options.
Print Preview-	View the design report before printing.
Preferences- implemented).	Allows the user to set various screen/display formats (not
Exit-	Quit the program and return to Windows.

View



Tool Bar- Toggles the tool bar on and off.

Calculate



Climatic Zone

Select the appropriate LTPP Climate Zone by either:

1. Choosing the appropriate LTPP Climate Zone for the design situation from the drop down box, or
2. Inputting appropriate environmental data elements known by the user and letting the program calculate the corresponding LTPP Climate Zone.

Subgrade Class

Select the appropriate subgrade condition for the design by either:

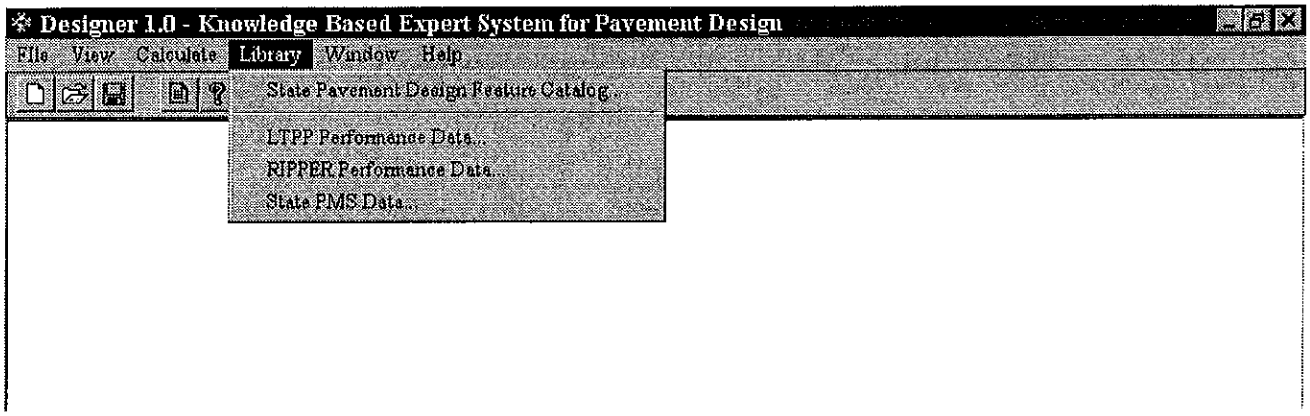
1. Choosing the appropriate average annual subgrade condition for the design situation from the drop down box, or
2. Inputting appropriate subgrade strength characteristics and letting the program calculate the corresponding Subgrade Classification.

Design Traffic Class

Select the appropriate Traffic class by either:

1. Choosing the appropriate Traffic Class form the drop down box, or
2. Inputting the 20 year design Equivalent Single Axle Value (ESAL) using either the flexible or rigid equivalency values and letting the program calculate the corresponding Traffic Class.

Library



State Catalog of Pavement Design Features

Synoptic table- Allows the user to view tables and values taken from the State Design Catalog.

Filters- Allows the user to narrow the selection of information displayed in the tables by pavement type and state.

Add- Add information to filter list.

Delete- Delete information from the filter list.

LTPP Performance Data

Pavement sections from the LTPP database that correspond to the site condition under consideration are listed in this section. (Not implemented.)

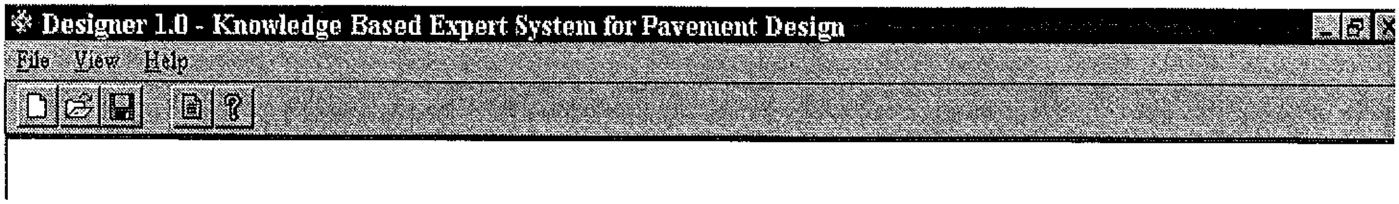
RIPPER Performance Data

Performance data from the RIPPER PCC database is listed in this section. (Not Implemented.)

State PMS Data

State PMS data in listed in this section. (Not implemented.)

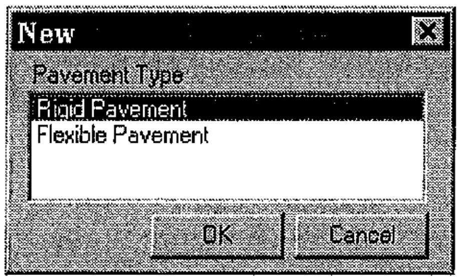
Tool Bar



New-	Begins a new design.
Open-	Opens an existing design.
Save-	Saves current design.

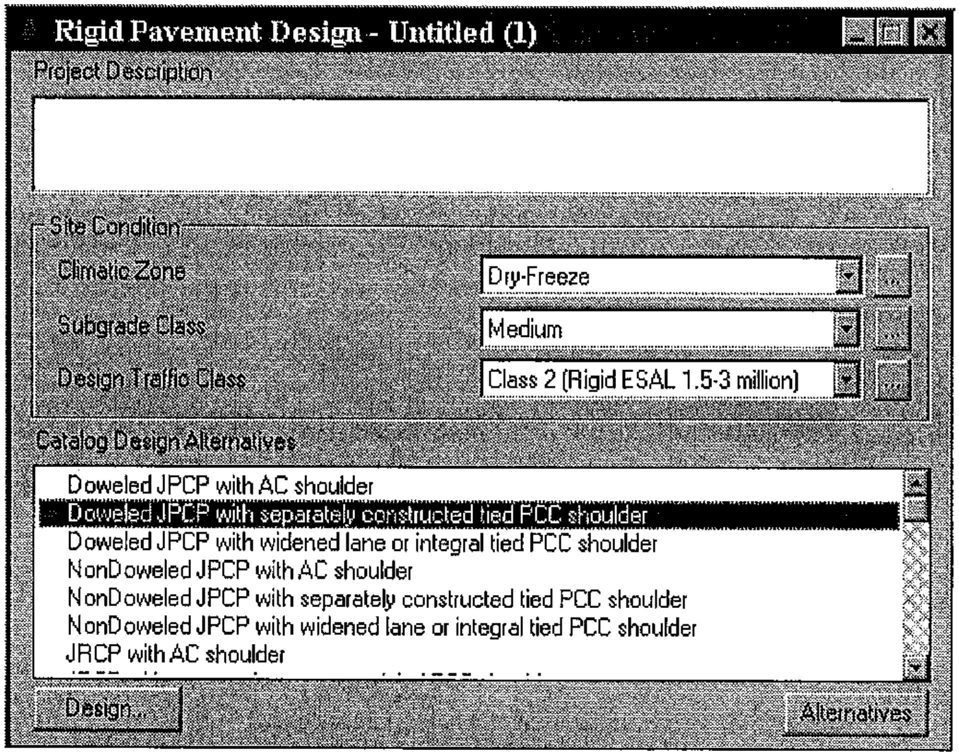
Chapter 2 Rigid Pavement Design Screen

Project description

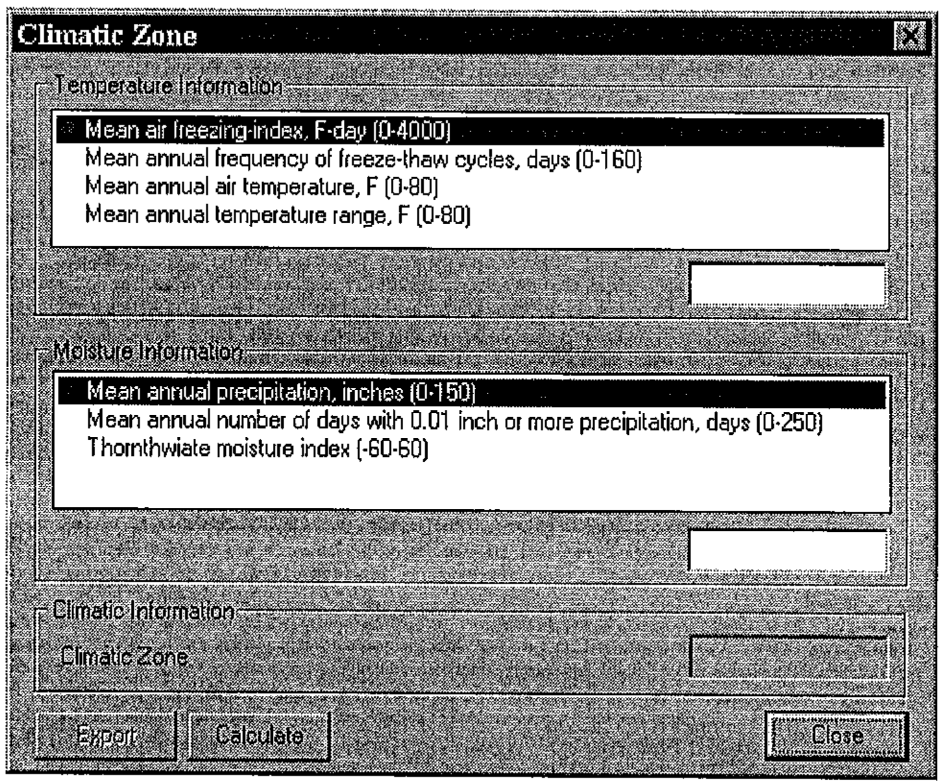


Description of the project being designed as determined by the user.

Site conditions



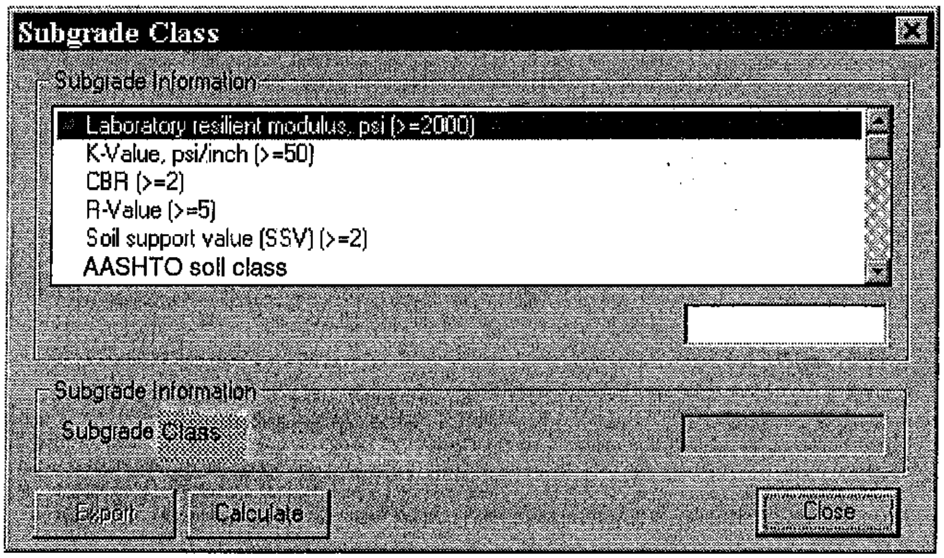
Climatic Zone-



Select the appropriate LTPP Climate Zone by either:

1. Choosing the appropriate LTPP Climate Zone for the design situation from the drop down box directly, or
2. In the "Climatic Zone" screen:
   i. Double click the known temperature or moisture parameter;
   ii. Input the value for the corresponding parameter;
   iii. "Calculate" the climatic zone from the inputs;
   iv. "Export" the result to the pavement design screen.

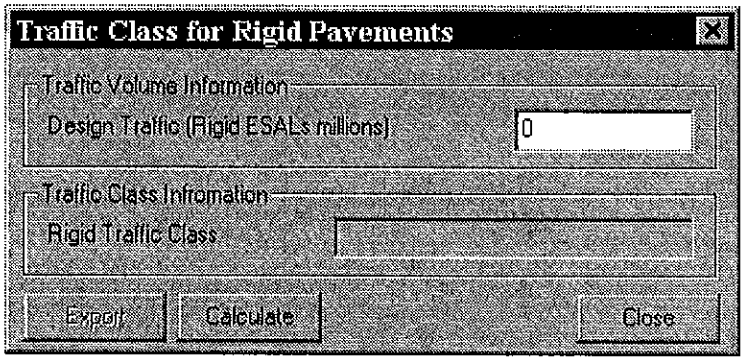
Subgrade class-



Select the appropriate subgrade condition for the design by either:

1. Choosing the appropriate average annual subgrade condition for the design situation from the drop down box directly, or
2. In the Subgrade class screen:
   i. Double click the known subgrade strength characteristics parameter;
   ii. Input the value for the corresponding parameter;
   iii. "Calculate" the subgrade class;
   iv. "Export" the calculated subgrade class to the pavement design screen.

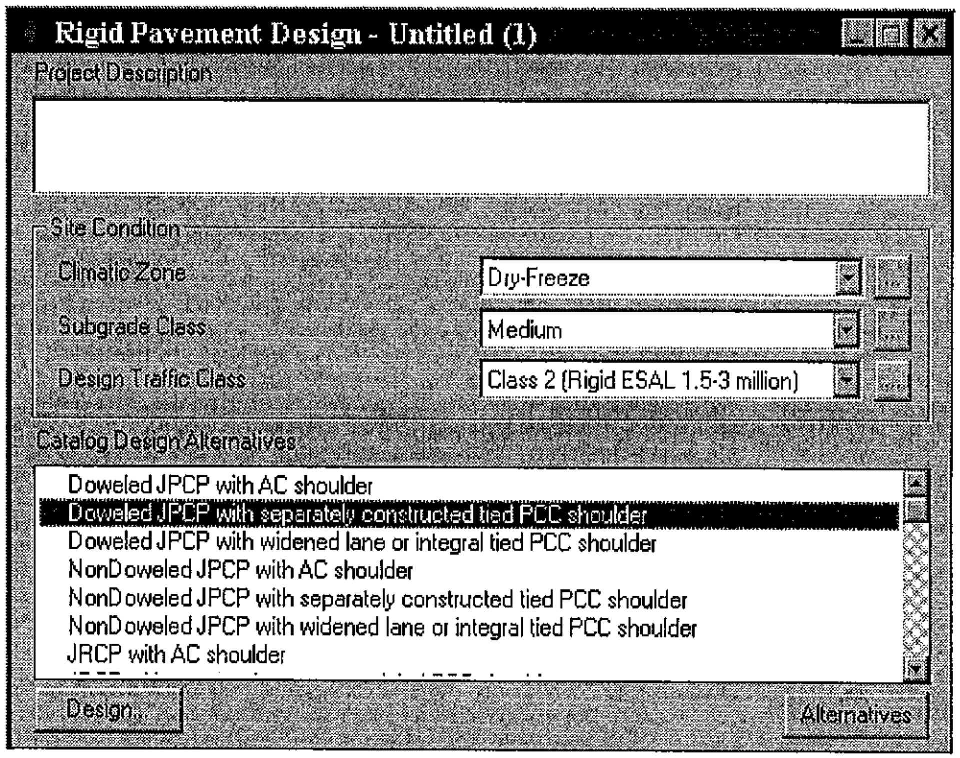
Design traffic class-



Select the appropriate Traffic class by either:

1. Choosing the appropriate Traffic Class form the drop down box, or
2. Inputting the 20 year design Equivalent Single Axle Value (ESAL) using either the flexible or rigid equivalency values and letting the program calculate the corresponding Traffic Class.

Catalog design alternative

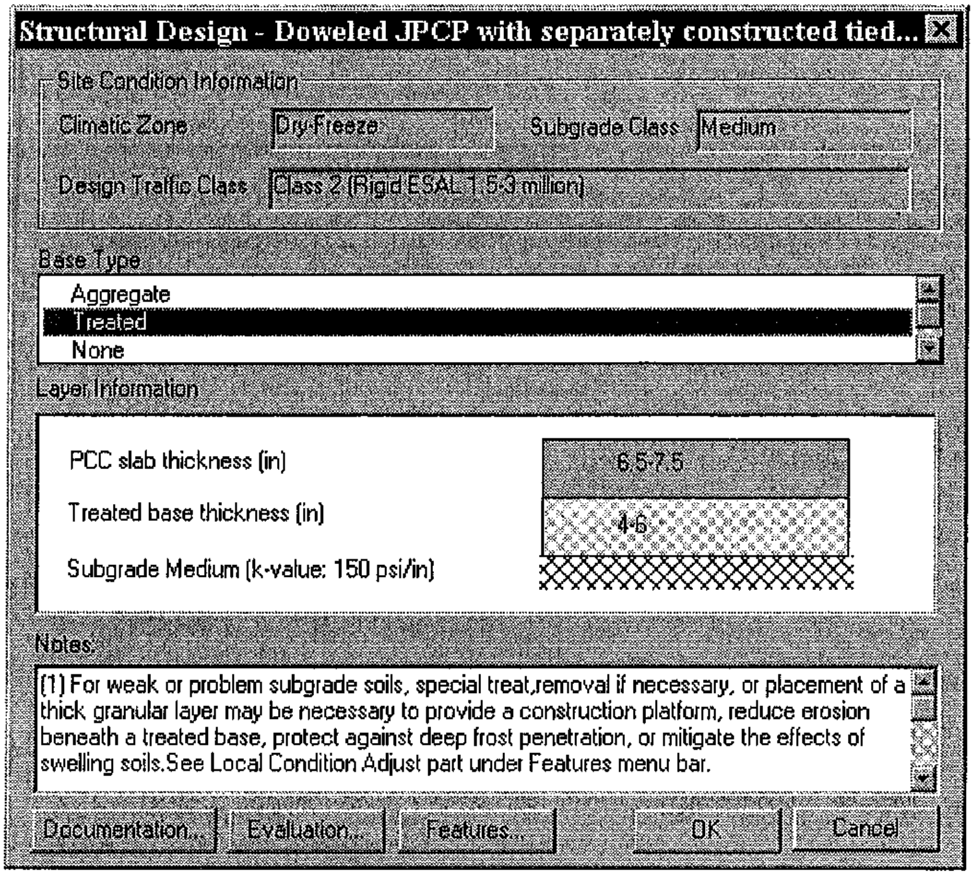


Alternatives

Provides various design alternatives based on the site conditions given and the pavement type selected. Selecting a design alternative (by double clicking the mouse

on the highlighted alternative) allows the user to obtain specific information about that design alternative by hitting the 'Design' button.

Structural Design



Site condition information

Displays the values entered for the following site condition:

Climatic Zone
Subgrade Class
Design Traffic Class

Base Type

Provides the base type considered for the structural design alternative. User selects the base type to be used in the design alternative by highlighting the appropriate base type.

Layer Information

Displays layer information for the selected design alternative and bas type.

Notes

Information important to the design is provided here.

Documentation

Provides information pertinent to the pavement type and design alternative selected.

Evaluation

Local conditions

Provides guidance regarding modifications to the structural design based on local site conditions.

Performance Predictions

Graphically displays performance curves for design period for various distresses.

State pavement design feature catalog

Catalog covering design details from the various state agencies.

LTPP performance comparison

Not implemented.

RIPPER Performance comparison

Not implemented.

Features

Cross Sections

Displays a cross section based on the pavement type and design alternative selected based upon various features selected in the 'Features Option' window.

JPCP Transverse Joint Details

Displays joint details after a joint type is selected under the 'Features Options' window.

Load Transfer Design (Dowel Bars)

Displays the placement of the dowel bars after a dowel spacing is selected under the 'Features Options' window.

Longitudinal Joints and Tie Bars

Displays the longitudinal joint showing the tie bar after a joint type is selected under the 'Features Options' window.

Expansion Joint Design

Displays a transverse expansion joint showing the dowel bars and joint filer measurements after a joint type is selected under the 'Features Options' window.

Joint Sealant Reservoir and Joint Sealants

Displays a sealed joint after sealant type is selected under the 'Features Options' window.

PCC Slab Material Properties

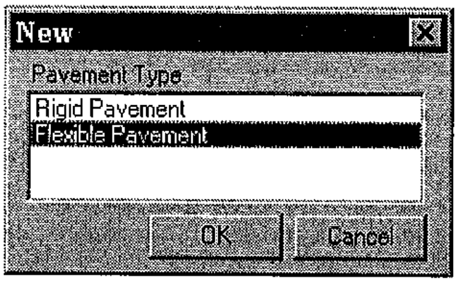
Displays the section on PCC Slab Material Properties.

Drainage System

Displays the section on the Subsurface Drainage System.

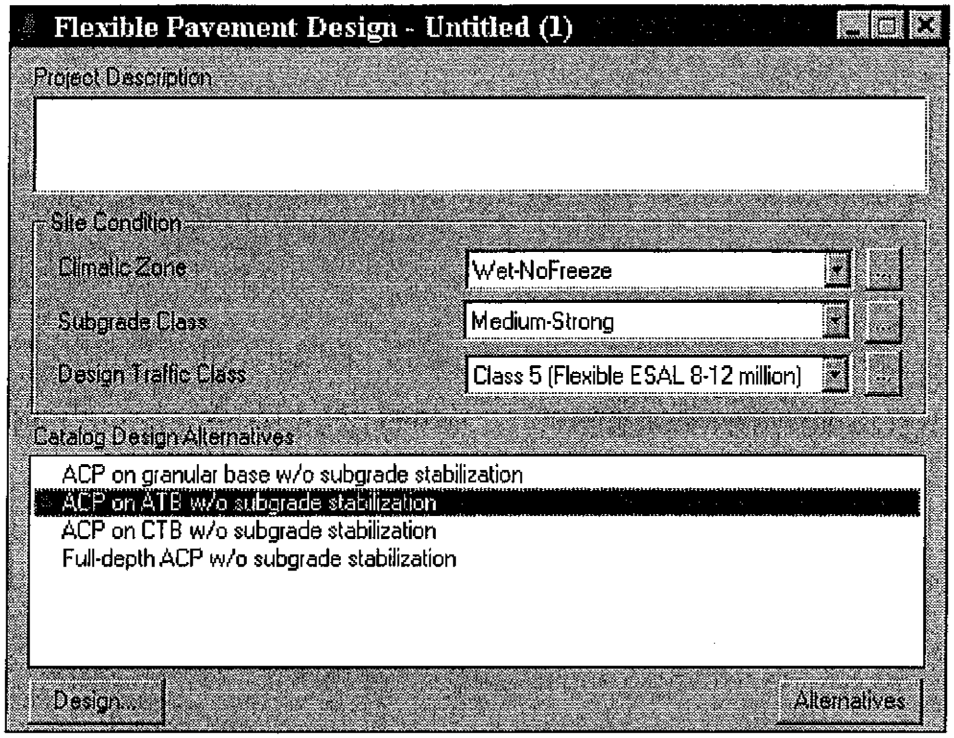
Chapter 3 Flexible Pavement Design Screen

Project description

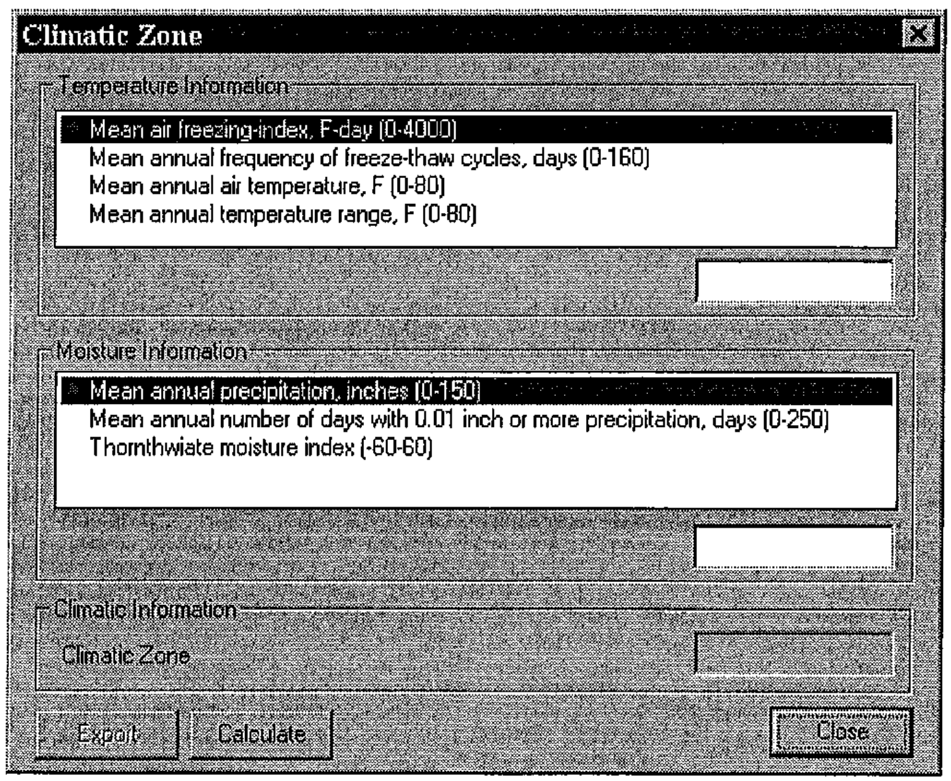


Description of the project being designed as determined by the user.

Site conditions



Climatic Zone-



Select the appropriate LTPP Climate Zone by either:

1. Choosing the appropriate LTPP Climate Zone for the design situation from the drop down box directly, or
2. In the "Climatic Zone" screen:
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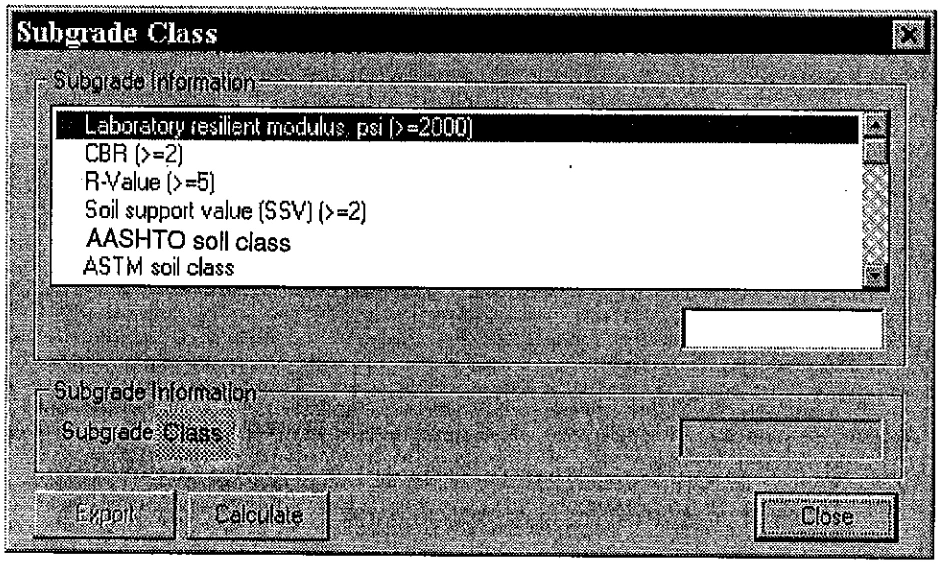
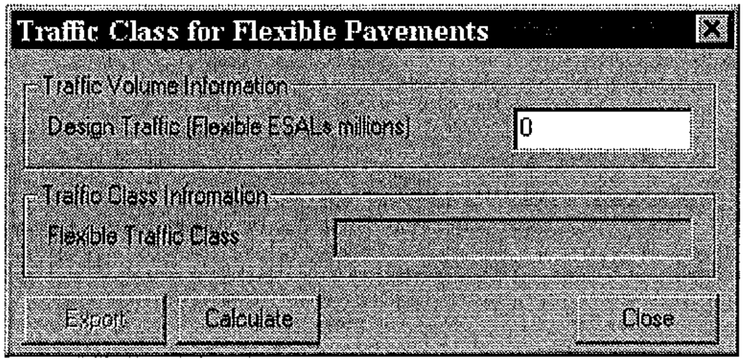
Subgrade class-



Select the appropriate subgrade condition for the design by either:

1. Choosing the appropriate average annual subgrade condition for the design situation from the drop down box directly, or
2. In the Subgrade class screen:
   i. Double click the known subgrade strength characteristics parameter;
   ii. Input the value for the corresponding parameter;
   iii. "Calculate" the subgrade class;
   iv. "Export" the calculated subgrade class to the pavement design screen.

Design traffic class-



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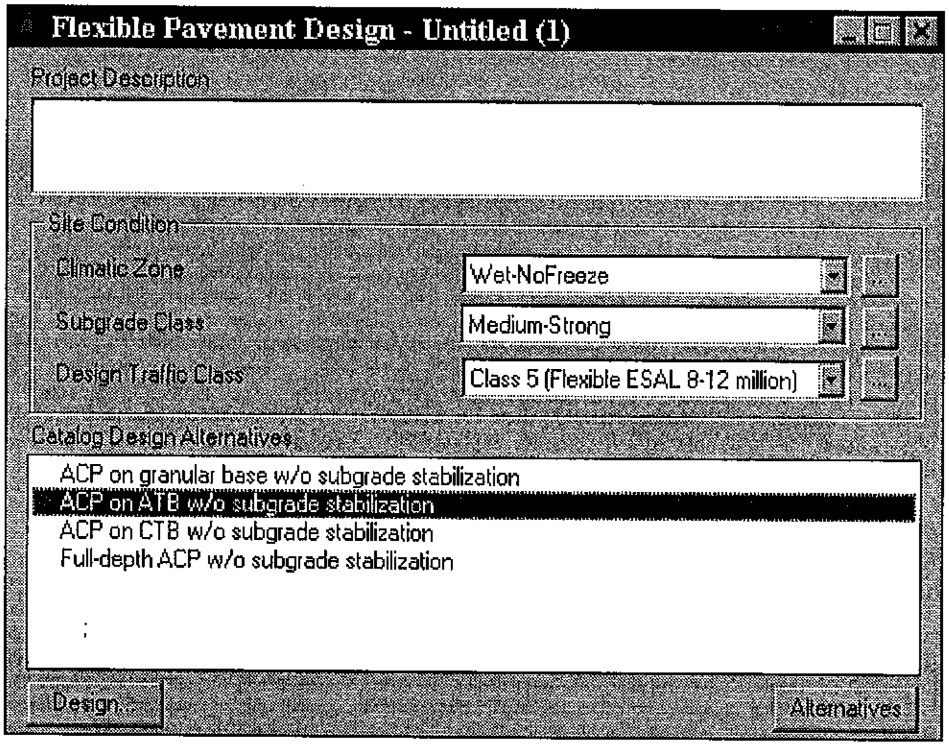
Catalog design alternative



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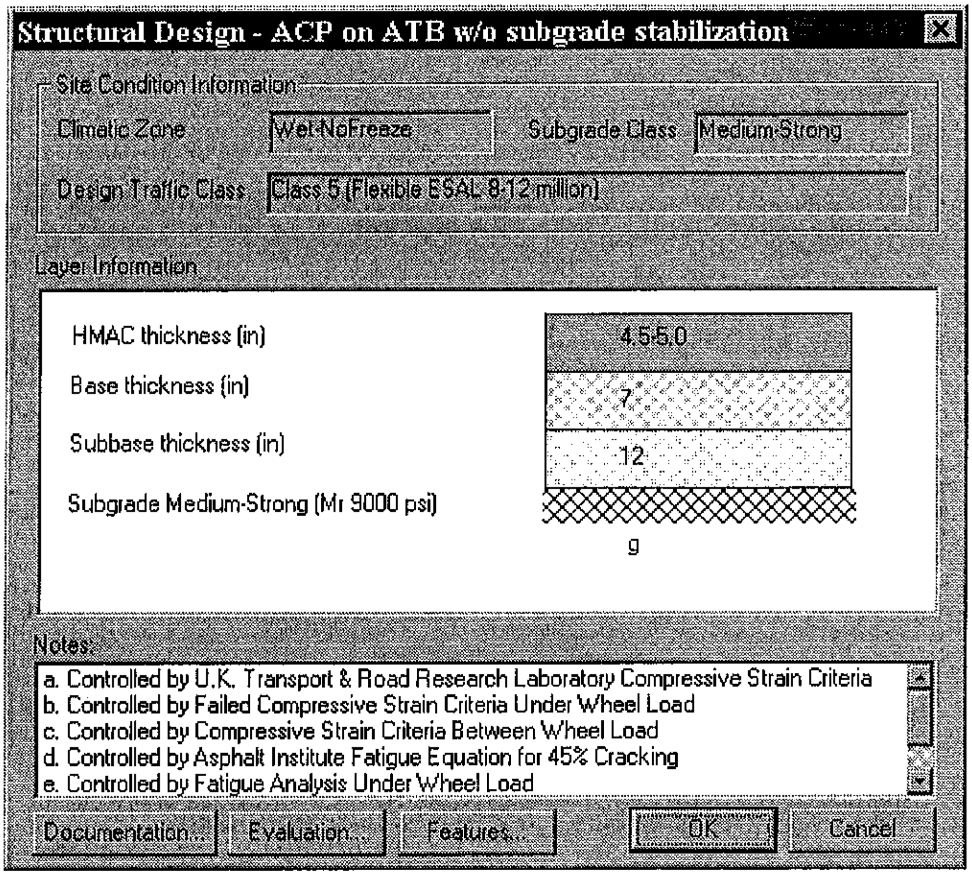

Site condition information

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- Subgrade Class
- Design Traffic Class

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LTPP performance comparison

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ACP Material Properties

Displays the section on the ACP Material Properties.

Drainage System

Displays the section on the Subsurface Drainage System.

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Submitted by

ERES CONSULTANTS, INC.

505 West University Avenue
Champaign, IL 61820-3915
Phone (217) 356-4500
Fax (217) 356-3088

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