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STRUCTURAL DESIGN OF ROADWAY SHOULDERS

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16. Abstract

This report describes the thickness design of roadway shoulders and is based on mechanistic principles of stress/strain analysis. Both flexible and rigid shoulders can be designed with this method. The shoulders may be adjacent to either rigid or flexible pavements. All combinations are possible, including the use of a widened rigid mainline lane with a flexible shoulder. Traffic analysis includes both encroaching and parked traffic. The inner and outer edges are designed using fatigue distress functions and stress/strains resulting from encroaching and parked vehicles. The design method includes a small interactive micro-computer program to evaluate the expected life of trial design sections. A main-frame version of this program is also provided for batch processing. Drainage design is also included, as is the evaluation of the adequacy of the proposed design.

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NOTICE

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

LIST OF TABLES (continued)

CHAPTER I

INTRODUCTION

1.1 Background

A highway shoulder is "the portion of the roadway contiguous with the traveled way for accommodation of stopped vehicles, for emergency use, and for lateral support of base and surface courses."[1] In addition, shoulders provide recovery space for errant vehicles, accident avoidance areas, lateral clearance to signs and guardrails, improved sight distance in cuts, and space for maintenance operations.[2]

The desirable features of a shoulder include:

1. Clear delineation between travel lanes and the shoulder to minimize encroachment.
2. Adequate cross-slope for good drainage.
3. Sufficient width for emergency use, drainage control, and guardrail installation.
4. A flush transition at the through lane edge.
5. Inherent structural stability.
6. A pavement-shoulder joint that remains sealed.
7. Efficient and economical maintenance.
8. Low total construction and maintenance costs.[3]

For safety reasons, a shoulder should be approximately 10 to 12 feet (3.0 to 3.7 m) wide. This allows 1 to 2 feet (0.3 to 0.6 m) of clearance from the edge of the traveled lane for commercial vehicles, and 3 to 4 feet (0.9 to 1.2 m) for passenger cars. It also allows sufficient width to use the shoulder as a travel lane during peak traffic periods and during maintenance operations. The shoulder should also be continuous, i.e., without variations in width or elevation with respect to the mainline pavement. It is recommended in NCHRP Synthesis 63, "Design and Use of Highway Shoulders," that the shoulder cross-slope be steeper than that of the traffic lane in order to drain surface water more rapidly; however, the cross-slope should not be so steep as to be a hazard.[2] FHWA guidelines recommend shoulder cross-slopes on the order of 2 to 8 percent, provided that the algebraic difference in cross-slopes between the shoulder and mainline pavement does not exceed 7 percent.[4]

The geometric design of shoulders is discussed in detail in the recently completed NCHRP Report 254, "Shoulder Geometrics and Use Guidelines," and in the AASHTO manual "A Policy on Geometric Design of Highway and Streets."[5,6] Appendix E of the proposed AASHTO Guide for the Design of Pavement Structures also discusses shoulder design. The user is referred to these publications for detailed guidelines on geometric design; this manual deals only with the structural design.[7]

Various types of shoulders, ranging from grass to continuously reinforced concrete, have been constructed in the U.S. However, grass and most gravel shoulders do not meet the desirable features discussed above. Therefore, only the following shoulder designs will be discussed:

1. Flexible over granular bases.

2. Flexible over stabilized bases.

3. PCC shoulders.

Recent surveys indicate that most States do not have a shoulder design method, with the result that performance has generally been unsatisfactory. A major conclusion of the NCHRP study was that most shoulders are considerably under-designed.[8] The poor shoulder performance has resulted, over the last decade, in a number of shoulder studies. The results of these studies are summarized in the NCHRP Synthesis 63 and Report 202 and show that shoulders that have structurally adequate design for the expected traffic generally perform satisfactorily, particularly if the pavement-shoulder joint is properly sealed, and/or if adequate drainage is provided.[2,8]

1.2 Scope of Study

The objective of this study is to develop a practical and implementable procedure for the structural design of roadway shoulders. Both flexible and rigid shoulders will be considered; the latter may be tied, or tied and keyed. Various shoulder rehabilitation strategies, including overlays, will also be addressed.

The procedures developed in this report are based on the review of existing strategies, methods, and performance studies. Mechanistic approaches have been used whenever possible, and some large finite element computer programs have been used in developing the design, but the end product utilizes only a simple computer program to evaluate regression equations for critical strains and stresses. The computer program has been written both for mainframes for batch processing as well as for micro computers for user-friendly interactive processing. The procedure is therefore simple to use and gives the design engineer maximum control over various options in the design.

Design tables have also been developed to be used as approximations or if a micro computer is not available.

1.3 Outline of Report

This report is divided into the following major sections:

Chapter I: Introduction.
Chapter II: Factors Affecting Shoulder Design.
Chapter III: Design Procedure.
Chapter IV: Design Examples.

The results of an exhaustive literature review are summarized in chapter II. Chapter III contains a description of the design procedures along with overlay design and rehabilitation strategies, and chapter IV contains illustrative design examples and serves as a user guide.

CHAPTER II

- FACTORS AFFECTING SHOULDER DESIGN

The following broad categories influence shoulder design:

1. Mainline pavement/shoulder type
2. Environment
3. Safety
4. Traffic
5. Longitudinal joint
6. Maintenance strategy

These will be discussed in more detail in the sections below.

2.1 Mainline Pavement/Shoulder Type Combinations

Hicks and Barksdale have reported that one of the major problem areas with shoulders is the pavement-shoulder joint.[8] This joint is particularly troublesome when asphalt-concrete shoulders are used adjacent to PCC pavements. This problem is further compounded by the fact that the life of joint sealers rarely exceeds about four years, requiring periodic resealing/reforming.[9-12]

In the FHWA Technical Advisory T5040.18 for pavement shoulder design, a general rule to improve pavement performance, reduce maintenance costs, and facilitate construction is to use rigid shoulders adjacent to rigid mainline pavements and flexible shoulders adjacent to flexible mainline pavements.[4] It is also indicated that the use of these shoulders will improve the mainline pavement performance because of reduced pavement edge deflections as well as result in tighter longitudinal joints that reduce water infiltration into the pavement structure, thus reducing pumping.[13] The selection of shoulder type should include factors that consider engineering as well as economic benefits of the pavement system; proper assumptions should be made in the selection process to account for lack of experience and/or difficulty in assigning economic values.

Recently, some States (Minnesota) have used the widened lane concept where the traffic lane is widened the full depth by 1 to 3 ft (0.3 to 0.9 m) with striping and rumble strips to discourage use by traffic.[13,14] The rest of the shoulder width is made up of a thinner section using asphaltic concrete. This concept results in reduced edge and corner deflections for the mainline pavement, thus resulting in reduced stresses as well as reduced pumping and moisture problems. This concept is also recommended by NCHRP Report 254.[5]

The primary problem with using flexible shoulders with rigid mainline pavements, or vice versa, is that dissimilar materials have different thermal properties and expand or contract at different rates. This difference adds to the stresses at the longitudinal joint, due to different vertical deflection response, and causes premature failure of joint sealers.

In order to minimize the problems with the longitudinal joint, the combinations presented in table 1 are recommended. For new rigid pavement design, it is recommended that tied and keyed longitudinal joints be considered since this design reduces edge-load stresses in both the shoulder and mainline pavement and results in longer service life, reduced pumping, and/or reduced pavement thickness.

Table 1
Recommended shoulder types.

Mainline Pavement	Shoulder Type
CRC	CRC, JCP
JRC	JRC, JCP
JCP	JCP
AC	AC

CRC = continuously reinforced concrete
JRC = jointed reinforced concrete with load transfer devices across transverse joints
JCP = plain jointed concrete
AC = asphalt concrete

If shoulders are to be added to an existing rigid pavement, rigid shoulders should be used and tie bars should be installed. The primary purpose of tie bars is to minimize pavement-shoulder separation, and reduce edge stresses somewhat, thus reducing differential settlement. Tie bars should be non-corroding.

Selection of the shoulder type is the first step in shoulder design. It is a very important step since, as was discussed above, improper shoulder type leads to problems with the longitudinal joint.

2.2 Environmental Effects

The magnitude and distribution of rainfall, maximum and minimum temperatures, number of freeze-thaw cycles, and depth of frost penetration have a significant effect on both mainline pavement and shoulder performance. The environmental effects on shoulder performance are more severe because shoulders have generally been built with lower quality materials and to lower materials standards and compaction requirements. Also, since structural thickness needed for shoulders is less than the mainline pavement, frost penetration and freeze-thaw cycles are likely to be more significant, especially for frost-susceptible soils. The effect of environment on flexible pavement (shoulder) performance is considered in detail in reference 15. Special consideration is needed to prevent differential frost heave in the mainline and shoulder pavement sections.

2.2.1 Moisture and Drainage Effects

Surface infiltration, high groundwater, capillary rise, and excess free water are the primary causes of pavement distress. Moisture related flexible pavement failures are characterized by excessive deflection, cracking, reduced load-bearing capacity, stripping, ravelling, and disintegration. Subgrade instability, pumping and the subsequent loss of support as well as deterioration of concrete due to "D" cracking or alkali-aggregate reaction are common indicators of moisture-induced damage in rigid pavements.

The NCHRP studies, as well as other shoulder studies, have concluded that moisture infiltration and improper drainage are the major causes of premature shoulder failure.[2,8,16] A design system to evaluate this potential for moisture accelerated distress and related pavement performance has been developed by Carpenter et al. and designated MAD (Moisture Accelerated Distress Identification System).[17] The MAD index is based on the climate of the area and properties of the pavement foundation materials and can be used for new design as well as for investigation of rehabilitation needs. This system is presented in appendix A.

Drainage, however, is not the answer to all shoulder distress problems. The MAD (Moisture Accelerated Distress Identification System) is a useful guide to indicate the relative potential for moisture to cause or accelerate distress as well as to improve performance.[10] The User Manual contains step by step instruction to perform the required analysis and develop the data for drainage, maintenance and/or rehabilitation needs.

The MAD system also contains a model to determine the adequacy of proposed drainage. This model rates the drainage layer as "acceptable," "marginal," or "unacceptable" based on drainage times and subgrade type. Although the models in MAD are somewhat simplistic, they appear to be adequate, particularly since theoretical investigation has shown that it is important to have some drainage with positive water removal, and that the benefits of increased drainage speed diminish as drainage times decrease.

2.2.2 Effect of Soil Type

Granular soils can aid in drainage, thus reducing the type of drainage system needed. Thus, soil type is an important variable in drainage design and, of course, soil type affects the subgrade bearing capacity and influences the required pavement thickness. Soil type takes on added importance in climates where frost depth is adequate to penetrate into the subgrade under the shoulder pavement, particulary if the soils are fine-grained and are susceptible to frost damage. Ideally, the thickness of stable (non frost-susceptible) material above the frost-susceptible soil should equal the maximum depth of frost penetration; however, lesser thicknesses have been found to give satisfactory performance depending on the degree of susceptiblity and traffic level. Both the U.S. Army Corps of Engineers and the National Stone Association have essentially similar design criteria to protect against frost damage, and both recommended soil stabilization (mixing in aggregate, sand, lime or cement) for F-4 (highly susceptible) soils.[18,19,20]

Where a relatively thick stabilized layer is required, a dense-graded subbase filter layer with permeability of around 1 to 10 ft/day (0.3 to 3 m/day) is recommended (in order to minimize differential frost heave) under a coarse crushed stone base with a k of at least 300 ft/day (90 m/day).[18]

2.2.3 Temperature Effects

The degree to which temperature influences shoulder design depends not only on the shoulder material, but also on the mainline pavement material. For asphaltic concrete shoulders adjacent to asphaltic concrete mainline pavement, temperature effects are primarily limited to temperature cracking at low temperatures and rutting at high temperatures. Both phenomena can be minimized by the proper selection of asphalt cement and mix design. The recommended grades of asphalt cement for various climates and layer thicknesses can be determined using the procedure developed by Basma and George.[21] This procedure is presented in appendix B.

The number of freeze-thaw cycles and the depth of frost penetration are pertinent information in material selection for all types of shoulder-pavement combinations, especially at locations with frost-susceptible soils, as was discussed in the previous section. Additionally, Dempsey, et al. have concluded, based on both theoretical analysis and field tests, that climate influences the location of subdrainage pipes.[22] The results of this study indicate that for climatic regions with frost depths less than the thickness of the surface layer, the minimum distance from the top of an impermeable subgrade to the bottom of the subdrainage pipe should be about 1 to 2 inches (25 to 51 mm), (pipe below subgrade). But for extreme winter climates, either very warm or very cold temperature, the drainage pipe should be moved closer to the surface than current specifications prescribe.

Annual temperature changes can lead to midslab cracking in PCC pavements if joint spacing is excessive, as well as to excessive transverse joint opening, allowing additional water and/or incompressibles to infiltrate under the pavement. Also, excessive joint movement contributes to premature sealant failure. Sawan and Slavis have recommended transverse joints in PCC pavements every 15 to 20 feet (4.6 to 6.1 m), not only to control cracking and minimize joint opening, but also to reduce crack spalling and blowups.[23,24]

Temperature also has a significant adverse effect on the longitudinal joint between shoulder and mainline pavement, particularly for asphaltic concrete shoulders adjacent to PCC mainlines pavements as well as for untied PCC shoulders adjacent to PCC pavements. Currently, there is no experience with PCC shoulders adjacent to flexible pavements, but theoretical considerations show that the joint problems for this combination would be similar to flexible shoulders adjacent to rigid pavement, and are therefore not recommended.

Daily and annual changes in average pavement temperature, along with the daily cycles in vertical temperature gradient (in concrete only) cause relative joint movements between the concrete pavement and the shoulder. Temperature changes are not the only cause of joint movement, however. Although traffic is primarily responsible for vertical movement, moisture variation, shrinkage (swelling), and volume change of non-stabilized materials also contribute, particularly long-term creep and consolidation (settlement). Densification of granular shoulder material and creep or consolidation of underlying soft foundation soil often results in downward relative settlement of the shoulder as large as 1 to 2 inches (25 to 51 mm).[25] Frost heave results in relative upward movement on the order of 0.8 to 2 inches (20 to 51 mm).[26,27]

The average transverse joint movement (W, in inches) for PCC pavements with asphalt shoulders can be determined from:

$$W = T(Lc\ ec + La\ ea) - (Lc\ Mc + La\ Ma) + (Lc\ Nc + La\ Na) + (Lc\ Kc + La\ Ka) + Lc\ (T\ ec - Mc + Nc + Kc) + LA\ (T\ ea - Ma + Na + Ka) \quad (1)$$

where:

L_c & L_a = Active width of PCC and AC slabs, in

T = Effective temperature differential or range, °F

e_c & e_a = Thermal coefficients of expansion of PCC and AC, in/in/°F

M_c & M_a = Moisture expansion coefficients of PCC and AC, in/in

N_c & N_a = Initial shrinkage coefficient for PCC and AC, in/in

K_c & K_a = Miscellaneous coefficients for PCC and AC not otherwise accounted for, in/in

and the longitudinal joint movement is predicted from:

$$W = L_c (T e_c - M_c + N_c + K_c) \quad (2)$$

In this case it is assumed that the asphalt shoulder does not move in the longitudinal direction.

Based on the above discussion, it is strongly recommended that asphaltic concrete shoulders be built only with asphaltic concrete mainline pavements, and that PCC shoulders with tie bars (and keyways for new construction) be built adjacent to PCC mainline pavements.

2.3 Safety Considerations

Various safety studies have shown that accident rates were lower for both wider and paved shoulders.[28-32] Hall concluded that shoulder widening or improvement had the highest benefit/cost ratio of any safety improvement.[31]

Safety considerations, therefore, should be carefully weighed in determining the shoulder width, alignment, and continuity. In order to facilitate traffic entering and leaving the shoulder, the width should be constant, the shoulder should be flush with the mainline pavement, and the cross-slope should not deviate from that of the mainline pavement by more than 7 percent. There is also some evidence that delineation of the shoulder from the mainline pavement by striping, color change, or use of rumble strips is effective in reducing wander and traffic encroachment on the shoulder.[33] The 1984 AASHTO policy states that some form texturing is desirable to minimize run off road accidents.[6]

2.4 Traffic

Traffic has generally not been considered in shoulder design, primarily because of the assumption that shoulders see very little traffic. However, a recent study by Emery has shown that at least 2.4 percent of the truck traffic encroaches on the shoulder.[33] This conclusion is more or less confirmed by a Texas study of lateral placement of trucks on a highway.[34] This study shows that only about one half percent of the trucks totally encroached the shoulder, but up to 12 percent are partially on the shoulder. Since the Texas study used 6 in (152 mm) wide detectors every 12 inches (305 mm), the actual percentage of encroaching traffic is difficult to determine. The encroachment distance is measured from the edge of the travel lane to the outside edge of the dual tire. Barksdale, et al. have recommended that 2.5 percent of the mainline truck traffic should be used in shoulder structural design; however, this value is most likely too low in view of the edge stress concentration factors for rigid pavements.[8,35] Stress concentration due to load placement is generally ignored in flexible pavement design - this may be appropriate for mainline design since the median outside wheel path is approximately 2.5 to 3 ft (0.8 to 0.9 m) from the pavement edge for pavements without paved shoulders. For flexible shoulder design adjacent to rigid mainline pavement, however, the wheel placement is much closer to the edge (based on Emery study); consequently, load placement also needs to be considered for flexible shoulder.[33]

There is some evidence to indicate that when there is a pavement shoulder and no lateral obstructions, there is a tendency of trucks traveling on the outer lane to shift by as much as 12 inches (300 mm) closer to the outer edge of the pavement than is the case with unpaved gravel or grass shoulders.[36] This shift tends to increase the number of encroachments, but the results of the Emery study are probably unaffected since his measurements were made on pavements with paved shoulders.[33] The shift, however, has an effect on the mainline design (particularly for rigid pavements), since the edge stresses increase significantly as the traffic moves closer to the edge. It is, therefore, desirable to construct concrete mainline pavements with tied (and keyed for new construction) concrete shoulders. Not only does this practice eliminate most of the longitudinal joint problems, but tied and keyed PCC shoulders reduce edge stresses and counteract the stress concentration due to traffic moving closer to the edge. The use of rumble strips on the shoulder at the pavement edge can also help to reduce encroachment, thus reducing edge stresses. The widened lane concept, where the mainline pavement is widened by 1 to 3 ft (0.3 to 0.9 m), with striping and rumble strips installed on this widened portion, is also very useful in reducing edge stresses on both the mainline and shoulder pavement.

In addition to traffic encroachment, the shoulder is also used by disabled vehicles for parking. Detailed traffic surveys are not available to determine the number or distribution of these parked vehicles, but it is reasonable to assume that parked vehicles tend to move close to the outer edge of the shoulder. The percentage of parked and encroaching traffic can be estimated from the results of national surveys, or from the procedure recommended by Sawan et al. in "Structural Analysis and Design of PCC Shoulder."[37] Since the above estimates are relatively imprecise, it is adequate to estimate the total traffic using the highway in terms of E18's, using vehicles types and conversion factors such as used by ODOT, and taking a percentage (avg. 3-5 percent) of these for shoulder design.[38]

Some States use the shoulder as an additional traffic lane during peak periods or during maintenance operations. If such a use is anticipated, this additional traffic must also be considered in the design of both inner and outer edges.

2.5 Longitudinal Joint

As was stated in the previous discussion, the longitudinal joint between the shoulder and mainline pavement is the most troublesome feature of flexible shoulders adjacent to concrete mainline pavements. Barksdale and Hicks have shown that both environmental and traffic factors (discussed in the previous sections) cause the joint to open, allowing water to enter the pavement structure.[8] Unless this joint is kept tight, it can admit more water than the base course can drain away, even when underdrains are used, with the result that the base course and upper surface of the subgrade can remain saturated for extended time periods, depending on base course and subgrade drainage characteristics.[39] It is, therefore, very important that the longitudinal joint be designed and sealed properly. Barksdale and Hicks have recommended a sawed and sealed longitudinal joint along with a positive means for removing water from the vicinity of the longitudinal joint.[8] They also recommend that "sealing of the longitudinal joint probably offers little benefit unless either the transverse joints in the mainline pavement are also effectively sealed or a continuously reinforced pavement is used."

It should be reemphasized that the use of dissimilar materials (AC shoulder with PCC pavement or vice-versa) is not recommended. However, most existing PCC pavements have AC shoulders; therefore, a proper joint sealing strategy is very important to the performance of both the shoulder and the mainline pavement.

The recommended PCC/AC mainline-shoulder longitudinal joint construction method is to saw a 1 inch (25 mm) wide by 1 inch (25 mm) deep joint groove into the shoulder.[8] Either a diamond blade or an abrasive wheel may be used, but the sawing should be done so as to leave the aggregate exposed on the asphaltic concrete side of the joint. The sides should not be primed with either liquid or emulsified asphalt, and any curing compound should be removed from the concrete during the sawing operation. The following is a recommended list of joint sealants and resealers, in the order of preference, based on both laboratory tests and field performance:[12]

1. Cutback asphalt with rubber.

2. Silicone Dow 888.

3. Asphalt emulsion with rubber.

4. Rubberized asphalt, cold applied.

5. Catalytically blown asphalt cement.

It is recommended in NCHRP Synthesis 98 that the shape factor (joint width/depth) be varied according to the material used for joint sealer.[12] The recommended shape factor for elastomers and rubberized and bituminous sealers is in the ratio 1:1, whereas this ratio is 2:1 for silicone sealers. This applies to both longitudinal and transverse joints.

Longitudinal joints between flexible shoulders and flexible mainline pavements generally do not experience serious problems if the foundation material under the shoulder is properly compacted during construction. These joints do not undergo the movements discussed previously, and even if some separation takes place, the sealing of these joints is much simpler than is the sealing of flexible-rigid combinations.

There is very little experience with untied PCC shoulders adjacent to PCC mainline pavements. Consequently, performance data is lacking for this combination. Based on theoretical considerations, however, the longitudinal joint is likely to have similar, although perhaps somwhat less severe, problems than the joint in flexible-rigid combination. This combination is not recommended, for the following reasons:

- Construction of tied, keyed joint is not significantly more expensive than construction of a properly sealed joint.

- Tied, keyed joints reduce edge stresses in the mainline pavements and in the shoulder, therefore reducing fatigue damage to both pavements.

- Tied, keyed joints reduce edge deflection, thus reducing the potential for pumping and void formation.

- Very little maintenance is required for tied, keyed joints.

2.6 Maintenance

The degree of maintenance required depends on the structural design, type of drainage, and the type of shoulder-mainline combination. Currently, a majority of existing shoulders are structurally underdesigned and show severe distresses in the form of joint separation (both transverse and vertical), cracking and rutting. The degree of severity of these distresses, as well as the condition of the mainline pavement, dictate the maintenance strategy to be used; i.e., patching and crack/joint resealing, reconstruction, recycling and/or overlay.

The amount of maintenance required for properly designed shoulders is primarily limited to maintaining the shoulder-pavement longitudinal joint. Based on laboratory and field evaluation studies, the life of a polyurethane seal is approximately 5 to 6 years and the improved rubber asphalt can effectively seal a joint for 3 to 4 years.[8] A recent study by ERES has shown that a low-modulus silicone joint sealer has performed well in all kinds of climates when installed properly.[40] The expected life of this sealer is six years or better. An economical maintenance practice is to apply either liquid or catalytically blown asphalt over the original rubber-asphalt sealant.[8] The results of a recent NCHRP synthesis show that the materials listed in section 2.5 are best for sealing and resealing joints and cracks in rigid pavements. The following sealers are recommended for flexible pavements:[12]

1. Cutback asphalt with rubber.

2. Rubberized asphalt, hot applied.

3. Catalytically blown asphalt.

4. Asphalt cement.

5. Asphalt emulsion with rubber.

However, as was stated previously, longitudinal joint sealing is not recommended unless the transverse joints in the mainline pavement are also effectively sealed.

2.7 Thickness Design Concepts

As was indicated previously, shoulders may be untied, tied, or tied and keyed. The design is somewhat different for each type. However, the design must consider two critical areas: the inner-edge design based on encroaching traffic and the outer-edge design primarily based on parked vehicles. The design is based on limiting critical stresses or strains to allowable values to prevent failure due to fatigue or excessive rutting as well as from sudden rupture.

The stresses and strains are calculated from regression equations that relate critical values to shoulder properties; these include concrete modulus and thickness, AC modulus and thickness, base/subbase modulus and thickness, subgrade modulus, and, of course, load location (inner edge or outer edge). The regression equations for both flexible and rigid shoulders have been developed from analyses conducted using the RISC program.[35] Although RISC is primarily intended for rigid pavements, it is also useful for flexible pavement analysis when the loads are close to the pavement edge, as is the case with parked vehicles (for all cases) and encroaching vehicles if the flexible shoulder is not an integral part of the flexible mainline pavement.

In the event that the shoulder is not tied (or keyed) to the mainline pavement, the inner and outer edges still behave differently since they see different traffic loading. Therefore, stress and strain calculations should be done for both loading conditions and thicknesses determined for both inner and outer edge loading.

The thickness design consists of evaluating the critical stress/strain for several trial shoulder thicknesses, computing the predicted life (Nf) from appropriate distress functions, plotting the computed Nf vs. shoulder thickness, and interpolating this graph to get thickness for the design life (Nd).

In the event that the projected thicknesses are less than the minimum 6 inches (152 mm) for rigid pavements or 3 in (76 mm) for flexible pavements, the use of the minimum values is recommended since various shoulder performance studies have shown these to be the minimum thicknesses for satisfactory performance.[41,42,43]

Although both inner and outer edges of flexible and rigid shoulders can be designed using the methods discussed above, the inner edges of shoulders (both flexible and rigid) should be constructed to the same thicknesses as the mainline pavement. Not only will this strategy minimize differential vertical deflection under load, the same construction is required to minimize the effects of differential frost heave. Also, theoretical studies have shown that for rigid shoulders the effects of slab curling and warping are minimized when both slabs have the same thicknesses.[44,45] Furthermore, although 6 in (152 mm) thick tied and keyed shoulders have performed adequately in some studies (Minnesota, Illinois), the experience in Ohio and Michigan has shown that if rigid shoulders are to be tied and/or keyed to the mainline pavement, it is desirable to make both shoulder and mainline pavement the same thickness in order to keep the tie bars and/or keyway from shearing and breaking up the concrete. [14,46] This conclusion is also reached in a theoretical study by Tabatabaie.[45]

2.8 Joint Spacing

Performance studies have shown that most problems with transverse joints in rigid shoulders can be avoided if the joint spacing is between 15 and 20 feet (4.6 and 6.1 m).[37] In order to eliminate rhythmic noise, a random spacing between 15 and 18 feet (4.6 and 5.5 m) is recommended for those areas where the shoulder will get significant usage as a travel lane.

If short joint spacing is used, dowel bars are not necessary, but joint sealing should be given careful attention. When rigid shoulders are added to an existing jointed pavement, shoulder joints should be aligned with those in the existing pavements, and if spacing between 15 and 20 feet (4.6 and 6.1 m) cannot be maintained, doweled joints with reinforcement are recommended.[37] In those areas where dowel bars and reinforcing are needed, the designer may consider shorter joint spacing instead; e.g., if the existing pavement has 42 ft joint spacing, reinforced shoulders with 21 ft spacing and dowel bars, or plain shoulders with 14 ft undoweled joints are possible.

CHAPTER III

DESIGN PROCEDURE

3.1 Traffic Analysis

As was stated in the previous chapter, the design method requires an estimate of traffic using (and/or parking on) the shoulder. This estimate is required in terms of equivalent 18 kip (80 kN) axles. Various forecasting methods or the results of surveys, such as the Emery survey or the Texas vehicle placement study, may be used for taffic analysis, but the method by Sawan, et al. described below is recommended. [33,34,37]

Three types of traffic use shoulders: encroached, parked, and regular traffic.

a. Encroached traffic is the part of the mainline traffic that encroaches the shoulder occasionally and then merges back to the mainline. The encroached traffic normally travels in the vicinity of the mainline/shoulder joint and within a transverse distance of 12 in (305 mm) on the shoulder. The percent of trucks that encroach on the shoulder should be obtained as a part of a field survey in the area where the PCC or AC shoulder is to be constructed. A stretch of several miles is recommended for such a survey. Trucks should be selected at random and followed by observers over the selected distance. Records are made of the time the truck travels on the shoulder to determine the longitudinal distance for each encroachment (by using the average truck speed which would be approximately the same as the observer vehicle's speed). The following information should be obtained from the shoulder field survey:

   Average number of encroachments per truck (NE) in the surveyed stretch (LS) and

   average longitudinal distance on the shoulder per encroachment in miles (ED).

   The above information can be used to compute the number of load applications on the shoulder edge near the lane/shoulder joint in terms of percent of mainline truck traffic as follows:

   1. Obtain the ADT, T, and LD for the design section. Compute the average daily truck volume in the lane next to the concrete shoulder (LTT). LTT = ADT x T x LD. (T is the percent of trucks in the ADT, and LD is the lane distribution factor).

2. Determine the total number of daily truck encroachments in the surveyed stretch by multiplying the average number of encroachments per truck (NE) times the average daily lane truck traffic in one direction (LTT) (Step 1).

3. Determine the total encroachment distances in the surveyed stretch by multiplying the total number of encroachments (Step 2) by the average longitudinal distance on the shoulder per encroachment (ED) (obtained from the survey) in miles.

4. Then the number of encroachments for a given point (or section of ED length) in the surveyed stretch is obtained by dividing the total encroachment distances in the surveyed stretch (Step 3) by the length of the surveyed stretch (LS).

5. Hence, the proportion of encroaching trucks on the shoulder (PET) is the ratio of the number of encroachments for a given point (Step 4) to the average daily truck traffic in one direction (Step 1).

$$PET = \frac{LTT \times NE \times ED}{LS \times LTT} \qquad (3)$$

where:

PET = Proportion of encroaching trucks on the shoulder, percent/100

LTT = Average daily lane truck traffic in one direction

NE = Average number of encroachments per truck in the surveyed stretch, miles

ED = Average encroachment distance per truck

NE x ED = Average length of total encroachments per truck in the surveyed stretch, miles

LS = Length of surveyed shoulder stretch, miles

This expression can be reduced to the following:

$$PET = \frac{NE \times ED}{LS} \qquad (4)$$

Various calculations show the PET may vary over ranges of approximately 0.01 to 0.08 (1 to 8 percent) of the adjacent lane truck volume. The revised Portland Cement Association (PCA) design method assumes a maximum of 6 percent for this value.[47]

The above procedure was used on I-75 in Perry, Georgia.[8] Out of all the trucks that use the highway, approximately 2.4 percent encroached the outside shoulder. The truck wheels were found to be concentrated primarily within about 12 in (305 mm) of the longitudinal joint, with an average transverse encroachment distance of 7.1 in (180 mm). This tends to justify the use of the full percentage of encroached truck traffic for structural PCC shoulder design. In some cases this value could be 25 to 35 percent of the ADT.

Taragin, as part of a study by the Highway Research Board to determine the relative effects of different magnitudes and configurations of axle loads on PCC pavements, also reported that an average of 2.5 percent of the mainline truck traffic encroached the outside shoulder of the test section to the extent of 12 inches (305 mm).[48]

The above studies were conducted on PCC pavements with either unpaved or paved shoulder types other than PCC. This suggests that the above percentages could be different when shoulder materials are the same as those of the mainline pavement. The location of the shoulder stretch under design could also affect this percentage. These factors make the traffic survey of the local condition of the highway a necessity.

b. Parked traffic is the percentage of mainline truck traffic that parks on the shoulder for emergency reasons or otherwise. This input may be estimated for the design section based upon traffic counts on similar highways. It varies greatly along a given project depending on geometric and interchange conditions. Typically, a much higher proportion of trucks park near ramps at interchanges. If this occurs, specific design sections should be selected. The proximity of weight stations and rest areas should also be considered, as should state laws regarding emergency use.

   As for encroaching traffic, it is necessary to compute the number of expected load applications that will occur along the outer shoulder edge in the selected design section. This is computed as follows:

   1. A length of project (in miles) must be selected that is representative of the design section (DL).

2. The ADT, T, and DD (directional distribution) in the section must be determined.

3. The mean length (in miles) that a truck drives on the shoulder during a typical stop is determined from actual observations (PL).

4. The mean number of trucks that actually used the shoulder in the design section for parking is determined by visual counting over a typical 24 hour period. It should be noted that most parking occurs during the very early morning hours; and therefore, this period of time must be included.

5. The percentage of trucks that park on the shoulder is then computed. The design section is divided conceptually into "subsections" of length PL (from step 3). It is assumed that probability of a truck to park on each "subsection" is equal to P, where:

$$P = \frac{1}{DL/PL} \tag{5}$$

Thus, the percentage of total truck traffic in one direction that parks on any random "subsection" (PPT) is computed as:

$$PPT = \frac{N \times P \times 100}{ADT \times T \times DD} \tag{6}$$

where: N= average number of parked trucks/day and other symbols are as defined above

Preliminary surveys and calculations show that the PPT may range from percentages of 0.0005 to 0.005. The total of the proportion of encroached as well as parked truck traffic is used as an input for encroached traffic percentage due to the fact that any truck has to encroach in order to park on the shoulder.

c. Regular Traffic: If it is anticipated that the PCC shoulder would be used by regular traffic at any stage of its design life, this extra amount of traffic should be accounted for as a part of the shoulder design traffic. The amount of traffic at both edges of the PCC shoulder should be increased accordingly. The ultimate case is to design the shoulder as an extra lane by considering its traffic to be similar to the mainline outer lane truck traffic. The outer and the inner edges of the PCC shoulder would carry such traffic; therefore, the percentage of encroached and parked truck traffic should be adjusted accordingly.

It needs to be emphasized that if the shoulder is to be used by regular traffic, this traffic increases the outer edge traffic significantly in view of the low values obtained for parked vehicles. The encroaching traffic also increases, but the relative increase is smaller. The above information still needs to be converted to equivalent 18 kip (80 kN) axle loads. Any rational method may be used. It is expected that States have their own methods of converting mixed traffic to equivalent axle loadings. However, the following method, illustrated in table 2, could be used.[38] In this table the type B trucks are defined as multiple unit trucks with 3 or more axles and type C trucks are 2-axle, 6-tire or 3 or more axle single-unit trucks. The conversion factors used in this table take into consideration vehicle weights as well as structural strength, and as such, represent an average for the vehicle type.

Table 2
Conversion to E-18's.

Vehicle Type	No. of Vehicles		Directional Factor		Conversion Factor	E-18's
RIGID PAVEMENT						
B	90	x	1/2	x	1.412	64
C	180	x	1/2	x	0.403	36
						100
FLEXIBLE PAVEMENT						
B	90	x	1/2	x	1.068	48
C	180	x	1/2	x	0.311	28
						76

3.2 Frost Effect

Frost susceptible soils are soils that have a potential for heaving (expanding) during freezing periods. They include all organic soils as well as inorganic soils that contain more than 3 percent (by weight) particles finer than 0.02 mm. These soils have been classified by the Corps of Engineers according to their degree of susceptibility, as shown in table 3.[19]

Both the Corps of Engineers and the National Stone Association have similar design methods to limit the damage due to frost.[19,20] The Corps of Engineers uses two concepts in design: (1) control of differential surface deformation by sufficient thickness to eliminate frost penetration, and (2) reduced strength design during melting periods. The Corps of Engineers has now revised and placed their design procedure on a microcomputer, as was indicated earlier.[19] The NSA design is based on partial protection (depending on traffic level), as is indicated in table 4. The minimum thickness of non frost-susceptible material is required only if the depth of frost penetration (given in figure 1) exceeds the values given in table 4. The Corps of Engineers procedure is summarized in table 5. It can be seen from this table that complete protection (subgrade at a depth greater than the frost penetration) is rarely used, except for heavy traffic in areas of highly variable soil conditions. However, for F4 soils, complete protection is required.

The limited subgrade frost penetration method is directed to control the pavement distortion caused by frost heave.[19] Sufficient thickness of pavement, base, and subbase is required to limit the penetration of frost into frost-susceptible subgrade to an acceptable level. The design method also includes an approach to prevent frost intrusion into the subgrade; however, this approach is usually uneconomical and is rarely used. The COE procedure (from reference 19 and 49) is summarized below:

> The freezing index used in the calculation is for the coldest year in a 10-year period or the average freezing index for the three coldest years in a 30-year period. Depth of frost penetration is determined by the modified Berggren equation. Charts for determining the depth of frost penetration are shown in figures 2 through 4. Steps in the procedure for design for control of surface deformation are as follows:
>
> The depth of frost penetration is determined from figure 2, 3, or 4 using the design freezing index and the moisture-density data of the subgrade and base course. The depth of base course, (c), is determined next. This value is entered into the abscissa of figure 5, and with the appropriate r value (ratio of water content of the subgrade over that of the base), the allowable depth of frost penetration is found. An example of the method is shown on the figure. If the calculated value of r is greater than 3.0, use 3.0 in figure 5 for highway design, and 2.0 for high traffic airfield pavement design.
>
> To preclude intrusion of the subgrade into the base course, the bottom 4 inches (102 mm) of the base are designed as a filter. If the combined thickness of base plus surface obtained by this diagram procedure is greater than 72 inches (1.83 m), the Corps of Engineers recommends a

Table 3
Frost-susceptible soils.[19]

Group	Description
F1	Gravelly soils containing between 3 and 20 percent finer than 0.02 mm by weight
F2	Sands containing between 3 and 15 percent finer than 0.02 mm by weight
F3	(a) Gravelly soils containing more than 20 percent finer than 0.02 mm by weight, and sands, except fine silty sands, containing more than 15 percent finer than 0.02 mm by weight. (b) Clays with plasticity indices of more than 12, except (c) varved clays existing with uniform conditions.
F4	(a) All silts including sandy silts. (b) Fine silty sands containing more than 15 percent finer than 0.02 mm by weight, (c) Lean clays with plasticity indices of less than 12. (d) Varved clays with nonuniform subgrade.

Table 4
Design thickness, frost group basis.[20]

Subgrade Soil Frost Group	Design Thickness (in) for Indicated Daily Traffic, E-18's 0-5	6-20	21-75	76-250	251-900	901-3000
F-1	9	10	12	13	15	17
F-2	10	12	14	16	18	20
F-3	15	18	22	25	28	30
F-4	Subgrade improvement recommended					

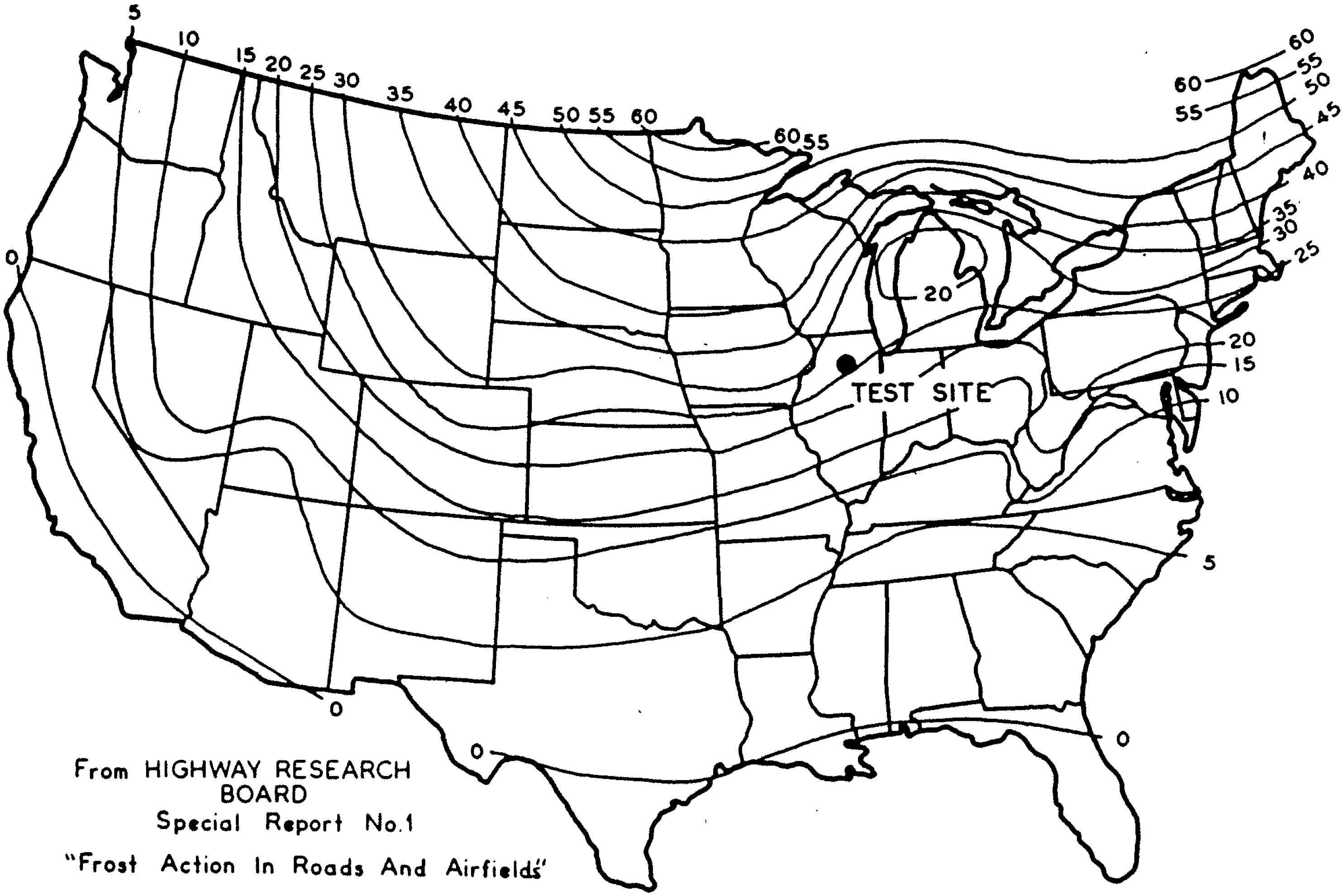


Figure 1. Average annual frost penetration, in inches.

Table 5

Summary of methods for design of airfield pavements for frost conditions.[49]

	Horizontal Variability of Subgrade Soil and Moisture Conditions			
	Uniform	Slightly Variable	Variable	Extremely Variable
Design method	Variations affecting heave potential virtually undetected by ordinary methods of investigation. Negligible differential frost heave and thaw settlement may be anticipated under reduced subgrade strength design.	Small variations of subgrade conditions apparent by ordinary methods of investigation.	Subgrade Conditions moderately variable. Widespread cracking of rigid pavements and appreciable surface deformation would be expected if reduced subgrade strength dedign method were used.	Very large, frequent, and abrupt changes in subgrade frost heave potential not permitting use of transition sections.
(1)	(2)	(3)	(4)	(5)
Complete protection				Applicable only under exceptionally adverse conditions for F3 and F4 subgrades.
Limited subgrade frost penetration (i) (ii) (iii)	Required for flexible and rigid pavements: 1. Over F4 subgrade soils (except as noted in col. (4) below. 2. Over other frost-susceptible subgrade soils when: a. Cracking of rigid pavements or unacceptable pavement roughness caused by nonuniform frost heave may be expected with lesser design thickness, or b. Limited subgrade frost penetration design requires less combined thickness or is otherwise more economical than reduced subgrade strength design.			
Reduced subgrade strength (i) (ii) (iii)	Applicable for flexible and rigid pavements over F1 through F3 subgrades when objectionable differential heave or cracking will not occur.	Applicable for flexible pavements over F1 through F3 subgrades when objectional differential heave or cracking will not occur.	Applicable for flexible pavements over F1 through F4 subgrades when pavements are minor, slow speed, and noncritical and heave can be tolerated, except not to be used for F4 subgrade under adverse moisture conditions.	

Table 5 (continued)

(i) Transition sections required at any substantial and abrupt changes in subgrade frost heave potential which would produce unacceptable pavement roughness and cracking.

(ii) When indicated combined thickness exceeds 72 in, consider alternatives: (1) limiting total thickness to 72 in and, in rigid-type pavements, using steel reinforcement; (2) reduced slab dimensions; or (3) base of higher moisture retention. OCE approval required for use of alternatives or thickness over 72 in.

(iii) Thickness intermediate between reduced subgrade strength and limited subgrade frost penetration design values may be adopted when justification based on field experience or special conditions of the design is provided.

(iv) Special provision for rigid pavements over uniform subgrades: Instead of base equal to slab thickness, 4-in minimum base is allowed over F1, F2, F3 subgrades when: (1) design freezing index is 1000, or (2) subgrade is susceptible to pumping and water table is below 10 ft; however, base drainage criteria must be met.

Note: Design of highway pavements should be based generally on the reduced subgrade strength design method, with additional thickness (based on local field data and experience) used where necessary to keep pavement heave and cracking within tolerable amounts. Where such added thicknesses are used for highways they should not exceed values obtained by the limited subgrade frost penetration design method. Thickness reduction up to 10% may also be allowed on substantial highway fills when justified by field data and experience.

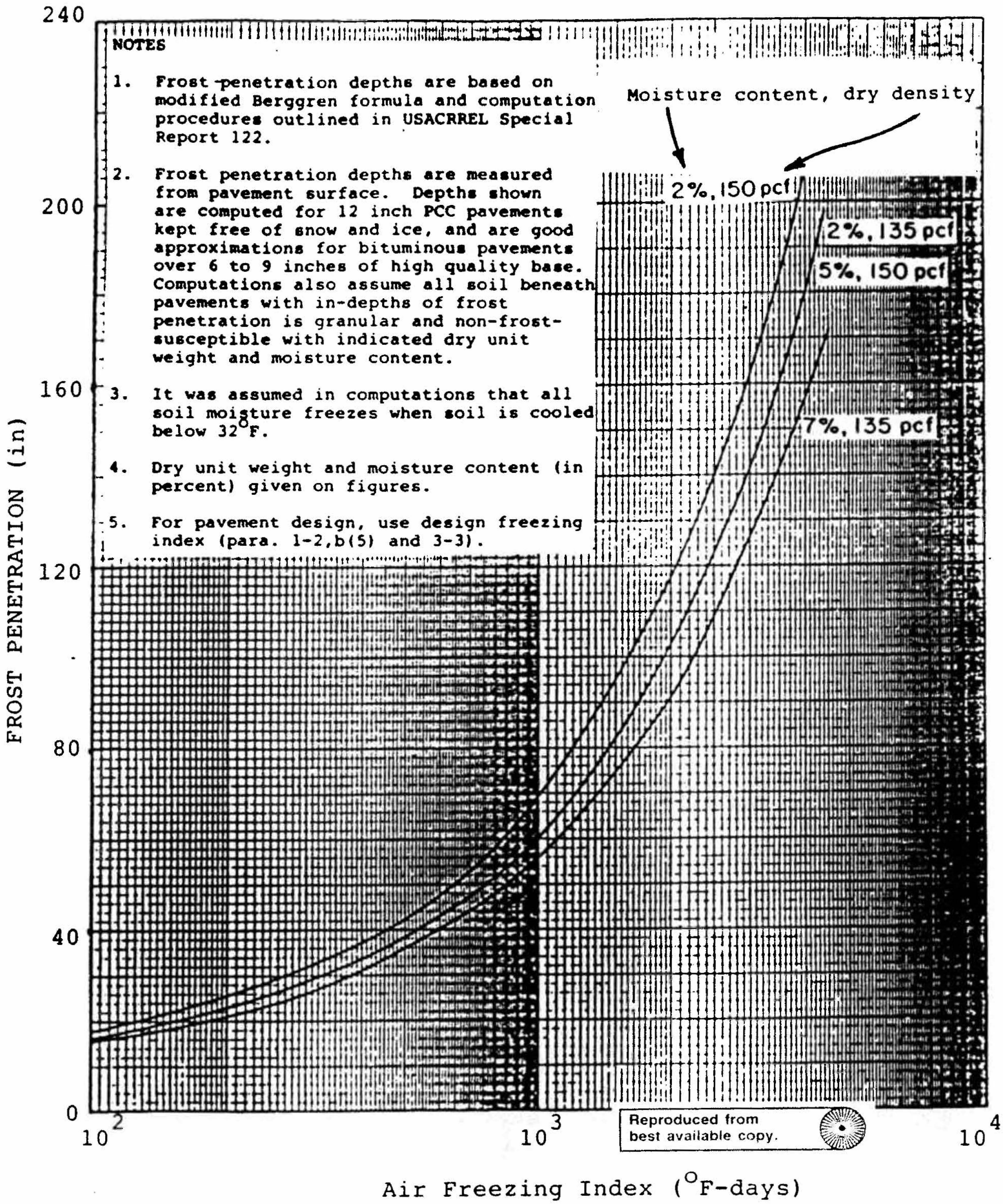


Figure 2. Frost penetration beneath pavements.[19]

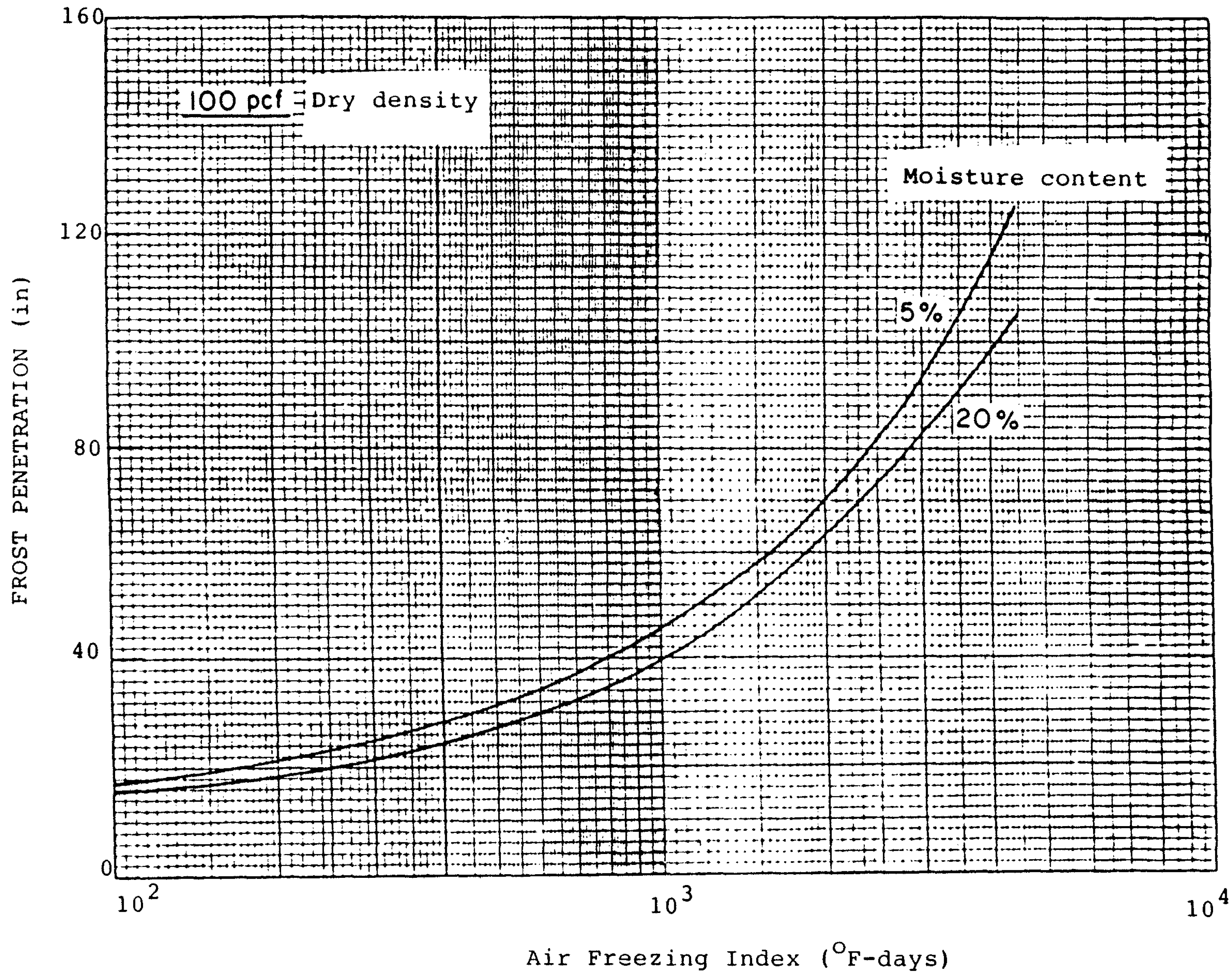


Figure 3. Frost penetration beneath pavements.[19]

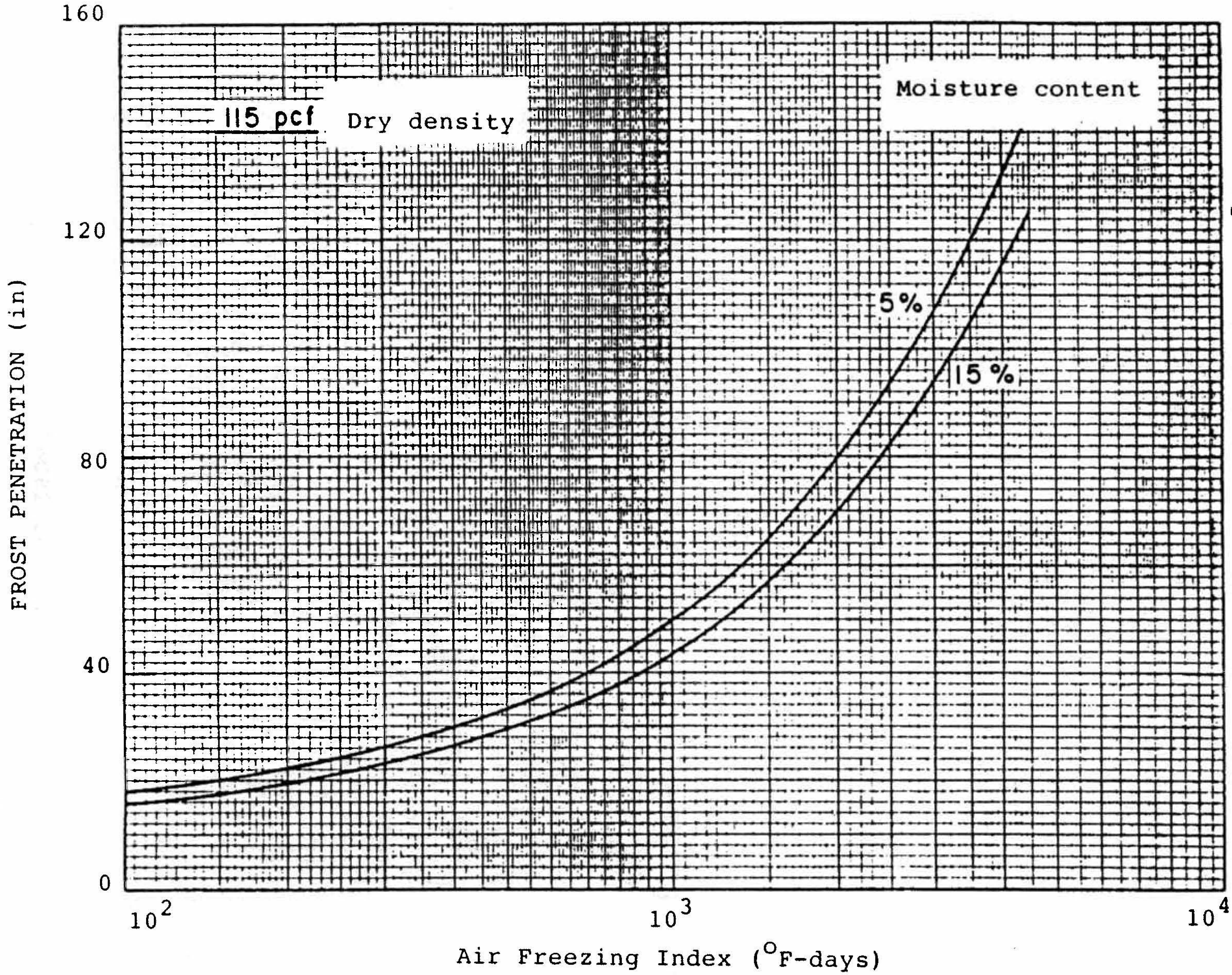
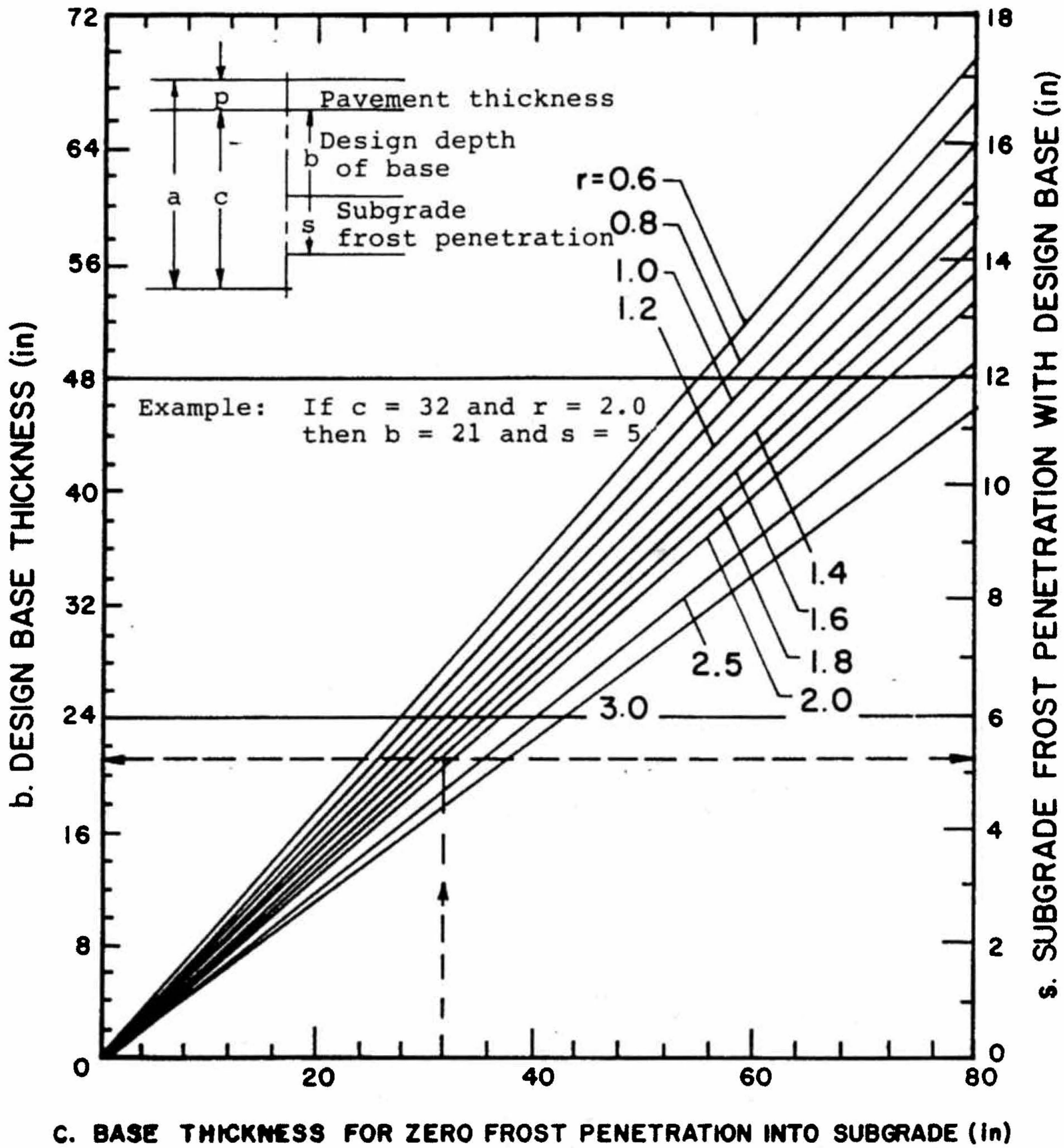


Figure 4. Frost penetration beneath pavements.[19]



NOTES: $\underline{a}$ = Combined thickness of pavement and non-frost-susceptible base for zero frost penetration into subgrade.

$\underline{c}$ = $\underline{a}$ - $\underline{p}$

$\underline{w}_b$ = Water content of base.

$\underline{w}_s$ = Water content of subgrade.

$\underline{r}$ = $\frac{\underline{w}_s}{\underline{w}_b}$ Not to exceed 2.0 for type A and B areas on airfiels and 3.0 for the other pavements.

Figure 5. Design depth of non frost-susceptible base for subgrade frost penetration.[19]

special study to determine if it is more economical to use rigid pavements with steel reinforcement to hold cracks tightly closed, or if surface roughness would be excessive for a 72-inch (1.83 m) pavement.

It should be kept in mind that the COE procedure is primarily designed for airport pavements. Shoulders, particularly those seeing low traffic levels, most likely will not need a filter layer. However, if the mainline pavement is constructed with a filter layer, the same construction should be used under the shoulder to minimize differential frost heave effects.

The NSA method may also be used (with figure 1 and table 4), but care should be exercised in determining the daily traffic range, particularly where the depth of frost penetration from figure 1 greatly exceeds the minimum value from table 4.

3.3 Drainage Requirements

Research studies across the country have established that improved pavement performance can be obtained if surface water is not permitted to accumulate within the pavement structure.[16,17] "The use of a drainage layer immediately below the lower bound layer of a pavement has been found to be the most effective means of achieving the necessary degree of internal drainage."[50] However, improved drainage is not the answer to all pavement problems. The MAD system is one means of determining when and what type of drainage is needed; the adequacy of a drainage layer is also evaluated using this system.[17] While there are often more sophisticated approaches to drainage design, the use of the MAD system is recommended because of its simplicity and ease of use.

The geometric design of the drainage system developed by Kozlov is recommended; it is described below:[50]

> "As already indicated and shown on standard details (figures 6 - 9), the drainage layer should be located immediately below the bound layer of a pavement under a minimum of 6 in (152 mm) of confinement. Figures 6 and 8 give the cross-sectional view of a drainage layer, its edge drains, and a typical cross drain for a generalized highway pavement. Figure 6 provides an alternative, whereby the longitudinal edge drains are positioned at the edge of the pavement, whereas figure 7 shows the same drains located at the edge of the shoulder. The alternative shown in figure 7 is preferred, but if construction costs are a major concern or if the design considerations require, the approach shown in figure 6 can be used. Figures 6 and 7 have the cross-slopes and grade breaks of the drainage layer mirroring the pavement surface. Details in figures 8 and 9 are basically duplicates of figures 6 and 7, except that a constant cross-slope is required of the drainage layer.

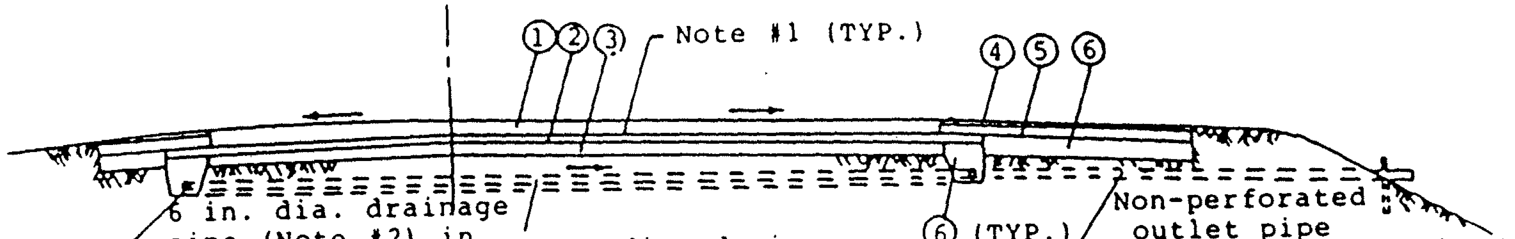
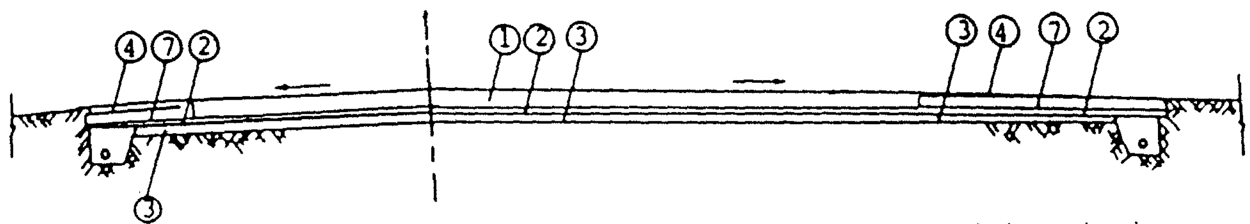


Figure 6. Internally drainable road cross-section with drains at the edge of pavement.[50]



1 B.C. or PCC Pavement, min. 6 in. thick
2 4 in. B.S.O.G. or N.S.O.G. Drainage Layer
3 Base or Subbase Layer
4 B.C. Shoulder
5 Soil Aggregate or Dense Graded Aggregate Base Layer
6 8 or 57 Course Aggregate
7 L.F.A. Plant Mixed Stabilized Base Course or Nonstabilized Base Course over Filter Fabric

Notes: 1. Use Prime Coat on the top of the NSOG Layer

2. Drainage Pipe shall be perforated or slotted corrugated metal, PVC or PE plastic or Porous wall Concrete Pipes.

Figure 7. Internally drainable road cross-section with drains at the edge of shoulder.[50]

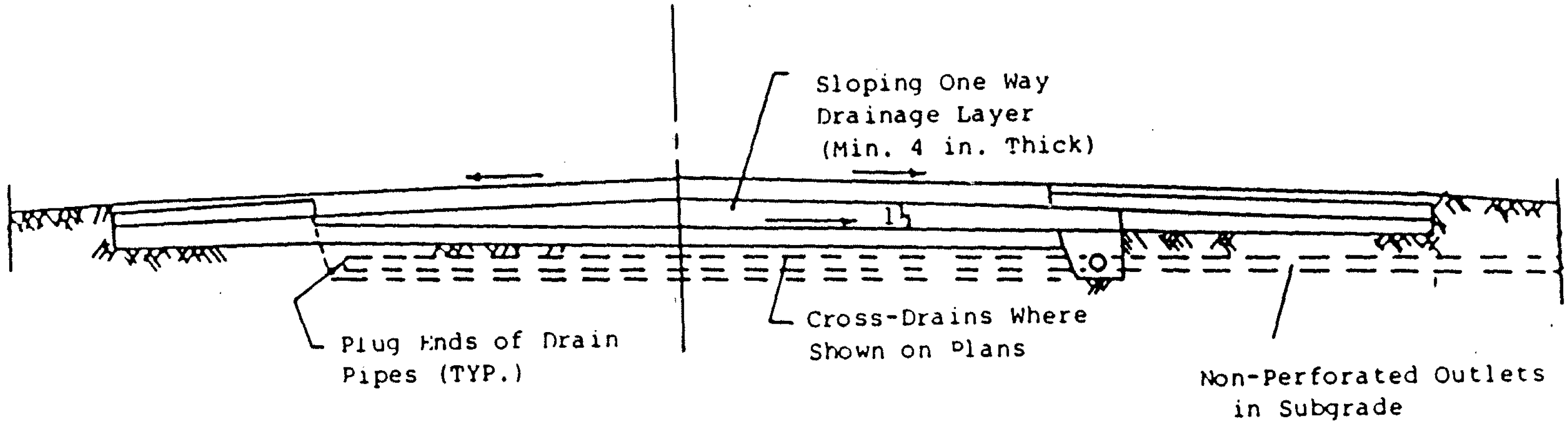
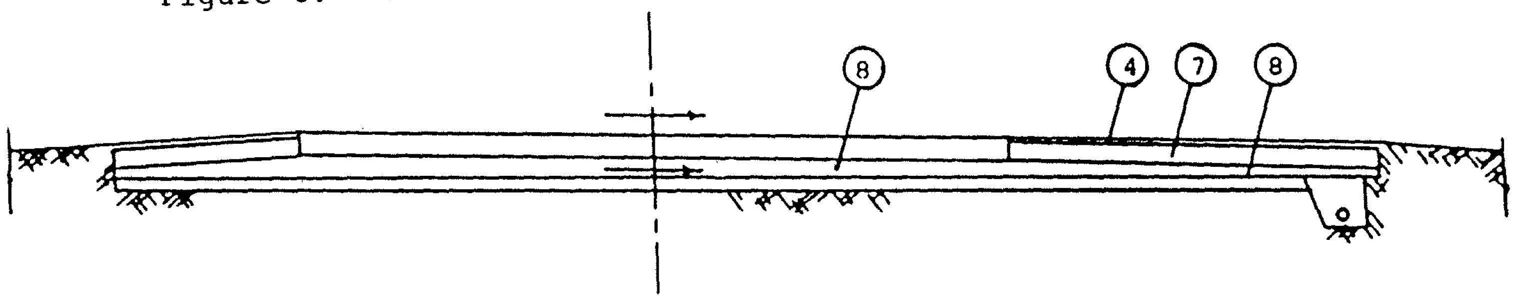


Figure 8. Road cross-section drainable to the edge of pavement collector.[50]



Notes: 1. Longitudinal Drains in these details can be located at either the edge of pavement or shoulder.
2. For additional detail and notes see Figures 7 and 8.

4 B.C. Shoulder

7 Non-Stabilized base course over filter fabric or stabilized

8 Drainage Layer, Min. 4 in. Thick

Figure 9. Road cross-section drainable to the edge of shoulder collector.[50]

From a long-term performance standpoint, construction in accordance with the details shown in figures 8 and 9 are best. However, for ease of construction, but not necessarily for minimized installation costs, the configuration shown in figures 6 and 7 will frequently be found more appropriate. Of course, variations of figures 6 through 9 are entirely feasible as long as they are appropriately developed."[50]

3.4 Material Properties

As was stated previously, the analysis of stresses and strains in thickness evaluation requires that certain material properties be input:

1. Concrete modulus, Poisson's ratio, flexural strength, or

2. Asphaltic concrete modulus, Poisson's ratio, and creep modulus

3. Base/subbase modulus and Poisson's ratio

4. Subgrade modulus and Poisson's ratio

Additionally, the effect of moisture and drainage on unbound material properties is needed.

Laboratory testing is the best method of obtaining the desired material properties; however, the following methods can be used to estimate the required parameters.

a. The flexural strength (modulus of rupture) of most highway concretes is around 600-800 psi (4.1 to 5.5 MPa). This value is generally available from test data but may be estimated from unconfined compressive strength tests using the following ACI relationship:[51]

$$fc = a * f'c^{.5} \qquad (7)$$

where:

fc is the flexural strength

f'c is the compressive strength of standard 6 x 12 in (152 x 305 mm) cylinders

a is a constant ranging from 7 to 10 for conventional (British) units and 0.58 to 0.83 for International units. The lower value should be used with high-strength concrete and the higher value with low-strength concrete. The value of a for the AASHO Road Test concrete is approximately 9.5.

b. The dynamic (tangent) modulus of highway concretes is around 5 million psi (34.5 GPa) within a range of 3.5 to 6 million psi (24.1 to 41.4 GPa). In the absence of specific test data, it may be estimated from the following ACI relationship:[51]

$$Ec = 43 * p^{1.5} * \sqrt{f'c} \text{ (in psi)} \tag{8}$$

$$Ec = 0.056\, p^{1.5} * \sqrt{f'c} \text{ (in kPa)}$$

where:

Ec is the tangent modulus

p is the concrete unit weight (in pci or Kg/cu m)

f'c is the compressive strength

Equation 8 is generally given for the secant modulus. Since the tangent modulus is generally 20 to 30 percent higher than the secant modulus, the coefficients in equation 8 have been increased by 30 percent over the values recommended by ACI for secant modulus (for a more conservative design) because critical stresses in concrete increase with increasing concrete modulus. It should be emphasized, however, that concrete modulus and flexural strength are not independent of each other but are related through equations 7 and 8. While it is desirable to have laboratory measured values for concrete flexural strength (fc) and concrete modulus (Ec), it is far better to use equations 7 and 8 to relate these properties than to make arbitrary assignments for these values.

c. The recommended Poisson's ratio values are tabulated below (table 6). The analysis is rather insensitive to variations in Poisson's ratio so precise values are not required.

d. The dynamic modulus of asphaltic concrete is temperature dependent and should be estimated at mean annual temperature. This mean depends on the layer thickness as well as on the mean annual air temperature; but, using mean annual air temperature will be adequate in most cases. Figure 10 may be used in the absence of test data or the methodology developed by Dempsey in reference 52 may be used. Additionally, the program RESMOD may be used to

Table 6
Recommended Poisson's ratio.

Material	Poisson's Ratio
Concrete	0.15
Asphaltic concrete	0.40
Granular base	0.37
Cement-treated base	0.20
Lime-stabilized soil	0.35
Subgrade	0.45

calculate the resilient moduli of asphalt, subbase and subgrade layers.[53] The RESMOD program results in moduli values that are more responsive to individual material properties. However, more detailed input information is required. Some of these values may not be routinely available.

e. The creep modulus for asphaltic concrete is both temperature and time of loading dependent. In the absence of laboratory test data (refer to the VESYS User Manual for test method and conditons), the following equation (from reference 54), which is applicable to standard dense graded asphaltic concrete, may be used:[55]

$$E = 10^{6}/[.25 + 5(10^{-7.91 + .113T}t)^{1/3}] \quad (9)$$

where:

E = creep modulus of AC, psi

t = loading time, seconds

T = temperature, degrees F

Alternatively, the procedure outlined by Heukelom and Klomp may be used to estimate the asphaltic concrete modulus at a particular temperature (To) from fundamental properties of the mix and bitumen.[56] The procedure is equally applicable to short and long loading times and covers a wide temperature range.

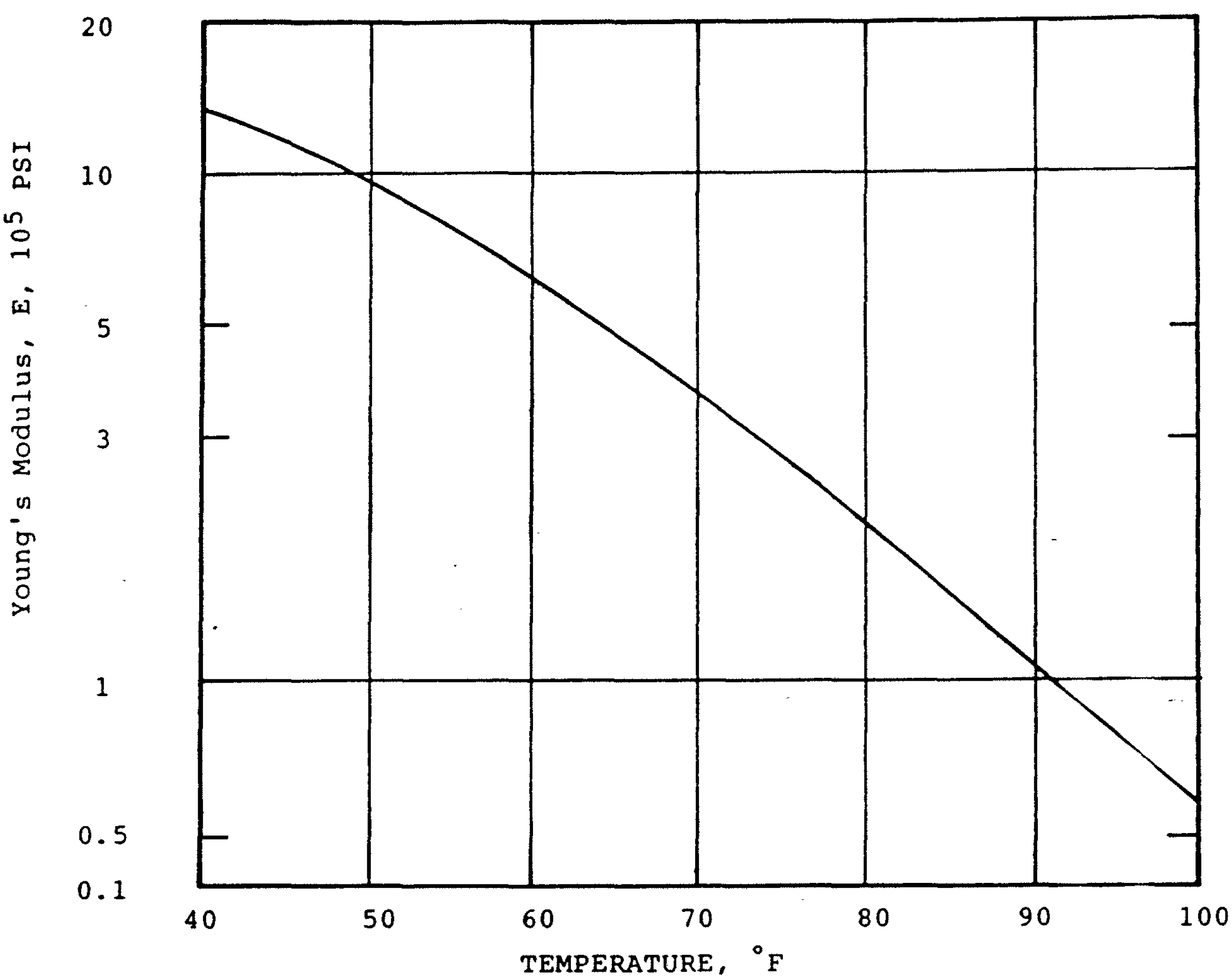


Figure 10. Assumed temperature dependence of Young's modulus of AC pavements and AC base materials.[57]

The following information is required:

A. Bitumen properties

1. Ring and Ball temperature (To') (ASTM D36)
2. Penetration (ASTM D5)
3. Temperature at penetration (Tpen)

B. Mix properties

1. Mix void coefficient (Cv) (Rice's method)

$$Cv = \frac{\text{volume of Minerals}}{\text{volume of (Minerals \& Bitumen)}} \qquad (10)$$

C. Design conditions

1. Loading time
2. Design temperature (To)

The AC modulus is determined using the following steps:

1. The penetration index is determined from figure 11 using the bitumen penetration value at Tpen and the difference between Ring and Ball temperature To' and Tpen, as shown by the example.

2. The stiffness modulus of the bitumen is determined from figure 12 for the desired loading time (frequency) and the design temperature To . Note that all temperatures are in degrees Celsius, and the stiffness modulus of bitumen is given in kg/sq. cm. The conversion factors are:

$$1 \text{ psi} = 14.223 \text{ kg/cm}$$

$$1 \text{ Pa} = 1.0197 \times 10^{-5} \text{ kg/cm}^2$$

$$C = 5 (F-32)/9$$

3. The stiffness modulus of the asphaltic concrete is determined from figure 13 using the stiffness modulus of the bitumen (in psi) and Cv for the mix. The AC modulus (in psi) may also be determined from:

$$Eac = 14.22 \text{ Ebit} \left(1 + \frac{3.012}{5.6-\log \text{Ebit}} \frac{Cv}{1-Cv} \right)^{.83(5.6 - \log \text{Ebit})} \qquad (11)$$

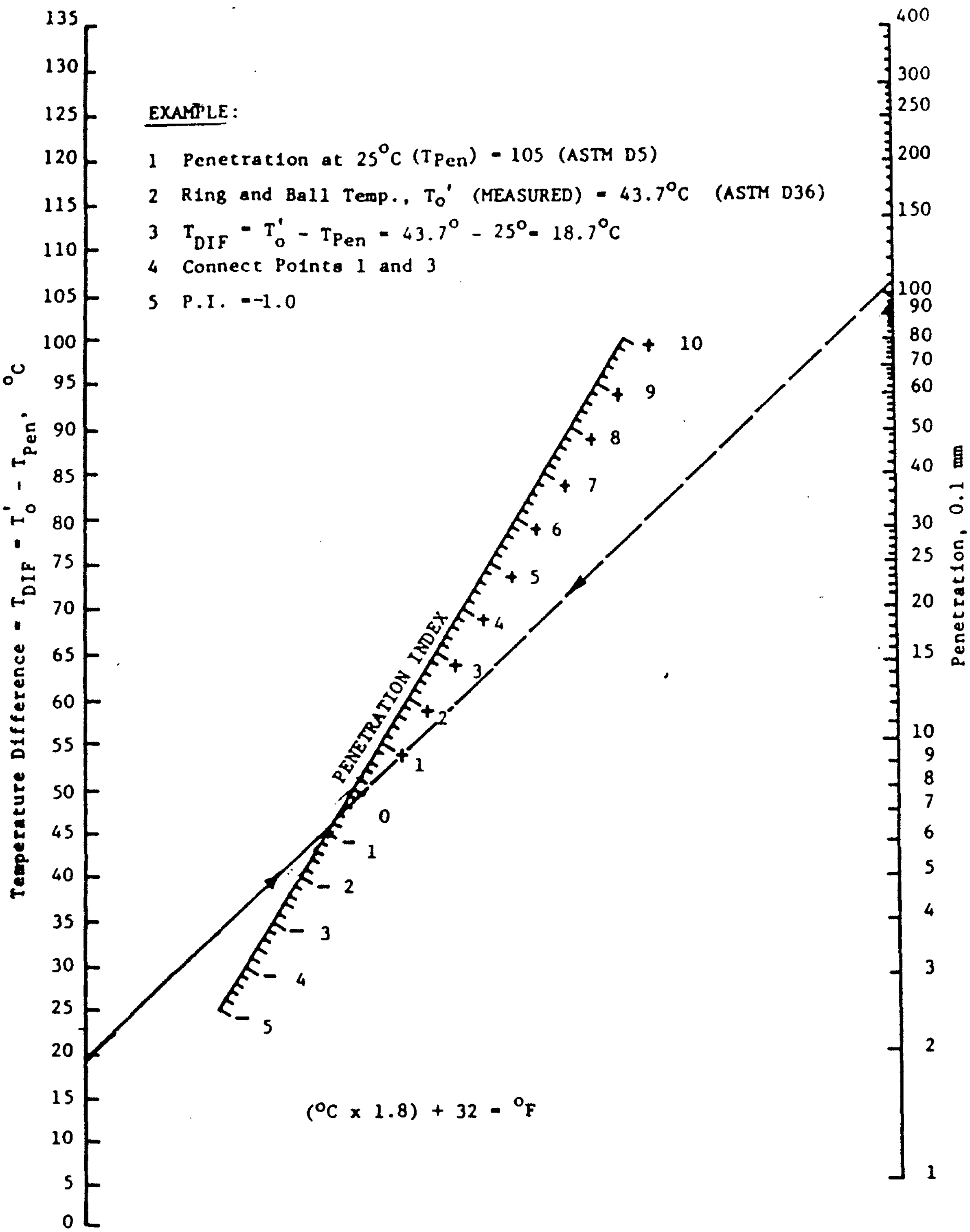
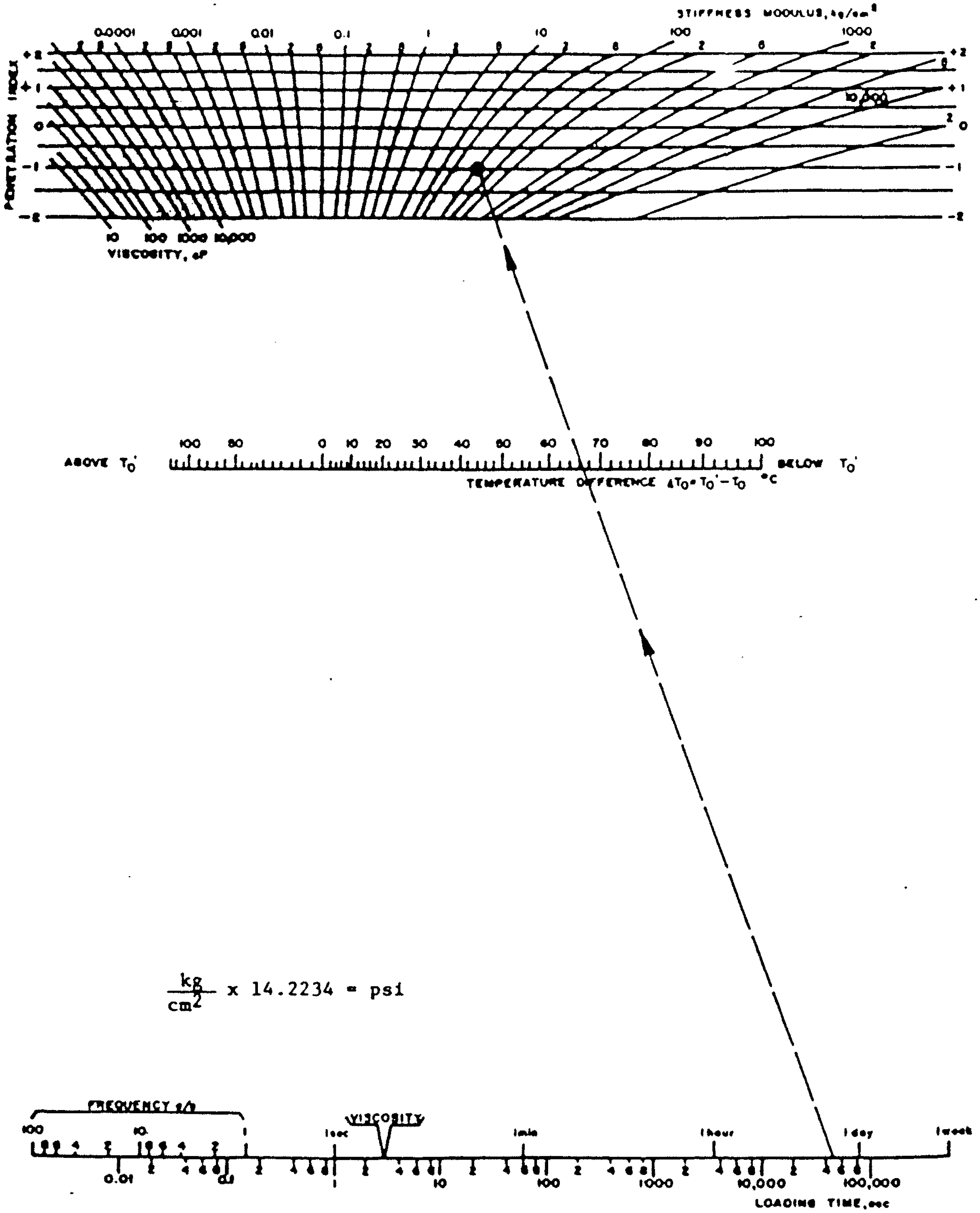


Figure 11. Nomograph for determining Pfeiffer and Van Doormaal's Penetration Index (ref. 56).



$\frac{kg}{cm^2} \times 14.2234 = psi$

Figure 12. Nomograph for predicting the stiffness modulus of asphaltic bitumens (after Heukelom and Klomp, ref. 56).

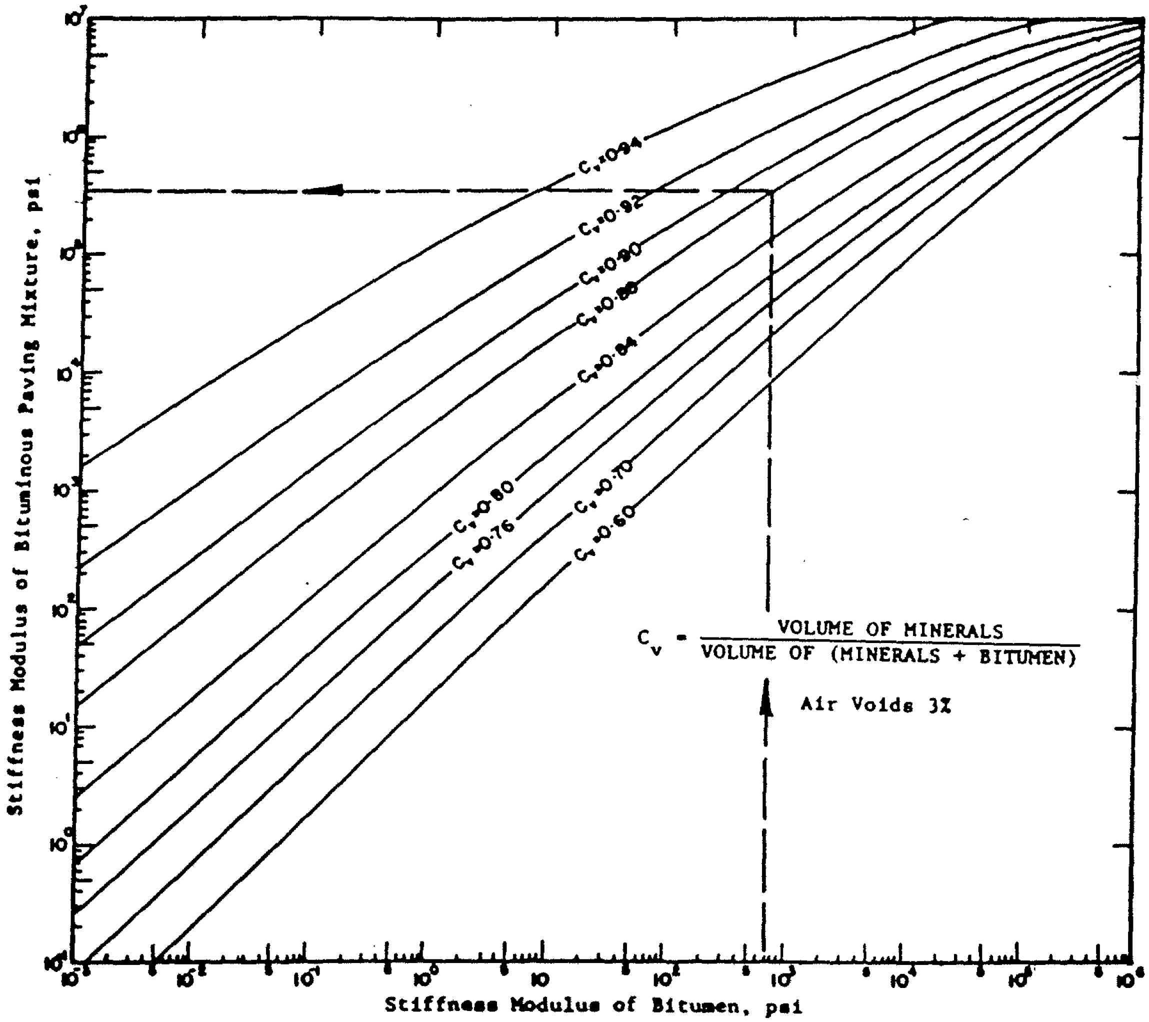


Figure 13. Relationships between moduli of stiffness of asphalt cements and of paving mixtures containing the same asphalt cements (ref. 56).

where:

E_{ac} = stiffness modulus of asphaltic concrete, psi

E_{bit} = stiffness modulus of bitumen (kg/cm^2)

C_v = volume concentration of minerals, equation 10

f. Subgrade modulus may be obtained from laboratory tests in triaxial compression, or may be estimated from AASHTO soil classification, soil support values, or modulus of subgrade reaction, using figure 14 to estimate the CBR value and equation 12 to compute the modulus.

$$E_s = 1500 \text{ CBR (in psi)}$$
$$E_s = 10.3 \text{ CBR (in MPa)} \qquad (12)$$

Where NDT deflection data is available or could be obtained, the subgrade modulus could also be back-calculated from these measurements using various procedures, such as those developed by Utah, ARE, or RII.[57,58,59]

g. Granular base/subbase moduli may be obtained from laboratory tests in triaxial compression, or may be estimated from equation 13.

$$E_{n-1} = 11.06\, E_n^{0.837} \text{ (in psi)} \qquad (13)$$

where:

E_n = modulus of the nth layer

E_{n-1} = modulus of the layer above it

This equation is a compromise between the Shell, COE and Kentucky models, and recognizes the fact that the degree of compaction of granular materials depends on the modulus of the underlying layer.[60,61,62] If both a subbase and a base layer is used, equation 13 should be applied twice, first to determine the subbase modulus from subgrade modulus, then the base modulus from subbase modulus.

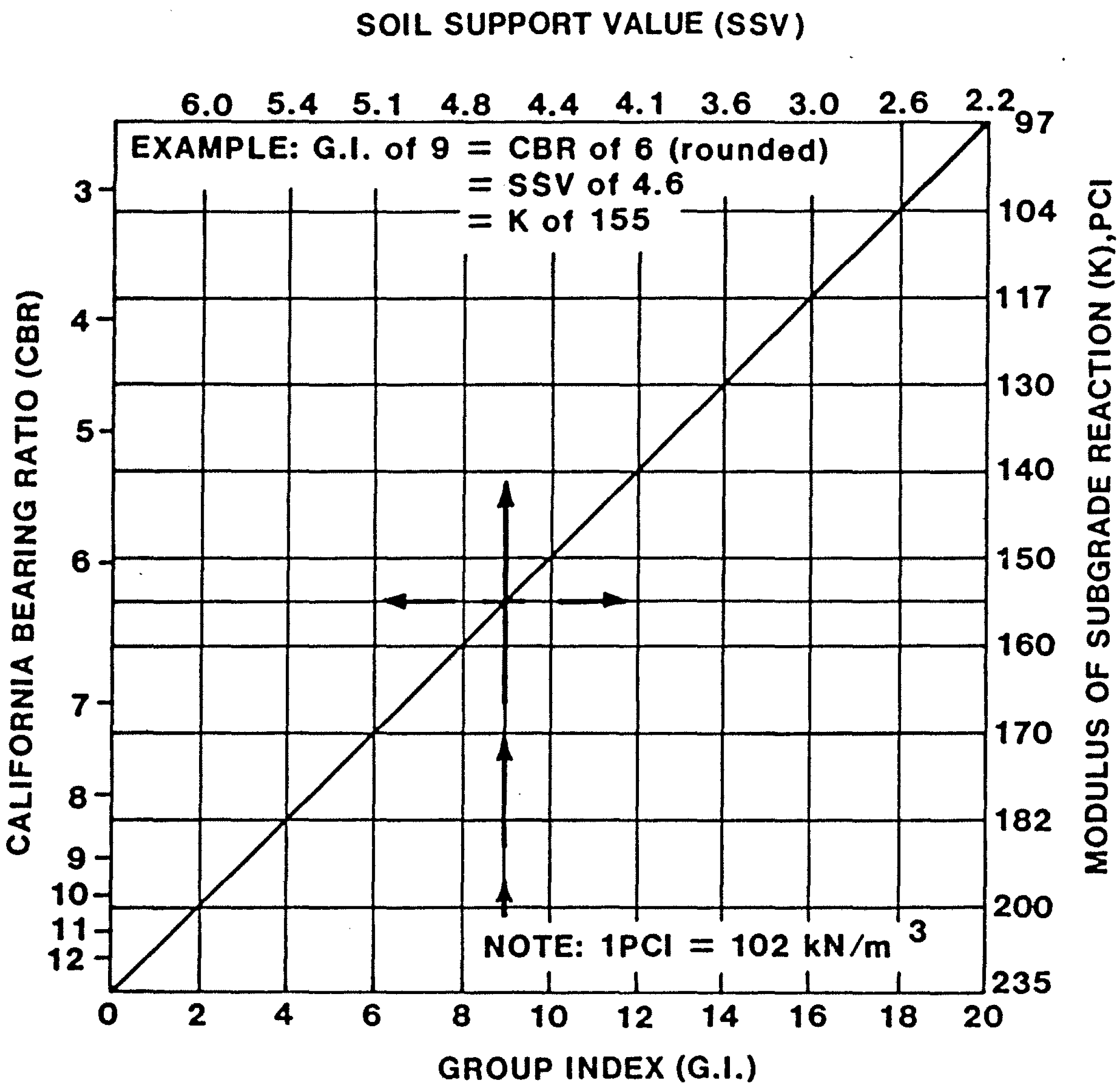


Figure 14. Relationships between soil properties and CBR.[38]

h. Unbound layer moduli are dependent on the moisture content in the material. There are various models to estimate the effect of moisture on layer moduli; the EAROMAR model is recommended.[63] This model assumes, as a conservative estimate, that the sublayer (base/subbase) modulus is reduced by 50 percent during the time required to drain 80 percent of the water from the saturated layer. The EAROMAR equations are:

$$twet = (season/iavg)[1-exp(-9C)]tdrain \quad (14)$$

$$C = (1/5280)([Lc + Ac)/Wlane]+[(SH \times Wwet)/2WlaneNlane]+(J \times Wwet) \quad (15)$$

$$Fred = (t season-0.5 twet)/tseason \quad (16)$$

where:

twet = duration of pavement wetness in days during which structural response is assumed to be affected;

season = seasonal rainfall in inches input by the user;

iavg = daily rainfall intensity, assumed to equal 0.5 in (12.7 mm);

c = fraction of pavement area having cracks or open (unsealed) joints;

tdrain* = time in days to drain the saturated pavement sublayers;

L,A,SH,J = quantities of damage components per lane mile computed by pavement simulation models within EAROMAR; L , SH, and J are the linear feet per lane mile of longitudinal cracks, lane-shoulder joints, and transverse joints; A is the area of alligator cracking in square feet per lane mile;

Wlane,Nlane= width of lane in feet and number of lanes in roadways, respectively, as input by user;

Wwet = width of subsurface zone wetted by open joint, assumed to be 6 ft (1.8 m);

Fred = reduction factor applied to moduli of granular pavement layers and to California bearing ratio (CBR) and moduli of subgrade;

tseason = length of season in days determined from season information input by user; and

tdrain* is evaluated from Casagrande-Shannon's drainage model to be approximately:[64]

$$tdrain = 2.5 \{\exp(-2S')\} nL^2/KH \quad (17)$$

where:

n = effective porosity of the base course,

L = the width of the base course,

K = the coefficient of permeability of the base course,

H = the thickness of the base course, assumed to be 1 foot, and

S' = an approximate slope factor, assuming a cross slope of 1/2 inch per foot (0.015 ft/ft) = 0.015L/H

Equation 14 applies a time-average correction to the pavement materials properties. Multiplication by 0.5 in equation 16 reflects the assumed loss in material strengths under wet conditions.

Equation 14 is composed of three factors: (1) the number of days in a season on which rainfall occurs, season/iavg; (2) the proportion of rainfall flowing into the base courses, 1-exp(-9c); and (3) the period of time over which the structural response is reduced to its 50 percent level (tdrain). These three factors are multiplied together in that equation and give the total amount of time (twet) when the base courses are at least 20 percent saturated. Briefly, the time in days, that a base course is in such a wet situation is equal to the number of wet days in a season multiplied by the time required to drain 80 percent of the water, where the proportion of infiltration is taken into consideration.

If equation 12 is used to characterize the subgrade modulus, the subgrade is assumed to be saturated, which is a conservative design. Proper drainage can improve subgrade support; the model described below may be used for this purpose.[65]

The subgrade modulus is calculated by:(66)

$$E_s = \frac{E_1 d_1^3 + E_2 d_2^3}{d^3} \tag{18}$$

where:

Es = calculated total subgrade modulus, psi,

d = depth of a subgrade = d1 + d2 < 70 in (1.78 m),

E1 = subgrade modulus under 100 percent saturated condition, which is evaluated from Thompson and Robnett equations, psi [67],

d1 = average depth of water penetrating into subgrade from the base course, in,

E2 = subgrade modulus under dry condition, psi, and

d2 = average depth of dry portion of the subgrade = 70-d1, in

3.5 Thickness Design

The thickness design of shoulders is influenced both by the type of mainline pavement and the condition of the longitudinal joint as well as the type of traffic using it; i.e., encroaching or parked vehicles. There are three primary combinations of mainline and shoulder pavement: PCC/PCC, PCC/AC and AC/AC. The longitudinal joint can be either tied and keyed or separate (tied only) for rigid shoulders adjacent to rigid mainline pavements; separate or monolithic for flexible shoulders adjacent to flexible mainline pavements; or separate for flexible shoulders adjacent to rigid mainline pavements. Thus the joint condition, rather than the type of mainline pavement, influences shoulder design.

The thickness of an asphalt or concrete shoulder is determined using critical stresses/strains and the appropriate distress functions. The required thickness is that value which reduces the developed stress/strain to the allowable value; alternately, the number of load repetitions, as determined from a distress function, is equal to or greater than the design repetitions. The distress function used with rigid shoulders is:

$$N = 22209\ (fc/\sigma)^{4.29} \tag{19}$$

where:

N = Number of equivalent 18 kip (80 kN) axle loads to failure

fc = concrete flexural strength, 28 days, psi

σ = critical stress developed in concrete, psi

This distress function is based on fatigue and has been derived, using the RISC program, from the AASHO Road Test data.[35,68]

This distress function is used with both inner and outer edge loading (due to encroached and parked traffic, respectively); however, the critical stresses are evaluated from different equations depending on edge condition, i.e., free or supported (tied or keyed).

The inner and outer edge designs differ for flexible shoulders. The inner edge sees moving traffic (dynamic loading), whereas the outer edge is subjected to creep (static) loading. For the inner edge, the distress function, developed from the AASHO Road Test flexible sections in reference (66), is used:

$$N = 4.2 \times 10^{-18} (1/\varepsilon)^{5.16} \tag{20}$$

where:

ε = critical tensile strain in the asphalt layer

N = as defined above

However, no comparable distress function for creep loading cases is available. Because the asphalt modulus is very low for parked vehicles (10,000 to 20,000 psi (69 to 138)), the critical strains are very high. If equation 20 were used, very thick shoulder sections would result. The Monismith curves, presented in Yoder and Witczak, appear promising since the allowable strain (for a given N) increases with decreasing asphalt modulus (E).[49] An equation was fitted to the Monismith curves:

$$\log N = \frac{2.176 - 0.7918 \log E - \log \varepsilon}{0.9075 - 0.1101 \log E} \tag{21}$$

where:

N = as defined previously

E = Modulus of asphalt concrete

ε = critical strain in AC

The use of this equation results in thicknesses that appear reasonable for the outer edge, at least for moving (encroaching traffic).

There is, however, a problem with using the horizontal tensile strains in the asphalt layer as the design criteria, particularly when the asphalt creep modulus is less than about three times that of the unstabilized base/subbase course. In these instances, the neutral axis is close to the asphalt/base interface so that increasing the asphalt layer thickness results in increased tensile strain, leading to the conclusion that thin pavements perform better than thicker pavements, which is debatable. Some engineers believe that flexible pavements should either be relatively thin (less than about 2 in (51 mm)) or greater than about 4 to 5 inches (102 to 127 mm) in order to overcome this problem.[69] Some caution should be used with flexible pavements in the 2 to 4 in (51 to 102 mm) range. Therefore, the rutting criterion developed by Dorman and Metcalf is used:[70]

$$N = 2.48 \times 10^{-10} (1/\varepsilon v)^{4.876} \qquad (22)$$

where εv is the vertical compressive strain on top of the subgrade. This value increases with decreasing pavement thickness for all values of pavement moduli. The design criterion is therefore the more critical of asphalt fatigue or subgrade rutting.

The critical stresses/strains can be determined using the RISC program; however, RISC is a very large finite element computer program requiring long execution times.[35] Therefore, RISC was used to run a large number of combinations of material properties and regression equations were developed relating these to critical stresses/strains. Initial single factorial screening runs were made to determine the relative importance of the independent variables; the regression results were obtained from partial factorial runs covering the expected range of all variables. The range as well as the number of levels of each variable used in developing the regression equations is shown in table 7. The variables used were pavement modulus (Ep) and thickness (Hp), base modulus (Eb) and thickness (Hb), subgrade modulus (Es), tie bar diameter (Db) and spacing (Sb), the condition of the shoulder - mainline interface; i.e., tied vs. tied - keyed joint for rigid shoulders and separate or monolithic for flexible shoulders, and load location (inner or outer edge). The tie bar diameter and spacing were excluded for the flexible shoulder case.

The variables that were included in the regression analyses are the pavement, base/subbase and subgrade modulus, base/subbase thickness (for flexible shoulders only) and condition of the

Table 7
Range of variables used in model development.

Variable	Low	High	No. of Levels
	Rigid Model		
Ep	3000000.	6000000.	4
Hp	4.	12.	5
Eb	10000.	40000.	4
Hb*	4.	12.	3
Es	3000.	30000.	7
Db*	4.	1.	3
Sb*	24.	48.	3
	Flexible Model, Encroaching Traffic		
Ep	150000.	1000000.	6
Hp	4.	12.	5
Eb	10000.	40000.	4
Hb	4.	12.	3
Es	3000.	30000.	7
	Flexible Model, Parked Traffic		
Ep	5000.	150000.	7
Hp	4.	12.	5
Eb	10000.	40000.	5
Hb	4.	12.	3
Es	3000.	30000.	7

*Did not enter regression model

mainline-shoulder interface; i.e., plain or tied vs. tied - keyed joint for rigid shoulders and separate or monolithic for flexible shoulders. Note that tie bar diameter is absent from these variables because the normal practice of using No. 5 or 6 bars, every 24 to 30 inches (610 to 762 mm) has a beneficial, but very small effect on critical stress for unkeyed shoulders, and the effect is totally insignificant in the case of keyed joint construction (the key is responsible for the reduction in stresses while the tie bars hold the joint tight). Therefore, in order to be conservative, and since the statistical significance of the bar diameter and spacing is negligible, the bar diameter and spacing have been excluded. Non-corroding tie bars should be used to assure satisfactory performance during the service life of the pavement.

The vertical compressive strain (εv), as a function of the pavement variables listed above, was determined using the ELSYM5 program and modified to take into consideration the edge loading effect.[71] The latter was determined from comparison of inner and edge load strains computed with the RISC program.[35] A regression equation was then fitted to the resulting strains.

The results of the regression analyses are presented in appendix C, in tables 23 through 29. Tables 23 and 24 are for rigid, tied-keyed and tied unkeyed shoulders, respectively, and 25 through 29 for flexible shoulders. The loading is assumed to be due to encroaching traffic in tables 23, 27 and 28, and due to parked vehicles in tables 24 through 26, and 29. The critical tensile stress/strain in the pavement layer (fatigue) is computed using tables 23 through 28; the rutting criterion is derived using table 29. The equations for the developed models are presented in equation 23 through 29, which correspond to the models in tables 23 through 29, respectively.

Stress in tied-keyed rigid shoulder due to encroaching traffic:

$$\begin{aligned} Sigma = {} & 2946.7/Hc - 14.987Log(Es) + 9.2109Log(Eb) + 688.75/(HcEs) \\ & - 686.93Log(Es)/Hc + 1074.35Log(Ec)/Hc - 111.58Log(Hc)/Es \\ & + 57.910Log(Es)/Ec + 27.5594Log(Eb)/Es \\ & - 2175.1Log(Hc)/Hc - 164.167Log(Eb) - .00304Hc^{3} \\ & - .18012EcHc + 4.1207Es/Hc + 4.1632Ec/Es + 74.264 \end{aligned} \tag{23}$$

Stress in rigid shoulder at the outer edge due to parked traffic:

$$\begin{aligned} Sigma = {} & 2931.1/Hc - 57.377Log(Eb) - 1255.6Log(Es)/Hc \\ & - 204.13Log(Hc)/Es + 668.55Log(Ec)/Es + 107.83Log(Ec) * \\ & * Log(Eb) + .01908HcEs - 7.9527Log(Es)Log(Eb) \\ & - .51792EcHc - .42611EcEs + 16.808Es/Hc \\ & + 88.522Ec/Hc - 36.483Ec/Es + 9.4409\ Hc/Ec - 114.71 \end{aligned} \tag{24}$$

Horizontal tensile strain in flexible monolithic shoulder at inner edge due to parked traffic:

$$\begin{aligned} Log(\ x) = {} & - 1.4539Ea - .08201Ha + .00142Eb - 1.1243/Ha \\ & + .52617Log(Ea) - 2.2729Log(Hc) - 1.1318Log(Es) \\ & - 1.4636Log(Ea)Log(Ha) + .32205Log(Ea)Log(Hb) \\ & + .21223Log(Ha)Log(Eb) + .55644Log(Ha)Log(Hb) \\ & + .50633Log(Ha)Log(Es) - .63976Log(Eb)Log(Hb) \\ & + .42811Log(Hb)Log(Es) - 1.1421/Eb - 1.4811Log(Ea)Hb \\ & + .32432Log(Ea)/Hb - 2.4971Log(Ha)/Eb + .13872EaHa \\ & - .00337Log(Es)/Ea + 1.0032Log(Es)/Eb + 5.4964 \end{aligned} \tag{25}$$

Horizontal tensile strain in flexible shoulder at outer edge due to parked traffic:

$$\begin{aligned} Log(\ x) = {} & - 1.7340Ea - .05872Ha + .00115Eb - .00664Hb \\ & - 2.1102/Ha + .76066Log(Ea) + .16674Log(Eb) \\ & - 1.1438Log(Es) - 1.5338Log(Ea)Log(Ha) + .18519 \\ & * Log(Ea)Log(Hb) + .60335Log(Ha)Log(Hb) + .52445 \\ & * Log(Ha)Log(Es) - .60249Log(Eb)Log(Hb) + .42310 \\ & * Log(Hb)Log(Es) - 1.4026Log(Ea)Hb + .59236Log(Ha)/Ha \\ & - 3.5699Log(Ha)/Eb + .17675EaHa - .00320Log(Es)/Ea \\ & + .93845Log(Es)/Eb - 2.7509Log(Ha) + 5.8218 \end{aligned} \tag{26}$$

Horizontal tensile strain in flexible monolithic shoulder at inner edge due to encroaching traffic due to encroaching traffic:

$$
\begin{aligned}
\mathrm{Log}(\ x) = &- .23838Ea - .03156Ha + .00391Eb - .00606Hb \\
&- .07166\mathrm{Log}(Hb) - 1.1878\mathrm{Log}(Ea)\mathrm{Log}(Ha) + .14954 \\
&* \mathrm{Log}(Ea)\mathrm{Log}(Hb) + .13579\mathrm{Log}(Ea)\mathrm{Log}(Es) + .32560 \\
&* \mathrm{Log}(Ha)\mathrm{Log}(Eb) + .50122\mathrm{Log}(Ha)\mathrm{Log}(Es) + .24668 \\
&* \mathrm{Log}(Ha)\mathrm{Log}(Es) - .37384\mathrm{Log}(Eb)\mathrm{Log}(Hb) - .38018 \\
&* \mathrm{Log}(Eb)\mathrm{Log}(Es) + .22583\mathrm{Log}(Hb)\mathrm{Log}(Es) + .18083 \\
&* \mathrm{Log}(Ea)/Ha + 19.280\mathrm{Log}(Ha)/Ha - .01072\mathrm{Log}(Eb)/Ea \\
&- .53323\mathrm{Log}(Eb)/Ha + .02993EaHa + .00009HaEs \\
&- 1.7378\mathrm{Log}(Es)/Eb + .02185
\end{aligned}
\tag{27}
$$

Horizontal tensile strain in flexible shoulder at outer edge due to encroaching traffic:

$$
\begin{aligned}
\mathrm{Log}(\ x) = &- .17742Ea - .00546Hb - .00149Es - 1.4105\mathrm{Log}(Ea) \\
&- .08302\mathrm{Log}(Eb) - .60364\mathrm{Log}(Es) + .33852\mathrm{Log}(Ea)\mathrm{Log}(Eb) \\
&+ .14081\mathrm{Log}(Ea)\mathrm{Log}(Hb) + .35677\mathrm{Log}(Ha)\mathrm{Log}(Eb) \\
&+ .48144\mathrm{Log}(Ha)\mathrm{Log}(Hb) + .25656\mathrm{Log}(Ha)\mathrm{Log}(Es) \\
&- .37382\mathrm{Log}(Eb)\mathrm{Log}(Hb) + .23116\mathrm{Log}(Hb)\mathrm{Log}(Es) \\
&+ .01227\mathrm{Log}(Ea)/Ea + 1.8157\mathrm{Log}(Ea)/Hb + 1.6396\mathrm{Log}(Ea)Hb \\
&+ .03118\mathrm{Log}(Hb)/Ea + 19.784\mathrm{Log}(Ha)/Ha - .33842\mathrm{Log}(Eb)/Ha \\
&+ .01010EaHa - .00959\mathrm{Log}(Es)/Ea - .13647
\end{aligned}
\tag{28}
$$

Vertical compressive strain on subgrade at outer edge due to parked vehicles:

$$
\begin{aligned}
\mathrm{Log}(\ z) = &- .03850Ha - .02989Hb - .00172Es - 1.5499\mathrm{Log}(Ha) \\
&- .64043\mathrm{Log}(Es) - .33594\mathrm{Log}(Ea)\mathrm{Log}(Ha) + .10001 \\
&* \mathrm{Log}(Ea)\mathrm{Log}(Eb) + .24065\mathrm{Log}(Ha)\mathrm{Log}(Eb) + .67717 \\
&* \mathrm{Log}(Ha)\mathrm{Log}(Hb) + .12234\mathrm{Log}(Ha)\mathrm{Log}(Es) - .26647 \\
&* \mathrm{Log}(Eb)\mathrm{Log}(Hb) - .16138\mathrm{Log}(Ea)/Ha - .73675\mathrm{Log}(Ea)/Hb \\
&- .00120\mathrm{Log}(Es)/Ea + 4.40328
\end{aligned}
\tag{29}
$$

where:

Ec = modulus of concrete, millions psi

Hc = concrete thickness, inches

Ea = modulus of asphaltic concrete, millions psi

Ha = AC thickness, inches

Eb = modulus of base/subbase, ksi

Hb = base/subbase thickness, inches

Es = subgrade modulus, ksi

As is seen from equations 23 through 29, the regression models are quite lengthy and are not suitable for evaluation manually. Therefore, a small computer program (BERM) has been written to evaluate these functions. This program is available in both a mainframe version for batch processing and a microcomputer version that has user-friendly interactive input-output. The program listings and input guide are presented in appendix D. The program also evaluates the expected life of each trial design (using equations 18 through 21 as appropriate), and computes the creep modulus for asphaltic concrete from equation 9 for parked vehicles if a creep modulus has not been input by the user.

In the event that rigid shoulders are not keyed or flexible shoulders are not constructed monolithically with the mainline pavement, the outer edge loading is used in stress/strain analysis. The asphalt layer properties need to be adjusted either in the program or as input by the user to reflect dynamic or static moduli corresponding to encroaching or parked vehicles, respectively. Thus, the stresses and strains are a function of the type of loading (encroached or parked vehicles) and the shoulder type, along with layer properties. The design program computes two shoulder thicknesses and the design life of each thickness due to the specified loading (see pages 115 and 117).

The inputs to this program are the variables used in the regression analysis (described above), plus the concrete flexural strength (fc) where applicable, and the output is the expected traffic (in terms of equivalent axle loads) the section will sustain as a function of section thickness.

In summary, the rigid shoulder thickness is determined from critical stress due to fatigue and the distress function presented in equation 19. The critical stress is determined either from equation 23 or equation 24, depending on whether the inner edge is tied-keyed, or is free (unkeyed and/or untied). Equation 23 is used only with encroaching traffic while equation 24 may be used with both encroaching and parked traffic, depending on the edge condition.

The thickness design for flexible shoulders is somewhat more complicated in that two failure criteria are used, and since the modulus of asphalt is dependent on the type of loading, the critical strains are not only dependent on the edge condition (free inner or outer edge vs. monolithic inner edge), but depend on the type of loading as well. Equation 27 is used together with the distress function given in equation 20 to determine the required thickness due to encroaching traffic for a monolithic flexible shoulder. Equations 20 and 28 are used for a non monolithic flexible shoulder due to encroaching traffic. Equations 21 and 26 are used to determine the thickness due to fatigue under parked vehicles at the outer edge (normal case) while equations 21 and 25 are used at the inner edge of a monolithic shoulder with parked traffic (rare). Additionally, equations 22 and 29 are used to determine the thickness under parked vehicles at the outer edge due to rutting criterion; this equation generally governs the outer edge design.

3.6 Sensitivity Anaylsis

The accuracy to which the input variables need to be determined depends on how sensitive the analysis model is to variations of the input variables.

Sensitivity analyses are typically conducted using the expected means and standard deviations of the input variables and determining the effect when these variables are at this mean +/- one standard deviation values. However, when variables have widely different coefficients of variation, this method tends to over-emphasize the effect of some variables and under-emphasize the effect of others. Therefore, the sensitivity analyses presented here have been done assuming that the extent of variation is the same for all variables; i.e., the sensitivity of a variable (in percent) is defined as:

$$100\ [N(1.2X)-N(0.8X)]/N(X) \qquad (30)$$

where N is the dependent variable (design life), and the X's are the independent variables. Table 8 gives the mean values of the variables used in this analysis and table 9 shows the effect of the independent variables on the design life developed using the above concept for rigid shoulders as well as for encroaching and parked traffic on non monolithic flexible shoulders. It should be pointed out that since the rigid shoulder in the above analysis is not tied and keyed to the mainline pavement, encroaching and parked vehicles produce the same stress since both loadings are on an unprotected edge and since concrete is assumed to be elastic rather than viscoelastic. Keying the rigid shoulder, or constructing the flexible shoulder monolithically with the mainline (flexible) pavement, increases the design life under encroaching traffic by 50 percent for rigid shoulder and by about 18 percent for flexible shoulders. The design life under parked traffic is unaffected.

It can be seen from table 9 that the ranking (relative importance) of variables depends on the type of model; i.e., whether rigid or flexible and encroaching or parked traffic. The pavement thickness (Hc) is the most important variable for the rigid and flexible encroaching models, whereas the flexible parking model is most sensitive to base thickness variations. The major reason for this is that the parking model considers the rutting distress, whereas the other two models are based on fatigue.

Another way to look at the effect of variables is to determine the change required in an independent variable in order to result in a specific change in the dependent variable. Here

Table 8
Mean values used in sensitivity analysis.

Variable	Flex Encroach	Flex Park	Rigid
Ec, 10^6 psi (GPa)	1.163(8.02)	0.02(.138)	4.2(2.90)
Hc, in (mm)	6.0(152.4)	6.0(152.4)	6.0(152.4)
Eb, ksi (MPa)	18.0(.124)	18.0(.124)	18.0(.124)
Hb, in (mm)	8.0(203.2)	NA	NA
Es, ksi (kPa)	7.5(51.7)	7.5(51.7)	7.5(51.7)
fc, psi (kPa)	NA	NA	690(4.76)
Nd, Thousand EAL	638	78	687

Table 9
% change in dependent variable (Nf) for a +/- 20% change in independent variables.

Variable	Flex Encroach	Flex Park	Rigid
Ec	226.1	25.9	-47.7
Hc	1046.	121.6	223.4
Eb	27.4	43.6	4.2
Hb	16.8	146.7	N A
Es	57.9	125.9	39.6
fc	NA	NA	180.3

NA - Not applicable

it is convenient to consider the shoulder thickness as the dependent variable, and to determine the variation required to produce a +/- 0.25 in (6.35 mm) change in thickness. Table 10 shows the percent change required in the independent variables to result in this change in shoulder thickness.

The analysis in table 10 shows that the rigid shoulder model is very sensitive to variations in flexural strength, (fc is not part of the stress model (equations 23 and 24) but enters through equation 19) is about equally sensitive to variations in concrete modulus, subgrade modulus, and design life (Nd), and is not at all sensitive to base modulus or thickness - the latter values never entered the regression models. This points out the fact that the function of a granular base under rigid pavements is to provide drainage and only marginally to improve support. It should, however, be kept in mind that poor quality subbases are subject to other problems such as pumping and consolidation, which drastically reduce pavement support and thus accelerate failure.

Table 10
% change in independent variables required to produce a +/-0.25 in change in shoulder thickness.

	Flex Encroach		Flex Park		Rigid Variable	
	-1/4 in	1/4 in	-1/4 in	1/4 in	-1/4 in	1/4 in
Ec	6.2	-6.2	18.7	-18.9	-16.4	31.8
Eb	60.0	-36.3	11.7	-10.6	>200*	<-100*
Hb	66.0	-76.2	3.5	-3.4	NA	NA
Es	23.7	-19.9	4.0	-3.9	22.0	-20.0
Nd	-27.2	36.5	12.8	-11.5	23.4	-19.2
fc	NA	NA	NA	NA	4.9	-4.9

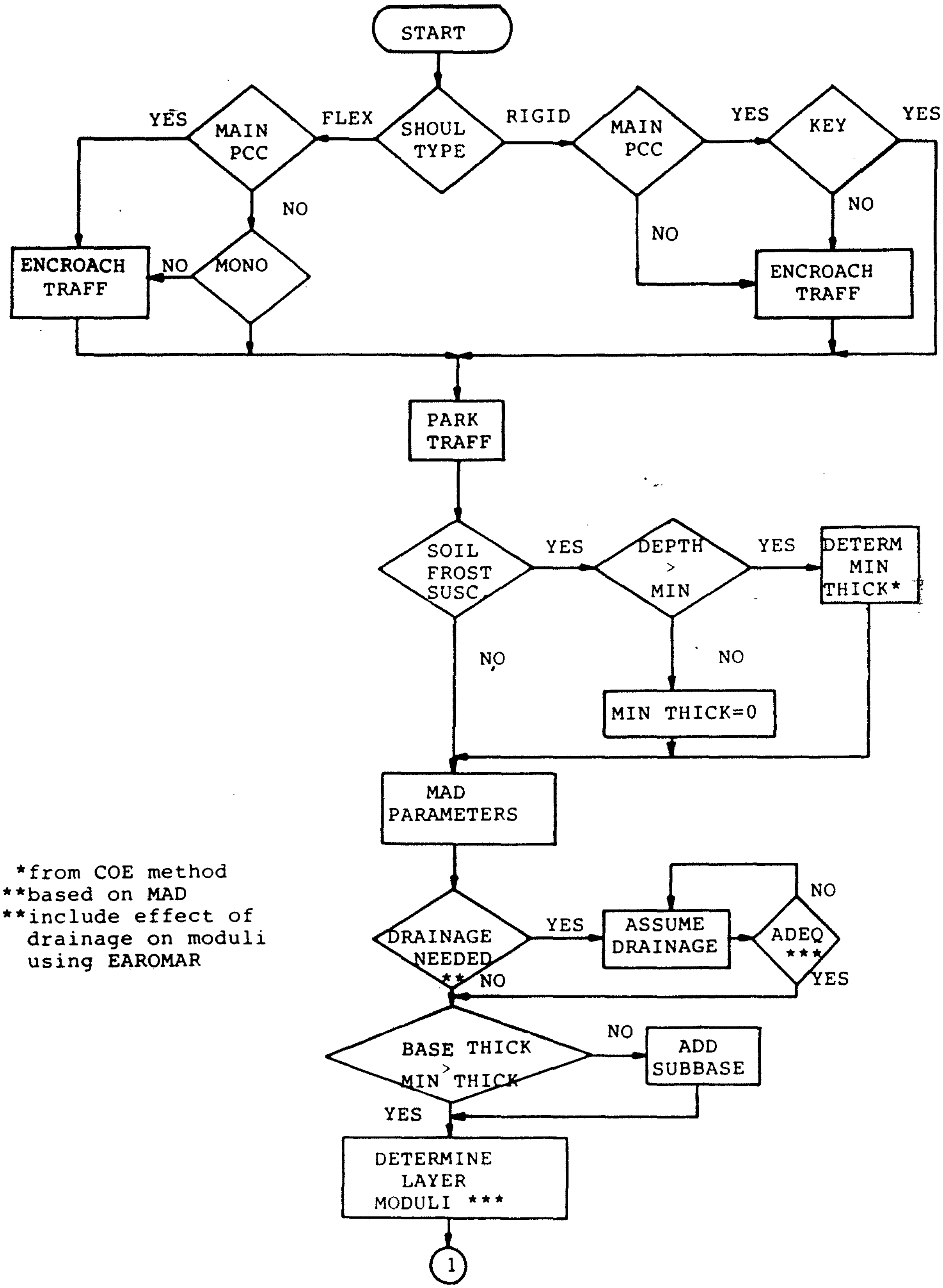
NA - Not applicable
* - Outside applicable range; estimated

For flexible shoulders under encroaching traffic, the shoulder thickness is most sensitive to variations in asphalt concrete modulus (Ec), and only slightly sensitive to variations in granular base properties. However, the thickness design due to rutting criteria of flexible shoulders under parked traffic is most sensitive to base and subgrade properties, and fairly sensitive to the variations in design traffic (Nd).

3.7 Use of Design

The basic design approach is presented in the flow chart in figure 15. It will be noted from this figure that the primary difference in designing rigid and flexible shoulders is the type of traffic analysis required. There is, of course, a fundamental difference in how the predicted life (Nf) of a particular shoulder section is determined. However, this analysis is done in the program BERM. It should be pointed out that it is assumed in the design presented in figure 15 that the shoulder will not be used by regular traffic during peak periods and during maintenance operations. If this usage is anticipated, then parking will be severely curtailed and the outer edge design for flexible shoulders will be somewhat different. This difference will be discussed later.

The first step in shoulder design is to select the shoulder type compatible with the mainline pavement. Although all combinations of pavement/shoulder type can be analyzed with this method, only the following combinations are recommended for use.



*from COE method
**based on MAD
***include effect of drainage on moduli using EAROMAR

Figure 15. Steps required for shoulder design.

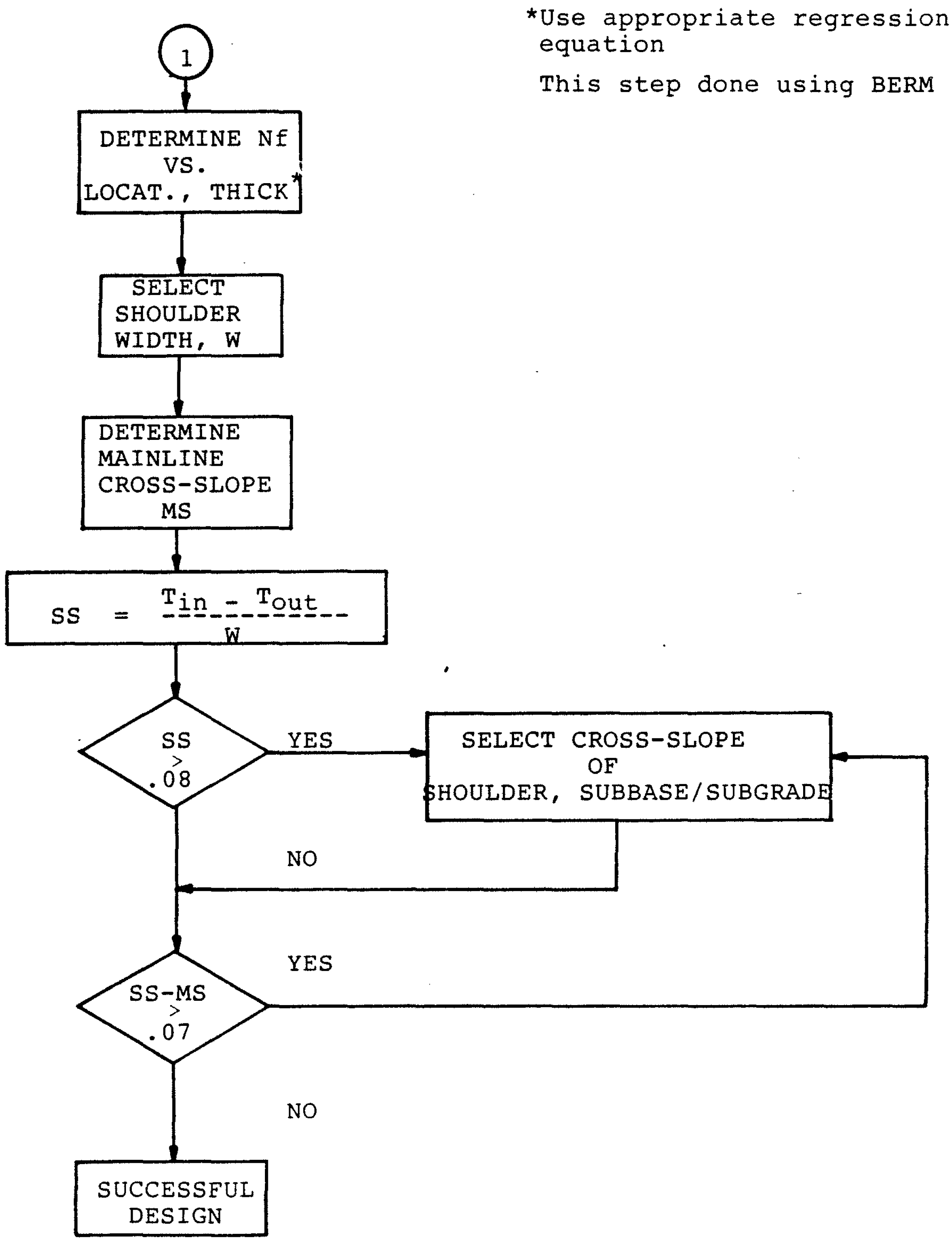


Figure 15 (continued). Steps required for shoulder design.

Pavement	Shoulder
New Rigid	- tied, keyed rigid
New Flexible	- flexible, monolithic
Old Rigid	- tied rigid
Old Flexible	- flexible
Rigid (widened lane)	- flexible

In the above cases, it is recommended that the inner edge of the shoulder be identical in construction with the outer edge of the mainline pavement. This approach reduces differential deflection due to load or differential frost heave where swelling clays and/or frost-susceptible materials are present. It is further recommended that if tied and keyed shoulders are used, the inner edge of the shoulder is the same thickness as the outer edge of the mainline pavement.

The inner edge thickness of the shoulder is determined based on encroaching traffic and the outer edge thickness from parked traffic. If the shoulder is to be used by regular traffic during peak periods, the extent of this traffic needs to be determined. The encroaching traffic has to be increased by this amount and the parked traffic replaced by this value.

Once the shoulder type has been selected, the following steps are required for shoulder design:

1. Traffic Analysis
2. Soil frost susceptibility
3. Drainage needs
4. Layer moduli
5. Stress/strain-life analysis
6. Cross-Slope analysis

The stress/strain-life analysis is done in BERM; the remainder of the steps are performed by the designer.

Only traffic analysis depends on the shoulder-pavement combination; the rest of the steps are the same regardless of the shoulder or the mainline pavement type - only the material properties differ. Of course, the stress/strain-life calculations are functions of shoulder type and longitudinal joint condition, but as mentioned before, these calculations are done internally in the BERM program.

The type of traffic analysis depends on both the shoulder type and the condition of the longitudinal joint. It will be noted that parked traffic analysis will be needed independent of the shoulder/mainline combinations and longitudinal joint conditions while encroaching traffic analysis is needed for some combinations and not needed for other cases. Criteria for determining the need for encroaching traffic analysis is as follows:

Flexible Shoulders

A flexible shoulder may be adjacent to both rigid and flexible mainline pavements. If the mainline pavement is rigid, then the shoulder is necessarily separate from the mainline pavement and encroaching traffic analysis is needed. This traffic will be needed for the determination of the shoulder inner edge thickness. However, if the inner edge of the shoulder is the same thickness as the outer edge of the mainline pavement (as recommended), then encroaching traffic analysis is not needed since the shoulder section will be more than adequate under normal use. If the shoulder is to be used by regular traffic during peak periods and during maintenance operations, then a careful traffic analysis is needed.

If the mainline pavement is flexible, the shoulder may be monolithic (new construction), or separate (shoulder added on). If the shoulder is monolithic with the mainline pavement, then the inner edge of the shoulder is the same thickness as the outer edge of the mainline pavement, and encroaching traffic analysis is not needed, even if the shoulder will be used by regular traffic during peak periods. However, it is necessary to estimate the extent of traffic during peak periods in order to determine the shoulder outer edge thickness.

In the event that the shoulder is monolithic but the inner edge of the shoulder is not the same thickness as the outer edge of the mainline pavement (not recommended), then encroaching traffic analysis is necessary. If the flexible shoulder is not monolithic with the mainline pavement but its inner edge thickness is the same as that of the mainline pavement, encroaching traffic analysis is again not needed for inner edge design but will be needed for outer edge design if the shoulder will be used by regular traffic during peak periods. If, however, the shoulder inner edge thickness is less than that of the mainline pavement, encroaching traffic analysis is necessary.

In the event that the widened lane concept is used (along with rumble strips), when the mainline pavement is widened by 1 to 3 ft (0.3 to 0.9 m) and a flexible shoulder built with reduced thickness, encroaching traffic analysis is again not needed for inner edge design since the widened edge of the mainline pavement will carry the majority of the encroaching traffic. However, some care should be exercised if the shoulder is to be used by regular traffic during peak periods and if it is wide enough that this traffic is expected to run wholly on the shoulder. And, as stated before, the extent of the regular traffic is needed for the outer edge design.

Rigid Shoulders

Encroaching traffic analysis is needed for rigid shoulders if these are not tied and keyed (to the rigid mainline pavement) or if the mainline pavement is flexible (rare). However, if the inner edge of the shoulder has the same thickness as the outer edge of the mainline pavement (recommended by the design method) encroaching traffic analysis will not be needed since the shoulder section will be more than adequate for the expected encroaching traffic, even if the shoulder is to be used by regular traffic during peak periods. The possible exception occurs when the flexible mainline pavement is less than about 8 inches (203 mm) thick and the shoulder is to be used by regular traffic during peak periods; a design check should be made in this case. If the shoulder is to be used by regular traffic during peak periods, this traffic should be used in the design of the outer edge thickness in place of parked traffic since parking on the shoulder will be severly curtailed under these circumstances.

The traffic analysis method described by Sawan, et al. in "Structural Analysis and Design of PCC Shoulders" is recommended.[37] This is discussed in section 3.1. However, the designer may use any method for estimating traffic usage. It should be pointed out that parked traffic should be added to encroaching traffic since a vehicle cannot park on the shoulder without first encroaching. The design method requires that traffic be converted to equivalent 18 kip (80 kN) axle loads. The EAL calculations from truck data are not included in the program since there are significant variations in the methods used by different agencies.

The next step in the design procedure is to evaluate the soil type and its susceptibility to frost damage. If the soil is susceptible to frost damage and the depth of frost penetration is greater than the minimum recommended shoulder thickness, 6 in (152 mm) for rigid shoulders and 3 in (76 mm) for flexible shoulders), then the total thickness (min thick) of subbase and/or base material above the frost-susceptible subgrade is determined using the Corps of Engineers' procedure.[19] The COE recommends that at least the bottom 4 inches (102 mm) of the granular base should consist of a well-graded sand subbase filter layer. This layer is not intended to serve as a drainage layer, but rather as an intermediate layer that prevents the intrusion of subgrade into the base layer. It should be emphasized that it is desirable to construct the inner edge of the shoulder to the same thickness (of non frost-susceptible materials) as the outer edge of the mainline pavement in order to minimize the possibility of differential frost heave.

Next, the environmental conditions are evaluated using the Moisture Accelerated Distress (MAD) System.[17] If the MAD Index indicates that drainage is needed, a drainage layer is assumed and its adequacy checked using the drainage evaluation criteria in the MAD System. If the drainage is inadequate, a different design is tried. Otherwise, the drainage layer thickness is checked to see if it equals or exceeds the minimum required for protection against frost damage (min thick). In the event that the drainage blanket is thinner than required for frost protection, a subbase is added (or its thickness increased) to bring this thickness to the value required (min thick). It should be noted here that the MAD System is also used to determine the need for underdrains.

Probably the most difficult step is the determination of layer moduli required for stress/strain calculations. The discussion in section 3.4 provides reasonable guidelines for determining the required input parameters. The designer should also take advantage of any available Non-Destructive Testing(NDT) data to determine support layer moduli. Sensitivity analyses presented in section 3.6 should be of help in deciding on the accuracies required.

The next step is to evaluate the expected life of a trial design section, in terms of equivalent 18 kip (80 kN) axle loads. The BERM program is used for this purpose. It may be possible that the thickness derived from this analysis is less than the minimum 6 in (152 mm) for rigid shoulders or 3 in (76 mm) for flexible shoulders; in that case, the minimum thickness should be constructed since experience has shown that under the combined effect of climate and traffic, the minimum thicknesses are required for satisfactory performance. In general, unless the shoulder is to be used by regular traffic during peak periods, or if the subgrade is very weak (6,000 psi (41 MPa)), the design is governed by the minimum thicknesses.

The effect of drainage on base/subbase/subgrade properties is investigated using the models developed in Economic Analysis of Roadway Occupancy for Maintenance And Rehabilitation (EAROMAR).[63]

While much of this design could be computerized, most of the steps in the design are left to the design engineer so that he can exercise various options in the design at his will.

The final steps in the shoulder design are to check compliance with geometric restraints. Specifically, the cross-slopes are checked to see if they meet current AASHTO criteria. The design engineer has options of sloping the subgrade as well as the shoulder, and placing underdrains near the pavement-shoulder joint or further out toward the shoulder outer edge. While it is preferred to place underdrains near the pavement-shoulder joint, particularly if flexible shoulders are used with rigid pavements, the requirements of cross-slope may dictate other locations.

In summary, if the shoulder is <u>not</u> to be used by regular traffic during peak periods and during maintenance operations, the following steps are required for normal flexible shoulder design:

1. Determine the shoulder-pavement joint condition.

   a. Shoulder is separate - MONO = 0.

   b. Shoulder is Monolithic - MONO = 1.

2. Decide if the inner edge of the shoulder will be the same thickness as the outer edge of the mainline pavement.

3. Determine the expected member of parked vehicles over the design period - the method by Sawan, et al. is recommended.[37]

4. Determine if encroaching traffic analysis is needed using the procedure described in the beginning of this section.

5. If encroaching traffic analysis is needed, determine the expected number of encroaching vehicles over the design period - the procedure by Sawan, et al. is recommended.[37] Add to this the number of parked vehicles from step 3 since a vehicle cannot park without first encroaching.

6. Convert the traffic values obtained in steps 4 and 5 to equivalent 18 kip (80 kN) axle loads. The method described in section 3.1 may be used, or the designer may use any other method.

7. Evaluate the soil frost susceptibility and determine the minimum thickness of stable (non frost-susceptible) material required under the pavement (min thick), using the COE procedure described in section 3.2.[19] Note that it is recommended in the COE procedure that the bottom 4 in (102 mm) of the drainage layer be constructed as a subbase filter layer to prevent the intrusion of subgrade into the base layer. While this practice is not strictly necessary for shoulder design, the use of a filter layer should be considered whenever minimum thickness exceeds about 8 in (203 mm).

8. Use the MAD procedure, described in appendix A, to evaluate drainage needs.[17] Chose a thickness of drainage layer consistent with the requirements from step 7 and evaluate its adequacy.

9. Develop the material properties required for input to the BERM program; section 3.4 should be consulted. Values for the following variables are needed:

a. Subgrade Modulus.

b. Base Thickness - from results of steps 7 and 8.

c. Base Modulus.

d. Design Temperature (mean annual temperature).

e. Asphalt Dynamic and Creep Moduli (at design temperature) - to be computed from default creep modulus equation or user supplied dynamic and creep moduli for asphaltic concrete shoulder at design temperature. If user supplied, the loading times are 0.02 and 10800 seconds for dynamic and static moduli, respectively.

f. Shoulder Thickness - if the inner edge thickness of the shoulder is to be the same as that of the outer edge of the mainline pavement and the analysis in step 4 shows that encroaching traffic is not needed, only the outer edge of the shoulder needs to be evaluated for its ability to resist parked vehicles. In this case 3 in (76 mm) is a reasonable starting point. Otherwise, 6 in (152 mm) might be tried for encroaching (inner edge) analysis and 3 in (76 mm) for parked (outer edge) analysis.

10. If an adequate drainage layer cannot be constructed, estimate the effect of inadequate drainage on base/subbase modulus using the EAROMAR models described in section 3.4.[63]

11. Run the BERM program according to instructions presented in appendix D. Note that the output of this program presents the expected lives (in terms of 18 kip (80 kN) equivalent axle loads) for two thicknesses in order to aid the user in interpolating the required thickness or extrapolating a new thickness for the next run of the program. Some caution should be exercised in the event that the thicker pavement results in a lower predicted life than the thinner pavement. This condition may arise when computing the expected life due to encroaching traffic. Some pavement engineers believe that flexible pavements should be relatively thin (less than about 2 in (51 mm)) or greater than about 4 to 5 in (102 to 127 mm) in order to overcome this problem. The designer is urged to use his experience and judgment in deciding this issue. It should, however, be noted that the minimum flexible shoulder thickness recommended in this procedure is 3 in (76 mm).

12. Compare the predicted lives obtained from step 11 to the design traffic values obtained in step 6 to decide if new runs are necessary or if the desired thickness can

be interpolated from previous results. The relationship between thickness and the logarithm of the expected life is approximately linear so that semi-log plots may be used for this purpose.

13. Select shoulder width, W.

14. Determine mainline cross-slope, MS.

15. Determine shoulder cross-slope SS. SS is equal to the difference in inner and outer edge thicknesses (in inches) divided by the shoulder width (in inches).

16. Check if the shoulder cross-slope is greater than 8 percent (the maximum recommended by AASHTO). If SS exceeds the allowable value, the shoulder outer edge thickness may be increased or the slope of the subgrade or base under the shoulder may be decreased. If the subgrade cross-slope is to be changed, the adequacy of the drainage layer may need to be reevaluated using step 8.

17. Check the difference in the cross-slopes of the shoulder and the mainline pavement. The algebraic difference may not exceed 7 percent according to current AASHTO standards. If this value is exceeded, the shoulder outer edge thickness may be inncreased or the base or subgrade slope under the shoulder may be decreased. In the latter case the adequacy of the drainage layer may need to be reevaluated using step 8.

If the shoulder is to be used by regular traffic during peak periods and during maintenance operations, the design is somewhat different. The following is required:

1. Same as step 1 of the normal (flexible shoulder design) procedure.

2. Same as step 2 of the normal procedure.

3. Estimate the amount of traffic that will use the shoulder during peak periods and during maintenance operations over the design period. This value replaces the regular parked traffic. Note that this is moving rather than stationary traffic.

4-8. Same as steps 4 through 8 of the normal procedure.

9. Develop material properties required for input to the BERM program; section 3.4 should be consulted. Values for the following variables are needed:

a. Subgrade Modulus.

b. Base Thickness - from results of steps 7 and 8.

c. Base Modulus.

d. Design Temperature (mean annual temperature).

e. Asphalt Dynamic Modulus (at design temperature) - to be computed from default creep modulus equation or user supplied. If user supplied, the loading time is 0.02 seconds for dynamic loading.

f. Same as step 9 of the normal procedure.

10. Same as step 10 of the normal procedure.

11. Same as step 11 of the normal procedure except that the analysis due to parked vehicles should be conducted as if this traffic were encroaching traffic on a separate shoulder. This is necessary because the "parked" traffic is moving rather than stationary.

12-17. Same as steps 12 through 17 of the normal procedure.

The design of rigid shoulders is somewhat simpler since portland cement concrete is assumed to be an elastic material so that its response is the same under both moving and parked vehicles. Therefore, if the rigid shoulder is to be used by traffic during peak periods, this traffic is merely added to the encroaching (inner edge) traffic and replaces the parked traffic. The following steps are required:

1. Determine the shoulder-pavement joint condition.

   a. Shoulder is separate or tied, MONO = 0.

   b. Shoulder is tied and keyed, MONO = 1.

2. Decide if the inner edge of the shoulder will be the same thickness as the outer edge of the mainline pavement. This is recommended except if a rigid shoulder is to be added to a flexible mainline pavement.

3. Determine the expected number of parked vehicles over the design period (using the Sawan method) or estimate the amount of traffic if the shoulder is to be used by regular traffic during peak periods and maintenance operations.[37] In the latter case parked vehicle analysis is not needed since parking will be curtailed, and the number of parked vehicles will be small compared to number using the shoulder during peak periods.

4. Determine if encroaching traffic analysis is needed using the procedure described above.

5. If encroaching traffic analysis is needed, determine the expected number of encroaching vehicles over the design period - the procedure by Sawan, et al. is recommended.[37] Add to this the number of parked vehicles from step 3. Note that if the shoulder is to be used by regular traffic during peak periods, this value is already included in step 3.

6-8. Same as steps 6 through 8 of the normal flexible shoulder design procedure.

9. Develop the material properties required for input to the BERM program; section 3.4 should be consulted. Values for the following variables are needed:

   a. Subgrade Modulus.

   b. Base Modulus.

   c. Concrete Modulus.

   d. Concrete Flexural Strength. Note that concrete modulus and flexural strength are not independent but are related to each other.

   e. Shoulder Thickness - if the inner edge thickness of the shoulder is to be the same as that of the outer edge of the mainline pavement and the analysis in step 4 shows that encroaching traffic is not needed, only the outer edge of the shoulder needs to be evaluated for its ability to resist parked vehicles. The minimum recommended shoulder thickness (6 in (152 mm)) is a reasonable starting point for all investigations.

10. Same as step 10 of the normal flexible shoulder design.

11. Run the BERM program according to instructions presented in appendix D. Note that the output of this program presents the expected lives (in terms of equivalent 18 kip (80 kN) axle loads) for two thicknesses in order to aid the user in interpolating the required thickness or extrapolating a new thickness for the next run of the program.

12-17. Same as steps 12 through 17 of the regular flexible shoulder design procedure.

3.8 Joint Design

The major concepts to be used for the design of the longitudinal joint between the shoulder and the mainline pavement were discussed in section 2.5. It was stated that because of the problems in maintaining a tight and sealed joint, asphalt shoulders should not be used with rigid pavements, and vice versa. On this basis only rigid shoulders should be used with rigid mainline pavement and flexible shoulders with flexible pavements. It is recommended that rigid shoulders adjacent to rigid mainline pavement be tied and keyed for new construction and tied butt joint design for added shoulders. In either case, the tie bars keep the joint tight so that joint sealer is not needed. It is recommended that the tie bars be non-corroding. The weakened plan concept used between lanes has also been used in cases where the shoulder is cast in the same pass as the traffic lane; it is recommended that these joints also be tied, but the tie bar diameter can be reduced or spacing increased over that used for mainline slab joints.[43] The weakened plane can be formed either by insertion of a plastic sheet or by sawing. If sawing is used, a hot-poured sealant is used to fill the groove.[43]

Flexible shoulders may either be added to existing flexible pavements, or built at the same time (new construction). In the former case, it is probably not possible to prevent a longitudinal crack at the interface, but this crack can be held to minimum dimensions, particularly if the inner edge of the shoulder is of the same design as the outer edge of the traffic lane. If a crack does form, it is recommended in reference 12 that no action be taken if the crack is less than 1/8 in (3 mm) in width; however, if it is wider, it should be filled with a sealant (hot or poured emulsion). For wide cracks (1/4 in) (6 mm) in width), a crack sealing program is recommended where the crack is first routed and then sealed with a suitable sealer.

Although this practice is not recommended, it is recognized that flexible shoulders will continue to be used with rigid mainline pavements. In this case the longitudinal joint should be sawed and sealed with an appropriate sealer. Several sealers, along with a joint preparation technique are described in section 2.5 and reference 12 lists additional methods and sealers. Another research study (DTFH61-85-C-00050) is underway to develop improved methods for shoulder joint sealing.[73] It is important to note that each sealer requires slightly different joint reservoir preparation; manufacturers instructions should be strictly followed.

As was discussed in chapter II, the flexible-rigid shoulder combination is prone to many temperature, environment, and load associated problems. While the problems (particularly those due to load and temperature) cannot entirely be eliminated, use of the design concepts discussed in this report can minimize these to a certain extent, especially if adequate structural strength, drainage, and frost protection are provided.

3.9 Other Design Concepts

Some States have recently used the widened lane concept for rigid pavements in an attempt to minimize load-associated problems with the longitudinal joint. The idea is to widen the traffic lane by 1 to 3 ft (.3 to .9 m) with striping and rumble strips to discourage traffic encroachment of this area; the rest of the shoulder is then built with a reduced section.[33] There is not enough experience with this concept to have reliable performance evaluations, but the idea deserves consideration. Of course, temperature effects will still be present, and those due to differential vertical temperature will be magnified somewhat because of increased slab width. Another approach that attempts to minimize differential deflection across the longitudinal joint is to extend the stabilized base (under the mainline pavement) out into the shoulder by 1 to 2 ft (.3 to .6 m) and build a thickened shoulder over this extended area only; the rest of the shoulder pavement is of reduced cross-section. Other approaches to minimizing traffic encroachment of the shoulder are to use rumble strips at the inner edge of the shoulder, singly or in conjunction with color (material) change between mainline and shoulder pavement. Performance data for these methods is scarce and cost-effectiveness data is not available.

3.10 Maintenance and Rehabilitation Strategies

The degree of maintenance required is very dependent on the structural design, type of drainage, and the type of shoulder-mainline combination. Currently, a majority of existing shoulders are structurally underdesigned and show severe distresses in the form of joint separation (both transverse and vertical), cracking and rutting.[23,37] The degree of severity of these distresses, as well as the condition of the mainline pavement, dictate the maintenance strategy to be used; i.e., patching and crack/joint resealing, reconstruction, and/or overlay.

The amount of maintenance required for properly designed shoulders is primarily limited to maintaining the shoulder-pavement longitudinal joint. If proper joint sealers are used, joints will not require resealing for approximately five to six years. Where resealing becomes necessary, the application of either liquid or catalytically blown asphalt over the original sealant has been found to be economical.[5]

When a shoulder is in need of rehabilitation, overlays may be considered. The overlay design of shoulders differs only slightly from the overlay design of mainline pavements. In most cases, the overlay design of the mainline pavement governs the choice of thickness. In the event that a shoulder requires a significantly thicker overlay than does the mainline pavement, shoulder recycling or reconstruction should be considered.

Numerous methods are available for overlay design including the recently published NCHRP synthesis on asphalt overlay design procedures.[74-77] The AASHTO Interim Guide has been revised and will be available shortly.[74] The methods recommended in that revision should be consulted before selecting an overlay design method.

3.11 Reflection Cracking

When cracked existing pavements are overlayed with flexible overlays, the cracks tend to reflect through the overlay. This is particularly true of overlays of shoulders which are usually relatively thin (1 to 2 in (25 to 51 mm)). A number of treatments to eliminate or minimize reflection cracking have been tried, both in the laboratory and in field installations, but none have been entirely successful. Some of the treatments that have been tried with asphalt overlays include the use of geotextiles, stress-absorbing membrane interlayers (SAMI), dust, sand, or gravel bond-breaker interlayers, open-graded asphalt "Arkansas" interlayers, thick overlays, and welded fabric reinforcement.[76,78-81] Another approach, used with overlays over rigid pavements, is the crack and seat method where the existing pavement is cracked into approximately 1 foot (.3 m) square pieces and seated using a heavy roller prior to placement of the overlay.[82]

The effectiveness of these treatments has been variable and inconsistent. The recent NEEP 10 study showed that fabrics delayed the formation of reflection cracking somewhat but did not prevent the formation of reflection cracking.[83] The final summary report on the NEEP 10 project is somewhat more encouraging in its assessment of various treatments to control or retard reflection cracking; however, experience indicates that the performance of the various methods is quite variable. While some treatments have retarded the rate of crack reflection in some studies, no benefit was seen in others. The overall conclusion is that the methods are probably not cost effective.[84] The same conclusion was also reached in a laboratory research study which evaluated the effectiveness of various treatments over both flexible and rigid pavements.[85] It was found in that study that fabrics are only very slightly effective in delaying cracking over flexible pavements, and somewhat more effective over rigid pavements. The use of rubber SAMI layer has been found to be fairly effective, particularly in Arizona, but has found mixed success in other trials.[76,78] Probably the most effective approach is to use the "Arkansas" open-graded interlayer over the existing pavement and under a conventional asphalt overlay.[80,85] The difficulty with the "Arkansas" method is that a minimum of 3 in (76 mm) of this layer is needed under a 2 to 3 in (51 to 76 mm) conventional overlay, making it somewhat expensive for use on shoulders, as well as creating vertical alignment problems, especially with guardrails.

Another method is the "band-aid" approach which has been applied fairly successfully over the longitudinal joint between the shoulder and the mainline pavement. In this approach a 12 to 24 in (304 to 610 mm) wide mastic-impregnated strip is applied over the crack, either with or without tack coating, depending on manufacturer's specifications, prior to the placement of the overlay.[75,86] Although this method does not prevent the formation of reflection cracking, the cracks that form are tighter, and the mastic-impregnated strip acts as a moisture sealer, preventing surface water from penetrating into the base/subgrade below; it also prevents fines from being pumped out from under the pavement. Cost-effectiveness data for this, or the other methods discussed above, are lacking.

The phenomenon of reflection cracking is relatively complex and theories to predict crack formation are still under development. A number of theories have been developed for the analysis of reflection cracking.[80,85,87,88,89] Most of these theories are based on mechanistic principles but use empirically derived distress functions for cracking prediction. Two recently developed theories show more promise than the rest for crack analysis and prediction. These are the reflection cracking model developed by Seeds, et al. for analysis and overlay design using the "Arkansas" open-graded interlayer, and the RII model for conventional and fabric-reinforced systems.[80,85] The RII model uses fundamental asphaltic concrete properties and visco-elastic theory to predict the formation of thermally-induced cracks in an unreinforced system, but utilizes an empirically derived effectiveness factor to predict cracking in reinforced systems. The load associated fatigue cracking is based on laboratory-derived fatigue distress functions for the various treatments.

The Arkansas design can be done both by using a computer program or with design charts and some simplifying assumptions, whereas the RII method requires the use of computer programs. Since the user instructions for the methods are relatively lengthy, the reader is referred to the user manuals, references 80 and 85.

In summary, both laboratory and field studies have shown that reflection cracking probably cannot be prevented, especially in overlays of rigid pavements. Some success has been achieved using the "band-aid" approach over the longitudinal joint between rigid mainline pavements and flexible shoulders. Even if a crack is formed, this method waterproofs the crack; thus, eliminating the major problems with cracks. However, cost-effectiveness data are still lacking for these methods.

CHAPTER IV
DESIGN GUIDE WITH EXAMPLES

4.1 Shoulder Type Selection

The first step in shoulder design is to select the shoulder type compatible with the mainline pavement. The pavement-shoulder combinations are shown in table 11.

Table 11
Pavement-shoulder combinations.

Pavement	Shoulder
Rigid (new construction)	tied, keyed rigid tied, rigid flexible
Rigid (existing pavement)	tied rigid flexible
Rigid (widened lane)	flexible
Flexible (new construction	flexible monolithic
Flexible (existing pavement)	flexible

It should be noted that not all of the above cases are recommended, however. It is strongly recommended that rigid shoulders be used with rigid pavements and flexible shoulders with flexible pavements. It is also recommended that if a tied and keyed shoulder is used, the inner edge of the shoulder should be the same thickness as the outer edge of the mainline pavement. Furthermore, the inner edge of the shoulder should preferably be identical in construction with the outer edge of the mainline pavement to reduce differential deflection due to load, swelling clays or frost penetration.

4.2 Traffic Analysis

4.2.1 Parked Traffic

The outer edge of the shoulder is designed to withstand parked traffic. Parked traffic analysis is needed in all cases of shoulder design.

Parked traffic is defined as the percentage of mainline truck traffic that parks on the shoulder or otherwise uses the outside edge of the shoulder.

Design Input

The percent parked trucks, PPT, is estimated by one of the following methods:

a) Use default value of 0.05 to 0.1 percent of mainline lane truck traffic

b) Estimate PPT from

$$PPT = \frac{N \times P \times 100}{ADT \times T \times DD} \quad (31)$$

and

$$P = \frac{1}{DL/PL} \quad (32)$$

where:

ADT = Average Daily Traffic

T = Percent trucks

DD = Directional distribution

DL = A length of project (in miles) that is representative of the design section

PL = The mean length (in miles) that a truck drives on the shoulder during a typical stop is determined from actual observations

P = The probability of a truck to park on each subsection

N = The number of parked trucks per day in the design section

Refer to pages 18 and 19 for more detailed description of this procedure.

DESIGN EXAMPLE

Given:

ADT = 8000 vehicles per day

T = 15 percent truck traffic

DL = 1 mile

From a field survey it is found that the number of trucks that park in the design section (N) is 3 trucks. It is also found that the mean length that a truck drives on the shoulder during a typical stop (PL) is 0.1 miles. From equation 32, P = 0.1, and from equation 31,

$$PTT = \frac{3 \times .1 \times 100}{8000 \times .15 \times .5} = 0.05 \text{ percent}$$

4.2.2 Encroaching Traffic

The inner edge of the shoulder is designed to withstand encroaching traffic. The need for encroaching traffic analysis is shown in table 12.

Encroaching traffic is defined as that part of the mainline traffic that encroaches the shoulder and then merges back to the mainline; it, however, also includes the parked traffic since a vehicle cannot park without first encroaching the shoulder.

Design Input

The percent encroached traffic, PET, is estimated by one of the following methods:

a) Use default values of 1 to 8 percent of the adjacent mainline lane truck traffic

b) Estimate PET from

$$PET = \frac{NE \times ED}{LS} \qquad (33)$$

where:

PET = Proportion of encroaching trucks on the shoulder, percent/100

LS = Length of the survey stretch in miles

NE = Average number of encroachments per truck in the surveyed stretch, miles

ED = Average encroachment distance per truck

Refer to pages 16 through 18 for more detailed description of this procedure.

Table 12
Design matrix for encroaching traffic need.

Shoulder Type	Mainline Type	Joint Condition	Thickness Ti < Tp	Encroaching Traffic Needed
Flexible	Flexible	Monolithic	No	No
Flexible	Flexible	Monolithic	Yes	Yes
Flexible	Flexible	Separate	No	No
Flexible	Rigid	Separate	No	No*
Flexible (Wm)	Rigid	Separate	No	No*
Flexible (Wm)	Rigid	Separate	Yes	Yes
Rigid	Rigid	tied, keyed	No	No
Rigid	Rigid	tied, keyed	Yes	Yes
Rigid	Rigid	tied/separate	No	No
Rigid	Rigid	tied/separate	Yes	Yes
Rigid	Flexible	Separate	No	No**
Rigid	Flexible	Separate	Yes	Yes

Ti = Thickness of shoulder inner edge
Tp = Thickness of pavement outer edge
* = Check design against encroaching traffic for design temperatures in excess of 70 degrees F (21 degrees C) if shoulder is to be used by regular traffic
** = Check design against encroaching traffic if shoulder is to be used by regular traffic and Tp < 8 in (203 mm).

DESIGN EXAMPLE

From a field survey it is found that a truck averages 2 encroachments (NE) over a mile survey stretch (LS), and that the average encroachment distance per truck (ED) = 0.02 miles, then

$$PET = 2 \times 0.02/1 = .04 \text{ or } 4 \text{ percent}$$

4.2.3. Regular Traffic

If it is anticipated that the shoulder will be used by regular traffic during peak periods and during maintenance operations, the amount of this traffic should be estimated. This amount depends on the length of time the shoulder is to be open to regular traffic (e.g., hours per day), the peak hour ADT, as well as the number of lanes. The ultimate case is to treat the shoulder as an extra lane by considering its traffic to be similar to the mainline outer lane truck traffic.

4.2.4. Traffic During Maintenance Operation

It should be noted that if the shoulder will be used by regular traffic during maintenance operations only, this traffic may be neglected since it represents a small portion of the parked or encroaching traffic.

4.2.5 Equivalent Axle Loads

Any rational method presently practiced by the States may be used to convert mixed traffic data to equivalent 18 kip (80 kN) axle loads. However, the method presented in table 13 could be used. Table 13 also illustrates the use of the method.

4.3 Soil Support Analysis

4.3.1 Frost Susceptibility

The AASHTO classification and table 14 are used to determine if the soil is frost-susceptible. If the soil is not susceptible to frost damage, the rest of this procedure is not necessary.

DESIGN EXAMPLE

Given a soil with AASHTO classification A-6, a group index of 10, and plasticity index of 13. This is a silt and clay soil. From table 14, this soil falls into frost group F3. Therefore, frost protection is necessary.

Table 13
Conversion to E-18's.

Vehicle Type	No. of Vehicles		Directional Factor		Conversion Factor	E-18's
RIGID PAVEMENT						
B	200	x	1/2	x	1.412	141
C	400	x	1/2	x	0.403	81
						--
						222
FLEXIBLE PAVEMENT						
B	200	x	1/2	x	1.068	107
C	400	x	1/2	x	0.311	62
						--
						169

* Type B trucks are multiple unit trucks with 2 or more axles
Type C trucks are two-axle six-tire or 3 or more axle single unit trucks
F is a factor that converts truck traffic to equivalent 18 kip (80 kN) axle loads

Table 14
Frost-susceptible soils.[19]

Group	Description
F1	Gravelly soils containing between 3 and 20 percent finer than 0.02 mm by weight
F2	Sands containing between 3 and 15 percent finer than 0.02 mm by weight
F3	(a) Gravelly soils containing more than 20 percent finer than 0.02 mm by weight, and sands, except fine silty sands, containing more than 15 percent finer than 0.02 mm by weight. (b) Clays with plasticity indices of more than 12, except (c) varved clays existing with uniform conditions.
F4	(a) All silts including sandy silts. (b) Fine silty sands containing more than 15 percent finer than 0.02 mm by weight, (c) Lean clays with plasticity indices of less than 12. (d) Varved clays with nonuniform subgrade.

4.3.2 Determination of Frost Depth

The frost depth can be estimated using one of the following methods:

a) Select a default value from figure 16

b) Estimate depth of frost penetration from steps 1 through 4 below.

1. Select the freezing index for the coldest year in a 10-year period or an average freezing index for the three coldest years in a 30-year period.

2. Select dry unit weight and expected moisture content of proposed base material.

3. Select appropriate curve in figure 17 corresponding to the dry unit weight and moisture content.

4. Determine the depth of frost penetration by entering figure 17 with the air freezing index (degree F days) and reading the depth corresponding to the appropriate curve.

DESIGN EXAMPLE

1. The freezing index for Delaware County, Ohio is 210 degree days.

2. Base unit weight is 135 pcf and base water content, after drainage, is 7 percent.

3. The appropriate curve corresponds to $\gamma d = 135$, moisture content of 7.

4. From figure 17, the depth of frost penetration is 22 in (559 mm).

4.3.3 Base Thickness Calculations

1. Determine $n = \dfrac{\text{water content of subgrade}}{\text{water content of base}}$

2. If $n > 3$ use $n = 3$

3. Determine base thickness for zero frost penetration, c

   c = depth of frost penetration from step 4 of section 4.3.2 minus the pavement thickness.

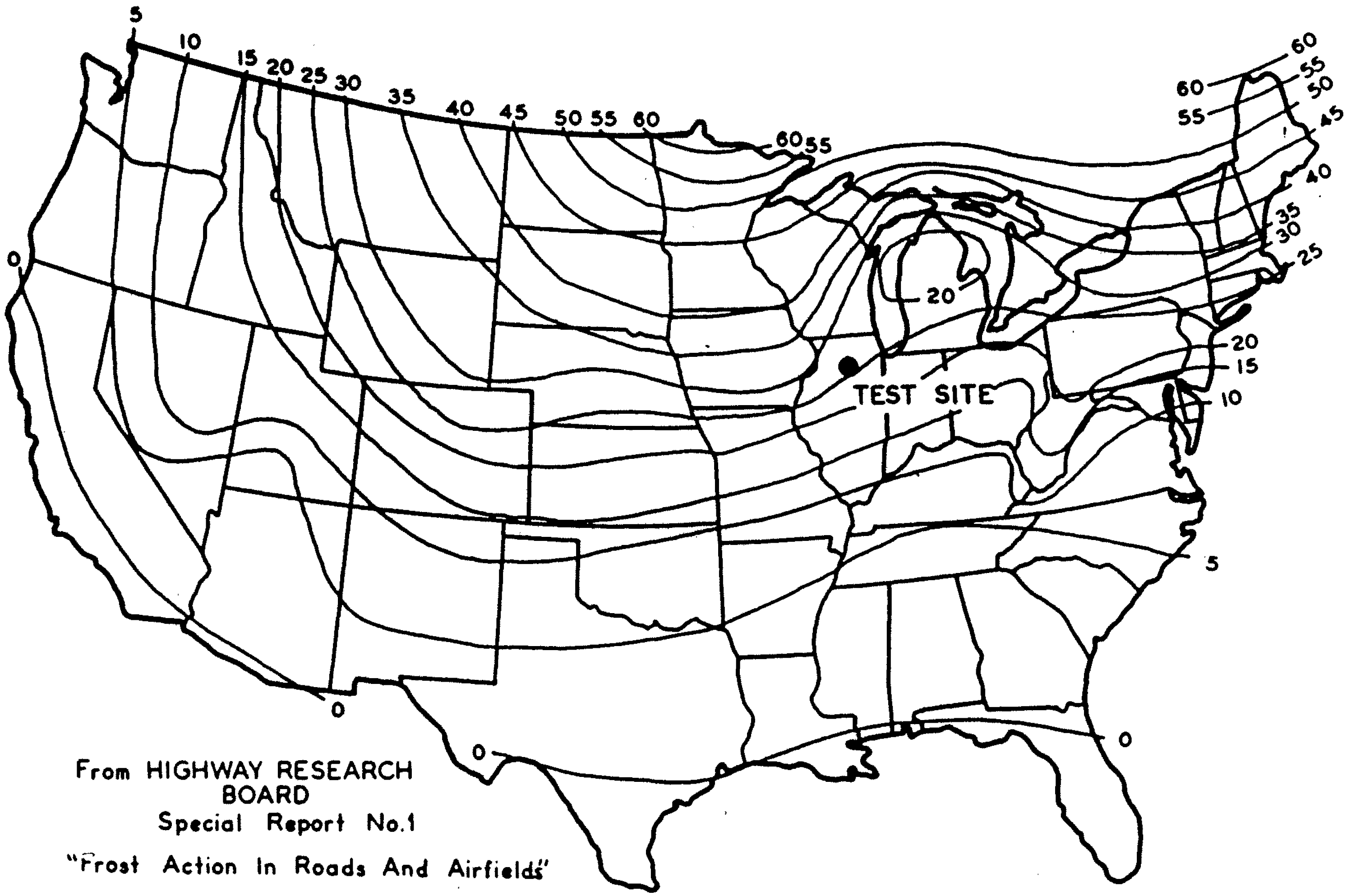


Figure 16. Average annual frost penetration, in inches.

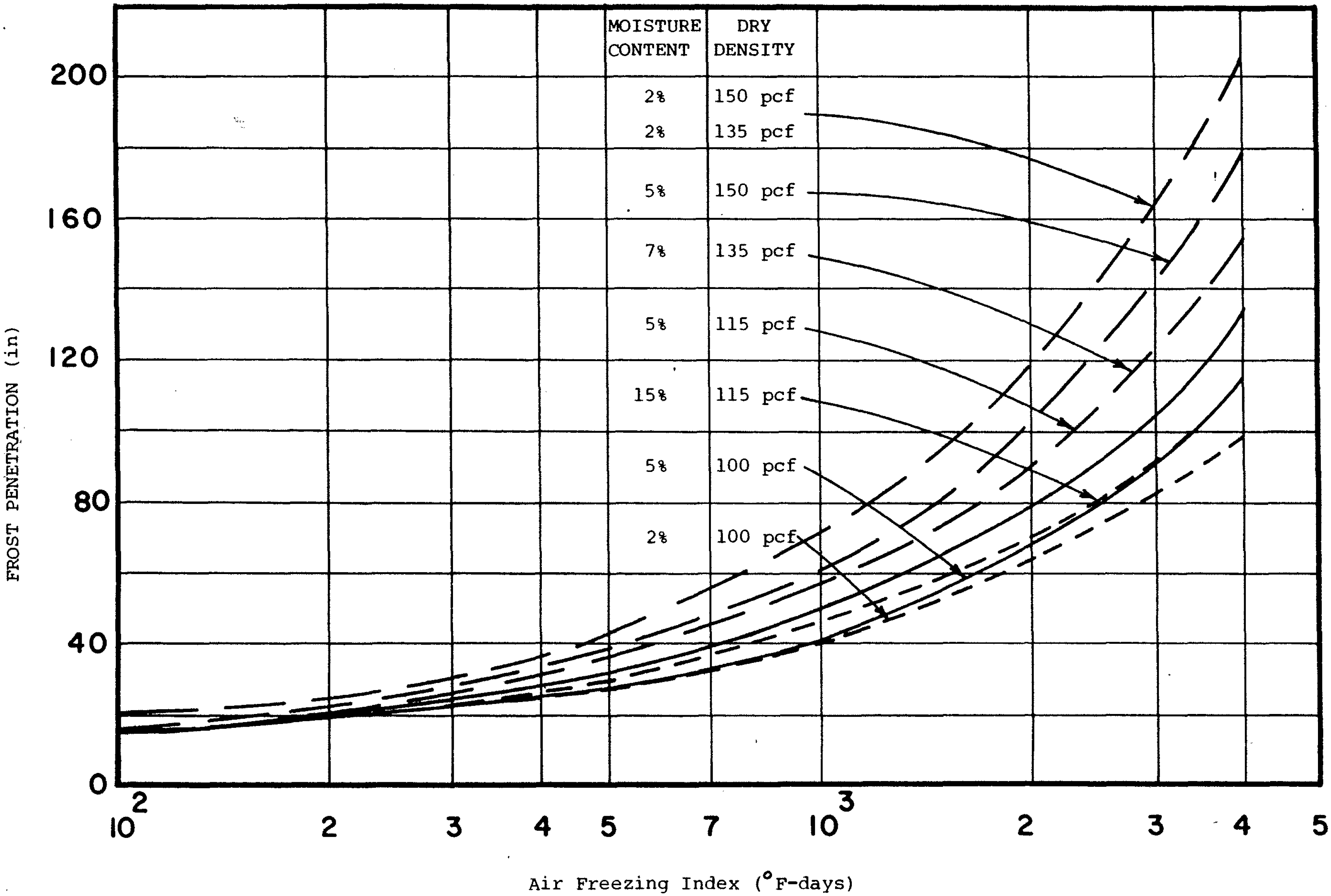


Figure 17. Frost penetration beneath pavements. [19]

4. Select the appropriate curve in figure 18 corresponding to the value of n determined above.

5. Determine the design base thickness by entering figure 18 with the value for c along the abscissa and reading the design base thickness from the ordinate.

DESIGN EXAMPLE

1. The material water content of the subgrade is 24 percent, and the drained water content of the base is 7 percent, therefore

$$n = 24/7 = 3.4$$

2. Use $n = 3$

3. Assume pavement thickness is 6 in (152 mm). Depth of frost penetration from step 4 of section 4.3.2 is 22 in (559 mm); then $c = 22-6 = 16$ in (406 mm)

4. The appropriate curve corresponds to $n = 3$

5. From figure 18, the design base thickness is 9 in (229 mm)

4.4 Drainage Design

4.4.1 Need for a Drainage System

The need for a drainage system and its adequacy is evaluated using the MAD (Moisture Accelerated Distress) system.[39]

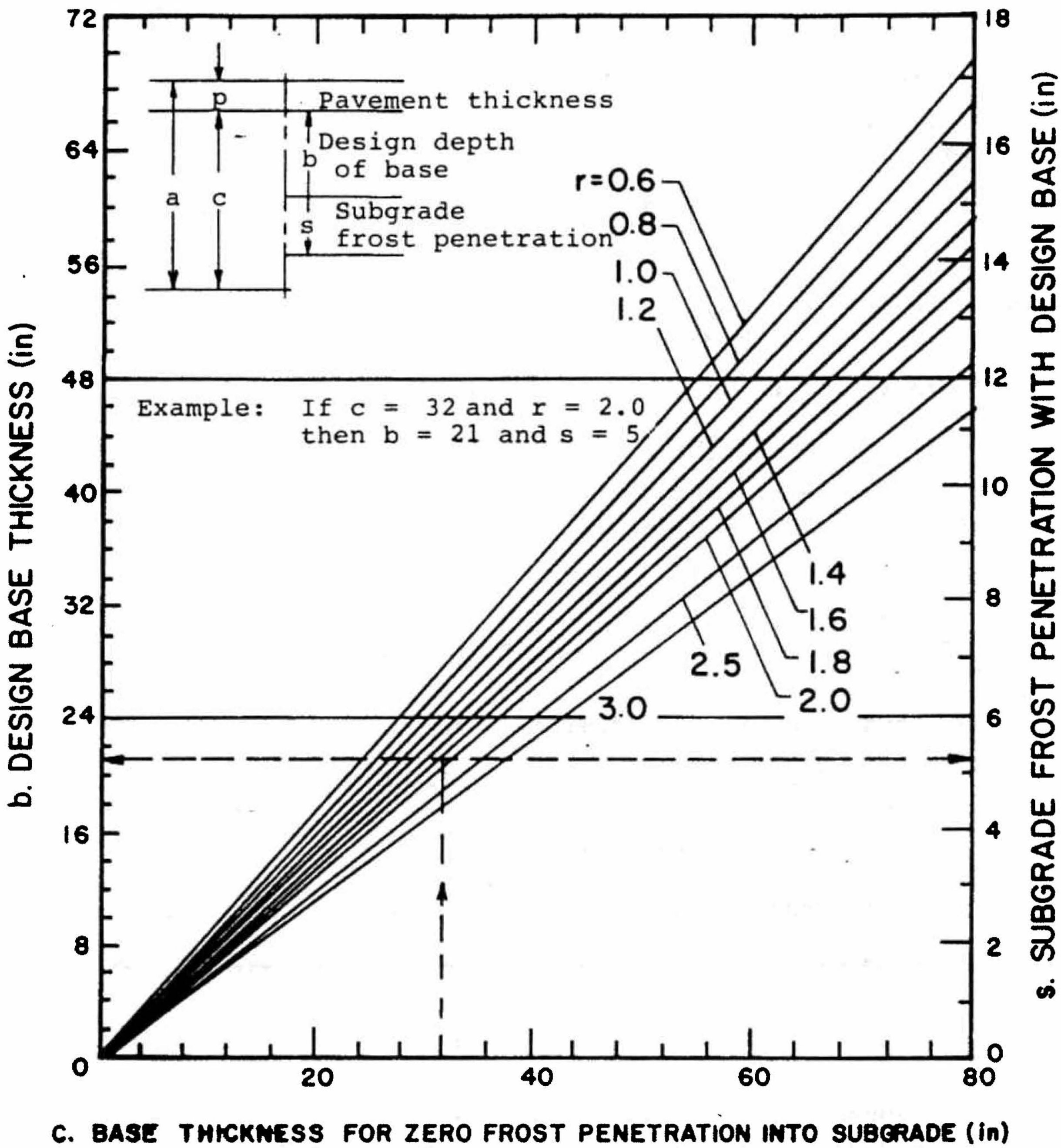
Case I: No drainage design is required if:

1. Existing pavement has adequate drainage

2. Underdrains are in place

3. Frost penetration is less than pavement thickness and MAD Index is greater than 85. (See figure 16 for depths of frost penetration)

THEN THE DESIGNER SHOULD PROCEED TO GEOMETRIC DESIGN



NOTES: $\underline{a}$ = Combined thickness of pavement and non-frost-susceptible base for zero frost penetration into subgrade.

$\underline{c}$ = $\underline{a} - \underline{p}$

$\underline{w}_b$ = Water content of base.

$\underline{w}_s$ = Water content of subgrade.

$\underline{r}$ = $\frac{\underline{w}_s}{\underline{w}_b}$ Not to exceed 2.0 for type A and B areas on airfiels and 3.0 for the other pavements.

Figure 18. Design depth of non frost-susceptible base for subgrade frost penetration.[19]

Case II: Drainage design is need if:

1. A new pavement and shoulder is designed with no previous drainage system available

2. Adequacy of existing pavement drainage is questionable

THEN THE DESIGNER MUST PROCEED WITH THE FOLLOWING STEPS TO CHECK THE NEED FOR DRAINAGE DESIGN:

1. Establish moisture region I, II or III from figure 19.

2. Establish temperature region A, B, or C from figure 19.

3. Establish subgrade drainage index i, J, or K from figure 20.

4. Assume base drainage is acceptable.

5. Enter figure 21 and establish MAD index based on moisture and temperature regions and subgrade and base drainage characteristics.

6. Determine the need for drainage from figure 22.

IF DRAINAGE DESIGN IS NEEDED, THEN PROCEED WITH DRAINAGE LAYER DESIGN AS OUTLINED BELOW.

<u>DESIGN EXAMPLE</u>

A pavement is to be built in Delaware County, Ohio

1. From figure 19, Delaware County is in climate region I.

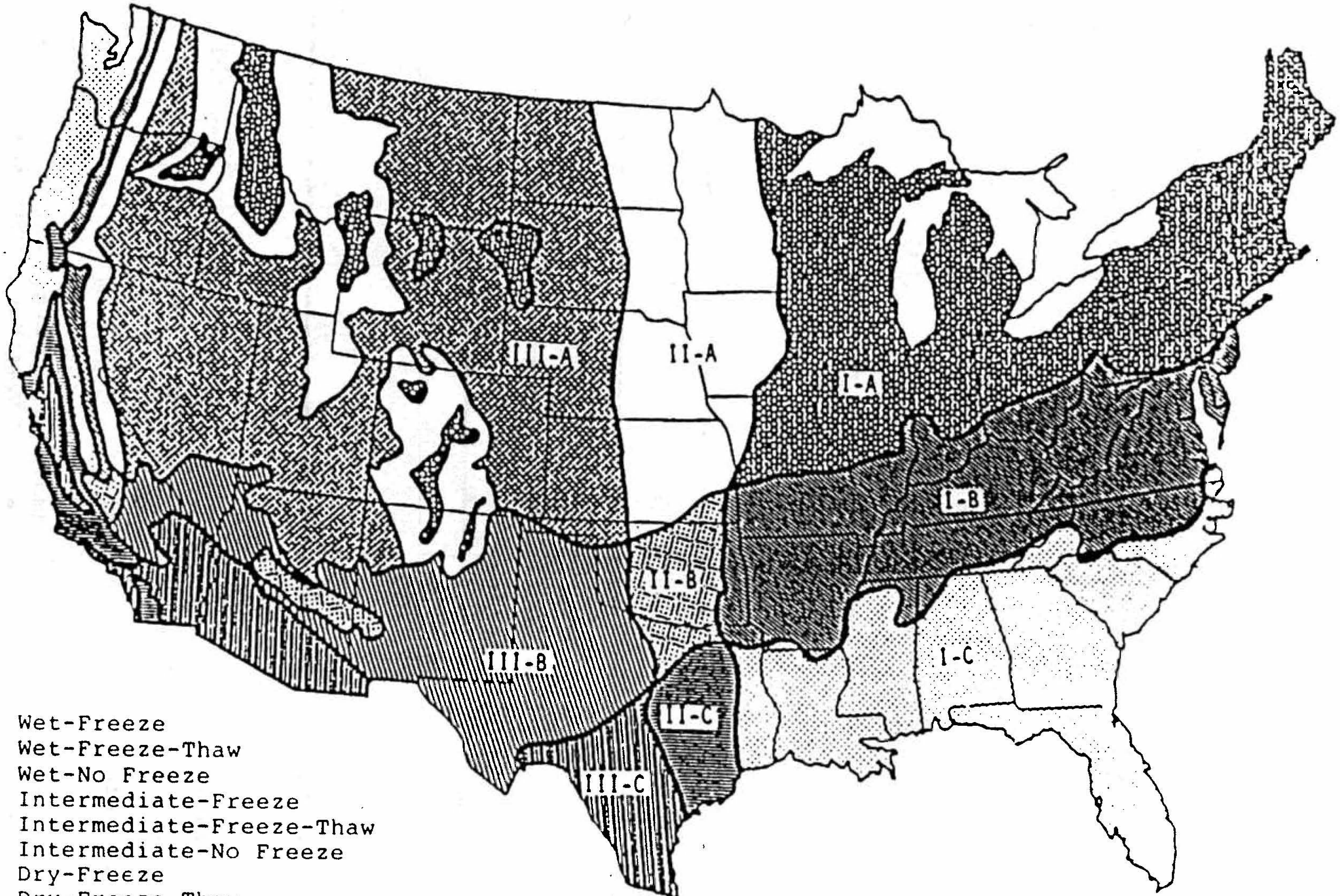
2. Figure 19 shows that Delaware County is in temperature zone A.

3. Figure 20 shows that a soil with AASHTO classification A-6 has a drainage index of i.

4. Assume that base drainage will be acceptable.

5. Figure 21 shows that the MAD index is 25.

6. Figure 22 shows that adequate drainage is needed.



I-A, Wet-Freeze
I-B, Wet-Freeze-Thaw
I-C, Wet-No Freeze
II-A, Intermediate-Freeze
II-B, Intermediate-Freeze-Thaw
II-C, Intermediate-No Freeze
III-A, Dry-Freeze
III-B, Dry-Freeze-Thaw
III-C, Dry-No Freeze

Figure 19. Climatic zones for the United States.[17]

AASHTO Class \ Position in Topography	Top of Hills	Sides of Hills	Depressions
A-1 A-3	K	K	K
A-2-4 A-2-5	K	K	J
A-2-6 A-2-7	K	K	J
A4	K	J	J
A-5	J	J	i
A-6	J	i	i
A-7-5 A-7-6	i	i	i

A group index above 20 will alter the NDI rating, K → J, J → i

A group index below 5 will alter the NDI rating, i → J, J → K.

Note: K,J,i are drainage indices

Figure 20. Approximate relationships for obtaining the natural drainage index from soil classification data.[17]

MAD Index	Damage Potential	Combinations
100	NEGLIGIBLE	Moisture Region (Figure 17)
99		
98		Temperature Region (Figure 17)
97		
96		Granular Material acceptability
95		(Figure 21)
94		Subgrade Drainability
93		(Figure 18)
92		III Cak
91		
90		
89		III Cmk
88		
87		
86		
85		III Caj III Bak
84	LOW	
83		
82		III Bmk
81		
80		
79		
78		III Caj III Cmj III Baj III Cuk III Aak
77		
76		
75		III Amk
74		II Cak
73		
72		
71		III Cuk III Bmj III Aaj III Buk II Cmk
70		III Cmi III Baj
69	NORMAL	
68		
67		II Caj II Bak
66		
65		
64		III Buk III Ami III Auk II Bmk
63		III Cui III Bmi III Aai
62		
61		
60		II Cmj II Baj II Cuk II Auk
59		II Cai
58		
57		III Auk II Amk
56		III Bui III Ami
55		

MAD Index	Damage Potential	Combinations
54	MODERATE	I Cak
53		II Cmi II Baj II Cuk II Bmj II Auj II Buk
52		
51		I Cmk
50		
49		III Aui
48		
47		I Caj I Bak
46		II Buk II Amj II Auk
45		II Cui II Bmj II Aui
44		I Bmk
43		
42		
41		
40		I Cmj I Bai I Cuk I Aa
39		II Auk I Cai
38		II Bui II Ami
37		I Amk
36		
35		
34	HIGH	
33		I Cuj I Bmj I Aaj I Buk
32		I Cmi I Bai
31		II Aui
30		
29		
28		
27		
26		I Buj I Amj I Auk
25		I Cui I Bmi I Aai
24		
23		
22		
21		
20		
19		I Aui
18		I Bui I Ami
17		
16		
15		
14	EXCESSIVE	
13		
12		
11		I Aui
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		
0		

Figure 21. The MAD Index.[17]

MAD Index

Negligible (85-100): This pavement would not show any moisture-related problems during its lifetime. Drainage not needed.

Low (70-85): This pavement contains a combination of properties that make it moisture insensitive, but climatic influences and maintenance must be carefully watched to maintain the good performance.

Normal (55-70): This pavement is composed of average materials exposed to average situations. Moisture damage is likely unless adequate drainage and maintenance are kept at a high level.

Moderate (35-55): Lower quality materials and a slightly inferior climate will produce large amounts of moisture damage unless extensive care is given to drainage considerations and routine maintenance.

High (15-35): Even with adequate drainage moisture damage will appear due to variability in materials. Without drainage there would be excessive moisture damage.

Excessive (0-15): The combination of climate and materials precludes any effectiveness of drainage in reducing moisture damage. Severe problems will develop, excessive maintenance should be planned for.

Figure 22. Potential for moisture accelerated problems in a pavement, as indicated by the MAD Index.

4.4.2 Drainage Layer Design

The determination of the quality of drainage for granular layers requires the determination of granular layer saturation as a function of time and evaluating the adequacy of the design criteria presented in figure 23.

1. Select the base course material properties.

   a. Percent fines (- #200)

   b. Type of fines

      - Inert - Substantially below "A" line in Unified Classification system, PI below 1.

      - Silty - Material plots near "A" line. PI above 1, but below "A" line.

      - Clay - Material has high PI, it plots above the "A" line in the Unified System.

   c. D10, effective grain size with 10 percent of the material passing this size, mm.

   d. Dry density, pcf and gm/cc.

   e. Specific gravity of solids, Gs. This may be obtained from construction records and initial material tests, and will not vary from section to section.

These should be recorded in the appropriate blank in figure 24. The permeability (in ft/day) can then be estimated from figure 25, as shown by the solid line.

2. Select base course geometric properties (these may be assumed)
   - -base thickness (H), ft
   - -Drainage layer width, (W), ft
   - -Transverse gradient (gt), ft/ft
   - -Longitudinal gradient (gl), ft/ft

3. Determine the slope factor, S. Perform the following calculations:

   a. Le = effective length of drainage path

$$= D\,[(gl/gt)^2 + 1]^{.5}$$

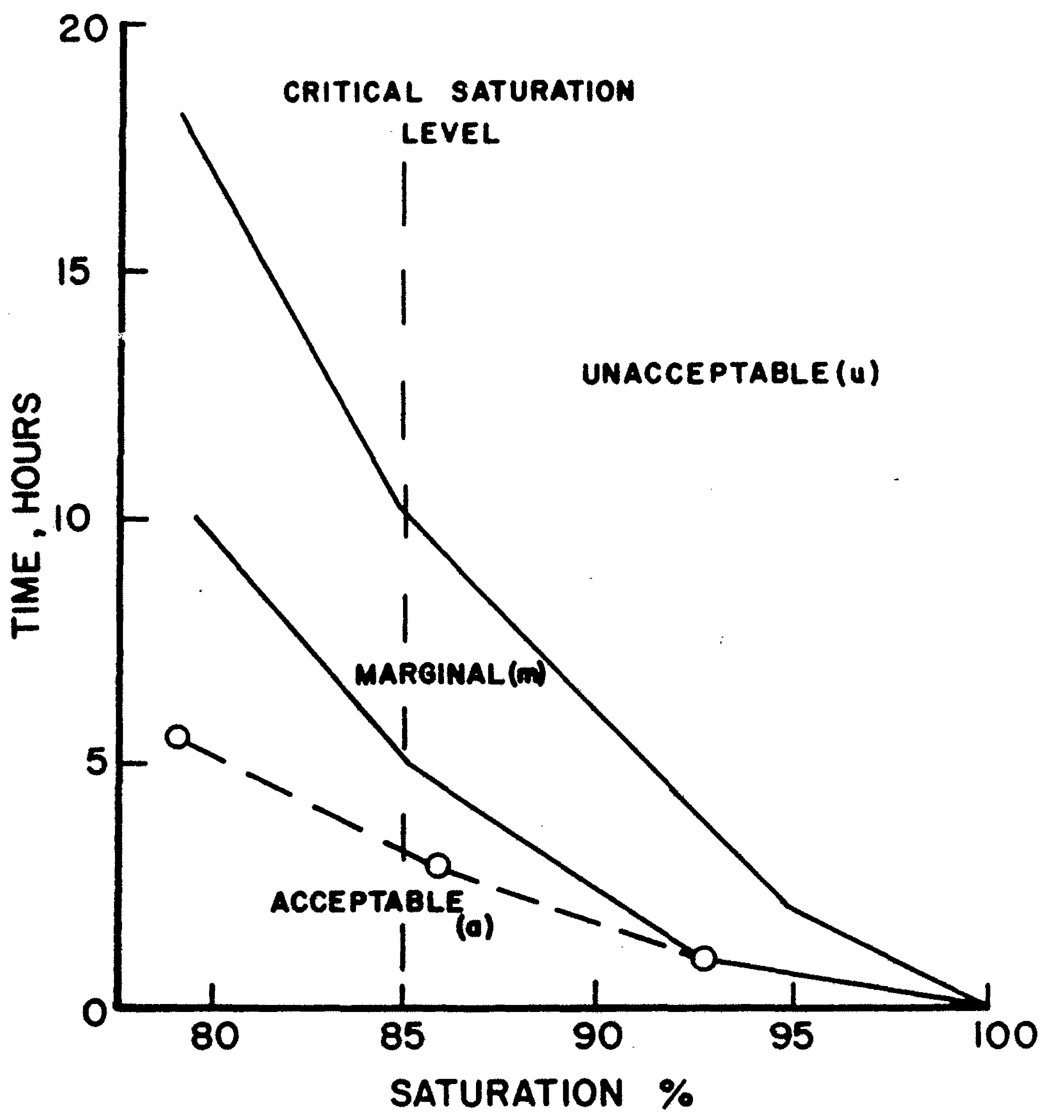


Figure 23. Drainability curves for granular base material.[17]

PAVEMENT SECTION Delaware County

STEP 1. INPUT BASE COURSE PROPERTIES

PERCENT FINES (-#200) 2.5 TYPE OF FINES inert

D_{10} 1.1 mm. DENSITY, γ_d 135 pcf

G_s 2.70 PERMEABILITY, K 150 ft/day

STEP 2. INPUT GEOMETRIC PROPERTIES

THICKNESS, H 0.50 ft WIDTH 22 ft

TRANSVERSE GRADIENT, gt 0.2 ft/ft LONGITUDINAL GRADIENT, gl 0 ft/ft

---

STEP 3. PERFORM GEOMETRIC CALCULATIONS

$Le = D\sqrt{(gl/gt)^2 + 1}$ = 22 $ge = \sqrt{gl^2 + gt^2}$ = .02

$S = H/(Le \cdot ge)$ = SLOPE FACTOR = 1.136

STEP 4. PERFORM VOLUME CALCULATIONS

$W_S = \gamma_d / 62.5$ 2.160 gm

$V_S^* = W_S / G_S$ = (2.160) / (2.70) = 0.80 cc

$V_V = 1 - V_S$ = .20 cc = B

STEP 5. a) ESTIMATE WATER LOSS (Fig. 21) C = 70 %

b) SPECIFIC YIELD, Ne = B.C / 100 = (.20)(70) / 100

c) PARAMETER X = Ne . Le / (H . K) = .140

---

* ASSUME $V_T = 1.0$

Figure 24. Form used for calculation of drainability.

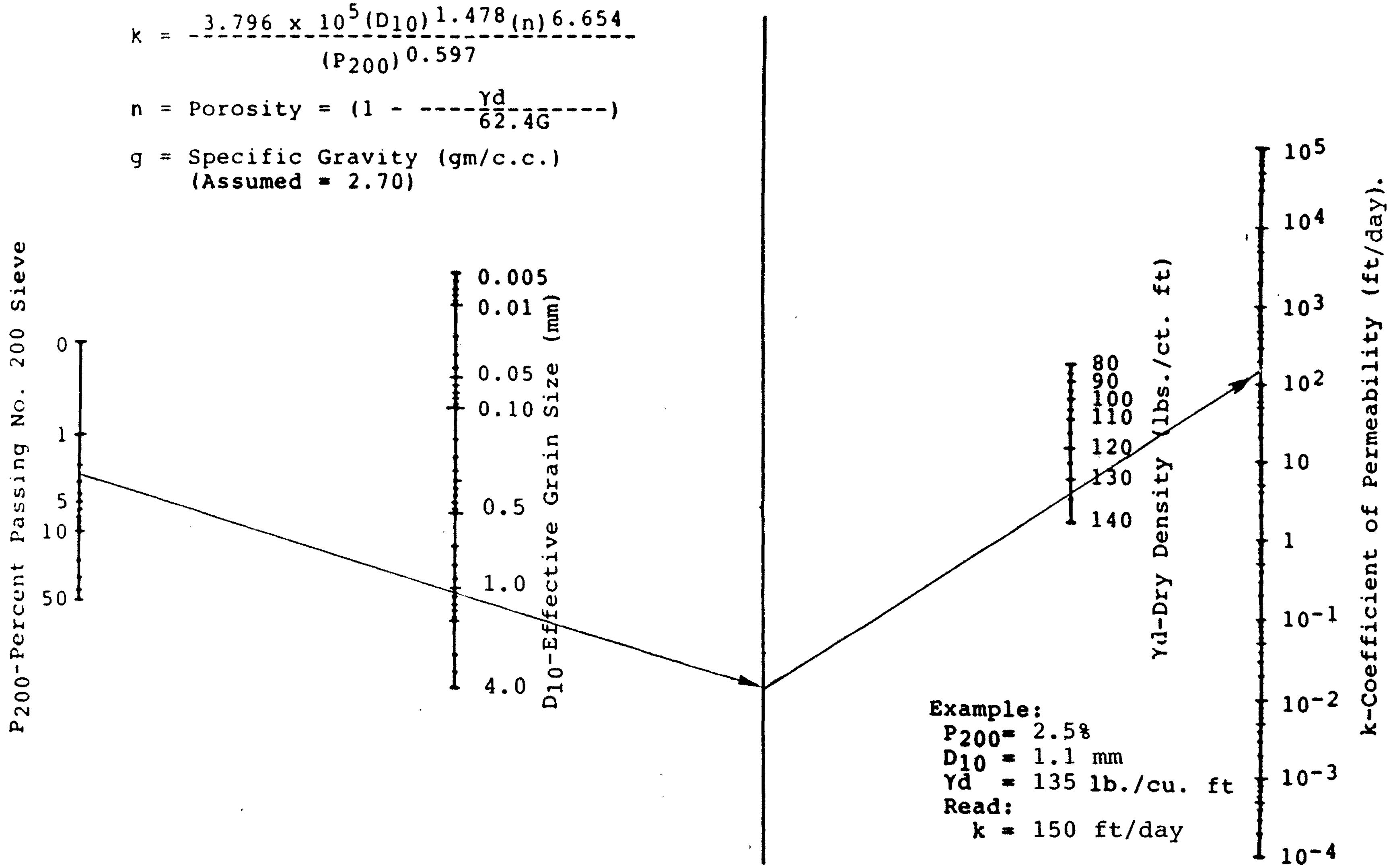


Figure 25. Nomographic procedure to estimate permeability of granular materials.[17]

b. ge = effective slope of drainage path

$$= (gl^2 + gt^2)^{.5}$$

c. S = Slope Factor
S = H/(Le x ge)

4. Using phase relationship in base material calculate the volume of water (Vv = B) filling all voids in granular base for 100 percent saturation. Enter this value on figure 24.

5. Determine the drainage layer characteristics; the results are recorded on figure 24.

   a. From figure 26 select the estimated water loss, C. Consult plasticity and grain size data for the material.

   b. Calculate the specific yield, Ne = (B x C/100) (figure 24).

   c. Calculate parameter X, X = (Ne x Le)/(H x k).

6. Calculate the saturation level as a function of drainage time on figure 27 using:

   a. From figure 28 select a time factor (T) for every value of U. The slope factor (S) previously calculated, is used to select the proper curve.

   b. Calculate the drainage time, in hours, for Column 3. (Column 2) x X x 24 = hours

   c. Specific yield (Ne) times U gives the amount of water drained during this time. Record this in Column 4.

   d. Subtract Column 4 from Vv = B. This is the amount of water remaining in the sample and goes in Column 5.

   e. Column 5 divided by Vv = B times 100 gives the saturation level of the sample and is recorded in Column 6.

The values of t in hours and the percent saturation is plotted on figure 21 to determine the suitability of the granular layer for drainage purposes. This classification will be either acceptable (a), marginal (m), or unacceptable (u).

AMOUNT OF FINES	2.5% FINES			5% FINES			10% FINES		
TYPE OF FINES	INERT FILLER	SILT	CLAY	INERT FILLER	SILT	CLAY	INERT FILLER	SILT	CLAY
GRAVEL	70	60	40	60	40	20	40	30	10
SAND	57	50	35	50	35	15	25	18	8

% Gravel, 0% fines, 75% greater than # 4: 80% water loss

* Sand, 0% fines, well graded: 65% water loss

* Gap graded material will follow the predominant size

Figure 26. Estimated value of water loss for calculating specific yield, C.[17]

(1) U	(2) T	(3) (2)·X·24=hrs	(4) $N_e \cdot U$	(5) $\underline{B}$-(4)	(6) (5/$\underline{B}$)·100
.1	.02	1.0	.014	.186	93
.2	.06	3.0	.028	.172	86
.3	.11	5.5	.042	.158	79
.4	.19	9.5	.056	.144	72
.5	.28	14.0	.070	.130	65
.6	.40	20.0	.084	.116	58
.7	.55	27.5	.099	.101	51
.8	.73	36.4	.112	.088	44
.9	1.12	55.9	.126	.074	37

Figure 27. Calculation table for obtaining saturation levels and drainage times.

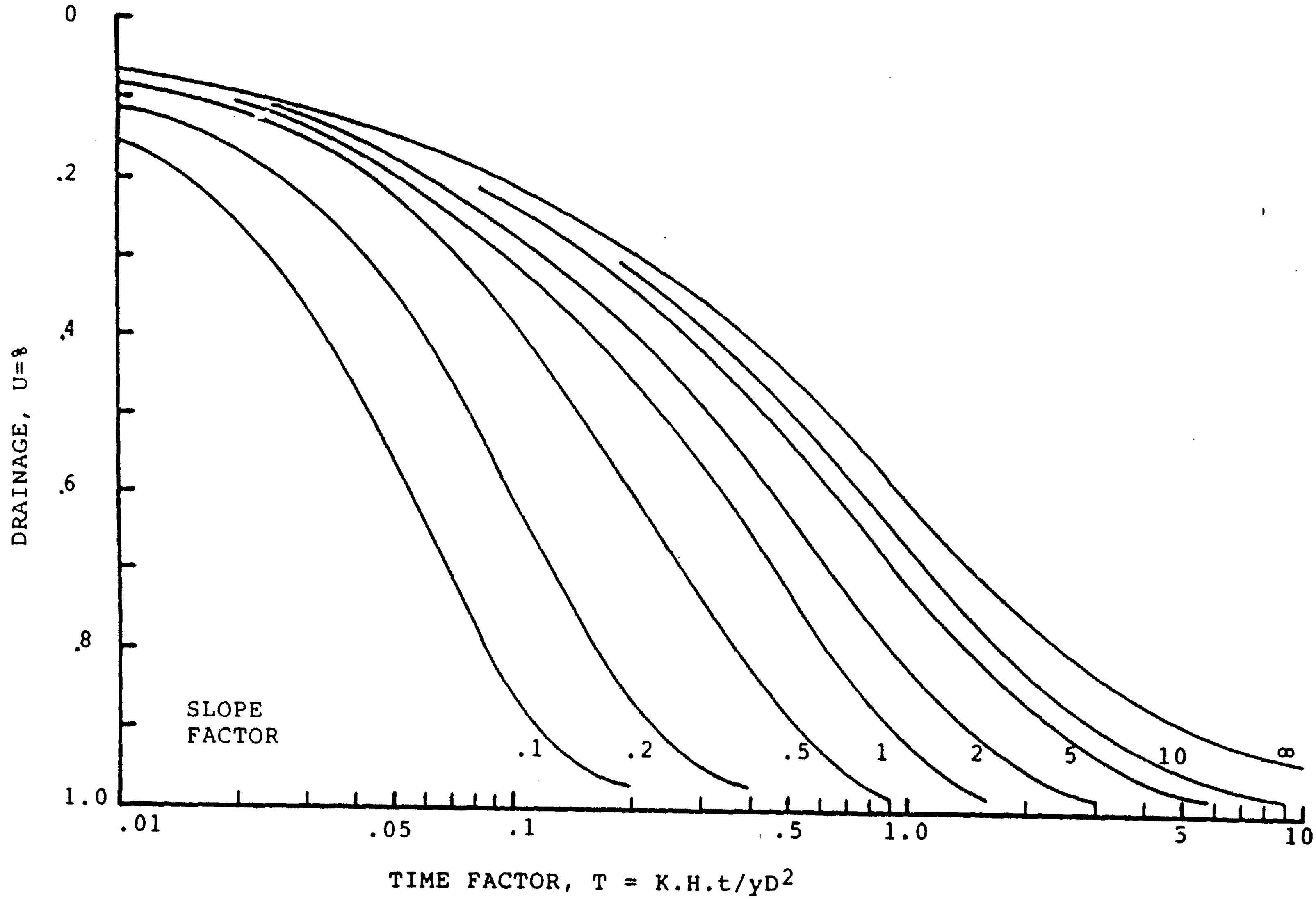


Figure 28. Curves for obtaining time factor, T, to be used in figure 23.[17]

DESIGN EXAMPLE

It is planned to build a crushed limestone base course.

1. The material properties are:

   a. Percent fines = 2.5

   b. Types of fines = inert

   c. D10 = 1.1 mm

   d. Dry density, γ_d = 135 pcf

   e. Gs = 2.70

   The permeability can then be estimated from figure 23:

   K = 150 ft/day

2. The geometric properties are:

   a. H = 0.5 ft

   b. W = 22 ft

   c. gt = 0.02 ft/ft

   d. gl = 0.0 ft/ft

3. Determine the slope factor S:

   a. Le = 22

   b. ge = 0.02

   c. S = 0.5/(22 x 0.02) = 1.136

4. Volume calculations are:

$$Ws = \gamma d/62.5 = 135/62.5 = 2.16$$

$$Vs = Ws/As = 2.16/2.70 = 0.80$$

$$Vv = 1-Vs = 1-0.80 = 0.20 = B$$

5. The drainage layer characteristics are:

   a. Estimated water loss (from figure 26)

      C = 70 percent

   b. Specific yield, Ne = .02x70/100 = .14

   c. Parameter X, X = 2.08

6. The calculated saturation levels as a function of time are presented in figure 27; these are plotted in figure 23 (dashed curve). It can be seen from figure 23 that the proposed drainage layer is acceptable.

4.4.3 Geometric Design of Drainage System

The geometric design of the drainage system developed by Kozlov is recommended.[50] The drainage layer should be located immediately below the bound layer of the pavement under a minimum of 6 in (152 mm) of confinement. A more detailed description of the geometric design is found on pages 30 through 33, along with figures 6 through 9, which show recommended cross-sections of drainage systems.

4.4.4 Drainage Pipe

Presently, several different drainage pipes of various lengths and diameters are being used in pavement subsurface drainage. Some of these are as follows:

1. Clay tile.
2. Concrete tile and pipe.
3. Vitrified clay pipe.
4. Perforated plastic bituminous fiber pipe.
5. Perforated corrugated-metal pipe.
6. Corrugated plastic tubing.

Most of the newer drainage pipes are flexible conduits rather than rigid conduits such as clay, concrete, or metal conduit. The flexible plastic drains can fail as a result of excessive deflection if inadequately installed. For this reason, the load-deflection characteristics are important considerations when this material is being used in subsurface drainage design. Impact resistance is also important from the standpoint of damage to the pipe while it is being placed.

4.4.5 Drainage Filter or Envelope Materials

When considering open graded transverse drains, longitudinal drains, drainage blankets, and drainage wells, it is necessary to evaluate the filter or envelope material. The primary functions of the envelope material around subsurface drains are as follows:

1. To prevent the movement into the drains of soil particles which might settle and clog the drain.
2. To provide material in the immediate vicinity of the drain openings which is more permeable than the surrounding soil.
3. To provide a suitable bedding for the drain.
4. To stabilize the soil in which the drain is being laid.

The most commonly used envelope materials are naturally graded coarse sands and gravels.

4.5 Material Properties Selection

The material properties required for shoulder analysis are shown in table 15. The values marked with an X are also needed if the design tables are used.

4.5.1 Subgrade Modulus

Subgrade modulus may be obtained from laboratory tests in triaxial compression, or may be estimated from AASHTO soil classification, soil support values or modulus of subgrade reaction, using figure 29 to estimate the CBR value. If soil support value (SSV) or AASHTO Group Index is used, enter the abscissa with the appropriate value and project this intersection horizontally and read off the CBR value from the ordinate. If modulus of subgrade reaction (k) is known, enter the right side of figure 29 with this value and project horizontally to read the CBR value from the ordinate. The subgrade modulus can then be determined using:

Table 15
Material properties required for input to BERM.

Material Property	Flexible Shoulder No Reg. Traffic	Flexible Shoulder Regular Traffic	Rigid Shoulder All Traffic
Subgrade modulus, Es	X	X	X
Base modulus, Eb	X	X	X
Base thickness, Hb	X	X	
Concrete modulus, Ec			X
Concrete flex. strength, fc			X
Asphalt creep modulus, Ec	*		
Asphalt dynamic modulus, EC1	*	*	
Design temperatures, T	X	X	

* Required if user opts to input values

$$Es = 1500 \text{ CBR (in psi)}$$

or (34)

$$Es = 10.3 \text{ CBR (in MPa)}$$

DESIGN EXAMPLE

Given a soil with AASHTO classification A-6 and Group Index of 10. From figure 29, this soil has a CBR of 6. Using equation 34,

$$Es = 1500 \times 6 = 9000 \text{ psi (62.1 MPa)}$$

4.5.2 Base Modulus

Granular base/subbase moduli may be obtained from laboratory tests in triaxial compression, or may be estimated from equation 35.

$$E_{n-1} = 11.06\, E_n^{0.837} \quad \text{(in psi)} \qquad (35)$$

where:

E_n = modulus of the nth layer
E_{n-1} = modulus of the layer above it

DESIGN EXAMPLE

The expected granular base modulus on a 9000 psi (62.1 MPa) subgrade, using equation 35, is:

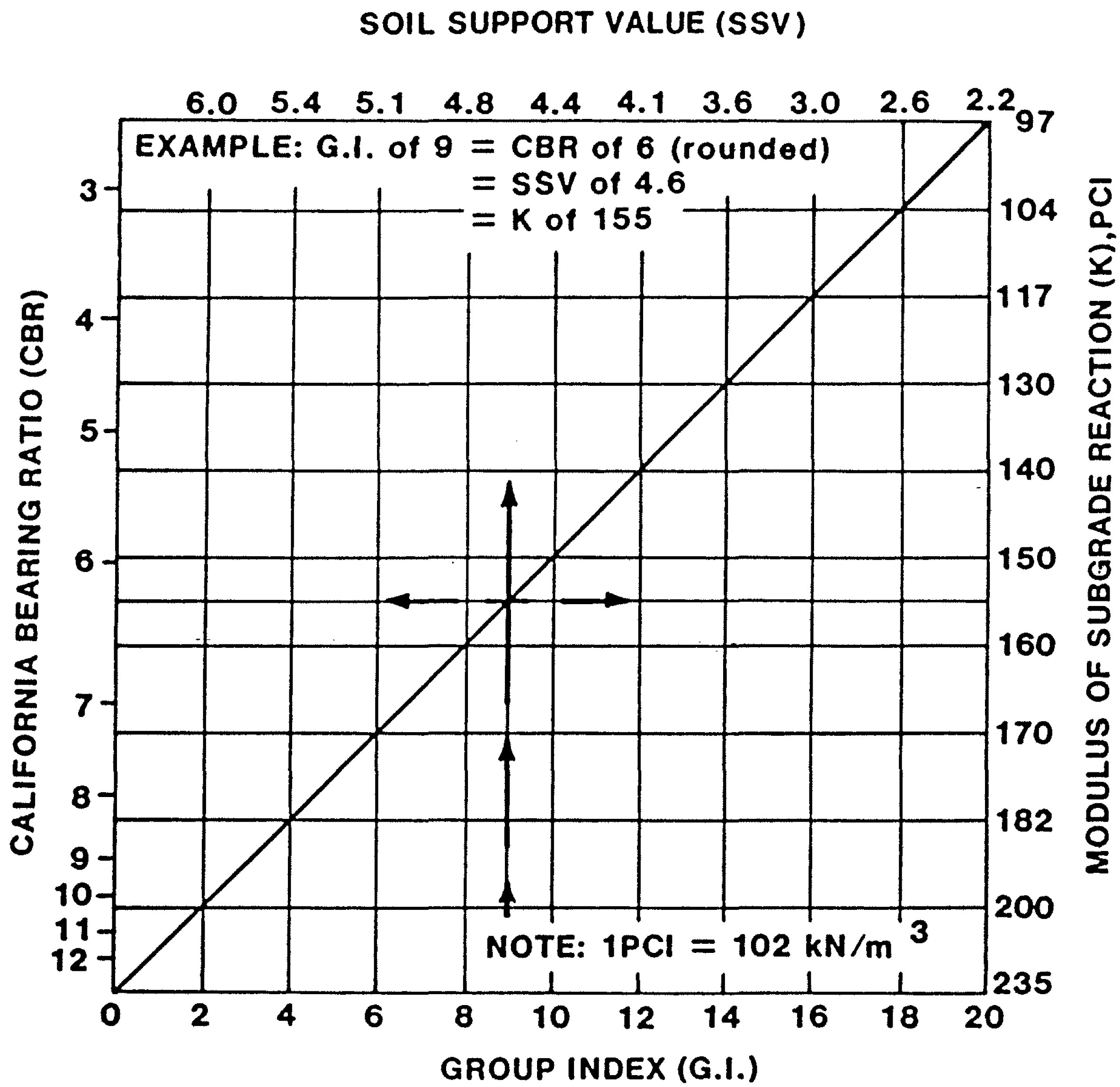


Figure 29. Relationships between soil properties and CBR.[38]

$$Eb = 11.06 \times 9000^{0.837} = 22{,}600 \text{ psi } (156 \text{ MPa})$$

4.5.3 Concrete Modulus

The dynamic (tangent) modulus of highway concretes is around 5 million psi (34.5 GPa) within a range of 3.5 to 6 million psi (24.1 to 41.4 GPa). In the absence of specific test data, it may be estimated from the following ACI relationship:[51]

$$Ec = 43 * p^{1.5} * f'c^{0.5} \quad \text{(in psi)}$$

$$Ec = 0.056\, p^{1.5} * f'c^{0.5} \quad \text{(in kPa} \qquad (36)$$

where:

Ec is the tangent modulus

p is the concrete unit weight (in pci or Kg/cu m)

f'c is the compressive strength

DESIGN EXAMPLE

Given a standard highway concrete with density of 145 pcf (2.32 gm/cc) and a compressive strength of 3100 psi (21.4 MPa). Using equation 36,

$$Ec = 33 * 145^{1.5} * 3100^{0.5} = 4{,}200{,}000 \text{ psi } (28.8 \text{ GPa})$$

4.5.4 Concrete Flexural Strength

Concrete flexural strength should preferably be determined by laboratory tests on beams using the procedure described in ASTM C75-84. However, the following relationship may be used:

$$fc = a * f'c^{.5} \qquad (37)$$

where:

fc is the flexural strength

f'c is the compressive strength of standard 6 x 12 in (152 x 305 mm) cylinders

a is a constant ranging from 7 to 10 for conventional (British) units and 0.58 to 0.83 for International units. The lower value should be used with high-strength concrete and the higher value with low-strength concrete. The value of a for the AASHO Road Test concrete is approximately 9.5.

DESIGN EXAMPLE

For the same concrete used in the previous example, and assuming a = 10.

$$fc = 10 * 3100^{0.5} = 560 \text{ psi } (3.8 \text{ MPa})$$

4.5.5 Asphalt Dynamic and Creep Moduli

Values for these variables are not needed since they are computed in BERM, and the design tables have been prepared using these values. However, as indicated in table 15 the user is given the option of providing his own dynamic and creep moduli, or even his own master creep compliance curve. Refer to sections 3.4 and D.1 for instructions in these cases.

4.5.6 Selection of Asphalt Cement Grade

The method developed by Basma and George is used to select the appropriate grade of asphalt cement.[21]

Design Input

a. Default - use figure 30 to determine proper asphalt cement grade.

b. Estimate the grade from figure 31. The following information is required:

   1. Seasonal air temperature variation.

   2. Mean air temperature.

   3. Monthly minimum pavement temperature.

DESIGN EXAMPLE

a. For Ohio, figure 30 shows that AC-20 is appropriate.

b. For Delaware County, Ohio:

   1. Seasonal air temperature variation = 46 degrees F (25.6 degrees C)

   2. Mean air temperature = 50 degrees F (10 degrees C)

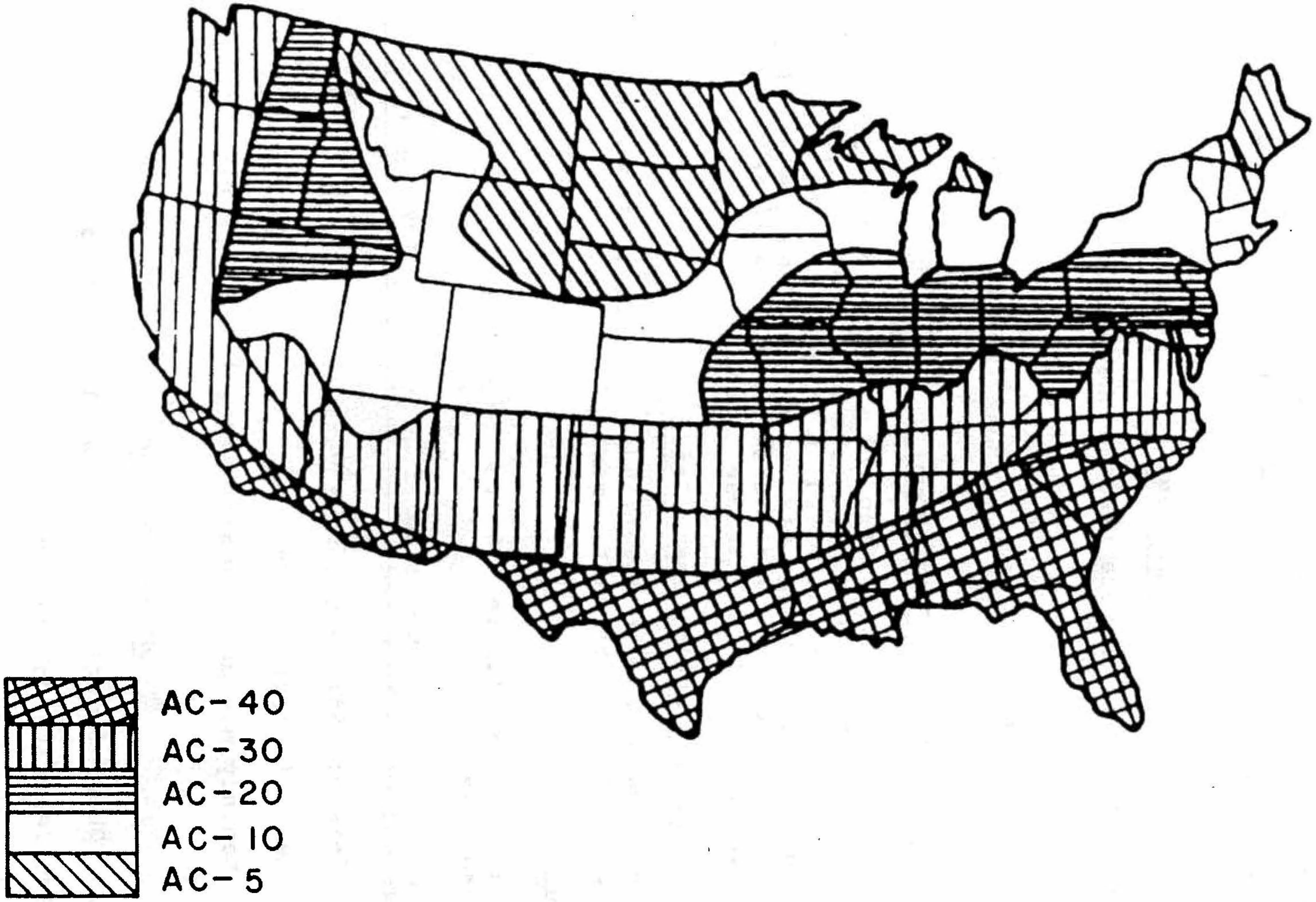


Figure 30. Recommended asphalt concrete grades for the United States.

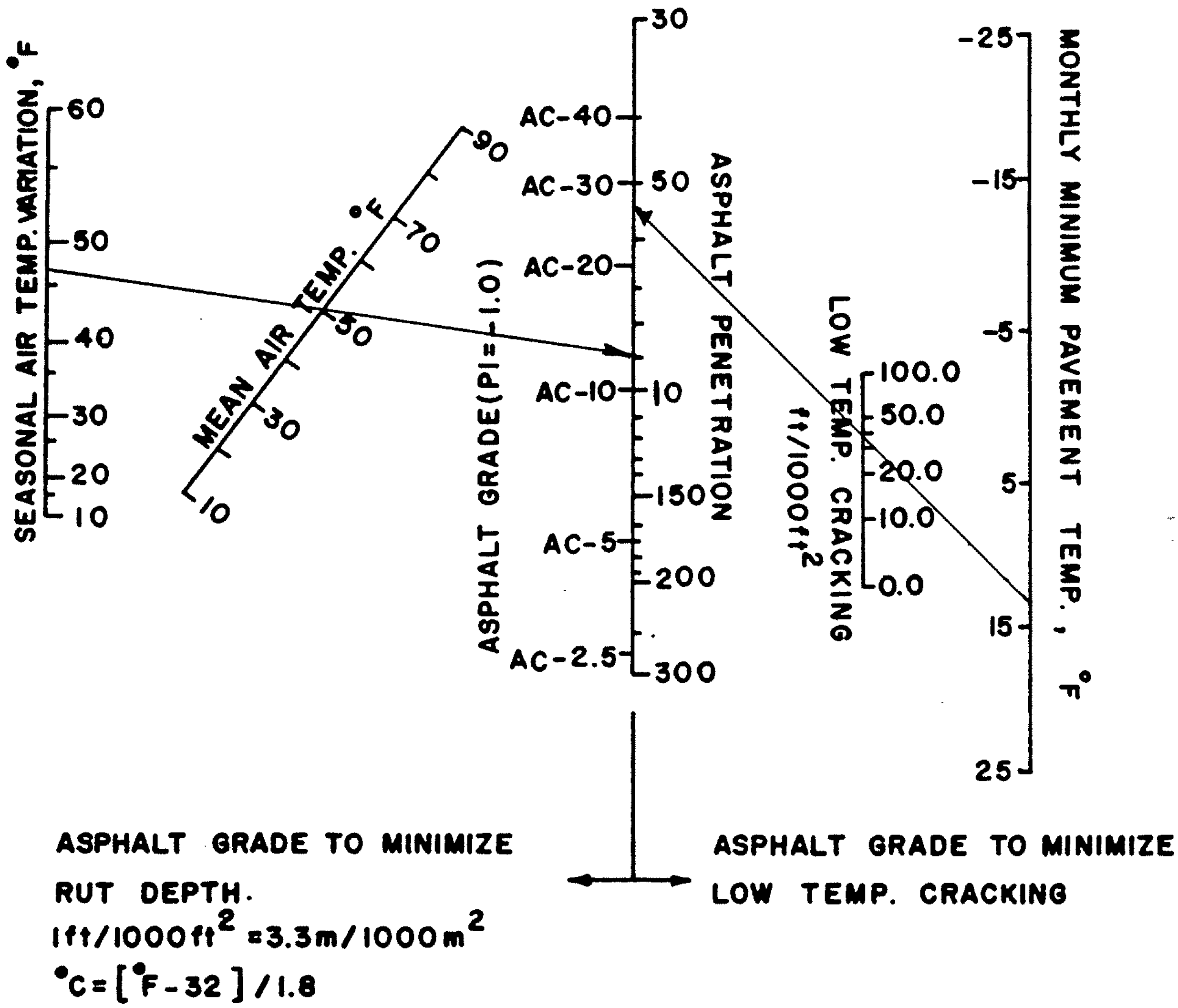


Figure 31. Asphalt-concrete grade selection to minimize rut depth and low-temperature cracking.[21]

3. Monthly minimum pavement temperature = 14 degrees F (-10 degrees C).

   From figure 31, the asphalt grade required to prevent excess rutting is somewhat stiffer than AC-10. The asphalt grade required to keep low temperature cracking to less than 35 ft/1000 sq. ft (115m/1000 sq. m) is slightly softer than AC-30. AC-20 is a reasonable compromise and will keep both rutting and low temperature cracking below tolerable values.

4.5.7 Design Temperature

The mean annual temperature (design temperature) can be determined from weather bureau publications.

DESIGN EXAMPLE

Weather department data show that the mean annual temperature (estimated from soil temperature at 4 in (102 mm) depth) for Delaware County, Ohio is 68 degrees F (20 degrees C).

4.5.8 Other Inputs to BERM

1. In order to run the BERM program, values are needed for the variables MFLEX, MONO, and MOD. Select the values for MFLEX and MONO from table 16 based on mainline-pavement type and longitudinal joint condition.

2. The program offers the user three options for determining asphalt moduli at design temperature through the use of the parameter MOD (along with an appropriate value for Ec):

   a. The value for the creep and dynamic moduli (EC, EC1) at design temperature can be input by the user: MOD=0. Loading time of 10800 and 0.02 seconds are applicable to creep and dynamic moduli, respectively.

   b. The values for Ec, Ec1 can be computed by the program from internal equation: MOD=0, Ec=0.

   c. The user may specify his own master creep compliance equation (MOD=1), but this <u>must</u> be in the form of equation 38.

$$E = 1/(XJO + XJ1 * ((10 ** (AO + A1 * T) **XM) \quad (38)$$

Table 16
Values of MFLEX and MONO for various mainline-shoulder combinations.

Mainline Pavement	Shoulder Pavement	Joint Condition	MFLEX	MONO
Rigid	Rigid	tied-keyed	0	1
Rigid	Rigid	separate/tied	0	0
Rigid	Flexible	separate	1	0
Rigid-widened	Flexible	separate	1	0
Flexible	Rigid	separate	0	0
Flexible	Flexible	separate	1	0
Flexible	Flexible	monolithic	1	1

where:

XJO, XJ1, AO, A1, XM are regression coefficients describing the master creep compliance curve and T is the design temperature. It is expected that this option (MOD=1) will be used very rarely.

DESIGN EXAMPLE

It is desired to add a flexible shoulder to an existing jointed concrete pavement. From table 16, for a separate shoulder added to a rigid pavement:

MFLEX = 1
MONO = 0

It is desired that the asphalt moduli be computed by the program from the design temperature; therefore:

MOD = 0
Ec = 0

4.5.9 Base Thickness

The base thickness required to provide adequate drainage and/or to provide protection against frost damage for frost-susceptible soils was determined in section 4.3.3.

DESIGN EXAMPLE

It was determined in section 4.3.3 that

Hb = 9 in (229 mm)

4.6 Shoulder Structural Design

4.6.1. Design Tables

Table 17 indicates which design table should be used for a particular shoulder analysis. Tables 19 and 21 (or 20 if the shoulder is to be used by regular traffic during peak periods) are used for all cases of rigid and flexible shoulder outer edge design, respectively. Table 12 indicates if analysis due to encroaching traffic is needed.

Table 17
Tables to be used for shoulder design.

Shoulder Type	Joint Condition	Traffic Encroaching	Traffic Parked
Rigid	Tied-keyed	18	19
Rigid	Tied/separate	19	19
Flexible	Separate	20	21*
Flexible	Monolithic	22	21*

* Use table 20 if parked traffic is due to use by regular traffic during peak periods.

To use the tables, select the appropriate table from table 16. Enter the table with material properties developed in section 4.5 and its subsections and select the rows and columns corresponding to values for these variables that are closest to the values developed in the previous section. The numbers in these tables represent the predicted traffic, in terms of equivalent 18 kip (80 kN) axle loads, that the shoulder section is expected to sustain. Find the thickness where the expected life is greater than the design traffic developed in section 4.2.5. Note that the minimum recommended thicknesses are 3 in (76 mm) for flexible shoulders and 6 in (152 mm) for rigid shoulders. If the design traffic is less than the predicted life of the thinnest section in each table, use the recommended minimum thicknesses.

Table 18

Design chart for inner edge design of rigid tied-keyed shoulders due to encroaching traffic.

E_s, Psi	E_b, Psi	f_c, Psi	SHOULDER THICKNESS H_c, in.											
			6 in.			7 in.			8 in.			9 in.		
			CONCRETE MODULUS E_c, 10^6 Psi											
			3	4	5	3	4	5	3	4	5	3	4	5
3,000	7,000	500	0.150	0.115	0.094	0.372	0.283	0.230	0.824	0.624	0.505	1.69	1.27	1.03
		600	0.328	0.144	0.206	0.812	0.252	0.503	1.80	1.36	1.10	3.69	2.78	2.24
		700	0.636	0.488	0.400	1.57	1.20	0.975	3.49	2.46	2.14	7.14	5.39	4.35
	12,000	500	0.155	0.118	0.097	0.379	0.288	0.234	0.832	0.630	0.510	1.68	1.27	1.03
		600	0.338	0.259	0.212	0.828	0.630	0.512	1.82	1.38	1.11	3.68	2.78	2.24
		700	0.654	0.501	0.410	1.61	1.22	0.992	3.52	2.67	2.16	7.13	5.38	4.35
6,000	12,000	500	0.287	0.218	0.177	0.697	0.529	0.428	1.50	1.14	0.926	2.95	2.26	1.84
		600	0.628	0.477	0.387	1.52	1.16	0.937	3.28	2.50	2.03	6.45	4.95	4.02
		700	1.22	0.924	0.749	2.95	2.24	1.82	6.35	4.84	3.92	12.5	9.58	7.79
	20,000	500	0.301	0.228	0.184	0.726	0.550	0.444	1.55	1.18	0.955	3.03	2.32	1.88
		600	0.658	0.498	0.403	1.59	1.20	0.97	3.39	2.58	2.09	6.63	5.07	4.12
		700	1.28	0.966	0.781	3.08	2.33	1.88	6.58	5.00	4.04	12.8	9.82	7.98
10,000	20,000	500	0.469	0.353	0.283	1.14	0.858	0.690	2.42	1.85	1.49	4.69	3.62	2.95
		600	1.03	0.771	0.619	2.48	1.88	1.51	5.29	4.04	3.26	10.3	7.92	6.45
		700	1.99	1.50	1.20	4.81	3.64	2.92	10.3	7.82	6.32	19.9	15.4	12.5
	30,000	500	0.492	0.369	0.296	1.19	0.894	0.717	2.54	1.91	1.54	4.85	3.74	3.04
		600	1.08	0.807	0.646	2.60	1.95	1.57	5.50	4.19	3.38	10.6	8.17	6.65
		700	2.09	1.56	1.25	5.03	3.79	3.04	10.7	8.11	6.54	20.5	15.8	12.9
20,000	30,000	500	0.873	0.649	0.514	2.13	1.60	1.28	4.54	3.48	2.80	8.73	6.85	5.59
		600	1.90	1.42	1.12	4.66	3.50	2.79	9.92	7.60	6.12	19.1	15.0	12.2
		700	3.70	2.75	2.18	9.02	6.79	5.41	19.2	14.7	11.9	37.0	29.0	23.7
	50,000	500	0.942	0.696	0.549	2.29	1.71	1.36	4.85	3.70	2.97	9.26	7.24	5.97
		600	2.06	1.52	1.20	5.00	3.75	2.97	10.6	8.09	6.49	20.2	15.8	12.9
		700	3.99	2.95	[illegible]	9.69	7.26	5.76	20.2	15.7	12.6	39.2	30.7	25.0

Table 19

Design chart for inner and outer edge design of rigid tied/separate shoulders due to both encroaching and parked traffic.

E_s, Psi	E_b, Psi	f_c, Psi	SHOULDER THICKNESS H_c, in.											
			6 in.			7 in.			8 in.			9 in.		
			CONCRETE MODULUS E_c, 10^6 Psi											
			3	4	5	3	4	5	3	4	5	3	4	5
3,000	7,000	500	0.091	0.066	0.052	0.205	0.147	0.115	0.428	0.301	0.234	0.833	0.580	0.451
		600	0.198	0.144	0.114	0.449	0.321	0.251	0.935	0.657	0.512	1.82	1.27	0.987
		700	0.383	0.279	0.220	0.870	0.621	0.487	1.81	1.27	0.99	3.53	2.46	1.91
	12,000	500	0.095	0.069	0.054	0.214	0.152	0.119	0.444	0.311	0.242	0.857	0.595	0.463
		600	0.207	0.150	0.118	0.469	0.333	0.261	0.970	0.680	0.529	1.87	1.30	1.01
		700	0.401	0.291	0.229	0.908	0.646	0.505	1.88	1.32	1.03	3.63	2.52	1.96
6,000	12,000	500	0.191	0.140	0.109	0.425	0.218	0.242	0.861	0.626	0.491	1.61	1.18	0.933
		600	0.417	0.306	0.239	0.929	0.677	0.529	1.88	1.37	1.07	3.53	2.59	2.04
		700	0.807	0.592	0.464	1.80	1.31	1.03	3.65	2.65	2.08	6.84	5.01	3.95
	20,000	500	0.202	0.148	0.115	0.450	0.326	0.254	0.906	0.657	0.513	1.69	1.23	0.970
		600	0.442	0.323	0.252	0.983	0.713	0.556	1.98	1.44	1.12	3.69	2.69	2.12
		700	0.856	0.626	0.488	1.91	1.38	1.08	3.84	2.78	2.17	7.15	5.22	4.11
10,000	20,000	500	0.340	0.246	0.190	0.754	0.543	0.420	1.50	1.09	0.849	2.76	2.03	1.60
		600	0.744	0.537	0.414	1.65	1.19	0.917	3.29	2.39	1.86	6.04	4.45	3.51
		700	1.44	1.04	0.803	3.19	2.30	1.78	6.37	4.62	3.60	11.70	8.62	6.79
	30,000	500	0.361	0.260	0.200	0.798	0.573	0.441	1.59	1.15	0.890	2.90	2.13	1.67
		600	0.789	0.568	0.436	1.75	1.25	0.964	3.47	2.51	1.95	6.34	4.65	3.66
		700	1.53	1.10	0.845	3.38	2.43	1.87	6.72	4.86	3.77	12.3	9.01	7.09
20,000	30,000	500	0.698	0.498	0.383	1.56	1.12	0.869	3.11	2.27	1.79	5.66	4.25	3.44
		600	1.53	1.09	0.838	3.41	2.45	1.90	6.80	4.97	3.92	12.4	9.29	7.52
		700	2.96	2.11	1.62	6.60	2.74	3.68	13.17	9.62	7.60	23.5	18.0	14.6
	50,000	500	0.770	0.546	0.417	1.72	1.23	0.947	3.42	2.48	1.95	6.18	4.62	3.73
		600	1.68	1.19	0.912	3.76	2.68	2.07	7.48	5.43	4.26	13.5	10.1	8.14
		700	3.26	2.31	1.77	7.29	5.20	4.01	14.6	10.5	8.26	26.2	19.6	15.8

Table 20

Design chart for inner edge design of flexible separate shoulders due to encroaching traffic.

E_s, Psi	E_b, Psi	H_b, in.	SHOULDER THICKNESS H_{AC}, in.											
			3 in.			5 in.			7 in.			9 in.		
			DESIGN TEMPERATURE T, °F											
			55	65	75	55	65	75	55	65	75	55	65	75
3,000	7,000	4	0.055	0.005	0.001	0.980	0.043	0.002	33.2	1.19	0.037	462.	16.1	0.414
		8	0.086	0.010	0.002	0.960	0.050	0.003	23.9	1.01	0.038	264.	10.8	0.338
		12	0.128	0.016	0.003	1.08	0.06	0.004	22.5	1.04	0.044	218.	9.76	0.343
	12,000	4	0.103	0.009	0.001	1.20	0.049	0.002	31.9	1.07	0.031	375.	12.2	0.288
		8	0.236	0.024	0.004	1.72	0.083	0.004	33.7	1.32	0.046	314.	12.0	0.345
		12	0.438	0.050	0.009	2.42	0.129	0.008	39.7	1.71	0.067	324.	13.6	0.437
6,000	12,000	4	0.504	0.045	0.006	4.56	0.193	0.009	103.	3.52	0.106	1000	35.5	0.886
		8	0.852	0.090	0.015	4.83	0.240	0.013	80.4	3.22	0.118	664.	25.8	0.783
		12	1.32	0.153	0.029	5.70	0.311	0.020	79.3	3.49	0.144	572.	24.5	0.831
	20,000	4	0.813	0.079	0.012	4.93	0.225	0.011	88.6	3.27	0.108	784.	28.1	0.769
		8	1.98	0.226	0.042	7.50	0.401	0.025	99.2	4.30	0.173	698.	29.4	0.977
		12	3.97	0.476	0.099	11.0	0.645	0.045	121.	5.76	0.260	744.	34.4	1.28
10,000	20,000	4	2.72	0.269	0.043	13.7	0.637	0.034	219.	8.20	0.282	1000	64.4	1.83
		8	5.29	0.613	0.118	16.7	0.911	0.058	196.	8.62	0.361	1000	53.8	1.86
		12	8.90	1.13	0.245	21.4	1.28	0.092	209.	10.1	0.475	1000	55.2	2.14
	30,000	4	3.79	0.423	0.078	13.9	0.73	0.045	185.	7.83	0.313	1000	54.1	1.79
		8	9.83	1.29	0.288	22.6	1.39	0.103	220.	11.0	0.533	1000	60.3	2.42
		12	19.6	2.82	0.706	34.2	2.31	0.193	279.	15.3	0.830	1000	73.2	3.29
20,000	30,000	4	21.6	2.46	0.476	61.8	3.31	0.212	696.	30.1	1.27	1000	184.2	6.39
		8	41.3	5.52	1.30	74.0	4.65	0.363	612.	31.1	1.59	1000	151.	6.29
		12	68.8	10.1	2.67	93.8	6.48	0.567	648.	36.2	2.07	1000	154.	7.28
	50,000	4	31.6	4.40	1.09	60.5	3.96	0.325	541.	28.7	1.54	1000	149.	6.63
		8	86.7	14.2	4.27	104.	8.01	0.799	685.	42.6	2.78	1000	176.	9.51
		12	179.	32.2	10.8	163.	13.8	1.54	896.	61.2	4.48	1000	222.	13.4

Table 21

Design chart for outer edge design of flexible shoulders due to parked traffic.

E_s, Psi	E_b, Psi	H_b, in.	SHOULDER THICKNESS H_{AC}, in.											
			3 in.			4.25 in.			5.5 in.			6.75 in.		
			DESIGN TEMPERATURE T,° F											
			55	65	75	55	65	75	55	65	75	55	65	75
3,000	7,000	4	0.001	0.001	0.001	0.002	0.001	0.001	0.002	0.001	0.001	0.003	0.002	0.001
		8	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.005	0.004	0.001
		12	0.002	0.001	0.001	0.004	0.002	0.001	0.008	0.004	0.002	0.016	0.007	0.004
	12,000	4	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.003	0.003	0.001
		8	0.001	0.001	0.001	0.002	0.001	0.001	0.004	0.002	0.001	0.008	0.003	0.002
		12	0.004	0.002	0.002	0.008	0.005	0.004	0.016	0.008	0.006	0.031	0.014	0.009
6,000	12,000	4	0.001	0.001	0.001	0.001	0.001	0.001	0.004	0.001	0.001	0.009	0.003	0.002
		8	0.005	0.004	0.004	0.013	0.008	0.008	0.030	0.015	0.014	0.061	0.028	0.024
		12	0.031	0.024	0.033	0.066	0.043	0.052	0.125	0.073	0.077	0.227	0.119	0.114
	20,000	4	0.001	0.001	0.001	0.002	0.001	0.001	0.005	0.002	0.001	0.011	0.004	0.003
		8	0.010	0.008	0.010	0.024	0.016	0.018	0.050	0.028	0.029	0.098	0.050	0.046
		12	0.069	0.058	0.089	0.133	-0.097	0.127	0.237	0.152	0.177	0.408	0.236	0.248
10,000	20,000	4	0.003	0.002	0.002	0.009	0.004	0.005	0.022	0.010	0.009	0.052	0.020	0.017
		8	0.052	0.044	0.079	0.118	0.085	0.132	0.235	0.150	0.206	0.443	0.255	0.316
		12	0.349	0.331	0.680	0.642	0.526	0.932	1.10	0.800	1.25	1.85	1.21	1.72
	30,000	4	0.004	0.002	0.003	0.012	0.006	0.007	0.029	0.014	0.014	0.064	0.027	0.025
		8	0.090	0.081	0.157	0.188	0.146	0.245	0.356	0.244	0.362	0.644	0.399	0.534
		12	0.658	0.673	1.49	1.13	0.995	1.90	1.83	1.43	2.42	2.95	2.09	3.16
20,000	30,000	4	0.039	0.028	0.056	0.109	0.068	0.115	0.254	0.140	0.211	0.544	0.271	0.367
		8	0.880	0.936	2.72	1.73	1.59	3.98	3.13	2.54	5.63	5.46	4.09	[illegible]
		12	6.46	7.82	25.8	10.4	10.8	30.9	16.1	14.9	37.6	25.0	20.3	47.4
	50,000	4	0.063	0.050	[illegible]	0.161	0.110	0.206	0.352	0.213	0.351	0.731	0.390	[illegible]
		8	1.74	2.03	6.44	3.13	3.16	8.68	5.29	4.72	11.5	8.75	7.04	[illegible]
		12	14.4	19.1	[illegible]	21.1	24.2	75.7	30.7	31.1	86.1	45.0	[illegible]	[illegible]

Table 22

Design chart for inner edge design of flexible monolithic shoulders due to encroaching traffic.

E_s, Psi	E_b, Psi	H_b, in.	SHOULDER THICKNESS H_{AC}, in. / DESIGN TEMPERATURE T, °F: 3 in. 55	3 in. 65	3 in. 75	5 in. 55	5 in. 65	5 in. 75	7 in. 55	7 in. 65	7 in. 75	9 in. 55	9 in. 65	9 in. 75
3,000	7,000	4	0.166	0.010	0.001	2.37	0.088	0.003	82.7	2.87	0.063	1000	49.4	0.861
		8	0.247	0.017	0.002	2.16	0.095	0.004	54.7	2.26	0.061	657.	30.5	0.655
		12	0.360	0.028	0.003	2.37	0.115	0.005	49.8	2.27	0.069	519.	26.7	0.646
	12,000	4	0.269	0.016	0.001	2.35	0.089	0.003	62.9	2.23	0.051	803.	32.1	0.584
		8	0.585	0.041	0.005	3.14	0.140	0.006	61.1	2.57	0.072	613.	29.0	0.651
		12	1.07	0.083	0.010	4.31	0.213	0.011	69.5	3.22	0.102	606.	31.7	0.803
6,000	12,000	4	0.878	0.061	0.007	5.99	0.264	0.011	136.	5.62	0.155	1000	71.3	1.57
		8	1.42	0.117	0.016	5.95	0.311	0.017	98.1	4.81	0.163	868.	48.0	1.30
		12	2.17	0.198	0.030	6.86	0.396	0.024	93.7	5.08	0.194	721.	44.1	1.35
	20,000	4	1.71	0.121	0.014	7.32	0.328	0.015	129.	5.44	0.156	1000	58.3	1.34
		8	3.96	0.332	0.046	10.5	0.556	0.031	134.	6.69	0.236	1000	56.4	1.59
		12	7.50	0.695	0.110	14.9	0.875	0.055	158.	8.73	0.348	1000	64.0	2.04
10,000	20,000	4	4.41	0.350	0.046	15.7	0.789	0.041	245.	11.5	0.38	1000	100.	2.95
		8	8.23	0.773	0.124	18.0	1.07	0.068	204.	11.4	0.462	1000	97.1	2.82
		12	13.7	1.42	0.258	22.6	1.49	0.107	212.	13.1	0.599	1000	87.0	3.18
	30,000	4	8.31	0.668	0.090	20.5	1.05	0.056	262.	12.5	0.426	1000	106.	[illegible]
		8	20.7	1.97	0.327	31.4	1.90	0.125	290.	16.5	0.691	1000	[illegible]	[illegible]
		12	40.8	4.30	0.805	46.6	3.11	0.231	357.	22.4	1.06	1000	[illegible]	[illegible]
20,000	30,000	4	35.0	3.29	0.535	66.3	3.94	0.254	703.	39.2	1.62	1000	249.	[illegible]
		8	64.7	7.20	1.44	75.3	5.31	0.421	580.	38.4	1.94	1000	222.	[illegible]
		12	107.	13.2	2.98	93.9	7.32	0.656	599.	43.8	2.51	1000	221.	10.1
	50,000	4	81.1	7.75	1.31	96.7	5.85	0.393	797.	45.3	1.94	1000	282.	9.65
		8	215.	24.4	5.10	158.	11.3	0.938	945.	63.7	3.36	1000	311.	[illegible]
		12	441.	55.2	13.0	243.	19.3	1.80	1000	89.9	5.36	1000	382.	14.2

DESIGN EXAMPLE

The following design inputs have been generated:

1. Traffic

   a. PPT = 0.05 percent

   b. PET = 4 percent

   c. Daily E18's

      = 222 for rigid shoulders

      = 169 for flexible shoulders

   From the above, the design traffic over a 20 year design period, in terms of E18's is:

	Parked Traffic	Encroaching Traffic
Rigid shoulder	810	65,600
Flexible shoulder	610	50,000

2. Material properties:

   a. Es = 9,000 psi (62.1 MPa)

   b. Eb = 22,600 psi (156 MPa)

   c. Hb = 9 in (229 mm)

   d. Ec = 4,200,000 psi (28.8 GPa)

   e. fc = 560 psi (3.8 MPa)

   f. T = 68 degrees F (20 degrees C)

Rigid Shoulder

If it is desired to build an add-on rigid shoulder, table 17 indicates that table 19 should be used for both parked and encroaching traffic design. Using the material properties in table 19 closest to those listed above (Es = 10,000; Eb = 20,000; Ec = 4,000,000; fc = 600) it is seen that a 6 in (152 mm) tied concrete shoulder can sustain 568,000 equivalent 18 kip axle loads. Therefore, the 6 in (152 mm) minimum thickness is adequate for both inner and outer edge designs.

Flexible Shoulder

If a flexible shoulder is to be added, table 17 shows that encroaching traffic design uses table 20 and parked traffic design uses table 21. Using the material values in tables 20 and 21 closest to the values developed above, it is seen from table 20 that a 3 in (76 mm) thick shoulder can sustain approximately 613,000 equivalent 18 kip axle loads due to encroaching traffic (Es = 10,000; Eb = 20,000; Hb = 8; T = 65). Table 21 shows that a 3 in (76 mm) shoulder can sustain approximately 44,000 load applications due to parked traffic. Therefore, 3 in thick asphalt shoulder is adequate.

However, the base thickness required to minimize frost damage was determined on the assumption that a 6 in (152 mm) pavement layer would be used. If a 3 in (76 mm) pavement layer will be used, the base layer thickness will have to be increased to 12 in (305 mm).

4.6.2. BERM Program

The BERM program is menu driven and interactive. To use this program, enter the disk into the disk drive and type BERM <RETURN>. The screen will display the menu; five options are given:

1. Interactive data entry
2. Edit data
3. Run the program
4. Exit the program
5. Batch processing

The interactive data entry also includes checks on the data to determine if the entered values are within the expected range.

The data file created under interactive data entry (option 1) is not saved after exiting from the program. However, the user can go back to modify (edit) the data file and rerun as many times as he wishes provided he does not exit from the program. In order to save a data file, the following steps are required.

1. Select option 1 and enter data
2. Run the program using option 3; the computer will ask: "DO YOU WANT TO STORE THE INPUT DATA?"
3. Type a Y for YES

4. The computer will prompt ENTER INPUT FILE NAME, FORMAT IS XXXXXXXX.XXXX; enter any name consistent with the format.

This file may now be edited using option 2 from the menu to create new input data files for batch processing. Note that option 3 does not use a named data (input) file. Note also that all YES or NO (Y or N) responses need to be in capital letters.

To enter the data, select option 1 from the menu and proceed as prompted. The sequence of data entry using option 1 from the menu depends on whether the shoulder is rigid or flexible, and how the user wishes to determine static and dynamic moduli for flexible shoulders (options 1, 2 and 3 of section D.1). If the shoulder is rigid, the computer asks for the appropriate input data, skipping over those data not needed in the analysis. For flexible shoulders, if MOD=0, the computer asks: DO YOU WANT TO ENTER STATIC AND DYNAMIC MODULI? If YES (option 1 of section D.1), the values for EC and EC1 are entered by the user. If NO, EC and EC1 are skipped and are computed in the program using the design temperature T. Note that when MOD=1, the values of EC and EC1 are computed from the user input equation (which must be of the form of equation 38), as discussed in section 4.5.8. The computer will prompt the user for the values of the constants in equation 38.

It should be noted that in addition to the data developed in step 4, the program also needs a value for the shoulder thickness. It is suggested that the minimum recommended thicknesses 6 in (152 mm) for rigid shoulders and 3 in (76 mm) for flexible shoulders) could be used as the first trial. The program automaticaly computes the expected life for this design and for a design shoulder thickness of plus 1 in (25.4 mm) in order to aid in interpolating for the next trial thickness. Or, the design tables could be used to estimate the thickness for the first trial.

Program Output

Typical outputs of the BERM program are shown in figures 32 and 33. The input information is reproduced on the output for easy checking of data. The output of the program is the expected life (in terms of equivalent 18 kip (80 kN) axle loads) the section can sustain. Note that the program computes the expected life for two thicknesses: Hc and Hc + 1 inch (25.4 mm); the latter value is provided to aid the user in interpolating the thickness for design traffic. The expected life is compared to the design life, evaluated in step 1. The required thickness, if greater than minimum, can be projected from the two values computed. The relationship between thicknesses and the logarithm of the expected life is approximately linear; semi-log plots are useful for interpolation.

RIGID SHOULDER DESIGN

PAVEMENT/SHOULDER JOINT IS TIED, KEYED	
CONCRETE MODULUS:	4200. ksi (29.0 GPa)
CONCRETE FLEX STRENGTH:	560. psi (3.86 MPa)
SUBBASE MODULUS:-	22.6 ksi (156. MPa)
SUBGRADE MODULUS:	9.0 ksi (62. MPa)

THE COMPUTED LIVES, IN MILLIONS EAL, ARE:

SURFACE THICKNESS (in)	(mm)	OUTER EDGE	INNER EDGE
6.0	(152.4)	.346	.507
7.0	(177.8)	.764	1.229

Figure 32. Predicted life of a tied, keyed rigid shoulder.

FLEXIBLE SHOULDER DESIGN

THE SHOULDER IS SEPARATE FROM THE MAINLINE PAVEMENT	
A.C. DYNAMIC MODULUS:	719. ksi (5.0 GPa)
A.C. CREEP MODULUS:	10.7 ksi (74. MPa)
BASE MODULUS:	22.6 ksi (156. MPa)
BASE THICKNESS:	9.0 ksi (62. MPa)
DESIGN TEMPERATURE:	68.0 F (20.0 C)

THE COMPUTED LIVES, IN MILLIONS EAL, ARE:

SURFACE THICKNESS (in)	(mm)	ENCROACHING TRAFFIC	PARKED TRAFFIC
3.0	76.2	.438	.069
4.0	101.6	.205	.109

Figure 33. Predicted life of a separate flexible shoulder.

DESIGN EXAMPLE

The data developed in section 4.5 and its subsections were input to the BERM program. Figures 32 and 33 show the outputs for a tied-keyed shoulder and a separate flexible shoulder; respectively. Note that the outer edge life also applies to inner edge life if the shoulder is separate and/or tied. The predicted lives, for the same shoulders used with design tables, are:

	Parked Traffic	Encroached Traffic
Rigid shoulder	346,000	346,000
Flexible shoulder	69,000	< 438,000

Note that the computed life of a 4 in (102 mm) flexible shoulder is lower than that of a 3 in (76 mm) shoulder. Therefore, some caution should be exercised in selecting a 3 in (76 mm) thickness, as discussed in section 3.5. As in the previous example, the base thickness needs to be increased by 3 in (76 mm) if a 3 in (76 mm) thick shoulder is to be built.

4.6.3 Slope Analysis

The last step in shoulder design is to check if the cross-slopes meet the AASHTO guidelines.

a) Determine the mainline pavement cross-slope, MS.

b) Determine the subgrade cross-slope under the shoulder

c) Select the shoulder width, W

d) Determine the shoulder cross-slope, SS. This is equal to the difference in inner and outer edge thicknesses (in inches) divided by the shoulder width (in inches), plus the subgrade cross-slope under the shoulder.

e) Check if the shoulder cross-slope (SS) is greater than 8 percent. If SS is greater than 8 percent, the shoulder outer edge thickness may be increased or the slope of the subgrade or base under the shoulder may be decreased. If the drainage (base) layer thickness will change as a result of slope adjustments, the adequacy of the drainage layer should be revaluated using step 3.

f) Check the difference in the cross-slope of the shoulder and mainline pavement. The algebraic difference may not exceed 7 percent according to current AASHTO standards. If this value is exceeded, the remedial actions suggested in step e above should be applied.

DESIGN EXAMPLE

a) Pavement cross-slope, MS = 2 percent

b) Subgrade cross-slope, gt = 2 percent

c) Width = 10 ft (3.05 m)

d) Shoulder cross-slope SS = 2 percent

e) SS < 8 percent, OK

f) MS - SS = 0, OK

APPENDIX A

Evaluation of Drainage Needs

A.1 Introduction

Climatic factors, such as rainfall, frost depth and temperature are among the most important parameters affecting pavement performance.

The influence of precipitation on pavement performance is reflected by moisture related damage in various pavement component layers and the weakening of pavement support conditions.

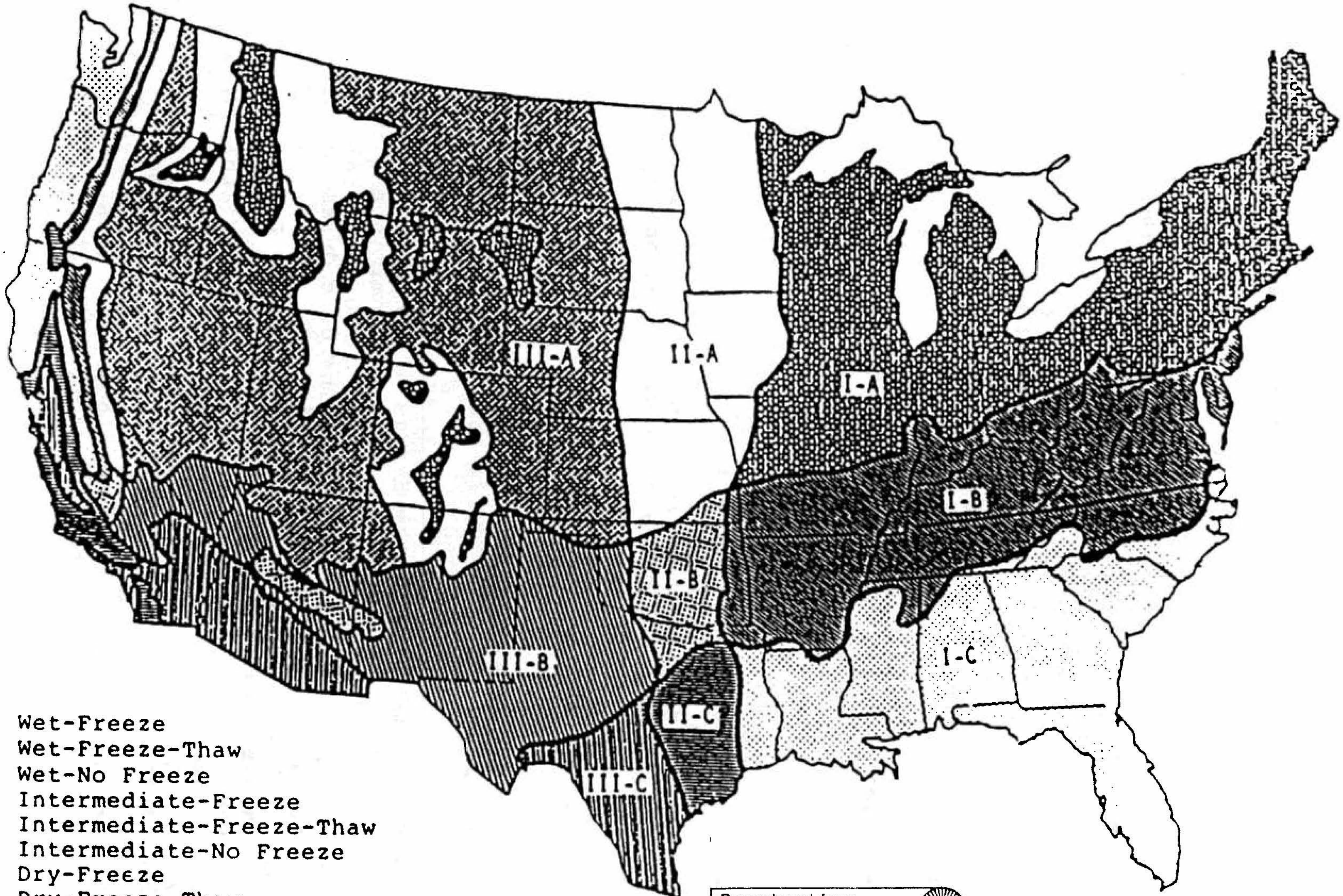
Surface water infiltration, high groundwater, and capillary rise in the pavement structure contribute significantly to pavement distresses. The damaging effects of adverse drainage on pavement performance have been documented and show that, if a pavement system is expected to perform well over its expected design life, an adequate drainage system should be designed and installed.

The infiltration of excess water into a pavement system can result in several distresses which would significantly reduce the life of the pavement. The fact that moisture problems may appear in any layer emphasizes the necessity of having a logical procedure for examining the pavement to determine where the problem is most likely originating. The amount of moisture in a pavement and the impact of that moisture on performance are primarily due to climatic factors. A large number of climatic variables have been studied and catalogued for nearly every region in the United States. FHWA studies have provided guidelines to identify climatic regions for the United States. These regions provide areas of similar expected pavement performance based on moisture availability in the subgrade and the influence of temperature. There are nine distinct zones shown in figure 34. They may be described as follows for the moisture regions:

I-A, Wet-Freeze
I-B, Wet-Freeze-Thaw
I-C, Wet-No Freeze

II-A, Intermediate-Freeze
II-B, Intermediate-Freeze-Thaw
II-C, Intermediate-No Freeze

III-A, Dry-Freeze
III-B, Dry-Freeze-Thaw
III-C, Dry-No Freeze



I-A, Wet-Freeze
I-B, Wet-Freeze-Thaw
I-C, Wet-No Freeze
II-A, Intermediate-Freeze
II-B, Intermediate-Freeze-Thaw
II-C, Intermediate-No Freeze
III-A, Dry-Freeze
III-B, Dry-Freeze-Thaw
III-C, Dry-No Freeze

Figure 34. Climatic zones for the United States.[17]

The zones are based on a yearly average and some discrepancies may exist on a localized basis. These should be checked by performing the calculations for any particular locality.

The performance of a pavement structure is also dependent on the internal factors and those properties of the pavement which protect the pavement system from detrimental effects of excess moisture.

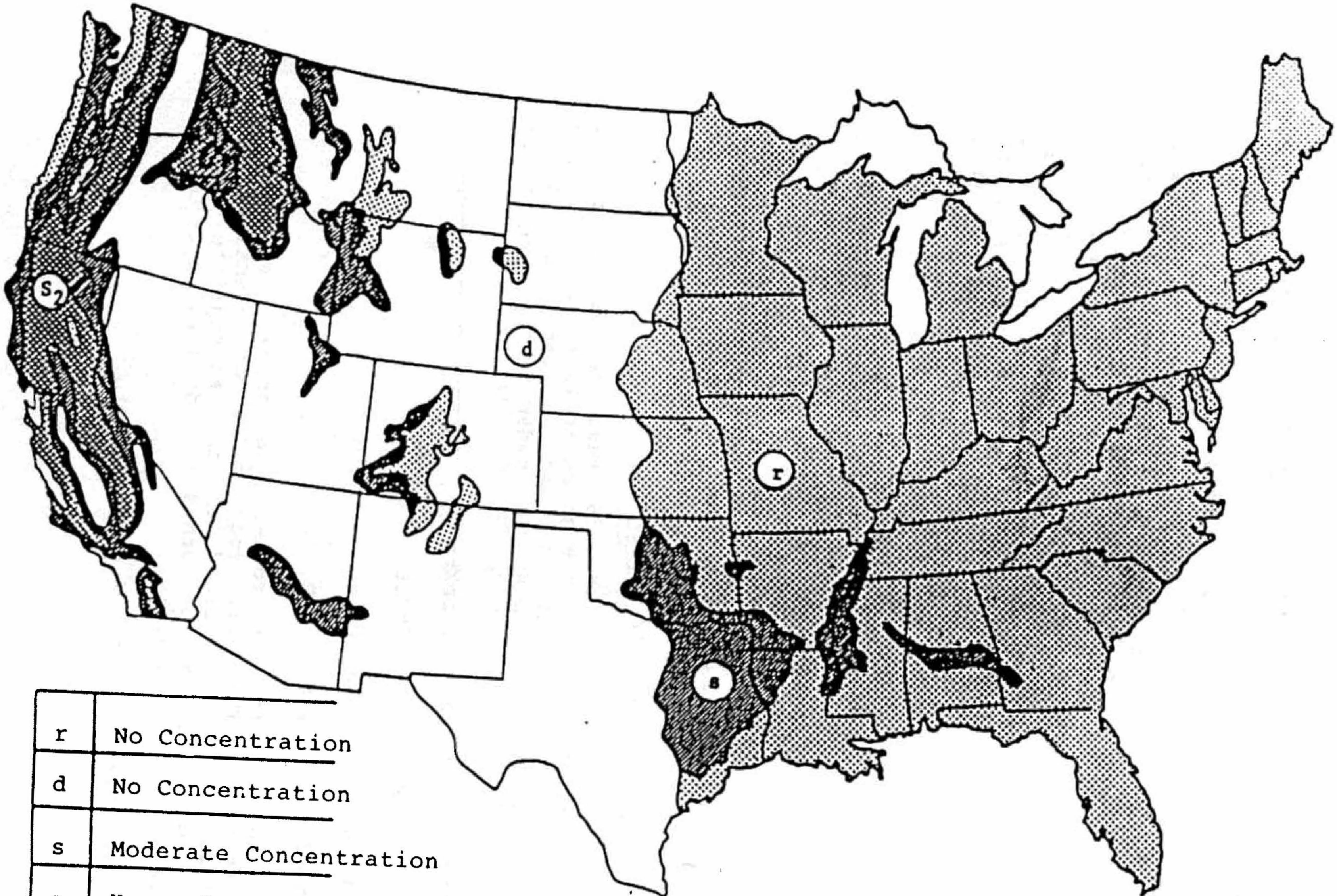
Seasonal variations must be examined. Two regions receiving the same annual moisture will have pavements that perform differently if one of the regions receives all of its rainfall in one period of several months while the other receives the same rainfall evenly distributed over the year. The distribution of seasonal moisture variations is shown in figure 35. The important point to consider is that in a moist region, with an S2 rating, the summers will be drier and the winters wetter than an area without an S2 rating. Likewise, in a dry region with an S2 rating. This is why California experiences pumping and faulting in a dry climate.

It has been recommended that in regions where relatively high annual rainfalls exist or where significant groundwater exists, consideration should be given to providing subsurface drainage systems. In a study by Cedergren et al. on subsurface drainage, it was recommended that a subsurface drainage system is required if:[89]

1. The average annual precipitation is more than 10 inches (254 mm), or

2. The pavement is expected to be subjected to more than 250 18 kip (80 kN) equivalent axle loads per day during the design life of the pavement.

The general guidelines for the design of subsurface drainage systems were developed for the Federal Highway Administration by Cedergren et al.[89] A more recent summary of drainage systems is found in the NCHRP Synthesis 96.[16] The procedures consider subsurface drainage layers as conveyors of water, and consider water in-flow rates; laboratory results of the permeability tests on the pavement materials are then used to determine the required thickness of a subsurface drainage layer that will accomodate the water flow. The drainage system is designed so that it would have an out-flow rate equal to the rate of infiltration water into the pavement during a one-hour per one-year rainfall. Liu and Lytton have also developed a mechanistic drainage analysis system; however, this requires several input parameters that are not readily available.[65]



r	No Concentration
d	No Concentration
s	Moderate Concentration
s_2	Heavy Concentration

Figure 35. Distribution of seasonal moisture variation across the United States, after Thornthwaite.[17]

A.2 Moisture Accelerated Distress Identification System (MAD System)

Drainage is not the answer to all moisture related distress problems. The MAD System (Moisture Accelerated Distress Identification System) developed by Carpenter et al. is a useful guide that indicates the relative potential for moisture to cause or accelerate distress, as well as to improve performance.[39] The MAD Index is formed based on the climate of the area and the properties of the pavement foundation materials and can be used for both new design as well as for investigation of rehabilitation needs. The MAD User Manual contains step-by-step instructions to perform the required analysis and develop the data for drainage, maintenance and/or rehabilitation needs.[90] The sections pertinent to new design are reproduced below.

A.2.1 Climatic Zone

First, determine the climatic zone the pavement is located in from figure 34. This will consist of a Roman numeral and a capital letter; e.g., I-A, which will be used later in the ranking procedure. The next step is to determine if the pavement will experience a moisture surplus during the year which would accelerate the deterioration. Figure 35 contains the areas where seasonal moisture imbalances will exist. This value should be recorded.

A.2.2 Drainability of Granular Layers

The form presented in figure 36 must be filled in to calculate the drainability of the granular layers. First, the pavement cross-sectional properties must be recorded. These include the following which should be recorded in the appropriate place on figure 36.

1. Longitudinal Slope, gl, ft/ft.

2. Transverse Slope, gt, ft/ft.

3. Thickness of Drainage Layer, H, ft.

4. Width of Drainage Layer, D, ft.

Sections having different cross-section properties must be analyzed separately. The terminology used to differentiate each pavement section should be recorded in the appropriate block. Three calculations must be performed as indicated in figure 36 for the cross-sectional properties.

1. Le = effective length of drainage path

$$= D\,[(gl/gt)^2 + 1]^{.5}$$

PAVEMENT SECTION ____________________

STEP 1. INPUT BASE COURSE PROPERTIES

PERCENT FINES (-#200) ________ TYPE OF FINES ________

D_{10} ________ mm. DENSITY, γ_d ________ pcf

G_s ________ PERMEABILITY, K ________ ft/day

STEP 2. INPUT GEOMETRIC PROPERTIES

THICKNESS, H ________ ft WIDTH ________ ft

TRANSVERSE GRADIENT, gt ____ ft/ft LONGITUDINAL GRADIENT, gl ____ ft/ft

STEP 3. PERFORM GEOMETRIC CALCULATIONS

$Le = D\sqrt{(gl/gt)^2 + 1}$ = ________ $ge = \sqrt{gl^2 + gt^2}$ = ________

$S = H/(Le \cdot ge)$ = SLOPE FACTOR = ________

STEP 4. PERFORM VOLUME CALCULATIONS

$W_s = \gamma_d / 62.5$ ________ gm

$V_s^* = W_s / G_s$ = (   ) / (   ) = ________ cc

$V_v = 1 - V_s$ = ________ cc = B

STEP 5. a) ESTIMATE WATER LOSS (Figure 37) C = ________ %

b) SPECIFIC YIELD, $Ne = B.C/100$ = (   )(   )/100

c) PARAMETER $X = Ne . Le/(H.K)$ = ________

* ASSUME $V_T = 1.0$

Figure 36. Form used for calculation of drainability.

2. ge = effective slope of drainage path

$$= (gl^2 + gt^2)^{.5}$$

3. S = Slope Factor
S = H/(Le x ge)

The soil properties section must be completed next. The gradation curve and plasticity characteristics must be known. These can be obtained from construction records and tests run on core samples. Initial results can be developed from construction records but final recommendations for rehabilitation or drainage work must be based on actual core data. The information to be recorded includes:

1. Percent fines (- #200)

2. Type of fines

   a. Inert - Substantially below "A" line in Unified Classification system, PI below 1.

   b. Silty - Material plots near "A" line. PI above 1, but below "A" line.

   c. Clay - Material has high PI, it plots above the "A" line in the Unified System.

3. D10, effective grain size with 10 percent of the material passing this size, mm.

4. Dry density, pcf and gm/cc.

5. Specific gravity of solids, Gs. This may be obtained from construction records and initial material tests, and will not vary from section to section.

These should be recorded in the appropriate blank in figure 36.

The next section to be completed on figure 36 involves calculation of drainability properties of the pavement section. This section involves performing some calculations which are outlined in figure 36 and may be listed as follows:

1. Assume Vt = 1.0.

2. Calculate Vs = Ws/Gs.

3. Calculate Vv = 1 - Vs = Nemax (= B). Nemax is the volume of water that completely fills the voids in the material.

4. From figure 37 select the estimated water loss, C. Consult plasticity and grain size data for the material.

AMOUNT OF FINES	2.5% FINES			5% FINES			10% FINES		
TYPE OF FINES	INERT FILLER	SILT	CLAY	INERT FILLER	SILT	CLAY	INERT FILLER	SILT	CLAY
GRAVEL	70	60	40	60	40	20	40	30	10
SAND	57	50	35	50	35	15	25	18	8

% Gravel, 0% fines, 75% greater than # 4: 80% water loss

* Sand, 0% fines, well graded: 65% water loss

* Gap graded material will follow the predominant size

Figure 37. Estimated value of water loss for calculating specific yield, C.[17]

5. Calculate the specific yield, Ne = (Nemax) x C/100 = (B x C/100).

6. Calculate X, X = (Ne x Le)/(H x k); k, the permeability may be estimated from figure 38.

These data are used in figure 39 to calculate drainage times and saturation levels as follows:

1. From figure 40 select a time factor (T) for every value of U. The slope factor (S) previously calculated, is used to select the proper curve.

2. Calculate the drainage time, in hours, for Column 3. (Column 2) x X x 24 = hours

3. Specific yield (Ne) times U gives the amount of water drained during this time. Record this in Column 4.

4. Subtract Column 4 from Nemax (labeled B). This is the amount of water remaining in the sample and goes in Column 5.

5. Column 5 divided by Nemax (labeled B) times 100 gives the saturation level of the sample and is recorded in Column 6.

The values of t in hours and the percent saturation should be plotted on figure 41 to determine the suitability of the granular layer for drainage purposes. This classification will be either acceptable (a), marginal (m), or unacceptable (u).

If the pavement being investigated for rehabilitation has distinct portions where different granular materials are used, each section with a different granular material should be evaluated separately. Each section will receive a separate rating for granular drainability. Areas which receive similar ratings may be combined. The areas of granular drainability should be noted on a strip map of the project to show their locations.

A.2.3 Drainability of Subgrade

The first step in evaluating the subgrade for potential contribution to moisture damage is to determine the type and distribution of subgrade materials present under the project. The USDA County Soil Maps are recommended to obtain this information. They will provide a very detailed picture of the soils present. A second choice would be to use soil test results taken from construction records which were used to delineate soil types for the original design.

$$k = \frac{3.796 \times 10^5 (D_{10})^{1.478} (n)^{6.654}}{(P_{200})^{0.597}}$$

$$n = \text{Porosity} = \left(1 - \frac{\gamma d}{62.4G}\right)$$

g = Specific Gravity (gm/c.c.)
(Assumed = 2.70)

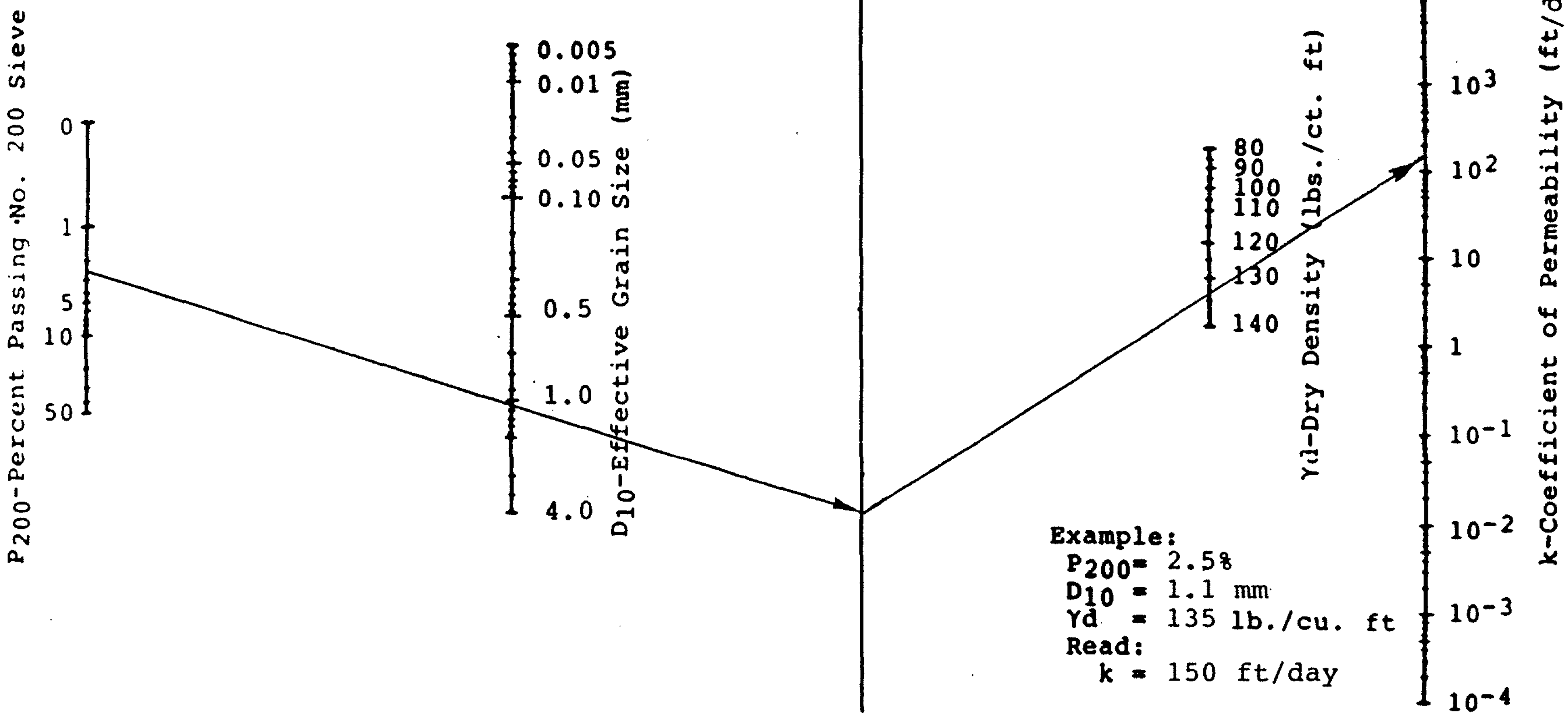


Figure 38. Nomographic procedure to estimate permeability of granular materials.[17]

(1) U	(2) T	(3) $(2) \cdot X \cdot 24 = hrs$	(4) $N_e \cdot U$	(5) $\underline{\underline{B}} - (4)$	(6) $(5/\underline{\underline{B}}) \cdot 100$
.1					
.2					
.3					
.4					
.5					
.6					
.7					
.8					
.9					

Figure 39. Calculation table for obtaining saturation levels and drainage times. [17]

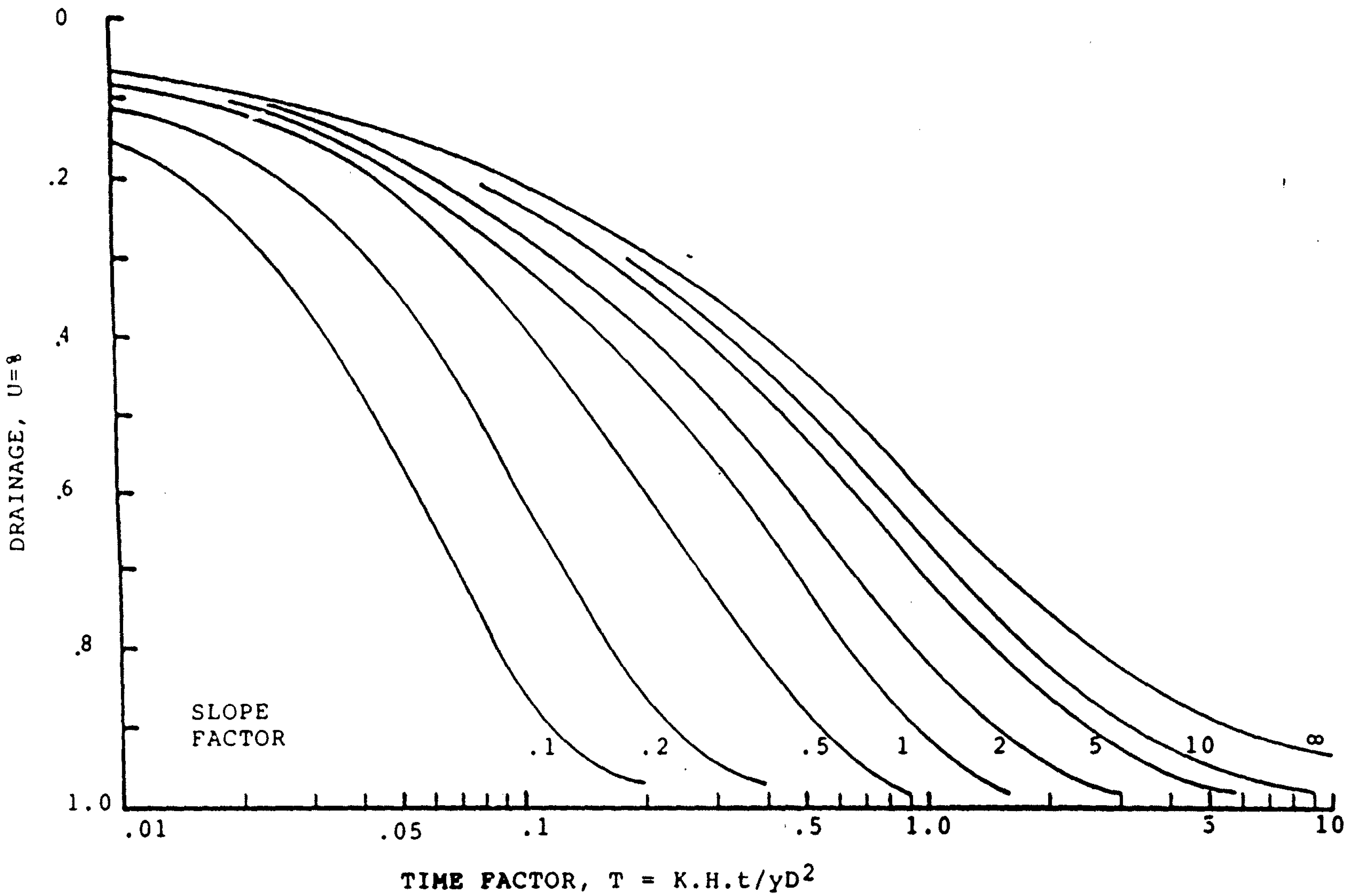


Figure 40. Curves for obtaining time factor, T, to be used in figure 39.[17]

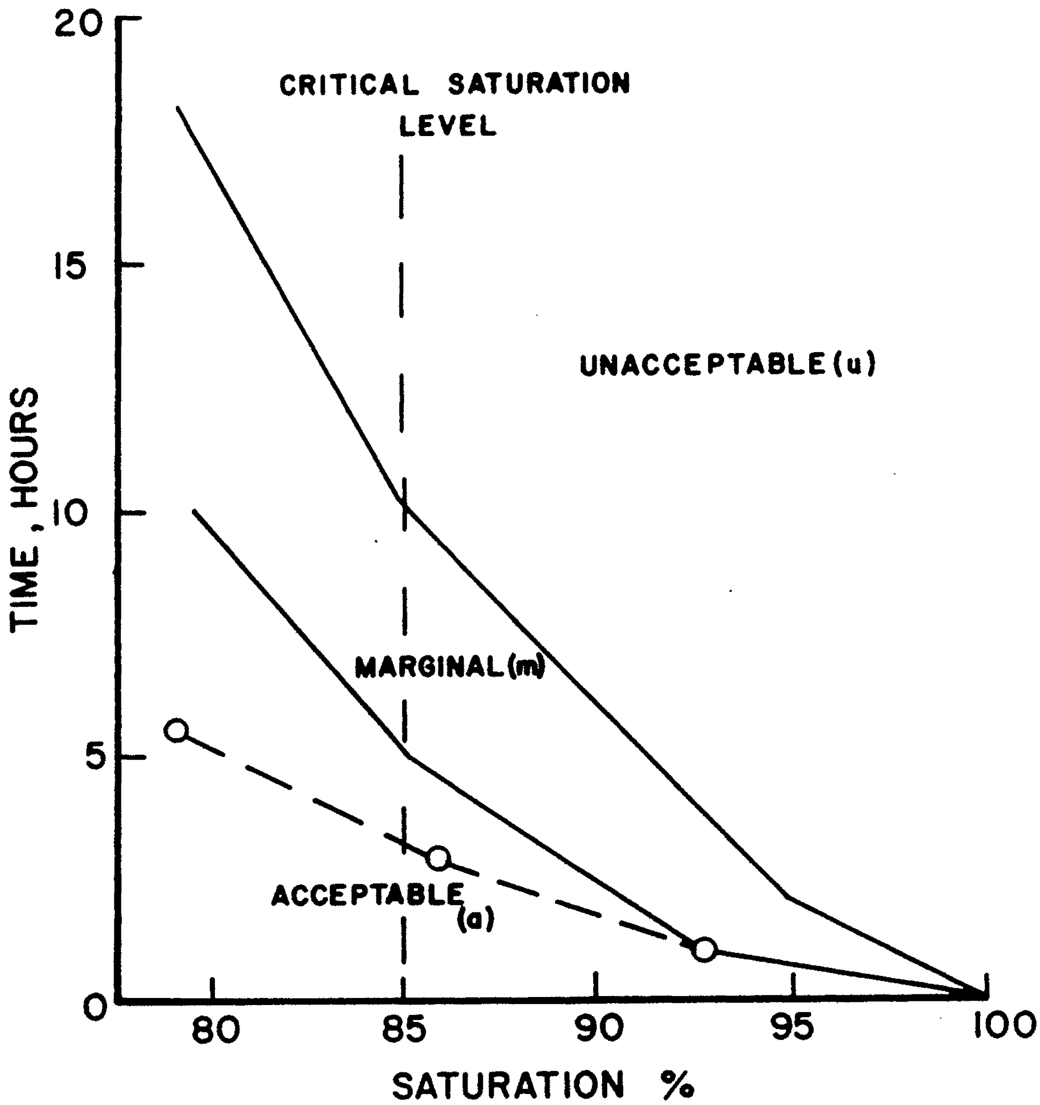


Figure 41. Drainability curves for granular base material.[17]

When the county soil maps are available, subgrade boundaries and types can be marked directly on a strip map of the project. The drainage class of each subgrade type can be noted from the soils map information and the Natural Drainage Index value selected from figure 42. When using only soil classification data, the approximate relationships in figure 43 can be used to determine the Natural Drainage Index. The problem of extensive reworking of soils during grading, for example, will not produce a change in the NDI, which will develop over several years once the pavement is completed. When a pavement is being investigated for rehabilitation, the intermixing will have been negated and the altered soils will have assumed the properties of the undisturbed underlying soil. Thus, the soil maps will very likely still accurately reflect the soil under the pavement. Extensive cuts or fills, greater than 4-6 feet (1.2-1.8 m) may take much longer to approach the condition of the original soil. These localized areas should be examined individually and assigned an average value indicating whether the cut or fill improved the material present under the roadway and improved the position relative to the water table.

A.2.4 Evaluation of Pavement

When a rating for each of the parameters discussed thus far has been determined, a combined rating for the different pavement sections may be obtained from figure 44. This rating (MAD Index) indicates the relative potential for moisture-related damage to develop. Because any one project will be in a uniform climatic area, the main differences will exist in the granular and subgrade materials. Specific areas with high potentials for MAD should be noted on the project strip map along with those areas having the lowest potential for MAD. These ratings can then be directly compared with the actual distress present to see if moisture is actually producing damage as predicted.

Existing drainage facilities, if present, should be noted on the project strip map. The adequacy of these facilities should be evaluated by visual inspection and discussion with personnel knowledgeable with the project. During the visual examination, other problems should be noted if they are observed. These would include improper grade lines, standing water in ditches or at shoulder edges, etc.

With these items indicated on the project strip map, the engineer will know exactly where good and poor materials are located, where good and poor drainage facilities are located, and where potential moisture problems could develop. Placing all of this information on the strip map will allow the engineer to examine interactions between these factors which should relate to the amount of distress that has developed, particularly the amount of moisture related distress present on the pavement. The quantification of this distress will be presented in the following section.

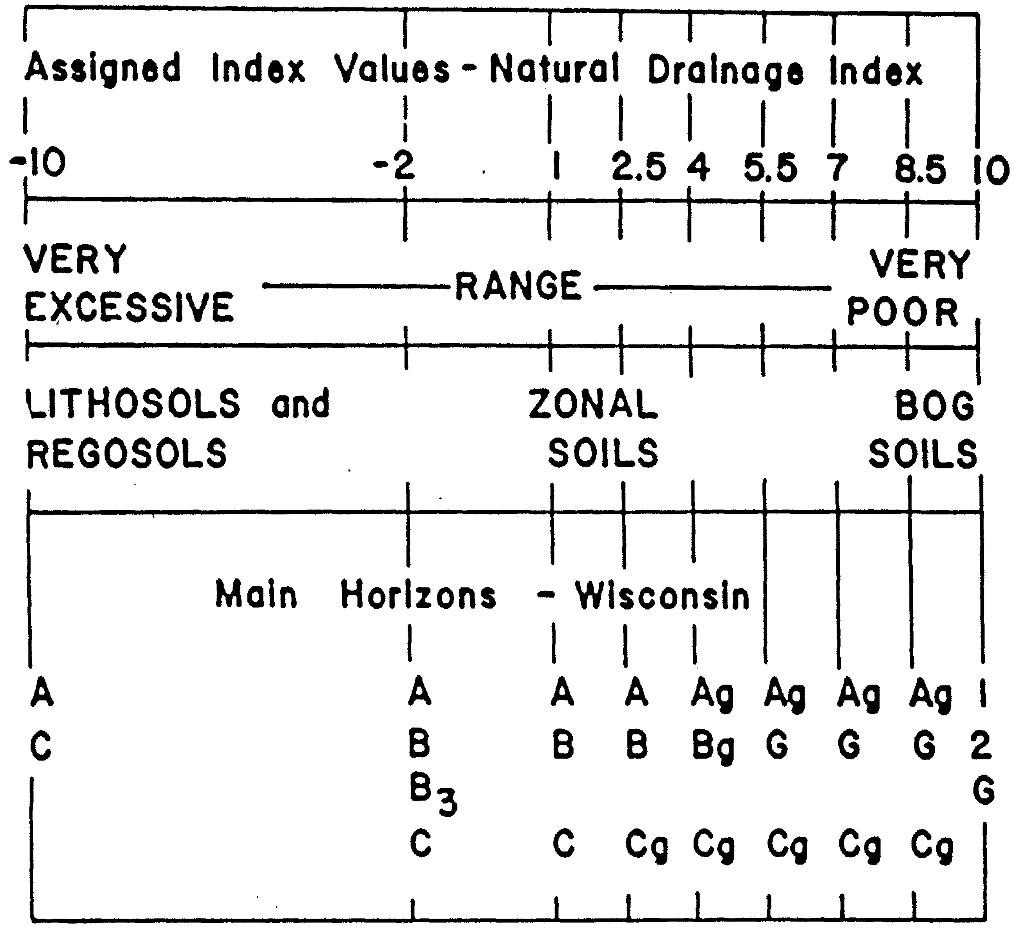


Figure 42. Natural drainage index relationships.[17]

AASHTO Class \ Position in Topography	Top of Hills	Sides of Hills	Depressions
A-1 A-3	K	K	K
A-2-4 A-2-5	K	K	J
A-2-6 A-2-7	K	K	J
A4	K	J	J
A-5	J	J	i
A-6	J	i	i
A-7-5 A-7-6	i	i	i

A group index above 20 will alter the NDI rating, K → J, J → i

A group index below 5 will alter the NDI rating, i → J, J → K.

Note: K,J,i are drainage indices

Figure 43. Approximate relationships for obtaining the natural drainage index from soil classification data.[17]

MAD Index	Damage Potential	Combinations
100	NEGLIGIBLE	Moisture Region (Figure 17)
99		
98		Temperature Region (Figure 17)
97		
96		Granular Material acceptability
95		(Figure 21)
94		Subgrade Drainability
93		(Figure 18)
92		III Cak
91		
90		
89		III Cmk
88		
87		
86		
85		III Caj, III Bak
84	LOW	
83		
82		III Bmk
81		
80		
79		
78		III Caj, III Cmj, III Baj, III Cuk, III Aak
77		
76		
75		III Amk
74		II Cak
73		
72		
71		III Cuk, III Bmj, III Aaj, III Buk, II Cmk
70		III Cmi, III Baj
69	NORMAL	
68		
67		II Caj, II Bak
66		
65		
64		III Buk, III Ami, III Auk, II Bmk
63		III Cui, III Bmi, III Aai
62		
61		
60		II Cmj, II Baj, II Cuk, II Auk
59		II Cai
58		
57		III Auk, II Amk
56		III Bui, III Ami
55		
54	MODERATE	I Cak
53		II Cmi, II Baj, II Cuk, II Bmj, II Auj, II Buk
52		
51		I Cmk
50		
49		III Aui
48		
47		I Caj, I Bak
46		II Buk, II Amj, II Auk
45		II Cui, II Bmj, II Aui
44		I Bmk
43		
42		
41		
40		I Cmj, I Bai, I Cuk, I Aa
39		II Auk, I Cai
38		II Bui, II Ami
37		I Amk
36		
35		
34	HIGH	
33		I Cuj, I Bmj, I Aaj, I Buk
32		I Cmi, I Bai
31		II Aui
30		
29		
28		
27		
26		I Buj, I Amj, I Auk
25		I Cui, I Bmi, I Aai
24		
23		
22		
21		
20		
19		I Aui
18		I Bui, I Ami
17		
16		
15		
14	EXCESSIVE	
13		
12		
11		I Aui
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		
0		

Figure 44. The MAD Index.[17]

A.2.5 MAD Index

The MAD Index is composed of factors representing the climate, granular layers, and the subgrade. Descriptions of the various levels for the MAD Index are given in figure 45. The breakdown by individual components is given in figure 44. Each individual component of the MAD Index will have an influence on the rehabilitation decision. Brief descriptions are given in figures 46 through 50 describing the factors which are important in moisture related distress.

For any one climatic zone, the materials could still be moisture susceptible and produce distress even with low moisture present (Region II and III). General recommendations are shown in figure 51.

A.3 Drainage Materials

A.3.1 Drainage Pipe

Presently, several different drainage pipes of various lengths and diameters are being used in pavement subsurface drainage. Some of these are as follows:

1. Clay tile.
2. Concrete tile and pipe.
3. Vitrified clay pipe.
4. Perforated plastic bituminous fiber pipe.
5. Perforated corrugated-metal pipe.
6. Corrugated plastic tubing.

The clay and concrete tile can be obtained in 1 to 3 ft (0.3 to 0.9 m) lengths. Metal and fiber pipes are usually manufactured in lengths of 8 ft (2.4 m) or longer. The thick-walled, semi-rigid plastic tubing may be obtained in about 20 ft (6 m) lengths. The corrugated plastic tubing is manufactured in rolls about 200 to 300 ft (61-91 m) long. For subsurface drainage, the pipe diameter generally ranges between 4 in and 6 in (102 and 152 mm). However, the California Department of Transportation uses slotted plastic pipe with an inside diameter of 1-1/2 in (38 mm).

Most of the newer drainage pipes are flexible conduits rather than rigid conduits such as clay, concrete, or metal conduit. The flexible plastic drains can fail as a result of excessive deflection if inadequately installed. For this reason, the load-deflection characteristics are important considerations

MAD Index

Negligible (85-100): This pavement would not show any moisture-related problems during its lifetime. Drainage not needed.

Low (70-85): This pavement contains a combination of properties that make it moisture insensitive, but climatic influences and maintenance must be carefully watched to maintain the good performance.

Normal (55-70): This pavement is composed of average materials exposed to average situations. Moisture damage is likely unless adequate drainage and maintenance are kept at a high level.

Moderate (35-55): Lower quality materials and a slightly inferior climate will produce large amounts of moisture damage unless extensive care is given to drainage considerations and routine maintenance.

High (15-35): Even with adequate drainage moisture damage will appear due to variability in materials. Without drainage there would be excessive moisture damage.

Excessive (0-15): The combination of climate and materials precludes any effectiveness of drainage in reducing moisture damage. Severe problems will develop, excessive maintenance should be planned for.

Figure 45. Potential for moisture accelerated problems in a pavement, as indicated by the MAD Index.

REGION	DESCRIPTION
A	This region experiences long winters with the temperature below freezing for extended periods. The potential for a slowly advancing freezing front into the subgrade is extremely high. Frost damage is to be expected, accompanied by other low-temperature problems.
B	This region experiences winters with more fluctuation of the temperatures about the freezing point. Freeze-thaw cycling into the base course is to be expected. Some thermal fatigue problems could be expected, with hot summers being a problem in the West due to radiation.
C	This region is characterized by relatively mild winters (compared to A to B) and damage may range from minimal thermal fatigue in the North to high temperature stability problems in the South.

Figure 46. Regional temperature descriptions.

REGION	DESCRIPTION
I	- Due to the climatic influences, the subgrade will remain wet for the majority of the year and little moisture variation will occur. Performance relationships indicate that the region will maintain a moisture level that will produce low load-related performance.
II	The state of moisture in the subgrade will vary during the year, but the average moisture condition is very much drier than Region I. Region II produces a moisture state that produces load related performance in a transitional portion between good and poor. Seasonal concentration of moisture will be important in determining which level of performance would be present.
III	In Region III, the annual moisture state is dry. The load-related performance is good for all materials. Seasonal concentrations of moisture will be responsible for producing slightly lower performance in one area than another where the moisture is not concentrated in one time period.

Figure 47. Regional moisture descriptions.

CONCENTRATION INDEX	DESCRIPTION
r & d	In these areas, there is little or no water surplus in any season and the performance will be as indicated by the regional description.
S	In these areas, there will be a moderate concentration of moisture during the winter months and slightly decreased performance during the winter may account for moderate performance differences between other areas that do not have this uneven input.
S2	In these areas, there will be a large concentration of moisture during the winter months. In these areas, accelerated deterioration due to moisture will occur as compared to areas without this concentration. Moisture damage should be similar to regions having higher annual moisture.

Figure 48. Seasonal moisture concentration.

Acceptable:	(a):	Will readily pass water to the down slope. Free draining. Load related granular moisture performance will be excellent and will not be influenced by the subgrade.
Marginal:	(m):	May let load related moisture damage accumulate in the granular layer. Drainage is an absolute necessity for this material. The moisture related performance may be improved by the subgrade.
Unsatisfactory:	(u):	Granular layer will absorb moisture and remain above the critical saturation level even with drainage. Moisture damage will be excessive in the granular layer and the subgrade cannot alter it.

Figure 49. Performance of granular layer defined by the quality level, best situation attainable.

i - poorly drained, depressional soil with high water table.

NDI < -2

J - moderately drained, larger texture, situated higher in the topographic relationship, with a greater depth to the water table.

-2 < NDI < 2

K - excessively drained, highest in the topography with the water table at a great depth where it does not interact with the pavement.

NDI > 2

Note: i, J, K from figure 43
NDI from figure 42

Figure 50. Subgrade classification.

Acceptable granular layer with:

-Excellent subgrade: No problems

-Acceptable subgrade: Watch water table fluctuations. If this section is a cut the table may be near the pavement.

-Poor subgrade: Subgrade may act as source of water for granular layers. If water table is high, drains should be considered to control the subsurface water and not the flow through the granular layer.

Marginal granular layer with:

-Excellent subgrade: Subgrade will assist drainage of granular layer to great extent, producing acceptable performance.

-Acceptable subgrade: For this combination edge drainage may be very effective in maintaining good drainage. The subgrade offers no assistance but does not hinder performance either.

-Poor subgrade: Edge drainage is a must for this combination. The subgrade actually decreases the level of performance in the granular layer. Drainage is critical to remove the moisture provided by the subgrade.

Unacceptable granular layer with:

-Excellent subgrade: Edge drains are of little or no use with a granular layer of this makeup. The subgrade provides the only beneficial drainage. Every attempt should be made to keep water from penetrating the surface layer.

-Acceptable subgrade: Again, drainage will add little benefit. In this combination the subgrade is not considered to assist the granular layer.

-Poor subgrade: There is very little hope for this combination to be improved through drainage.

Figure 51. General recommendations for the MAD Index.

when this material is being used in subsurface drainage design. Impact resistance is also important from the standpoint of damage to the pipe while it is being placed.

A.3.2 Drainage Filter or Envelope Materials

When considering open graded transverse drains, longitudinal drains, drainage blankets, and drainage wells, it is necessary to evaluate the filter or envelope material. The primary functions of the envelope material around subsurface drains are as follows:

1. To prevent the movement into the drains of soil particles which might settle and clog the drain.
2. To provide material in the immediate vicinity of the drain openings which is more permeable than the surrounding soil.
3. To provide a suitable bedding for the drain.
4. To stabilize the soil in which the drain is being laid.

Until recently, the most commonly used envelope materials were naturally graded coarse sands and gravels. There is a considerable range of gradations used for drainage envelopes. Figures 52 and 53 show a comparison of the range that can be found between two different state transportation departments. The general procedure for designing the drainage envelope for a given soil is to make a mechanical analysis of both the soil and the proposed envelope material, compare the two particle size distribution curves, and decide by some criteria whether the envelope material is satisfactory.

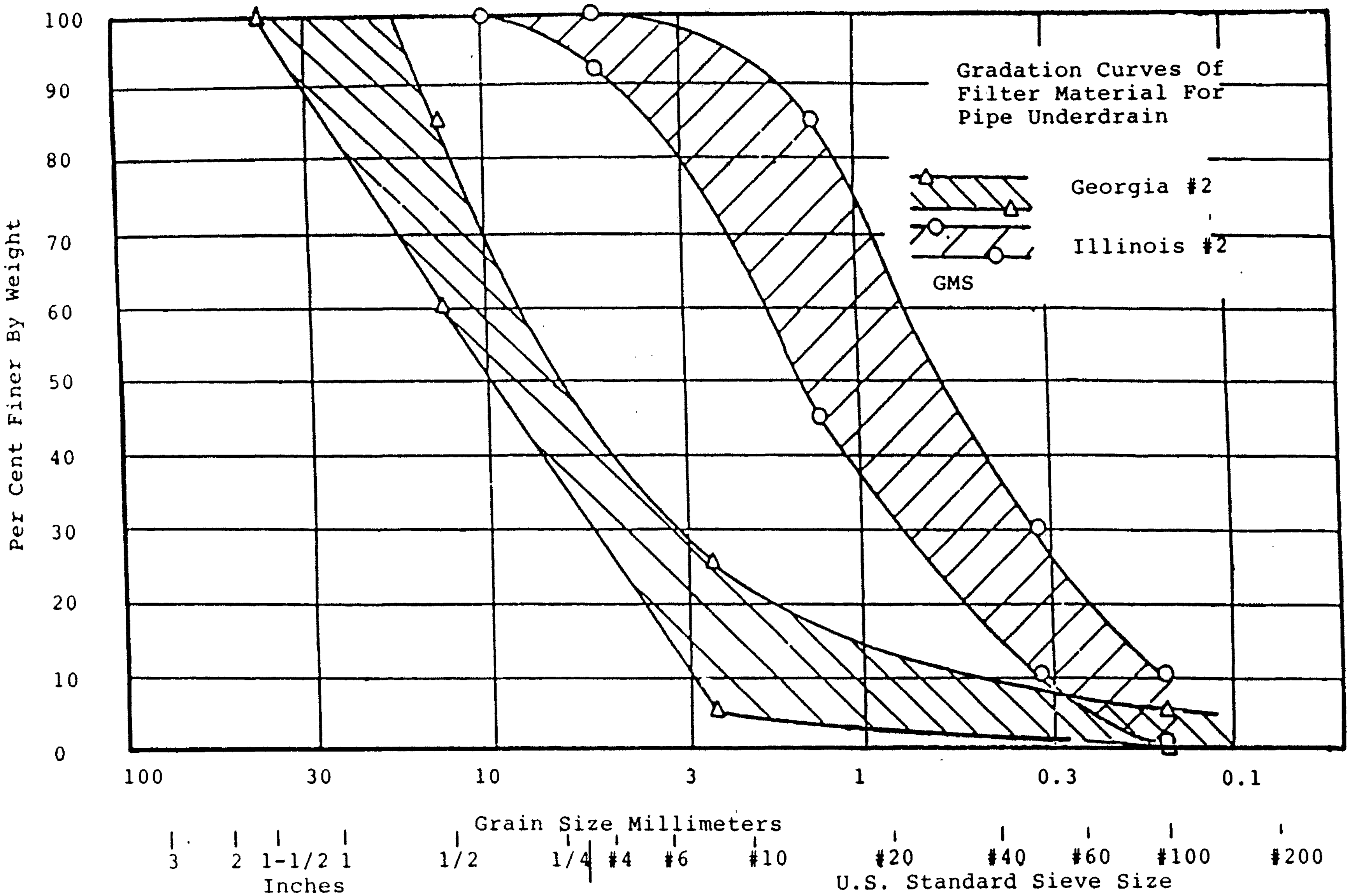


Figure 52. Gradation for filter material for pipe underdrain in Illinois.[17]

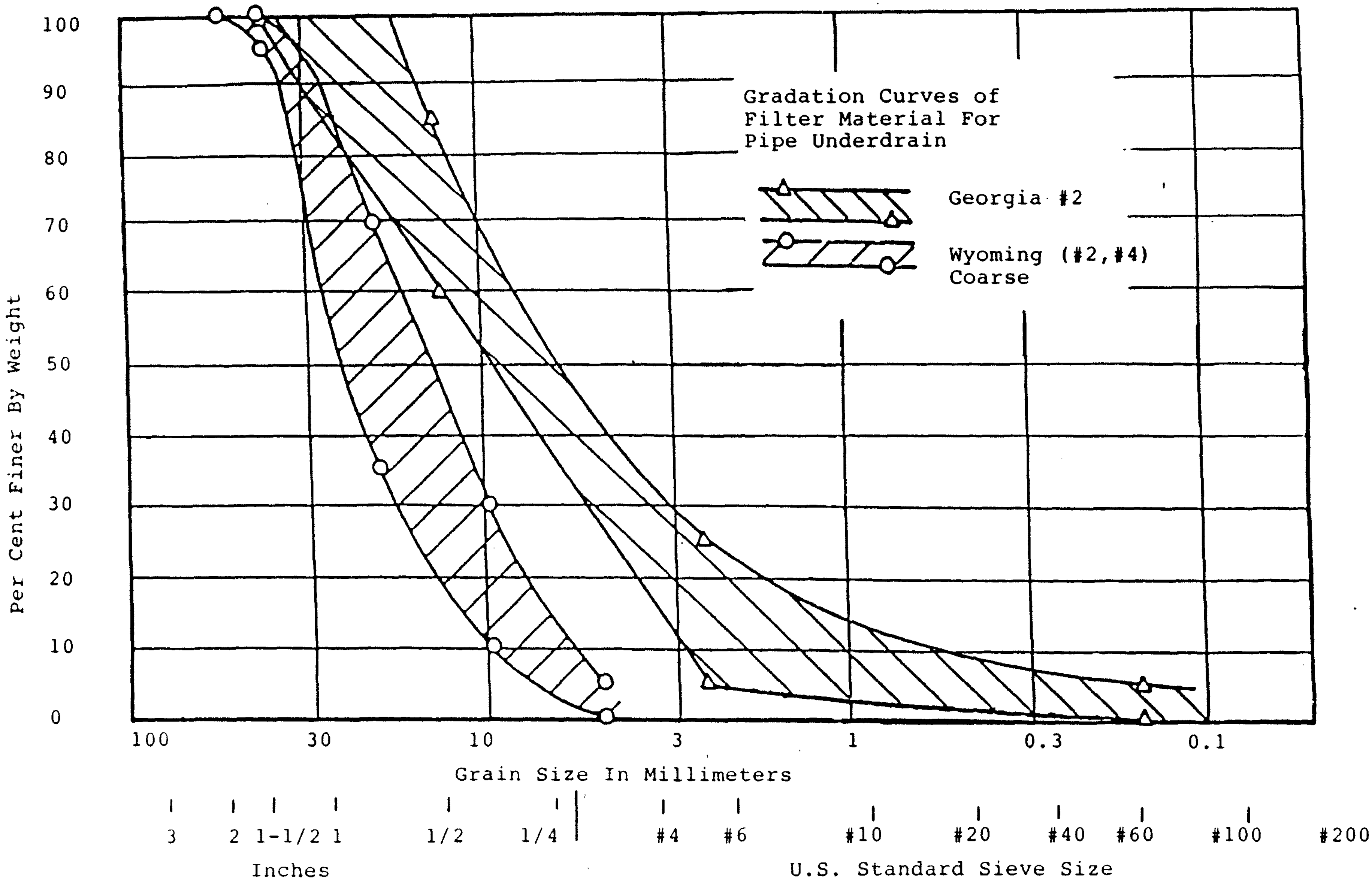


Figure 53. Gradation for filter material for pipe underdrain in Wyoming.[17]

APPENDIX B

Selection of Asphalt Cement to Minimize Both Cracking and Rutting.[21]

The effect of climate on the asphalt layer is well documented in that the asphalt modulus fluctuates substantially with ambient temperature. Therefore, it is customary to specify softer-grade asphalt in colder climates to reduce thermal cracking while harder-grade asphalt is recommended in warmer climates to reduce rutting. There is as yet no complete procedure for selecting the asphalt grade appropriate to the climate, except for a graphical solution proposed in premium pavement design to minimize low-temperature cracking.[91] Not only low-temperature cracking but also excessive rutting must be taken into account in the asphalt selection process; accordingly, the graphical plot of Von Quintus et al. is modified as in figure 54.[91] In the development of this nomograph two criteria are specified: the thermal cracking is not to exceed 35 ft/1,000 ft (115 m/1000 m) and rutting is to be no more than 0.5 in (12.7 mm).

Asphalt-Grade Selection to Minimize Thermal Cracking

Von Quintus et al. used the TC-1 program in developing the asphalt-grade selection chart.[91,92] Basma and George also have used this program because it provides the capability of estimating low-temperature cracking and material properties for asphalt-concrete surfaces. By using the program for asphalt of a given penetration index, the relation between low-temperature cracking and expected minimum pavement temperature can be obtained. Subsequently this relation was plotted in nomographical form as shown on the right-hand side of figure 54.

Asphalt-Grade Selection to Minimize Rutting

Climatologically representative stations were selected throughout the United States, and pertinent air temperature data were gathered for those stations from U.S. Weather Bureau records. AASHO flexible pavement designs were prepared for typical subgrade conditions. With the VESYS computer program, the asphalt penetration grade required for each station was determined, with the stipulation that rutting be no more than 0.5 in (12.7 mm). In other words a relation was established between the mean air temperature in combination with seasonal variations and the asphalt grade; it is nomographed on the left-hand side of figure 54.

Asphalt Selection to Minimize Both Cracking and Rutting

Employing the nomographs in figure 54, the appropriate asphalt grades for the entire country can be determined. To accomplish this, weather data such as the mean air temperature

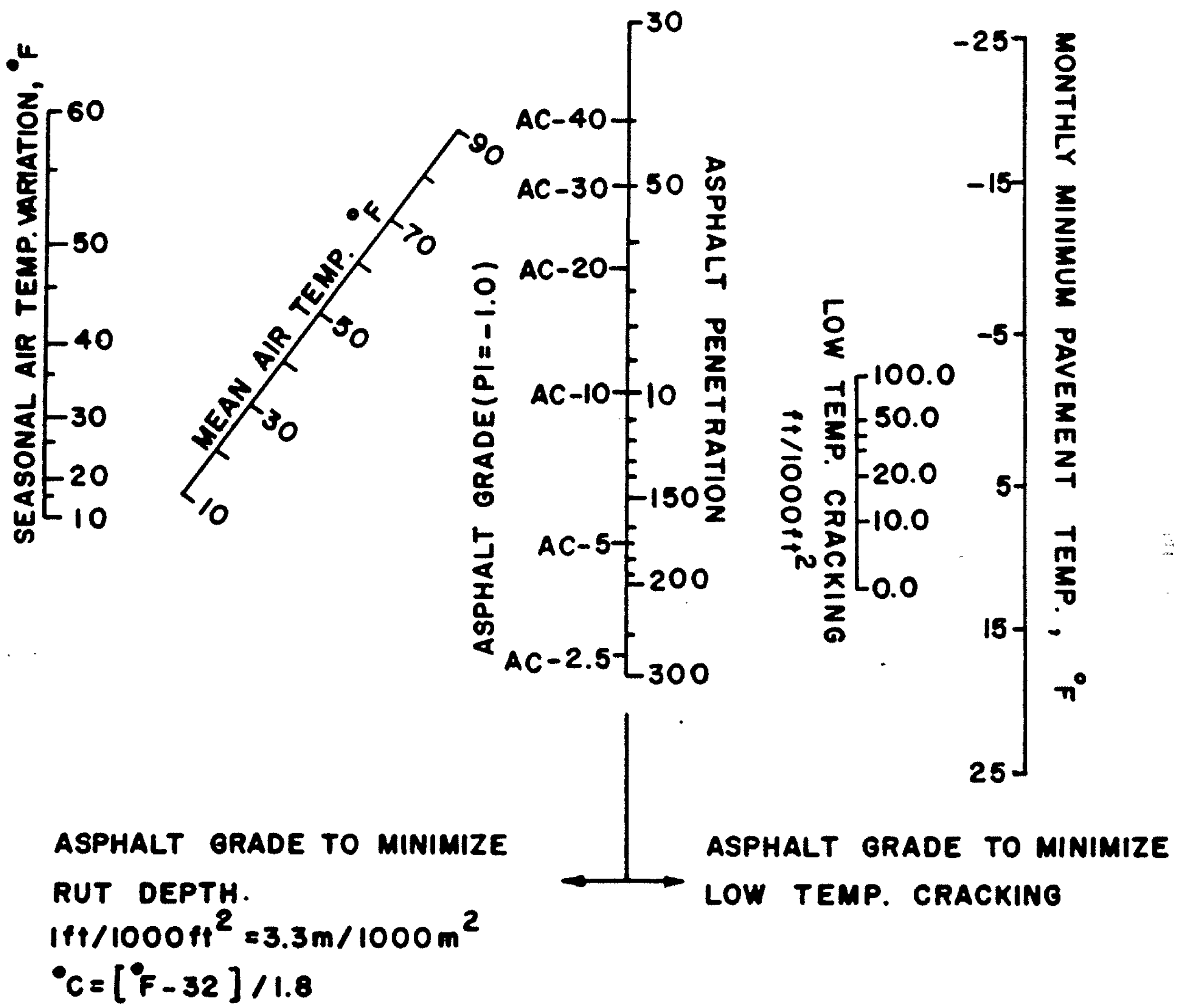


Figure 54. Asphalt-concrete grade selection to minimize rut depth and low-temperature cracking.[21]

and monthly mean air temperature variation at some 175 typical stations covering the United States were gathered from U.S. Weather Bureau records. These temperature data were used in a graph proposed by Von Quintus et al. to estimate the expected minimum temperature of the pavement at each station.[90] With the minimum pavement temperature, and the criterion of thermal cracking no more than 35 ft/1000 ft (115 m/1000 m), the minimum penetration, and therefore the asphalt grade, are obtained from figure 54. The maximum allowable penetration to satisfy the rutting criterion is obtained by placing the appropriate ambient temperature information on the left-hand side of figure 54. A grade of asphalt that will provide penetration no less than that required to prevent low-temperature cracking, and no more than that required to prevent rutting, is construed to be the right grade for that station. Note that for this study, a penetration index (PI) of -1.0 is used.

APPENDIX C

Regression Models of Equations 23-29.

Table 23
Stress in tied keyed rigid shoulder due to encroaching traffic.

PROBLEM TITLE: regression for step 21

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	UNSTANDARDIZED REGRESSION COEFFICIENT	STANDARDIZED REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED F VALUE
6	.12583	.02994	.89464	2946.72600	1.27869	199.40150	218.38490
9	.91739	.27726	-.39245	-14.98661	-.06023	6.47635	5.35484
11	1.31862	.21931	-.25189	9.21093	.02928	3.05815	9.07169
12	.01861	.01343	.69530	688.75400	.13410	118.30970	33.89127
13	.11546	.04616	.19560	-686.92630	-.45965	70.25588	95.59934
14	.07618	.02783	.67727	1074.34500	.43333	25.77120	1737.87500
15	.13346	.08491	.24058	-111.57880	-.13733	17.18540	42.15449
24	.26145	.30615	-.12452	57.90987	.25698	1.23010	2216.26000
25	.18530	.11473	.34727	27.55938	.04583	7.37955	13.94696
28	.11177	.01375	.88968	-2175.14100	-.43360	490.89480	19.63350
29	.16565	.04770	.56546	-164.16640	-.11352	22.30711	54.16038
34	691.20000	465.93910	-.80892	-.00304	-.02055	.00320	.90598
36	35.82000	12.63161	-.49295	-.18012	-.03298	.03267	30.39597
44	1.28292	.98236	-.04644	4.12073	.05868	1.18086	12.17727
47	.62636	.43643	.45590	4.16321	.02634	1.47391	7.97836
DEPENDENT							
5	193.20830	68.98849					

INTERCEPT	74.26395
MULTIPLE CORRELATION (R)	1.00006
R-SQUARED (R*R)	1.00012
STD. ERROR OF ESTIMATE	.88388
NUMBER OF OBSERVATIONS	60

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	15	280839.600	18722.640	-23964.98000
DEVIATION FROM REGRESSION	44	-34.375	-.781	
TOTAL	59	280805.300		

Table 24

Stress in rigid shoulder at the outer edge due to parked traffic.

PROBLEM TITLE: regression for step 21

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	UNSTANDARDIZED REGRESSION COEFFICIENT	STANDARDIZED REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED F VALUE
6	.12965	.03013	.83214	2931.12600	1.14034	43.55965	4527.93500
11	1.31102	.23253	-.28491	-57.37680	-.17225	4.98690	132.37670
13	.11771	.04905	.06906	-1255.58700	-.79513	38.50011	1063.57800
15	.13848	.09015	.28868	-204.12940	-.23760	18.09506	127.25980
18	.09274	.06599	.50002	668.54560	.56959	82.53868	65.60651
19	.53491	.23731	-.23295	107.82820	.33037	15.08489	51.09526
31	1.17893	.24956	-.66868	57.67283	.18582	5.06203	129.80540
32	81.23077	59.97929	-.60475	.01908	.01477	.01142	2.79249
33	1.21822	.52671	-.44402	-7.95273	-.05408	2.55023	9.72462
36	33.83077	12.19382	-.36619	-.51792	-.08154	.05633	84.54595
37	41.42308	31.03467	-.31689	-.42611	-.17073	.05657	56.73645
44	1.32484	1.04864	-.16866	16.80832	.22756	1.24119	183.38950
45	.54119	.20976	.71439	88.52223	.23973	5.59000	250.77290
47	.64692	.46528	.52528	-36.48330	-.21916	9.43357	14.95672
48	2.38462	2.58020	-.23835	9.44087	.31450	.49578	362.61430
DEPENDENT							
5	227.46540	77.45432					

INTERCEPT	-114.71300
MULTIPLE CORRELATION (R)	.99997
R-SQUARED (R*R)	.99993
STD. ERROR OF ESTIMATE	.76660
NUMBER OF OBSERVATIONS	52

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	15	305936.600	20395.770	34705.95000
DEVIATION FROM REGRESSION	36	21.156	.588	
TOTAL	51	305957.800		

Table 25
Horizontal tensile strain in flexible monolithic shoulder at inner edge due to parked traffic.

PROBLEM TITLE: strain-y in step 28 in idition to variable 9

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	UNSTANDARDIZED REGRESSION COEFFICIENT	STANDARDIZED REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED F VALUE
1	.08208	.04506	-.81620	-1.45388	-.26843	.22720	40.94804
2	7.53933	1.95749	-.06150	-.08201	-.65781	.01240	43.75639
3	18.32022	10.06329	-.81410	.00142	.05857	.00052	7.39055
7	.14369	.04445	.03745	-1.12428	-.20477	.51788	4.71288
8	-1.16860	.28782	-.84341	.52617	.62054	.07967	43.62078
9	.86103	.12287	-.05032	-2.27292	-1.14434	.38459	34.92857
12	.85348	.29011	-.77099	-1.13177	-1.34538	.02709	1745.10200
13	-1.01518	.31861	-.65100	-1.46361	-1.91074	.07723	359.19980
15	-.98437	.30939	-.52542	.32205	.40828	.02001	259.01560
17	1.03495	.24695	-.67978	.21223	.21475	.05571	14.51092
18	.73040	.19107	-.17809	.55644	.43564	.02078	717.36720
19	.73504	.27318	-.71907	.50633	.56678	.02564	389.83800
20	1.01989	.30382	-.66831	-.63976	-.79645	.01760	1320.92700
22	.72193	.29715	-.74367	.42811	.52126	.01685	645.50040
24	.07141	.03426	.79084	-1.14206	-.16034	.25096	20.70958
27	-.08888	.05851	-.87238	-1.48110	-.35508	.11847	156.29300
28	-.18397	.09819	-.54583	.32432	.13049	.04500	51.94028
31	.06146	.03115	.73115	-2.49706	-.31873	.44788	31.08430
35	.59888	.36194	-.82149	.13872	.20574	.02663	27.13438
37	14.15952	8.55857	.55131	-.00337	-.11832	.00029	139.18200
38	.05297	.01662	.53253	1.00324	.06832	.11944	70.54865
DEPENDENT							
6	2.83443	.24405					

INTERCEPT	5.49642
MULTIPLE CORRELATION (R)	.99970
R-SQUARED (R*R)	.99940
STD. ERROR OF ESTIMATE	.00637
NUMBER OF OBSERVATIONS	178

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	21	10.536	.502	12352.21000
DEVIATION FROM REGRESSION	156	.006	.000	
TOTAL	177	10.542		

Table 26
Horizontal tensile strain in flexible shoulder at outer edge due to parked traffic.

PROBLEM TITLE: strain-x in step 24 in addition to variable 9

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	UNSTANDARDIZED REGRESSION COEFFICIENT	STANDARDIZED REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED F VALUE
1	.08208	.04506	-.81433	-1.73396	-.32082	.20214	73.58064
2	7.53933	1.95749	-.05397	-.05872	-.47202	.01221	23.13609
3	18.32022	10.06329	-.81868	.00115	.04760	.00048	5.72456
4	7.66292	3.00261	-.19277	-.00664	-.08189	.00084	62.64708
7	.14369	.04445	.03028	-2.11024	-.38517	.56409	13.99474
8	-1.16860	.28782	-.84185	.76066	.89898	.06650	130.84390
10	1.20177	.22864	-.82452	.16674	.15654	.04127	16.32112
12	.85348	.29011	-.77625	-1.14381	-1.36257	.02575	1973.18100
13	-1.01518	.31861	-.65265	-1.53381	-2.00663	.06863	499.43510
15	-.98437	.30939	-.52291	.18519	.23527	.00932	395.08980
18	.73040	.19107	-.17546	.60335	.47337	.02057	860.21210
19	.73504	.27318	-.72116	.52445	.58831	.02390	481.65730
20	1.01989	.30382	-.67273	-.60249	-.75164	.01890	1016.49900
22	.72193	.29715	-.74904	.42310	.51626	.01644	662.09970
27	-.08888	.05851	-.87417	-1.40263	-.33698	.08668	261.83270
30	.11829	.01587	.04553	.59236	.03860	1.86137	.10128
31	.06146	.03115	.73756	-3.56990	-.45664	.21410	278.03210
35	-.59888	.36194	-.81537	.17675	.26269	.02400	54.22763
37	14.15952	8.55857	.54847	-.00320	-.11229	.00027	136.28080
38	.05297	.01662	.53410	.93845	.06404	.11583	65.63836
9	.86103	.12287	-.04291	-2.75095	-1.38795	.54430	25.54403
DEPENDENT							
6	2.84800	.24353					

INTERCEPT	5.82183
MULTIPLE CORRELATION (R)	.99973
R-SQUARED (R*R)	.99945
STD. ERROR OF ESTIMATE	.00607
NUMBER OF OBSERVATIONS	178

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	21	10.492	.500	13566.65000
DEVIATION FROM REGRESSION	156	.006	.000	
TOTAL	177	10.498		

Table 27

Horizontal tensile strain in flexible monolithic shoulder at inner edge due to encroaching traffic.

PROBLEM TITLE: Analysis of strain-y in step 29

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	UNSTANDARDIZED REGRESSION COEFFICIENT	STANDARDIZED REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED F VALUE
1	.44695	.26170	-.73935	-.23838	-.26187	.04748	25.20590
2	6.85366	2.15999	-.50158	-.03156	-.28612	.00979	10.37915
3	25.18293	11.74748	-.36381	.00391	.19270	.00082	22.64577
4	7.97561	3.21032	-.10907	-.00606	-.08160	.00254	5.69318
11	.86153	.19393	-.12996	-.07166	-.05833	.06822	1.10325
13	-.34510	.23317	-.58047	-1.18781	-1.16260	.05635	444.29540
15	-.36870	.25215	-.61494	.14954	.15828	.02247	44.29042
16	-.40170	.30862	-.39322	.13579	.17592	.02143	40.15257
17	1.08890	.26893	-.60940	.32560	.36756	.06283	26.85763
18	.70201	.20458	-.38635	.50122	.43043	.04157	145.37300
19	.76202	.29528	-.60984	.24668	.30576	.06559	14.14364
20	1.15759	.33536	-.32970	-.37384	-.52627	.04166	80.52740
21	1.32327	.61725	-.43203	-.38018	-.98507	.02891	172.93030
22	.81004	.33348	-.43618	.22583	.31613	.03530	40.92678
26	-.07090	.05262	-.76220	.18083	.03994	.16494	1.20199
30	.12434	.01833	.49477	19.28037	1.48334	1.41138	186.61250
32	4.35701	2.89385	.50174	-.01072	-.13025	.00344	9.70778
33	.21939	.08857	.23036	-.53323	-.19826	.13818	14.89253
35	3.12439	2.29681	-.84629	.02993	.28861	.00552	29.42925
36	77.74390	68.42457	-.51871	.00009	.02611	.00009	1.04083
38	.04240	.01520	.12981	-1.73775	-.11086	.40733	18.20030
DEPENDENT							
6	2.37679	.23822					

INTERCEPT .02185

MULTIPLE CORRELATION (R) .99828

R-SQUARED (R*R) .99655

STD. ERROR OF ESTIMATE .01498

NUMBER OF OBSERVATIONS 164

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	21	9.218	.439	1955.07900
DEVIATION FROM REGRESSION	142	.032	.000	
TOTAL	163	9.250		

Table 28
Horizontal tensile strain in flexible shoulder at outer edge due to encroaching traffic.

PROBLEM TITLE: analysis of strain-x in step 25

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	UNSTANDARDIZED REGRESSION COEFFICIENT	STANDARDIZED REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED F VALUE
1	.44695	.26170	-.73107	-.17742	-.20001	.06639	7.14239
4	7.97561	3.21032	-.11789	-.00546	-.07544	.00275	3.92805
5	11.34146	8.66588	-.44258	-.00149	-.05549	.00050	8.93669
8	-.42802	.26938	-.71414	-1.41052	-1.63670	.20080	49.34571
11	.86153	.19393	-.13885	-.08302	-.06936	.07216	1.32303
12	.93962	.31766	-.47570	-.60364	-.82599	.05372	126.24980
14	-.57543	.38493	-.55380	.33852	.56129	.08278	16.72124
15	-.36870	.25215	-.60529	.14081	.15294	.02433	33.50671
17	1.08890	.26893	-.61921	.35677	.41329	.04080	76.47699
18	.70201	.20458	-.38028	.48144	.42425	.04495	114.72620
19	.76202	.29528	-.63102	.25656	.32633	.05413	22.46181
20	1.15759	.33536	-.35729	-.37382	-.54002	.04298	75.63909
22	.81004	.33348	-.46901	.23116	.33206	.03698	39.06931
25	-1.90793	2.03401	-.61453	.01227	.10751	.00933	1.72975
26	-.07090	.05262	-.74872	1.81566	.41154	.40941	19.66794
27	-.02277	.02143	-.74488	1.63960	.15133	.58649	7.81543
29	2.62582	1.75813	.50795	.03118	.23615	.01635	3.63916
30	.12434	.01833	.47331	19.78372	1.56188	.68708	829.08970
33	.21939	.08857	.19940	-.33842	-.12912	.11782	8.25014
35	3.12439	2.29681	-.82844	.01010	.09990	.00545	3.42690
37	3.05820	2.33373	.30818	-.00959	-.09642	.00356	7.24425
DEPENDENT							
6	2.39889	.23215					

INTERCEPT	-.13647
MULTIPLE CORRELATION (R)	.99787
R-SQUARED (R*R)	.99575
STD. ERROR OF ESTIMATE	.01621
NUMBER OF OBSERVATIONS	164

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	21	8.747	.417	1584.62600
DEVIATION FROM REGRESSION	142	.037	.000	
TOTAL	163	8.785		

Table 29
Vertical compressive strain on subgrade at outer edge due to parked vehicles.

PROBLEM TITLE: Analysis of strain-z in step 20

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	UNSTANDARDIZED REGRESSION COEFFICIENT	STANDARDIZED REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED F VALUE
2	7.25714	2.04742	-.26100	-.03850	-.28228	.00947	16.54477
4	7.77143	2.89285	-.37288	-.02989	-.30966	.00435	47.26350
5	9.50000	6.98683	-.76305	-.00172	-.04307	.00106	2.62160
9	.84162	.13284	-.25311	-1.54988	-.73728	.25162	37.94064
12	.87846	.28943	-.79851	-.64043	-.66377	.08104	62.45763
13	-1.03328	.32756	-.29805	-.33594	-.39406	.04345	59.77314
14	-1.45524	.35515	.08571	.10001	.12719	.04184	5.71218
17	1.02356	.24388	-.79346	.24065	.21017	.07798	9.52476
18	.72074	.18713	-.44292	.67717	.45377	.10784	39.43268
19	.73542	.26243	-.85305	.12234	.11497	.08939	1.87306
20	1.04801	.30728	-.77285	-.26647	-.29321	.04838	30.33824
26	-.18139	.06609	-.53734	-.16138	-.03819	.19241	.70344
28	-.18552	.09482	-.56985	-.73675	-.25017	.10935	45.39372
37	17.18981	12.54760	.11481	-.00120	-.05401	.00063	3.66044
DEPENDENT							
6	2.90016	.27925					

INTERCEPT	4.40328
MULTIPLE CORRELATION (R)	.99230
R-SQUARED (R*R)	.98466
STD. ERROR OF ESTIMATE	.03580
NUMBER OF OBSERVATIONS	210

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	14	16.048	1.146	894.33670
DEVIATION FROM REGRESSION	195	.250	.001	
TOTAL	209	16.298		

Table 18
Variables used in rigid shoulder analysis, tables 23 and 24.

```
X(5)=Sigma
X(6)=1./Hc
X(9)=log10(Es)
X(11)=log10(Eb)
X(12)=1/(HcEs)
X(13)=log(Es)/Hc
X(14)=log(Ec)/Hc
X(15)=log(Hc)Es
X(18)=log(Ec)/Es
X(19)=log(Ec)*log(Es)
X(24)=log(Es)/Ec
X(25)=log(Eb)/Es
X(28)=log(Hc)/Hc
X(29)=log(Eb)/Hc
X(31)=log(Hc)*log(Eb)
X(32)=log(Hc)/log(Es)
X(33)=log(Es)*log(Eb)
X(34)=Hc**3.
X(36)=HcEc
X(37)=EcEs
X(44)=Es/Hc
X(45)=Ec/Hc
X(47)=Ex/Es
X(48)=Hc/Ec
```

Note: Ec in millions psi
Eb, Es in thousands psi
Hb in inches
Sigma in psi
Hc in inches

Table 19
Variables used in flexible shoulder analysis, tables 25 through 29.

X(1)=Ea
X(2)=Ha
X(3)=Eb
X(4)=Hb
X(5)=Es
X(6)=log(strain)
X(7)=1/Ha
X(8)=log(Ea)
X(9)=log(Ha)
X(10)=log(Eb)
X(11)=log(hb)
X(12)=log(Es)
X(13)=log(Ea)log(Ha)
X(14)=log(Ea)log(Eb)
X(15)=log(Ea)log(Hb)
X(16)=log(Ea)log(Es)
X(17)=log(Ha)log(Eb)
X(18)=log(Ha)log(Hb)
X(19)=log(Ha)log(Es)
X(20)=log(Eb)log(Hb)
X(21)=log(Eb)log(Es)
X(22)=log(Hb)log(Es)
X(23)=1/Ea
X(24)=1/Eb
X(25)=log(Ea)/Ea
X(26)=log(Ea)/Ha
X(27)=log(Ea)Hb
X(28)=log(Ea)/Hb
X(29)=log(Ha)/Ea
X(30)=log(Ha)/Ha
X(31)=log(Ha)/Eb
X(32)=log(Eb)/Ea
X(33)=log(Eb)/Ha
X(35)=EaHa
X(36)=HaEs
X(37)=log(Es)/Ea
X(38)=log(Es)/Eb

Note: Ea in millions psi
Eb, Es is thousands psi
Ha, Hb in inches
Strain in microinches

APPENDIX D

Design Program BERM.

D.1. User Guide

The primary function of the program BERM is to evaluate the regression models given by equations 23 through 29 and to evaluate the expected number of equivalent axle loads (in terms of 18 kip (80 kN) loads) the section can sustain, using the appropriate distress functions given by equations 19 through 22. The program permits the analysis of all combinations of mainline-shoulder type through appropriate selection of the parameters MFLEX and MONO. The shoulder may be either rigid or flexible (MFLEX = 0, 1, respectively) and the mainline-shoulder condition may be either separate or tied-keyed (monolithic) for rigid shoulders, and separate or monolithic for flexible shoulders (MONO = 0, 1 for separate, monolithic, respectively). Additionally, the mainline pavement may be either rigid or flexible, but this is taken care of by the mainline-shoulder conditions.

The other option that exists is the use of the widened lane concept (rigid mainline) together with a flexible shoulder. In this case, MONO = 0 but encroaching traffic (inner edge) analysis is needed only if this shoulder is to be used by regular traffic during peak periods, as was discussed in section 3.7. The program, however, carries out the analysis for both inner and outer edges of the shoulder for all cases.

The following input data are required for rigid shoulders: concrete modulus EC and flexural strength FC (28 day, 3 point loading or indirect tension tests), subbase modulus EB, subgrade modulus ES, and concrete thickness HC. Similar input data are required for flexible shoulders except that both creep and dynamic moduli (EC and EC1, respectively) are required, in addition to the subbase thickness HB. In the case of flexible shoulders, the user is given three options:

1. The values for EC, EC1, can be input, MOD = 0

2. Equation 9 can be used to compute these values (MOD = 0, EC = 0), in which case the mean annual air temperature T (design temperature) is required; the evaluation of equation 9 is done in the program.

3. The user may specify his own master creep modulus, (MOD = 1), but it must be in the form of equation 9; i.e.,

```
E=1/(XJO+XJ1*((10.**(A0+A1*T))*TI)**XM)          (39)
```

where:

T = mean annual design temperature, F

TI = loading time, seconds
= .02 seconds for dynamic loading
= 10800 seconds for creep loading

The remainder of the constants are regression coefficients, derived by the method presented in appendix F of reference 56. The user inputs XJO, XJ1, AO, A1, XM, and T. The data is input on one line (or if the last option is excercised, on two lines) using free format (data separated by commas, no comma after the last entry). The sequence of data is:

MFLEX, MONO, MOD, EC, EC1, HC, EB, HB, ES, FC, T

where:

MFLEX = 0, rigid shoulder
= 1, flexible shoulder

MONO = 0, separate or tied rigid shoulder, separate flexible shoulder
= 1, tied and keyed rigid shoulder or monolithic flexible shoulder

MOD = 0, creep modulus input by user (EC, EC1 given non-zero values), or computed from equation 9 (EC, EC1 = 0)
= 1, creep modulus computed from user input equation

EC = modulus of concrete shoulder or creep modulus of flexible shoulder, psi

EC1 = dynamic modulus of flexible shoulder; not needed with rigid shoulders, but must be included in data string with mainframe program, psi

EB = modulus of base/subbase, psi

HB = thickness of base/subbase, in

ES = subgrade modulus, psi

FC = concrete flexural strength, psi

T = mean annual design temperature, F as defined previously

Note that a value is required for each variable, but that value may be 0 if it is not used; e.g., FC may be 0 for flexible shoulders (MFLEX=1). If option 3 is exercised, then values for the parameters in equation 39 have to be specified in the following sequence:

XJO, XJ1, XM, AO, A1

All data is input in U.S. customary (British) units; i.e., moduli are in psi and thicknesses in inches. MFLEX, MONO, MOD are integers, the rest of the data is real.

As was stated above, the program is capable of analyzing all combinations of mainline-shoulder pavement, including widened rigid mainline lane with a flexible shoulder. This is done by the appropriate selection of the parameters MFLEX and MONO. Table 32 gives the possible combinations, as well as the values of MFLEX and MONO required to carry out the desired analysis. It will be noted from this table that the shoulder type, rather than the mainline type, influences the predicted life analysis. However, the mainline pavement type influences the selection of the shoulder type, as was discussed in section 3.1.

The outputs corresponding to the cases shown in table 32 are presented in figures 55 through 58. Even though seven cases are presented in table 20, these represent four distinct outputs.

Table 32
Values of MFLEX and MONO for various mainline-shoulder combinations.

Mainline Pavement	Shoulder Pavement	Joint Condition	MFLEX	MONO	FIGURE
Rigid	Rigid	tied-keyed	0	1	55
Rigid	Rigid	separate/tied	0	0	56
Rigid	Flexible	separate	1	0	57
Rigid-widened	Flexible	separate	1	0	57
Flexible	Rigid	separate	0	0	56
Flexible	Flexible	separate	1	0	57
Flexible	Flexible	monolithic	1	1	58

D.2 <u>Typical Output</u>

Figures 55 through 58 show typical outputs of the BERM program. The input information is reproduced in the output for easy checking of data. The output of the program is the expected life (in terms of equivalent 18 kip (80 kN) axle loads) the

```
* * * RIGID SHOULDER DESIGN * * *

PAVEMENT/SHOULDER JOINT IS TIED, KEYED
CONCRETE MODULUS:           4200. ksi (29.0 GPa)
CONCRETE FLEX STRENGTH:      690. psi (4.76 MPa)
SUBBASE MODULUS:             22.6 ksi (156. MPa)
SUBGRADE MODULUS:             9.0 ksi ( 62. MPa)

THE COMPUTED LIVES, IN MILLIONS EAL, ARE:
   SURFACE       OUTER      INNER
  THICKNESS       EDGE       EDGE
(in)    (mm)
 6.0 (152.4)     0.848      1.242
 7.0 (177.8)     1.872      3.010
```

Figure 55. Example output for a tied-keyed rigid shoulder adjacent to a rigid mainline pavement.

```
* * * RIGID SHOULDER DESIGN * * *

PAVEMENT/SHOULDER JOINT IS TIED
CONCRETE MODULUS:           4200. ksi (29.0 GPa)
CONCRETE FLEX STRENGTH:      690. psi (4.76 MPa)
SUBBASE MODULUS:             22.6 ksi (156. MPa)
SUBGRADE MODULUS:             9.0 ksi ( 62. MPa)

THE COMPUTED LIVES, IN MILLIONS EAL, ARE:
   SURFACE       OUTER      INNER
  THICKNESS       EDGE       EDGE
(in)    (mm)
 6.0 (152.4)     0.848      0.848
 7.0 (177.8)     1.872      1.872
```

Figure 56. Example output for a tied rigid shoulder adjacent to a rigid mainline pavement.

Note: Two thicknesses are used for computing expected lives the sections can sustain to aid the designer in projecting the required thickness for his design traffic.

* * * FLEXIBLE SHOULDER DESIGN * * *

THE SHOULDER IS SEPARATE FROM THE MAINLINE PAVEMENT

A.C. DYNAMIC MODULUS:	719. ksi	(5.0 GPa)
A.C. CREEP MODULUS:	10.7 ksi	(74. MPa)
BASE MODULUS:	22.6 ksi	(156. MPa)
BASE THICKNESS:	8.0 in	(203. mm)
SUBGRADE MODULUS:	9.0 ksi	(62. MPa)
DESIGN TEMPERATURE:	68.0 F	(20.0 C)

THE COMPUTED LIVES, IN MILLIONS EAL, ARE:

SURFACE THICKNESS (in)	SURFACE THICKNESS (mm)	ENCROACHING TRAFFIC	PARKED TRAFFIC
6.0	152.4	1.086	0.146
7.0	177.8	3.103	0.217

Figure 57. Example output for a separate flexible shoulder adjacent to a rigid or flexible mainline pavement.

* * * FLEXIBLE SHOULDER DESIGN * * *

THE SHOULDER IS MONOLITHIC WITH THE MAINLINE PAVEMENT

A.C. DYNAMIC MODULUS:	719. ksi	(5.0 GPa)
A.C. CREEP MODULUS:	10.7 ksi	(74. MPa)
BASE MODULUS:	22.6 ksi	(156. MPa)
BASE THICKNESS:	8.0 in	(203. mm)
SUBGRADE MODULUS:	9.0 ksi	(62. MPa)
DESIGN TEMPERATURE:	68.0 F	(20.0 C)

THE COMPUTED LIVES, IN MILLIONS EAL, ARE:

SURFACE THICKNESS (in)	SURFACE THICKNESS (mm)	ENCROACHING TRAFFIC	PARKED TRAFFIC
6.0	152.4	1.431	0.146
7.0	177.8	4.400	0.217

Figure 58. Example output for a monolithic flexible shoulder adjacent to a flexible pavement.

section can sustain. The expected life has been computed from fatigue for rigid shoulders and from the more critical of fatigue and rutting for flexible shoulders. Note that the program automatically computes the expected life for two thicknesses, HC and HC + 1 inch (25.4 mm); the latter value is provided to aid the user in interpolating the thickness for the design traffic. The expected life is compared to the design life (evaluated manually by the designer per section 3.1). The required thickness (if greater than minimum) can then be projected from the two values computed.

D.3 Instructions for Micro Computer Program

The micro computer version of the program BERM is menu driven and interactive. Five options are given:

1. Interactive data entry
2. Edit data
3. Run the program
4. Exit the program
5. Batch processing

The interactive data entry also includes checks on the data to determine if the entered values are within the expected range. The data editor for interactive processing has been written in Fortran, rather than utilizing the micro computer editor software, in order to make it usable universally; it is therefore somewhat more cumbersome than might be possible if it were to utilize a machine-specific editor. It should be pointed out that the data file created under interactive data entry (option 1) is not saved after exiting from the program. However, the user can go back to modify (edit) the data file and rerun as many times as he wishes provided he does not exit from the program. In order to save a data file, the following steps are required:

1. Select option 1 and enter data
2. Run the program using option 3; the computer will ask: "DO YOU WANT TO STORE THE INPUT DATA?"
3. Type a Y for YES
4. The computer will prompt ENTER INPUT FILE NAME, FORMAT IS XXXXXXXX.XXXX; enter any name consistent with the format.

This file may now be edited using option 2 from the menu to create new input data files for batch processing. Note that option 3 does not use a named data (input) file. Note also that all YES or NO (Y or N) responses need to be in capital letters.

The program is executed with one data set at a time. The execution time will vary somewhat from machine to machine; it takes about 2 seconds to run on a Columbia.

Other than following the instructions given by the interactive program, the user needs to type: BERM <return> to call up the program after inserting the diskette into the drive.

The sequence of data entry using option 1 from the menu depends on whether the shoulder is rigid or flexible, and how the user wishes to determine static and dynamic moduli for flexible shoulders (options 1, 2 and 3 of section D.1). If the shoulder is rigid, the computer asks for the appropriate input data, skipping over those data not needed in the analysis. For flexible shoulders, if MOD=0, the computer asks: DO YOU WANT TO ENTER STATIC AND DYNAMIC MODULI?" If YES (option 1 of section D.1), the values for EC and EC1 are entered by the user. If NO, EC and EC1 are skipped and are computed from equation 9 using the design temperature T. Note that when MOD=1, the values of EC and EC1 are computed from the user input equation (which must be of the form of equation 31), as discussed in section D.1. The computer will prompt the user for the values of the constants in equation 31.

When using the data editor (option 2), the computer will first ask: "DOES THE FILE YOU WISH TO EDIT ALREADY EXIST ON DISK?" If YES, the name of the existing file is input along with the name of the new file (these may be the same if editor is used to correct an error). If NO, the latest file used in the interactive mode (options 1, 2, 3 of the menu) is edited. Note that if option 2 is selected as the first option after entering the program, no data file exists and the screen will display the error message: "DATA HAS TO BE ENTERED BEFORE YOU CAN EDIT OR RUN IT."

The diskette contains the following files: BERM.FOR, EDIT.FOR, CLEAR.FOR, BERM.EXE, plus six data files labeled D.39, D.40, D.41, D.42, D.42A, D.42B. The CLEAR and EDIT file are subroutines of BERM and the data files D.39 through D.42 are the input data files corresponding to the conditions described in table 20 (the outputs appear in figures 39 through 42, respectively). The asphalt static and dynamic moduli have been computed from equation 9 (option 2 of section D.1) in data sets D.41 and D.42; option 1 of section D.1 is used in D.42A, (user inputs values for EC, EC1) and options 3 for D.42B, (user inputs equation) these six data sets cover all the possible cases of mainline-shoulder combinations as well as methods of determining asphalt static and dynamic moduli and are included for illustrative purposes. They may be run using batch processing (option 5 on the menu).

D.4. Mainframe program listing.

```
C
C >>> EC=SHOULDER PAVEMENT MODULUS (STATIC)
C >>> EC1=SHOULDER PAVEMENT MODULUS (DYNAMIC)
C >>> HC=SHOULDER PAVEMENT THICKNESS
C >>> EB=BASE MODULUS
C >>> HB=BASE THICKNESS
C >>> ES=SUBGRADE MODULUS
C >>> FC=CONCRETE FLEXURAL STRENGTH
C >>> SIG=STRESS
C >>> EPS=STRAIN
C    *******************************************************************
C *** TYPE OF ANALYSIS:
C
C     MFLEX =  0 , RIGID SHOULDER
C              1 , FLEXIBLE SHOULDER
C ***
C     MONO  =  0 , SEPARATE ( OR TIED RIGID )
C              1 ,  MONOLITHIC ( OR TIED AND KEYED RIGID )
C ***
C     MOD=0 , CREEP MODULUS COMPUTED FROM EQUATION 9
C     MOD=1 , CREEP MODULUS COMPUTED FROM USER INPUT EQUATION
C     *******************************************************************
      DIMENSION EPS(2),XNFX(2),XNFZ(2),XNF(2),TI(2),XNFO(2),XNFI(2)
      DIMENSION TITLE(20)
      DATA TI/10800.,0.02/
      EC=0.0
C     *******************************************************************
C     READ CONTROL CARDS AND INPUT   ************************************
C     *******************************************************************
  998 READ(5,997,END=999)TITLE
  997 FORMAT(20A4)
      READ(5,*) MFLEX,MONO,MOD,EC,EC1,HC,EB,HB,ES,FC,T
      XJO=0.25E-6
      XJ1=5.0E-6
      XM=1./3.
      AO=-7.91
      A1=0.113
C
C     XJO,XJ1,XM,AO,A1 ARE REGRESSION COEFFICIENTS IN THE MASTER
C     CREEP MODULUS FUNCTION WHEN THIS VALUE IS EXPRESSED IN THE
C     FORM GIVEN BY EQUATION 31 IN THE REPORT.  REFER TO APPENDIX F
C     OF REFERENCE 53 FOR A METHOD TO DERIVE THESE VALUES.
C
      NH=0
      EC=EC/1000000.
      EC1=EC1/1000000.
      EB=EB/1000.
      ES=ES/1000.
      IF (MFLEX.EQ.1) GO TO 1000
C * ANALYSIS IS FOR RIGID SHOULDER   ************************************
C
C      STRESS IN RIGID SHOULDER AT THE OUTER EDGE DUE TO PARKED
C      TRAFFIC, TABLE 12.
C
  100 CONTINUE
      F=2931.126/HC-57.3768*ALOG10(EB)-1255.587*ALOG10(ES)/HC
     1 -204.1294*ALOG10(HC)/ES+668.5456*ALOG10(EC)/ES
     2 +107.8282*ALOG10(EC)*ALOG10(ES)+57.67283*ALOG10(HC)*ALOG10(EB)
     3 +0.01908*HC*ES-7.95273*ALOG10(ES)*ALOG10(EB)
     4 -0.51792*EC*HC-0.42611*EC*ES+16.80832*ES/HC+88.52223*EC/HC
```

```
     5 -36.4833*EC/ES
     6 +9.44087*HC/EC -114.713
      XNFO(NH+1)=22209.*(FC/F)**4.29
      IF(MONO.EQ.1)GO TO 200
      XNFI(NH+1)=XNFO(NH+1)
      GO TO 250
C
C       STRESS IN TIED-KEYED RIGID SHOULDER DUE TO ENCROACHING
C       TRAFFIC, TABLE 11
C
  200 F=2946.726/HC-14.98661*ALOG10(ES)+9.21093*ALOG10(EB)+688.754/HC/ES
     1-686.9263*ALOG10(ES)/HC+1074.345*ALOG10(EC)/HC-111.5788*ALOG10(HC)
     2/ES+57.90987*ALOG10(ES)/EC+27.55938*ALOG10(EB)/ES-2175.141*
     3ALOG10(HC)/HC-164.1664*ALOG10(EB)/HC-0.00304*HC**3-0.18012*EC*HC
     4 +4.12073*ES/HC+4.16321*EC/ES +74.26395
      XNFI(NH+1)=22209.*(FC/F)**4.29
  250 IF (NH.GT.0) GO TO 300
      HC=HC+1.
      NH=NH+1
      GO TO 100
 300  H=HC-1.
      WRITE(6,1100)
 1100 FORMAT(1H1,////,16X,'* * * RIGID SHOULDER DESIGN * * *',//)
      IF(MONO.EQ.0)WRITE(6,1101)
      IF(MONO.EQ.1)WRITE(6,1102)
 1101 FORMAT(10X,'PAVEMENT/SHOULDER JOINT IS TIED')
 1102 FORMAT(10X,'PAVEMENT/SHOULDER JOINT IS TIED, KEYED')
      ECM=EC*6.894
      ECB=EC*1000.
      FCM=FC*6.894/1000.
      EBM=EB*6.894
      ESM=ES*6.894
      HM=H*25.4
      HCM=HC*25.4
      DO 10 I=1,2
      XNFO(I)=XNFO(I)*1.E-6
      XNFI(I)=XNFI(I)*1.E-6
   10 CONTINUE
      WRITE(6,1103)ECB,ECM,FC,FCM,EB,EBM,ES,ESM
 1103 FORMAT(10X,'CONCRETE MODULUS:',8X,F5.0,' ksi (',F4.1,' GPa)',/,
     *10X,'CONCRETE FLEX STRENGTH:',3X,F4.0,' psi (',F4.2,' MPa)',/,
     *10X,'SUBBASE MODULUS:',10X,F4.1,' ksi (',F4.0,' MPa)',/,
     *10X,'SUBGRADE MODULUS:',9X,F4.1,' ksi (',F4.0,' MPa)',//)
      WRITE(6,1104)H,HM,XNFO(1),XNFI(1),HC,HCM,XNFO(2),XNFI(2)
 1104 FORMAT(10X,'THE COMPUTED DESIGN LIVES, IN MILLIONS EAL, ARE:',/,
     *13X,'SURFACE',6X,'OUTER',5X,'INNER',/,
     *12X,'THICKNESS',6X,'EDGE',6X,'EDGE',/,
     *10X,'(in)',3X,'(mm)',/,
     *10X,F4.1,' (',F5.1,')',4X,F6.3,4X,F6.3,/,
     *10X,F4.1,' (',F5.1,')',4X,F6.3,4X,F6.3)
      GO TO 998
 1000 CONTINUE
      IF (EC.GT..000001) GO TO 400
      IF(MOD.NE.0)READ(5,*)XJO,XJ1,XM,AO,A1
C
C          CREEP MODULUS
C
      TT=TI(1)
      TEMP=AO+A1*T
      IF(TEMP.LE.0.)GO TO 1
```

```
      XJ=XJO+XJ1*((TT*10.**(AO+A1*T))**XM)
      GO TO 2
    1 XJ=XJO+XJ1*((TT*0.1**(-A1*T-AO))**XM)
    2 EC=1./XJ
C
C          DYNAMIC MODULUS
C
      TT=TI(2)
      XJ=XJO+XJ1*((TT*10.**(AO+A1*T))**XM)
      EC1=1./XJ
      EC=EC/1000000.
      EC1=EC1*1.E-6
  400 CONTINUE
C
C         ENCROACHING LOAD
C
      X1=EC1
      X2=HC
      X3=EB
      X4=HB
      X5=ES
      X7=1./X2
      X8=ALOG10(X1)
      X9=ALOG10(X2)
      X10=ALOG10(X3)
      X11=ALOG10(X4)
      X12=ALOG10(X5)
      X13=X8*X9
      X14=X8*X10
      X15=X8*X11
      X16=X8*X12
      X17=X9*X10
      X18=X9*X11
      X19=X9*X12
      X20=X10*X11
      X21=X10*X12
      X22=X11*X12
      X23=1./X1
      X24=1./X3
      X25=X8*X23
      X26=X7*X8
      X27=X8*X24
      X28=X8/X4
      X29=X9*X23
      X30=X9*X7
      X31=X9*X24
      X32=X10*X23
      X33=X10*X7
      X34=X10*X24
      X35=X1*X2
      X36=X2*X5
      X37=X12*X23
      X38=X12*X24
      IF (MONO.EQ.1) GO TO 500
C
C      HORIZONTAL TENSILE STRAIN IN FLEXIBLE SHOULDER AT OUTER
C      EDGE DUE TO ENCROACHING TRAFFIC, TABLE 16
C
      F=-.17742*X1-.00546*X4-.00149*X5-1.41052*X8-.08302*X11
     A  -.60364*X12+.33852*X14+.14081*X15+.35677*X17+.48144*X18
```

```
     B  +.25656*X19-.37382*X20+.23116*X22+.01227*X25+1.81566*X26
     C  +1.6396*X27+.03118*X29+19.78372*X30-.33842*X33+.0101*X35
     D  -.00959*X37-.13647
      F=10.0**F
      F=F/1000000.
      GO TO 510
  500 CONTINUE
C
C     HORIZONTAL TENSILE STRAIN IN FLEXIBLE MONOLITHIC SHOULDER
C     AT INNER EDGE DUE TO ENCROACHING TRAFFIC, TABLE 15
C
      F=-.23838*X1-.03156*X2+.00391*X3-.00606*X4-.07166*X11-1.18781*X13
     1  +.14954*X15+.13579*X16+.3256*X17+.50122*X18+.24668*X19-.37384
     2  *X20-.38018*X21+.22583*X22+.18083*X26+19.28037*X30-.01072*X32
     3  -.53323*X33+.02993*X35+.00009*X36-1.73775*X38+.02185
      F=10.0**F
      F=F*1.E-6
  510 CONTINUE
      XNF(NH+1)=4.2E-18*(1./F)**6.312
C
C         PARKED LOAD
C
      X1=EC
      X8=ALOG10(X1)
      X13=X8*X9
      X14=X8*X10
      X15=X8*X11
      X16=X8*X12
      X23=1./X1
      X25=X8*X23
      X26=X7*X8
      X27=X8*X24
      X28=X8/X4
      X29=X9*X23
      X32=X10*X23
      X37=X12*X23
      X35=X1*X2
C
C     HORIZONTAL TENSILE STRAIN IN FLEXIBLE MONOLITHIC SHOULDER
C     AT OUTER EDGE DUE TO PARKED TRAFFIC, TABLE 13
C
C    F=-1.45388*X1-.08201*X2+.00142*X3-1.12428*X7+.52617*X8-2.27292*X9
C    A-1.13177*X12-1.46361*X13+.32205*X15+.21223*X17+.55644*X18
C    B  +.50633*X19-.63976*X20+.42811*X22-1.14206*X24-1.4811*X27
C    C  +.32432*X28-2.49706*X31+.13872*X35-.00337*X37+1.00324*X38
C    D  +5.49642
C
C      HORIZONTAL TENSILE STRAIN IN FLEXIBLE SHOULDER AT OUTER
C      EDGE DUE TO PARKED TRAFFIC, TABLE 14
C
      F=-1.73396*X1-.05872*X2+.00115*X3-.00664*X4-2.11024*X7+.76066*X8
     1  +.16674*X10-1.14381*X12-1.53381*X13+.18519*X15+.47337*X18
     2  +.52445*X19-.60249*X20+.42310*X22-1.40263*X27+.59236*X30
     3-3.5699*X31+.17675*X35-.0032*X37+.93845*X38-2.75095*X9+5.82183
      F=10.0**F
      EPS(NH+1)=F/1000000.
      ECC=EC*1000000.
      F=F/1000000.
      XNFX(NH+1)=(2.176-ALOG10(ECC)*0.7918-ALOG10(F))
     A          /(0.9075-.1101*ALOG10(ECC))
```

```
      XNFX(NH+1)=10.0**XNFX(NH+1)
C
C      VERTICAL COMPRESSIVE STRAIN ON SUBGRADE AT OUTER EDGE DUE
C      TO PARKED VEHICLES, TABLE 17
C
      F=-.0385*X2-.02989*X4-.00172*X5-1.54988*X9-.64043*X12
     1  -.33594*X13+.10001*X14+.24065*X17+.67717*X18
     2  +.12234*X19-.26647*X20-.16138*X26-.73675*X28
     3  -.0012*X37 +4.40328
      F=10.0**F
      F=F/1000000.
      XNFZ(NH+1)=2.48E-10 *(1./F)**4.876
      IF (NH.GT.0) GO TO 600
      HC=HC+1.
      NH=NH+1
      GO TO 400
 600  CONTINUE
      H=HC-1.0
      WRITE(6,1200)
 1200 FORMAT(1H1,////,16X,'* * * FLEXIBLE SHOULDER DESIGN * * *',//)
      IF(MONO.EQ.0)WRITE(6,1201)
      IF(MONO.EQ.1)WRITE(6,1202)
 1201 FORMAT(10X,'THE SHOULDER IS SEPARATE FROM THE MAINLINE PAVEMENT')
 1202 FORMAT(10X,'THE SHOULDER IS MONOLITHIC WITH THE MAINLINE PAVEMENT
     *')
      EC1M=EC1*6.894
      ECB=EC*1000.
      ECM=EC*6894.
      EC1B=EC1*1000.
      EBM=EB*6.894
      HBM=HB*25.4
      ESM=ES*6.894
      HM=H*25.4
      HCM=HC*25.4
      TM=5.*(T-32.)/9.
      DO 20 I=1,2
      XNF(I)=XNF(I)*1.E-6
      XNFX(I)=XNFX(I)*1.E-6
      XNFZ(I)=XNFZ(I)*1.E-6
   20 CONTINUE
      WRITE(6,1203)EC1B,EC1M,ECB,ECM,EB,EBM,HB,HBM,ES,ESM,T,TM
 1203 FORMAT(10X,'A.C. DYNAMIC MODULUS:',4X,F5.0,' ksi (',F4.1,' GPa)'
     1,/,
     *10X,'A.C. CREEP MODULUS:',7X,F4.1,' ksi (',F4.0,' MPa)',/,
     *10X,'BASE MODULUS:',13X,F4.1,' ksi (',F4.0,' MPa)',/,
     *10X,'BASE THICKNESS:',11X,F4.1,' in  (',F4.0,' mm )',/,
     *10X,'SUBGRADE MODULUS:',9X,F4.1,' ksi (',F4.0,' MPa)',/,
     *10X,'DESIGN TEMPERATURE:',7X,F4.1,'  F  (',F4.1,'  C )',//)
      IF(EPS(2).GT.EPS(1)) GO TO 700
      IF(XNFX(2).LT.XNFZ(2)) GO TO 700
C     ****************************************************************
C  *** CALL OUTPUT 2
      WRITE(6,1204)H,HM,XNF(1),XNFX(1),HC,HCM,XNF(2),XNFX(2)
 1204 FORMAT(10X,'THE COMPUTED DESIGN LIVES, IN MILLIONS EAL, ARE:',/,
     *13X,'SURFACE',6X,'ENCROACHING',5X,'PARKED',/,
     *12X,'THICKNESS',7X,'TRAFFIC',7X,'TRAFFIC',/,
     *10X,'(in)',3X,'(mm)',/,
     *10X,F4.1,2X,F5.1,7X,F6.3,8X,F6.3,/,
     *10X,F4.1,2X,F5.1,7X,F6.3,8X,F6.3)
C     ****************************************************************
```

```
      GO TO 998
 700  CONTINUE
C  *** CALL OUTPUT 1
      WRITE(6,1204)H,HM,XNF(1),XNFZ(1),HC,HCM,XNF(2),XNFZ(2)
C      ***********************************************************************
      GO TO 998
 999  CALL EXIT
      END
```

D.5 Micro computer program listing.

```
$DEBUG
C     ****************************************************************
C >>> EC=PAVEMENT MODULUS (STATIC)
C >>> EC1=PAVEMENT MODULUS (DYNAMIC)
C >>> HC=PAVEMENT THICKNESS
C >>> EB=BASE MODULUS
C >>> HB=BASE THICKNESS
C >>> ES=SUBGRADE MODULUS
C >>> FC=CONCRETE FLEXURAL STRENGTH
C >>> SIG=STRESS
C >>> EPS=STRAIN
C
C *** TYPE OF ANALYSIS:
C
C     MFLEX =  0 , RIGID SHOULDER
C              1 , FLEXIBLE SHOULDER
C
C     MONO  =  0 , SEPARATE (OR TIED RIGID)
C              1 ,  MONOLITHIC (OR TIED AND KEYED RIGID)
C
C     MOD=0 , CREEP MODULUS COMPUTED FROM EQUATION 9
C     MOD=1 , CREEP MODULUS COMPUTED FROM USER INPUT EQUATION
C     ****************************************************************
      CHARACTER*12 OUTFILE,INFILE
      CHARACTER*40 TITLE
      CHARACTER*1 ANS,ANSWER
      DIMENSION EPS(2),XNFX(2),XNFZ(2),XNF(2),TI(2),XNFO(2),XNFI(2)
      DATA TI/10800.,0.02/
      COUNT=0
      NH=0
      EC=0
      HB=0
      FC=0
      ANS='1'
      MOD=0
      EC1=0
C     ****************************************************************
C     READ DATA FROM THE SCREEN
C     ****************************************************************
      CALL CLEAR
 997  WRITE (*,'(A)')
     1'        1) INTERACTIVE DATA ENTRY'
      WRITE (*,'(A)')
     2'        2) EDIT DATA          '
      WRITE (*,'(A)')
     3'        3) RUN THE PROGRAM'
      WRITE (*,'(A)')
     4'        4) EXIT THE PROGRAM'
      WRITE (*,'(A)')
     5'        5) BATCH PROCESSING'
      WRITE(*,'(A)')'  '
      WRITE (*,'(A\)')' ENTER YOUR SELECTION ----->'
      READ (*,*,ERR=997) IRESP
      CLOSE(2)
      CLOSE(5)
      IF ((IRESP .LT.1).OR.(IRESP.GT.5)) GO TO 997
      IF (IRESP.EQ.1) THEN
         COUNT=COUNT+1
      ENDIF
      IF (IRESP.EQ.4) GO TO 999
      IF (IRESP.EQ.5) THEN
```

```
      WRITE (*,'(A\)')
     1   ' ENTER INPUT FILE NAME. FORMAT IS XXXXXXXX.XXX ---->'
      READ(*,'(A12)') INFILE
      OPEN (2,FILE=INFILE,STATUS='OLD')
      WRITE (*,'(A\)')
     1 ' ENTER OUTPUT FILE NAME. FORMAT IS XXXXXXXX.XXX ---->'
      READ (*,'(A12)') OUTFILE
      OPEN (5,FILE=OUTFILE,STATUS='NEW')
      WRITE(*,'(A1)') ' '
      READ(2,*)MFLEX,MONO,MOD,EC,EC1,HC,EB,HB,ES,FC,T
      IF (MOD.NE.0) THEN
         READ(2,*) XJO,XJ1,XM,AO,A1
      ELSE
         XJO=0.25E-6
         XJ1=5.0E-6
         XM=1./3.
         AO=-7.91
         A1=0.113
      ENDIF
      NH=0
      EC=EC/1000000.
      EC1=EC1/1000000.
      EB=EB/1000.
      ES=ES/1000.
      GO TO 4700
   ENDIF
   IF ((IRESP.EQ.2).OR.(IRESP.EQ.3)) THEN
      IF (IRESP.EQ.2) THEN
8010  WRITE(*,'(A)')
     1' DOES THE FILE YOU WISH TO EDIT ALREADY EXIST ON THE DISK ?'
      WRITE(*,'(A\)')
     1'                                 PLEASE ANSWER  Y OR N --->'
      READ(*,'(A1)')ANSWE
      IF ((ANSWE.NE.'Y').AND.(ANSWE.NE.'N')) GO TO 8010
      IF (ANSWE.EQ.'Y') THEN
         COUNT=COUNT+1
         WRITE (*,'(A\)')
     1      ' ENTER EXISTING FILE NAME. FORMAT IS XXXXXXXX.XXX ---->'
         READ(*,'(A12)') INFILE
         OPEN (2,FILE=INFILE,STATUS='OLD')
         WRITE (*,'(A\)')
     1      ' ENTER NEW INPUT FILE NAME. FORMAT IS XXXXXXXX.XXX ---->'
         READ (*,'(A12)') OUTFILE
         OPEN (5,FILE=OUTFILE,STATUS='NEW')
         WRITE(*,'(A1)') ' '
         READ(2,*)MFL,MO,MD,ECV,ECV1,HCV,EBV,HBV,ESV,FCV,TV
         IF (MD.NE.0) THEN
            READ(2,*) XJOV,XJV1,XMV,AVO,AV1
         ELSE
            XJOV=0.25E-6
            XJV1=5.0E-6
            XMV=1./3.
            AVO=-7.91
            AV1=0.113
         ENDIF
         CALL CLEAR
         CALL EDIT(MFL,MO,MD,ECV,ECV1,HCV,EBV,HBV,ESV
     1,FCV,TV,XJOV,XJV1,XMV,AVO,AV1)
         WRITE(5,8000)MFL,MO,MD,ECV,ECV1,HCV,EBV,HBV,ESV,FCV,TV
         IF (MD.EQ.1) THEN
            WRITE(5,8001)XJOV,XJV1,XMV,AVO,AV1
         ENDIF
         MFLEX=MFL
         MONO=MO
         MOD=MD
         EC=ECV
```

```
            EC1=ECV1
            HC=HCV
            EB=EBV
            HB=HBV
            ES=ESV
            FC=FCV
            T=TV
            XJO=XJOV
            XJ1=XJV1
            A1=AV1
            AO=AVO
            XM=XMV
            CALL CLEAR
            GO TO 997
            ENDIF
         ENDIF
         IF (COUNT.EQ.0) THEN
            WRITE(*,'(A)')'  '
            WRITE(*,'(A)')
     1      ' DATA HAS TO BE ENTERED BEFORE YOU CAN EDIT OR RUN IT'
            WRITE(*,'(A)')
     1      ' PLEASE CHOOSE OPTION 1 FROM THE MENU, AND INPUT THE DATA'
            WRITE(*,'(A)')'  '
            WRITE(*,'(A)')'  '
            GO TO 997
         ENDIF
      ENDIF
      IF (IRESP.EQ.2) GO TO 4600
      IF (IRESP.EQ.3) THEN
         MFLEX=MFL
         MONO=MO
         MOD=MD
         EC=ECV
         EC1=ECV1
         HC=HCV
         EB=EBV
         HB=HBV
         ES=ESV
         FC=FCV
         T=TV
         XJO=XJOV
         XJ1=XJV1
         A1=AV1
         AO=AVO
         XM=XMV
7000     WRITE(*,'(A\)')
     1   ' DO YOU WANT TO STORE THE INPUT DATA? (Y OR N) ---->'
         READ(*,'(A1)') INPUT
         IF ((INPUT.NE.'N').AND.(INPUT.NE.'Y')) GO TO 7000
         IF (INPUT.EQ.'Y')THEN
           WRITE (*,'(A\)')
     1     ' ENTER INPUT FILE NAME, FORMAT IS XXXXXXXX.XXX ---->'
           READ(*,'(A12)') INFILE
           OPEN (2,FILE=INFILE,STATUS='NEW')
           WRITE(2,8000)MFL,MO,MD,ECV,ECV1,HCV,EBV,HBV,ESV,FCV,TV
           IF (MOD.NE.0) THEN
              WRITE(2,8001)XJOV,XJV1,XMV,AVO,AV1
           ENDIF
8000       FORMAT(3(I1,1X),2(F8.0,1X),F3.1,1X,F6.0,1X,
     *     F4.1,1X,F5.0,1X,F4.0,1X,F5.1)
8001       FORMAT(2(F9.8,1X),F5.4,1X,F5.2,1X,F5.3)
         ENDIF
         IF (COUNT.GT.1) THEN
            CLOSE(5)
         ENDIF
         WRITE (*,'(A\)')
```

```
     1 ' ENTER OUTPUT FILE NAME. FORMAT IS XXXXXXXX.XXX ---->'
          READ (*,'(A12)') OUTFILE
          OPEN (5,FILE=OUTFILE,STATUS='NEW')
          MFLEX=MFL
          MONO=MO
          MOD=MD
          EC=ECV
          EC1=ECV1
          HC=HCV
          EB=EBV
          HB=HBV
          ES=ESV
          FC=FCV
          T=TV
          XJO=XJOV
          XJ1=XJV1
          A1=AV1
          AO=AVO
          XM=XMV
          NH=0
          EC=EC/1000000.
          EC1=EC1/1000000.
          EB=EB/1000.
          ES=ES/1000.
          GO TO 4700
       ENDIF
       WRITE (*,'(A)')
       CALL CLEAR
6      WRITE(*,'(A\)')
     1' ENTER (0) FOR RIGID OR (1) FOR FLEXIBLE SHOULDER  --->'
       READ(*,'(I1)') MFL
       IF ((MFL.NE.1).AND.(MFL.NE.0)) THEN
          WRITE(*,'(A)')'                                   '
          WRITE(*,'(A)')' ANSWER SHOULD BE 0 OR 1, TRY AGAIN !!!'
          GO TO 6
       ENDIF
 7     WRITE(*,'(A\)')
     1' ENTER (0) IF SEPARATE OR (1) IF MONOLITHIC ----->'
       READ(*,'(I1)') MO
       IF ((MO.NE.1).AND.(MO.NE.0)) THEN
          WRITE(*,'(A)')'                                   '
          WRITE(*,'(A)')' ANSWER SHOULD BE 0 OR 1, TRY AGAIN !!!'
          GO TO 7
       ENDIF
       IF (MFL.EQ.1) THEN
8         WRITE(*,'(A)')
     1' ENTER (0) FOR DEFAULT VALUES OR (1) FOR USER INPUT EQUATION'
          WRITE(*,'(A\)')
     1'      (FOR DEFAULT VALUES SEE EQUATION (9) IN THE REPORT) --->'
          READ(*,'(I1)') MD
          IF ((MD.NE.1).AND.(MD.NE.0)) GO TO 8
          IF (MD.EQ.0) THEN
601          WRITE(*,'(A\)')
     1    ' DO YOU WANT TO ENTER STATIC & DYNAMIC MODULI? (Y OR N) -->'
             READ(*,'(A1)') ANSWER
             IF ((ANSWER.NE.'Y').AND.(ANSWER.NE.'N')) GO TO 601
          ENDIF
       ENDIF
       IF (MFL.EQ.1)THEN
          IF ((MD.EQ.0).AND.(ANSWER.EQ.'Y')) THEN
2001         WRITE(*,'(A\)')
     1       ' ENTER ASPHALT MODULUS (STATIC) psi, EC (F8.0)----->'
             READ(*,*,ERR=2001) ECV
             IF ((ECV.LT.5000.).OR.(ECV.GT.50000.)) THEN
                WRITE(*,'(A)')
     1    ' ERROR -- EC SHOULD BE >5000 AND <50000 psi, TRY AGAIN !!'
```

```
              GO TO 2001
           ENDIF
2002       WRITE(*,'(A\)')
    1      ' ENTER ASPHALT MODULUS (DYNAMIC)psi, ECI(F8.0)----->'
           READ(*,*,ERR=2002) ECVI
           IF ((ECVI.LT.300000.).OR.(ECVI.GT.1500000.)) THEN
              WRITE(*,'(A)')
    1 ' ERROR, ECI SHOULD BE >300,000 AND <1,500,000 psi, TRY AGAIN !'
              GO TO 2002
           ENDIF
        ENDIF
2003    WRITE(*,'(A\)')
    1   ' ENTER ASPHALT THICKNESS inch, HC (F3.1)----->'
        READ(*,*,ERR=2003) HCV
        IF ((HCV.LT.3.).OR.(HCV.GT.10.)) THEN
              WRITE(*,'(A)')
    1    ' ERROR -- HC SHOULD BE >3 AND <10 inches, TRY AGAIN !!'
              GO TO 2003
         ENDIF
      ELSE
2004    WRITE(*,'(A\)')
    1   ' ENTER CONCRETE MODULUS (STATIC) psi, EC (F8.0)----->'
        READ(*,*,ERR=2004) ECV
        IF ((ECV.LT.2000000.).OR.(ECV.GT.7000000.)) THEN
              WRITE(*,'(A)')
    1 ' ERROR -- EC SHOULD BE >2,000,000 AND <7,000,000, TRY AGAIN !'
              GO TO 2004
           ENDIF
2005    WRITE(*,'(A\)')
    1   ' ENTER CONCRETE THICKNESS inch, HC (F3.1)----->'
        READ(*,*,ERR=2005) HCV
        IF ((HCV.LT.3.).OR.(HCV.GT.10.)) THEN
              WRITE(*,'(A)')
    1         ' ERROR -- HC SHOULD BE >3 AND <10 inches, TRY AGAIN !!'
              GO TO 2005
        ENDIF
      ENDIF
2006 WRITE(*,'(A\)')
    1' ENTER BASE MODULUS psi, EB (F6.0)----->'
      READ(*,*,ERR=2006) EBV
      IF ((EBV.LT.3500.).OR.(EBV.GT.70000.)) THEN
        WRITE(*,'(A)')
    1'  ERROR -- EB SHOULD BE >3,500 AND <70,000 psi, TRY AGAIN !!'
        GO TO 2006
      ENDIF
      IF (MFL.EQ.1) THEN
2007    WRITE(*,'(A\)')
    1   ' ENTER BASE THICKNESS inch, HB (F4.1)----->'
        READ(*,*,ERR=2007) HBV
        IF ((HBV.LT.4.).OR.(HBV.GT.16.)) THEN
           WRITE(*,'(A)')
    1'     ERROR -- HB SHOULD BE >4 AND <16 inches, TRY AGAIN !!'
           GO TO 2007
         ENDIF
      ENDIF
2008 WRITE(*,'(A\)')
    1' ENTER SUBGRADE MODULUS psi, ES (F5.0)----->'
      READ(*,*,ERR=2008) ESV
      IF ((ESV.LT.1000.).OR.(ESV.GT.30000.)) THEN
        WRITE(*,'(A)')
    1'  ERROR -- ES SHOULD BE >1,000 AND <30,000 psi, TRY AGAIN !!'
        GO TO 2008
      ENDIF
      IF (MFL.EQ.0)THEN
2009    WRITE(*,'(A\)')
    1   ' ENTER CONCRETE FLEXURAL STRENGTH psi, FC (F4.0)----->'
```

```
         READ(*,*,ERR=2009) FCV
         IF ((FCV.LT.400.).OR.(FCV.GT.1000.)) THEN
               WRITE(*,'(A)')
     1       ' ERROR -- FC SHOULD BE >400 AND <1,000 psi, TRY AGAIN !!'
               GO TO 2009
         ENDIF
      ENDIF
2010  WRITE(*,'(A\)')
     1 ' ENTER DESIGN TEMPERATURE, (degrees fahrenheit, F5.1) ---->'
      READ(*,*,ERR=2010) TV
      IF ((TV.LT.40.).OR.(TV.GT.90.)) THEN
         WRITE(*,'(A)')
     1'  ERROR -- T SHOULD BE >40 AND <90, TRY AGAIN !!'
         GO TO 2010
      ENDIF
      XJO=0.25E-6
      XJOV=XJO
      XJ1=5.0E-6
      XJV1=XJ1
      XM=1./3.
      XMV=XM
      AO=-7.91
      AVO=AO
      A1=0.113
      AV1=A1
      IF(MD.EQ.1) THEN
        CALL CLEAR
2011    WRITE(*,'(A\)')
     1' ENTER COEFFICIENT, XJO psi(E7.5)---->'
        READ(*,*) XJOV
        IF ((XJOV.LT..00000001).OR.(XJOV.GT..00001)) THEN
           WRITE(*,'(A)')
     1'    ERROR -- XJO SHOULD BE >.1 E-7 AND <.1 E-4, TRY AGAIN !!'
           GO TO 2011
        ENDIF
2012    WRITE(*,'(A\)')
     1' ENTER COEFICIENT, XJ1 psi(E6.4) ---->'
        READ(*,*) XJV1
        IF ((XJV1.LT..1E-7).OR.(XJV1.GT..1E-4)) THEN
           WRITE(*,'(A)')
     1'    ERROR -- XJ1 SHOULD BE >.1E-7 AND <.1E-4, TRY AGAIN !!'
           GO TO 2012
        ENDIF
2013    WRITE(*,'(A\)')
     1' ENTER COEFICIENT, XM (F5.4) ----->'
        READ(*,*,ERR=2013) XMV
        IF ((XMV.LT..2).OR.(XMV.GT..6)) THEN
           WRITE(*,'(A)')
     1'    ERROR -- XM SHOULD BE >.2 AND <.6, TRY AGAIN !!'
           GO TO 2013
        ENDIF
2014    WRITE(*,'(A\)')
     1' ENTER COEFICIENT, AO (F5.2)----->'
        READ(*,*,ERR=2014) AVO
        IF ((AVO.LT.-15).OR.(AVO.GT.-3)) THEN
           WRITE(*,'(A)')
     1'    ERROR -- AO SHOULD BE >-15 AND <-3, TRY AGAIN !!'
           GO TO 2014
        ENDIF
2015    WRITE(*,'(A\)')
     1' ENTER COEFICIENT, A1 (F5.3)----->'
        READ(*,*,ERR=2015) AV1
        IF ((AV1.LT..04).OR.(AV1.GT.1)) THEN
           WRITE(*,'(A)')
     1'    ERROR -- A1 SHOULD BE >.04 AND <1, TRY AGAIN !!'
           GO TO 2015
```

```
          ENDIF
        ENDIF
        CALL CLEAR
        GO TO 997
 4600   IF (IRESP.EQ.2) THEN
C       *********************
C       *   EDITING THE DATA
C       *********************
           CALL CLEAR
           CALL EDIT(MFL,MO,MD,ECV,ECV1,HCV,EBV,HBV,ESV
     1,FCV,TV,XJOV,XJV1,XMV,AVO,AV1)
           CALL CLEAR
           GO TO 997
        ENDIF
 4700   IF ((IRESP.EQ.3).OR.(IRESP.EQ.5)) THEN
        IF (MFLEX.EQ.1) GO TO 1000
C ****************************************
C * ANALYSIS IS FOR RIGID SHOULDER
C
C         STRESS IN THE RIGID SHOULDER OF THE
C         OUTER EDGE DUE TO PACKED TRAFFIC
C                  TABLE 12
C ****************************************
  100 CONTINUE
      F=2931.126/HC-57.3768*ALOG10(EB)-1255.587*ALOG10(ES)/HC
     1 -204.1294*ALOG10(HC)/ES+668.5456*ALOG10(EC)/ES
     2 +107.8282*ALOG10(EC)*ALOG10(ES)+57.67283*ALOG10(HC)*ALOG10(EB)
     3 +0.01908*HC*ES-7.95273*ALOG10(ES)*ALOG10(EB)
     4 -0.51792*EC*HC-0.42611*EC*ES+16.80832*ES/HC+88.52223*EC/HC
     5 -36.4833*EC/ES+9.44087*HC/EC -114.713
      XNFO(NH+1)=22209.*(FC/F)**4.29
      IF(MONO.EQ.1)GO TO 200
      XNFI(NH+1)=XNFO(NH+1)
      GO TO 250
C ****************************************
C        STRESS IS TIED KEYED RIGID SHOULDER
C             DUE TO ENCROACHING TRAFFIC.
C                  TABLE 11
C ****************************************
  200 F=2946.726/HC-14.98661*ALOG10(ES)+9.21093*ALOG10(EB)+688.754/HC/ES
     1-686.9263*ALOG10(ES)/HC+1074.345*ALOG10(EC)/HC-111.5788*ALOG10(HC)
     2/ES+57.90987*ALOG10(ES)/EC+27.55938*ALOG10(EB)/ES-2175.141*
     3ALOG10(HC)/HC-164.1664*ALOG10(EB)/HC-0.00304*HC**3-0.18012*EC*HC
     4 +4.12073*ES/HC+4.16321*EC/ES +74.26395
      XNFI(NH+1)=22209.*(FC/F)**4.29
  250 IF (NH.GT.0) GO TO 300
      HC=HC+1.
      NH=NH+1
      GO TO 100
 300  H=HC-1.
      WRITE(5,1100)
 1100 FORMAT(1H0,////,16X,'* * * RIGID SHOULDER DESIGN * * *',//)
      IF(MONO.EQ.0)WRITE(5,1101)
      IF(MONO.EQ.1)WRITE(5,1102)
 1101 FORMAT(10X,'PAVEMENT/SHOULDER JOINT IS TIED')
 1102 FORMAT(10X,'PAVEMENT/SHOULDER JOINT IS TIED, KEYED')
      ECM=EC*6.894
      ECB=EC*1000.
      FCM=FC*6.894/1000.
      EBM=EB*6.894
      ESM=ES*6.894
      HM=H*25.4
      HCM=HC*25.4
      DO 10 I=1,2
      XNFO(I)=XNFO(I)*1.E-6
      XNFI(I)=XNFI(I)*1.E-6
```

```
   10 CONTINUE
      WRITE(5,1103)ECB,ECM,FC,FCM,EB,EBM,ES,ESM
 1103 FORMAT(10X,'CONCRETE MODULUS:',8X,F5.0,' ksi (',F4.1,' GPa)',/,
     *10X,'CONCRETE FLEX STRENGTH:',3X,F4.0,' psi (',F4.2,' MPa)',/,
     *10X,'SUBBASE MODULUS:',10X,F4.1,' ksi (',F4.0,' MPa)',/,
     *10X,'SUBGRADE MODULUS:',9X,F4.1,' ksi (',F4.0,' MPa)',//)
      WRITE(5,1104)H,HM,XNFO(1),XNFI(1),HC,HCM,XNFO(2),XNFI(2)
 1104 FORMAT(10X,'THE COMPUTED DESIGN LIVES, IN MILLIONS EAL, ARE:',/,
     *13X,'SURFACE',6X,'OUTER',5X,'INNER',/,
     *12X,'THICKNESS',6X,'EDGE',6X,'EDGE',/,
     *10X,'(in)',3X,'(mm)',/,
     *10X,F4.1,' (',F5.1,')',4X,F6.3,4X,F6.3,/,
     *10X,F4.1,' (',F5.1,')',4X,F6.3,4X,F6.3)
      CALL CLEAR
      GO TO 997
 1000 CONTINUE
      IF (EC.GT..000001) GO TO 400
C
C         CREEP MODULUS
C
      TT=TI(1)
      TEMP=AO+A1*T
      IF(TEMP.LE.0.)GO TO 1
      XJ=XJO+XJ1*((TT*10.**(AO+A1*T))**XM)
      GO TO 2
    1 XJ=XJO+XJ1*((TT*0.1**(-A1*T-AO))**XM)
    2 EC=1./XJ
C
C           DYNAMIC MODULUS
C
      TT=TI(2)
      XJ=XJO+XJ1*((TT*10.**(AO+A1*T))**XM)
      EC1=1./XJ
      EC=EC/1000000.
      EC1=EC1*1.E-6
  400 CONTINUE
C
C          ENCROACHING LOAD
C
      X1=EC1
      X2=HC
      X3=EB
      X4=HB
      X5=ES
      X7=1./X2
      X8=ALOG10(X1)
      X9=ALOG10(X2)
      X10=ALOG10(X3)
      X11=ALOG10(X4)
      X12=ALOG10(X5)
      X13=X8*X9
      X14=X8*X10
      X15=X8*X11
      X16=X8*X12
      X17=X9*X10
      X18=X9*X11
      X19=X9*X12
      X20=X10*X11
      X21=X10*X12
      X22=X11*X12
      X23=1./X1
      X24=1./X3
      X25=X8*X23
      X26=X7*X8
      X27=X8*X24
      X28=X8/X4
```

```
      X29=X9*X23
      X30=X9*X7
      X31=X9*X24
      X32=X10*X23
      X33=X10*X7
      X34=X10*X24
      X35=X1*X2
      X36=X2*X5
      X37=X12*X23
      X38=X12*X24
      IF (MONO.EQ.1) GO TO 500
C ***********************************************
C     HORIZONTAL TENSILE STRAIN IN FLEXIBLE SHOULDER
C       AT OUTER EDGE DUE TO ENCROACHING TRAFFIC.
C                     TABLE 16
C ***********************************************
      F=-.17742*X1-.00546*X4-.00149*X5-1.41052*X8-.08302*X11
     A  -.60364*X12+.33852*X14+.14081*X15+.35677*X17+.48144*X18
     B  +.25656*X19-.37382*X20+.23116*X22+.01227*X25+1.81566*X26
     C  +1.6396*X27+.03118*X29+19.78372*X30-.33842*X33+.0101*X35
     D  -.00959*X37-.13647
      F=10.0**F
      F=F/1000000.
      GO TO 510
  500 CONTINUE
C
C ****************************************************
C     HORIZONTAL TENSILE STRAIN IN FLEXIBLE MONOLITHIC
C     SHOULDER AT INNER EDGE DUE TO ENCROACHING TRAFFIC.
C                     TABLE 15
C ****************************************************
C
      F=-.23838*X1-.03156*X2+.00391*X3-.00606*X4-.07166*X11-1.18781*X13
     1  +.14954*X15+.13579*X16+.3256*X17+.50122*X18+.24668*X19-.37384
     2  *X20-.38018*X21+.22583*X22+.18083*X26+19.28037*X30-.01072*X32
     3  -.53323*X33+.02993*X35+.00009*X36-1.73775*X38+.02185
      F=10.0**F
      F=F*1.E-6
  510 CONTINUE
      XNF(NH+1)=4.2E-18*(1./F)**6.312
C
C        PARKED LOAD
C
      X1=EC
      X8=ALOG10(X1)
      X13=X8*X9
      X14=X8*X10
      X15=X8*X11
      X16=X8*X12
      X23=1./X1
      X25=X8*X23
      X26=X7*X8
      X27=X8*X24
      X28=X8/X4
      X29=X9*X23
      X32=X10*X23
      X37=X12*X23
      X35=X1*X2

C ****************************************************
C     HORIZONTAL TENSILE STRAIN IN FLEXIBLE MONOLITHIC
C       SHOULDER AT INNER EDGE DUE TO PACKED TRAFFIC.
C                     TABLE 13
C ****************************************************
C
C    F=-1.45388*X1-.08201*X2+.00142*X3-1.12428*X7+.52617*X8-2.27292*X9
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```
C     A-1.13177*X12-1.46361*X13+.32205*X15+.21223*X17+.55644*X18
C     B  +.50633*X19-.63976*X20+.42811*X22-1.14206*X24-1.4811*X27
C     C  +.32432*X28-2.49706*X31+.13872*X35-.00337*X37+1.00324*X38
C     D  +5.49642
C
C ********************************************************
C      HORIZONTAL TENSILE STRAIN IN FLEXIBLE SHOULDER
C          AT OUTER EDGE DUE TO PACKED TRAFFIC.
C                     TABLE 14
C ********************************************************
C
      F=-1.73396*X1-.05872*X2+.00115*X3-.00664*X4-2.11024*X7+.76066*X8
     1  +.16674*X10-1.14381*X12-1.53381*X13+.18519*X15+.47337*X18
     2  +.52445*X19-.60249*X20+.42310*X22-1.40263*X27+.59236*X30
     3-3.5699*X31+.17675*X35-.0032*X37+.93845*X38-2.75095*X9+5.82183
      F=10.0**F
      EPS(NH+1)=F/1000000.
      ECC=EC*1000000.
      F=F/1000000.
      XNFX(NH+1)=(2.176-ALOG10(ECC)*0.7918-ALOG10(F))
     A           /(0.9075-.1101*ALOG10(ECC))
      XNFX(NH+1)=10.0**XNFX(NH+1)
C ********************************************************
C  VERTICAL COMPRESSIVE STRAIN ON SUBGRADE AT OUTER
C          EDGE DUE TO PACKED VEHICHLES.
C                     TABLE 17
C ********************************************************
C
      F=-.0385*X2-.02989*X4-.00172*X5-1.54988*X9-.64043*X12
     1  -.33594*X13+.10001*X14+.24065*X17+.67717*X18
     2  +.12234*X19-.26647*X20-.16138*X26-.73675*X28
     3  -.0012*X37 +4.40328
      F=10.0**F
      F=F/1000000.
      XNFZ(NH+1)=2.48E-10 *(1./F)**4.876
      IF (NH.GT.0) GO TO 600
      HC=HC+1.
      NH=NH+1
      GO TO 400
 600  CONTINUE
      H=HC-1.0
      WRITE(5,1200)
 1200 FORMAT(1H0,////,16X,'* * * FLEXIBLE SHOULDER DESIGN * * *',//)
      IF(MONO.EQ.0)WRITE(5,1201)
      IF(MONO.EQ.1)WRITE(5,1202)
 1201 FORMAT(10X,'THE SHOULDER IS SEPARATE FROM THE MAINLINE PAVEMENT')
 1202 FORMAT(10X,'THE SHOULDER IS MONOLITHIC WITH THE MAINLINE PAVEMENT
     *')
      EC1M=EC1*6.894
      ECB=EC*1000.
      ECM=EC*6894.
      EC1B=EC1*1000.
      EBM=EB*6.894
      HBM=HB*25.4
      ESM=ES*6.894
      HM=H*25.4
      HCM=HC*25.4
      TM=5.*(T-32.)/9.
      DO 20 I=1,2
      XNF(I)=XNF(I)*1.E-6
      XNFX(I)=XNFX(I)*1.E-6
      XNFZ(I)=XNFZ(I)*1.E-6
   20 CONTINUE
      WRITE(5,1203)EC1B,EC1M,ECB,ECM,EB,EBM,HB,HBM,ES,ESM,T,TM
 1203 FORMAT(10X,'A.C. DYNAMIC MODULUS:',4X,F5.0,' ksi (',F4.1,' GPa)'
     1,/,
```

```
     ....
     *10X,'A.C. CREEP MODULUS:',7X,F4.1,' ksi (',F4.0,' MPa)',/,
     *10X,'BASE MODULUS:',13X,F4.1,' ksi (',F4.0,' MPa)',/,
     *10X,'BASE THICKNESS:',11X,F4.1,' in  (',F4.0,' mm )',/,
     *10X,'SUBGRADE MODULUS:',9X,F4.1,' ksi (',F4.0,' MPa)',/,
     *10X,'DESIGN TEMPERATURE:',7X,F4.1,'  F  (',F4.1,'  C )',//)
      IF(EPS(2).GT.EPS(1)) GO TO 700
      IF(XNFX(2).LT.XNFZ(2)) GO TO 700
C     ************************************************************
C  *** CALL OUTPUT 2
      WRITE(5,1204)H,HM,XNF(1),XNFX(1),HC,HCM,XNF(2),XNFX(2)
 1204 FORMAT(10X,'THE COMPUTED DESIGN LIVES, IN MILLIONS EAL, ARE:',/,
     *12X,'SURFACE',6X,'ENCROACHING',5X,'PARKED',/,
     *12X,'THICKNESS',7X,'TRAFFIC',7X,'TRAFFIC',/,
     *10X,'(in)',3X,'(mm)',/,
     *10X,F4.1,2X,F5.1,7X,F6.3,8X,F6.3,/,
     *10X,F4.1,2X,F5.1,7X,F6.3,8X,F6.3)
C     ************************************************************
 700  CONTINUE
C  *** CALL OUTPUT 1
      WRITE(5,1204)H,HM,XNF(1),XNFZ(1),HC,HCM,XNF(2),XNFZ(2)
C     ************************************************************
      CALL CLEAR
      ENDIF
      GO TO 997
 999  CALL EXIT
      END
```

```
C  ******************************************************************
C    THIS SUBROUTINE IS USED TO CLEAR THE SCREEN PRIOR TO RUN A PROGRAM
C  ******************************************************************

      SUBROUTINE CLEAR

      DO 100 I=1,25

      WRITE (*,'(A)')'
100
      CONTINUE

      RETURN

      END
```

```
C  **********************************************************************
C   THIS SUBROUTINE IS USED TO EDIT THE DATA ENTERED INTERACTIVELY
C  **********************************************************************
      SUBROUTINE EDIT(MFL,MO,MD,ECV,ECV1,HCV,EBV,HBV,ESV,FCV,TV
     1,XJOV,XJV1,XMV,AVO,AV1)
 5000 WRITE(*,'(A33,I1)')' (0) : RIGID - (1) : FLEXIBLE =  ',MFL
      WRITE(*,'(A\)')' DO YOU WANT TO REENTER ? (Y OR N)'
      READ(*,'(A1)') CHOICE
      IF ((CHOICE.NE.'Y').AND.(CHOICE.NE.'N')) THEN
         WRITE(*,'(A)')' PLEASE ANSWER Y OR N)'
         GO TO 5000
      ELSE
         IF (CHOICE.EQ.'Y') THEN
 5001       WRITE(*,'(A\)')
     1      ' ENTER (0) FOR RIGID OR (1) FOR FLEXIBLE SHOULDER --->'
            READ(*,'(I1)') MFL
            IF ((MFL.NE.1).AND.(MFL.NE.0)) THEN
               WRITE(*,'(A)')'                          '
               WRITE(*,'(A)')' ANSWER SHOULD BE 0 OR 1, TRY AGAIN !!!'
               GO TO 5001
            ENDIF
         ENDIF
      ENDIF
 5003 WRITE(*,'(A10,I1)')' MONO   =  ',MO
      WRITE(*,'(A\)')' DO YOU WANT TO REENTER ? (Y OR N)'
      READ(*,'(A1)') CHOICE
      IF ((CHOICE.NE.'Y').AND.(CHOICE.NE.'N')) THEN
         WRITE(*,'(A)')' PLEASE ANSWER Y OR N)'
         GO TO 5003
      ELSE
         IF (CHOICE.EQ.'Y') THEN
 5004       WRITE(*,'(A\)')
     1      ' ENTER (0) IF SEPERATE OR (1) IF MONOLITHIC --->'
            READ(*,'(I1)') MO
            IF ((MO.NE.1).AND.(MO.NE.0)) THEN
               WRITE(*,'(A)')'                          '
               WRITE(*,'(A)')' ANSWER SHOULD BE 0 OR 1, TRY AGAIN !!!'
               GO TO 5004
            ENDIF
         ENDIF
      ENDIF
 5005 WRITE(*,'(A10,I1)')' MOD    =  ',MD
      WRITE(*,'(A\)')' DO YOU WANT TO REENTER ? (Y OR N)'
      READ(*,'(A1)') CHOICE
      IF ((CHOICE.NE.'Y').AND.(CHOICE.NE.'N')) THEN
         WRITE(*,'(A)')' PLEASE ANSWER Y OR N)'
         GO TO 5005
      ELSE
         IF (CHOICE.EQ.'Y') THEN
 5006       WRITE(*,'(A\)')
     1      ' ENTER (0) FOR DEFAULT VALUE, (1) FOR USER INPUT --->'
            READ(*,'(I1)') MD
            IF ((MD.NE.1).AND.(MD.NE.0)) THEN
               WRITE(*,'(A)')'                          '
               WRITE(*,'(A)')' ANSWER SHOULD BE 0 OR 1, TRY AGAIN !!!'
               GO TO 5006
            ENDIF
         ENDIF
      ENDIF
 5007 WRITE(*,'(A\)')' EC     =  '
      WRITE(*,*) ECV
```

```
        WRITE(*,'(A\)')' DO YOU WANT TO REENTER ? (Y OR N)'
        READ(*,'(A1)') CHOICE
        IF ((CHOICE.NE.'Y').AND.(CHOICE.NE.'N')) THEN
           WRITE(*,'(A)')' PLEASE ANSWER Y OR N)'
           GO TO 5007
        ELSE
           IF (CHOICE.EQ.'Y') THEN
             IF (MFL.EQ.1)THEN
5008            WRITE(*,'(A\)')
     1          ' ENTER ASPHALT MODULUS (STATIC) psi, EC(F8.0)----->'
                READ(*,*) ECV
                IF (ECV.NE.0) THEN
                IF ((ECV.LT.5000.).OR.(ECV.GT.50000.)) THEN
                  WRITE(*,'(A)')
     1' ERROR -- EC SHOULD BE >5000 AND <50000 psi, TRY AGAIN !!'
                  GO TO 5008
                ENDIF
                ENDIF
             ELSE
5058            WRITE(*,'(A\)')
     1          ' ENTER CONCRETE MODULUS (STATIC) psi, EC(F8.0)----->'
                READ(*,*) ECV
                IF (ECV.NE.0) THEN
                IF ((ECV.LT.2000000.).OR.(ECV.GT.7000000.)) THEN
                  WRITE(*,'(A)')
     1' ERROR -- EC SHOULD BE >2000000 AND <7000000 psi, TRY AGAIN !'
                  GO TO 5058
                ENDIF
                ENDIF
            ENDIF
          ENDIF
        ENDIF
5009    WRITE(*,'(A\)')' EC1    =  '
        WRITE(*,*) ECV1
        WRITE(*,'(A\)')' DO YOU WANT TO REENTER ? (Y OR N)'
        READ(*,'(A1)') CHOICE
        IF ((CHOICE.NE.'Y').AND.(CHOICE.NE.'N')) THEN
           WRITE(*,'(A)')' PLEASE ANSWER Y OR N)'
           GO TO 5009
        ELSE
           IF (CHOICE.EQ.'Y') THEN
5010         WRITE(*,'(A\)')
     1       ' ENTER ASPHALT MODULUS (DYNAMIC)psi, EC1(F8.0)----->'
             READ(*,*) ECV1
             IF (ECV1.NE.0) THEN
             IF ((ECV1.LT.300000.).OR.(ECV1.GT.1500000.)) THEN
                WRITE(*,'(A)')
     1 ' ERROR - EC1 SHOULD BE >300000 AND <1,500,000 psi, TRY AGAIN !!'
                GO TO 5010
             ENDIF
             ENDIF
          ENDIF
       ENDIF
5011    WRITE(*,'(A\)')' HC     =  '
        WRITE(*,*) HCV
        WRITE(*,'(A\)')' DO YOU WANT TO REENTER ? (Y OR N)'
        READ(*,'(A1)') CHOICE
        IF ((CHOICE.NE.'Y').AND.(CHOICE.NE.'N')) THEN
           WRITE(*,'(A)')' PLEASE ANSWER Y OR N)'
           GO TO 5011
        ELSE
           IF (CHOICE.EQ.'Y') THEN
5012          WRITE(*,'(A\)')
     1        ' ENTER ASPHALT THICKNESS inch, HC (F4.1)----->'
              READ(*,*) HCV
              IF ((HCV.LT.3).OR.(HCV.GT.10)) THEN
```

```
          IF (CHOICE.EQ.'Y') THEN
5026         WRITE(*,'(A\)')
     1       ' ENTER COEFICIENT, XJ1 psi(E6.4) ---->'
             READ(*,*,ERR=5026) XJV1
             IF ((XJV1.LT..1E-7).OR.(XJV1.GT..1E-4)) THEN
               WRITE(*,'(A)')
     1 ' ERROR -- XJ1 SHOULD BE >.1E-7 AND <.1E-4, TRY AGAIN !'
               GO TO 5026
             ENDIF
          ENDIF
       ENDIF
5027   WRITE(*,'(A\)')' XM      =  '
       WRITE(*,*) XMV
       WRITE(*,'(A\)')' DO YOU WANT TO REENTER ? (Y OR N)'
       READ(*,'(A1)') CHOICE
       IF ((CHOICE.NE.'Y').AND.(CHOICE.NE.'N')) THEN
          WRITE(*,'(A)')' PLEASE ANSWER Y OR N)'
          GO TO 5027
       ELSE
          IF (CHOICE.EQ.'Y') THEN
5028         WRITE(*,'(A\)')
     1       ' ENTER COEFICIENT, XM (F5.4) ----->'
             READ(*,*,ERR=5028) XMV
             IF ((XMV.LT..2).OR.(XMV.GT..6)) THEN
               WRITE(*,'(A)')
     1         ' ERROR -- XM SHOULD BE >.2 AND <.6, TRY AGAIN !!'
               GO TO 5028
             ENDIF
          ENDIF
       ENDIF
       WRITE(*,'(A\)')' AO      =  '
       WRITE(*,*) AVO
       WRITE(*,'(A\)')' DO YOU WANT TO REENTER ? (Y OR N)'
       READ(*,'(A1)') CHOICE
       IF ((CHOICE.NE.'Y').AND.(CHOICE.NE.'N')) THEN
          WRITE(*,'(A)')' PLEASE ANSWER Y OR N)'
          GO TO 5027
       ELSE
          IF (CHOICE.EQ.'Y') THEN
5029         WRITE(*,'(A\)')
     1       ' ENTER COEFICIENT, AO (F5.2)----->'
             READ(*,*,ERR=5029) AVO
             IF ((AVO.LT.-15).OR.(AVO.GT.-3)) THEN
                WRITE(*,'(A)')
     1          ' ERROR -- AO SHOULD BE >-15 AND <-3, TRY AGAIN !!'
                GO TO 5029
             ENDIF
          ENDIF
       ENDIF
5030   WRITE(*,'(A\)')' A1      =  '
       WRITE(*,*) AV1
       WRITE(*,'(A\)')' DO YOU WANT TO REENTER ? (Y OR N)'
       READ(*,'(A1)') CHOICE
       IF ((CHOICE.NE.'Y').AND.(CHOICE.NE.'N')) THEN
          WRITE(*,'(A)')' PLEASE ANSWER Y OR N)'
          GO TO 5030
       ELSE
          IF (CHOICE.EQ.'Y') THEN
5031         WRITE(*,'(A\)')
     1       ' ENTER COEFICIENT, A1 (F5.3)----->'
             READ(*,*,ERR=5031) AV1
             IF ((AV1.LT..04).OR.(AV1.GT.1)) THEN
                WRITE(*,'(A)')
     1' ERROR -- A1 SHOULD BE >.04 AND <1, TRY AGAIN !!'
                GO TO 5031
             ENDIF
```

```
            ENDIF
        ENDIF

RETURN

END
```

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