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# PAVEMENT MOISTURE ACCELERATED DISTRESS (MAD) IDENTIFICATION SYSTEM

Vol. 1
September 1981
Final Report

Prepared for

U.S. Department of Transportation
**Federal Highway Administration**

Offices of Research & Development
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Division
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# FOREWORD

These two reports present partial results of research conducted by the University of Illinois for the Federal Highway Administration (FHWA), Office of Research, under contract DOT-FH-11-9175. The research study was part of FCP Project 5D, Structural Rehabilitation of Pavement Systems. Volume 1 describes the development of an analysis method for the engineer to identify areas where climate and subgrade soils contribute to moisture accelerated distress in pavements. Volume 2 is intended as an aid to implementation of the analysis method.

Three other reports resulting from the same study are:

(1) FHWA/RD-81/122, Structural Analysis and Design of PCC Shoulders

(2) FHWA/RD-81/077, Improving Subdrainage and Shoulders of Existing Pavements - State-of-the-Art

(3) FHWA/RD-81/078, Final Report - Improving Subdrainage and Shoulders of Existing Pavements.

Sufficient copies of the two reports are being distributed to provide a minimum of two copies to each FHWA regional office, two copies to each FHWA division office and three copies to each State highway agency. Direct distribution is being made to the division offices.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

# NOTICE

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16. Abstract

This report details the development of extrinsic (climate) and intrinsic (material property) factors that impact on the moisture-related performance of a pavement. Procedures are presented which allow the engineer to classify a pavement as to the potential for moisture accelerated damage (MAD) to occur. This analysis can be performed in the office during initial planning stages to indicate areas where moisture damage may be expected. The areas noted with a high potential for MAD can be investigated further by visual, NDT, or coring operations during the normal development of the rehabilitation project. This simplified analysis allows the engineer to see where, and why moisture damage should develop, and aids him in evaluating drainage problems of particular materials and considering the need for further drainage studies.

Volume 2 is FHWA/RD-81/080, Users Manual.

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# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

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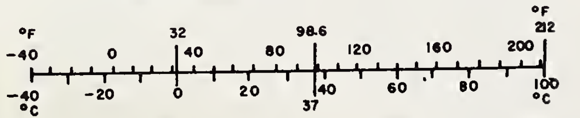
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



METRIC CONVERSION FACTORS

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# CHAPTER I

# INTRODUCTION

The occurrence of premature distress in a pavement system should be predictable through an examination of the components of the pavement, its environment, and loads. Coupling this examination with knowledge of the moisture related behavior of the materials present should provide the engineer with indications of the cause and effect of pavement damage. Although moisture problems have long been recognized and mechanisms proposed to account for the distress appearance, there has yet to be a simplified procedure developed which the field or maintenance engineer can use to tell whether his pavements are performing as desired. Because of this lack there has undoubtedly been a substantial amount of money spent to correct suspected moisture related problems that actually were not moisture induced. This money served very little purpose. However, it is more likely that there have been instances where moisture related damage has not been recognized, and timely and correct preventive maintenance has not been applied until it was too late. As a result, major rehabilitation work is often necessary.

Distress can be directly related to the presence of moisture, but more importantly, it is accelerated by moisture at varying rates. The need to be able to examine moisture accelerated distress and predict the future behavior of the pavement has led to the development of the methodology presented in this report. Moisture accelerated distress, given the acronym MAD, either already exists, or has a level of potential development in all pavements. The procedures developed in this report allow an existing pavement to be examined with a minimum of effort in a logical step by step progression that ultimately indicates the following:

1. The present condition of the pavement.
2. What portion of this condition can be related to moisture.
3. What factors and/or materials caused the moisture accelerated distress (MAD).
4. What is the potential for MAD to continue developing.
5. What maintenance strategies are best suited to stopping or alleviating the MAD.

The methodology presented is a valuable tool that can be used by the maintenance engineer managing a system of pavements, the design engineer rehabilitating a single pavement, and even the design engineer considering construction of a new pavement.

The factors that best indicate MAD in a pavement are those which produce MAD. These factors can be divided into two influences, external and internal. The external influences which can alter the moisture in a pavement are primarily climatic, viz., how much moisture is being supplied to the pavement. The internal influences that can alter the moisture in a pavement are the properties of the materials used in the pavement that retard or prevent the moisture from leaving the pavement system. Any properties which result in higher moisture levels over a long time are almost always detrimental, and the level of influence is important. These factors are termed the extrinsic (external) and intrinsic (internal) factors in the analysis to be presented.

An extrinsic analysis made in this study produced zones of interrelated factors where similar pavements and materials should behave similarly because similar amounts of moisture are retained in the pavement structure. The intrinsic analysis examines the influence of granular layers and the subgrade on the retention of that moisture in the pavement system.

If the properties of these materials are such that moisture entering the pavement is retained in the pavement during the application of loads for an excessively long time, reduced performance will result, compared to distress associated with materials which permit faster drainage. An analysis of both extrinsic and intrinsic features will indicate the potential for MAD to develop in any given pavement. If the pavement is old and has never received maintenance an unfavorable extrinsic and intrinsic analysis would indicate that there should be a large amount of MAD. Likewise, a favorable extrinsic and intrinsic analysis indicates a low potential for MAD. If an evaluation of the actual pavement condition seriously contradicts the predicted potential for MAD, the material properties utilized should be more accurately determined to show why there is a difference.

Because of the importance of the present condition of the pavement in arriving at useful estimates of MAD it must be determined very carefully. The procedure presented in this report provides a detailed step by step method which produces a valid indication of the condition of the pavement. As part of the procedure, it is necessary to estimate what proportion of the damage is moisture related.

These analyses allow the development of maintenance recommendations to reduce, eliminate, or prevent moisture damage from recurrring. The maintenance can be tailored to the areas where the analyses indicate the damage is concentrated. The proposed maintenance is logically derived in a manner that can be performed by a technician with a minimum of training and is repeatable.

The following chapters present the development of the phases of the analysis.

# CHAPTER 2

# EXTRINSIC FACTORS

## Introduction

The presence of water in a pavement system, and the length of time it remains there can alter the behavior of the materials used in the pavement in a detrimental manner. This alteration of material behavior produces deterioration at an accelerated rate. The distress that appears as a result of the moisture can be termed moisture accelerated distress, or MAD. There are two very broad categories that deliniate the moisture condition of the pavement, the external properties and the internal properties of the pavement system. The external, or extrinsic, properties are those factors that control the amount of moisture that is available to potentially enter the pavement system. The internal, or intrinsic, properties are the material properties of the pavement itself that determine the effect that moisture entering the pavement system will have on the performance.

The extrinsic factors allow the engineer no direct control over their activity. Once the extrinsic factors have been recognized and their influences cataloged, the engineer will be more aware of the magnitude of critical factors and the potential for deterioration. Knowledge of the intrinsic factors will then allow for more logical choices of possible rehabilitation strategies. Identifying and cataloguing the extrinsic factors represent the first step in evaluating a pavement, either existing or proposed, for either potential or existing MAD.

### Extrinsic Factors

The extrinsic factors that produced MAD are principally the climatic variables of an area which combine to alter the moisture condition that could exist in the granular material composing the pavement system. The most obvious of these are among the following:

1. Rainfall
2. Temperature
3. Evaporation

Using only these three variables, as has sometimes been done in the past, in describing climatic influence on pavements usually results in an oversimplification that gives little insight into the actual relationships involved between distress and climate. The climatic classification currently used by the FHWA uses four regions differentiated solely on the basis of freeze index and precipitation-evaporation data (1). The regions are:

1. Wet-Freeze
2. Dry-Freeze
3. Wet-No Freeze
4. Dry-No Freeze

The Wet-Freeze region is differentiated solely on the basis of where precipitation equals or exceeds evaporation and the average annual freezing index is above 100. While this is a very simplistic relationship, it does indicate very broad areas of similar moisture and temperature. The simple comparison of rainfall and evaporation moisture values, however does not relate to moisture that can do damage to the pavement. That is, the moisture that is in the subgrade or base course of the structure. For example, when evaporation exceeds rainfall the soil will normally be dry, but the degree of dryness and the manner in which this moisture influences the pavement behavior are questions that cannot be answered using these parameters. Similar questions can be posed for the wet areas and the degree of influence of temperature. Also, the water concentration in the soil must be indicated, and it must be calculable to allow for differentiation within each zone.

One way of indicating the amount of moisture normally in the soil, as practiced by agronomists, is by the type of vegetation that the soil will support. Different plants require different amounts of moisture. This is the basis for many of the climatological classification schemes. The climate is differentiated on the basis of similar vegetation first, and then the climatic variables in the different areas are compared. The important factors that must be included for the agricultural classification to have a relationship with MAD of pavements include the following:

1. Average moisture in the soil (long term)
2. Seasonal variation in moisture (short term)
3. Temperatures
    a. Summer
    b. Winter

The geographical areas with potential for MAD will be those areas that have moisture accumulation over either the short or long term, and an interaction with temperature.

The long term moisture accumulation will occur in a climatic area that has a surplus of moisture during the year that continually provides moisture to the soil system, maintaining the soil in a moist state during the entire year. This moisture state is the result of the balance between incoming and outgoing moisture, showing more incoming moisture over the entire year. The short term moisture presence is indicated by the short term intensity of rainfall that occurs during a certain portion of the year. Although the remainder of the year may be very dry and produce an overall indication of a dry climate, short duration excesses may provide enough moisture to significantly alter the performance of the pavement over a short time. During this short time, the traffic damage will be accelerated and will resemble that found in the moist climates, although to a lesser annual extent perhaps.

Consideration of short term moisture presence may help to describe problems such as faulting commonly seen in drier climates as well as wet climates.

The moisture in the soil system will exert different influences depending on temperature. This has been illustrated in any number of reports examining pavement response as influenced by temperature (2, 3, 4). The present classification scheme in FHWA considers only the effect of low temperature, as indicated by the freezing index, is the only temperature effect being considered. The reasoning for this approach is that high temperatures are indicated by the higher evaporation rates in the moisture balance. Low temperatures must be included because frost damage and spring breakup are highly dependent on the combination of the magnitude and duration of moisture and low temperature.

Some provision is necessary to account for the different temperature influences between winter and summer, and the effect on the moisture present in the pavement system. Because moisture movement is an energy process and temperature is an energy input, there is a relationship.

The following sections present the various climatic factors that influence MAD. Eventually, the factors are included in a unified approach which permits the engineer to evaluate his pavement from commonly recorded climatic data to determine whether the extrinsic factors indicate a potential for MAD.

In 1929 Eno (5) presented various maps of climatic data and interpretations of the climatic influence of each value. The two basic quantities of moisture and temperature, acting singularly or in conjunction, can produce the following distress types, as catalogued by Barenberg, Bartholomew, and Herrin (6) in a report prepared for the Department of the Army Construction Engineering Research Laboratory.

1. Flexible Pavement Systems
    a. Potholes
    b. Loss of cover aggregate

    c. Ravelling
    d. Weathering
    e. Contraction cracking
    f. Alligator cracking
    g. Reflective cracking
    h. Shoving
    i. Frost heave
    j. Shrinkage cracking

2. Rigid Pavement Systems
    a. Faulting
    b. Joint failure
    c. Pumping
    d. Corner cracking
    e. Diagonal cracking
    f. Longitudinal cracking
    g. Blowup or buckling
    h. Curling
    i. D-Cracking
    j. Surface Spalling
    k. Steel corrosion

The major problem to be solved in determining moisture related distress is to determine the potential amount of water that could enter the pavement system. This problem has been addressed indirectly in the study of climatology, or bioclimatology, where crops are matched to the climate. This matching involves knowing the amount of moisture in a soil system in an attempt to grow a crop that will not require more moisture than is there. This problem is essentially one of an energy flow problem relating moisture and solar radiation. There have been several schemes proposed to rate the climate in terms of its ability to support vegetation and add or remove moisture. The two most common schemes are those of Koeppen (7) and Thornthwaite (8).

Koeppen's classification scheme was originally derived to relate vegetation to climate and provide a standardized differentiation between climatic types based on the climatic elements of moisture and temperature. While vegetation is critically influenced by dry periods and pavements by wet periods, the yearly average may very roughly provide a comparison between the two. Initially derived from a world map of vegetation, it was later revised with more attention given to temperature, rainfall, and seasonal variations (7). The system has six general divisions subdivided by rainfall, temperature and special features. Each division is given a letter to indicate the breakdown of the climatic elements.

For the United States the following climate categories are identified:

A. Tropical Forest Climate: Average temperature of the coolest month is 18°C or higher.

B. Dry Climates: There are several classifications of the dry climate areas that fall into the B classification.

1. More than 70% of the rainfall occurs in April through September and the average annual precipitation is less than the following

$$r < 2t + 28 \qquad (2\text{-}1)$$

r is the average annual rainfall in cm

t is the average annual temperature in °C

2. More than 70% of the annual rainfall occurs in October through March and the average annual rainfall is less than

$$r < 2t \qquad (2\text{-}2)$$

3. Neither six month period contains more than 70% of the precipitation and the average annual rainfall is less than

$$r < 2t + 14 \qquad (2\text{-}3)$$

The next breakdown is primarily on the basis of precipitation amount and time of occurrence. In the A climatic area the following breakdowns are used:

f. Precipitation in driest month greater than 6 cm.

m. Precipitation in driest month less than 6 cm but greater than (10 - r/25)cm.

w. Precipitation in driest month less than (10 - r/25)cm where r is the average annual rainfall in cm.

In the B climatic area the following definitions to subdivide the area are used:

w. r is less than half of the upper limit defined in equation (2.1)

s. r is less than the upper limit, but greater than half of that amount.

In the C and D climatic areas the following breakdowns are used:

s. Precipitation in driest month of April through September is less than 4 cm and less than 1/3 the amount in the wettest month during October through March.

w. Precipitation in driest month of October through March is less than 0.10 of the amount in the April through September period.

f. Precipitation differing from either of the above.

The third breakdown compares the temperature range during the year. Area A has no further breakdown. Area B uses the following:

h. Average annual temperature greater than 18°C.

k. Average annual temperature less than 18°C.

Areas C and D have the following tertiary breakdown:

a. Average temperature of warmest month is greater than 22°C.

b. Average temperature of the four warmest months is above 10°C.

c. Average temperature of one, two or three months is greater than 18°C with the temperature of the warmest month less than 22°C.

There are other classification terms, but none of them are applicable to the United States.

Although this method of climatic classification is the more accepted procedure in use today, it has several deficiencies that do not allow its use in this study. The major temperature differentiation is in the warm period of the year because this is the period that primarily effects the growth of crops. Cold weather is differentiated only on the basis of being mild or severe. Precipitation is examined over both the short and long term. Although an effective indicator of climate, it provides no means of assessing moisture as it could relate to pavement behavior in a quantifiable manner. Inherent in the system, however, are the basic considerations of a breakdown of climate influence on pavement behavior. The breakdown based on temperature only is vaguely illustrated in Figure 2-1. These boundaries were taken from monthly average maps and there will be variations when using actual data for a location. The choice of the 0°C line as a climatic crop boundary and the zero mean freezing index line shown in Figure 2-2 are similar. The major differences are in Eastern California and West Virginia where the non-winter months do not contribute appreciably to the freezing index and they have only one month of low temperature.

The Thornthwaite method for classifying climatic variations utilizes the concept of potential evapotranspiration. This is the amount of moisture that would be returned to the atmosphere by evaporation and transpiration from plants if an unlimited supply of water were available to the soil system. This is a measure of energy flow. If a plant is well supplied with water, the quantity used by the plants will depend upon the amount of solar energy received at the surface and the surrounding temperature; not the vegetation types. Thus the area would not be represented by the type of vegetation or the most common plants (9).

The separation of the evapotranspiration from vegetation type and rainfall provides a truly independent quantity to compare against the actual value of precipitation. Comparisons of rainfall and evapotranspiration quantities throughout the year will illustrate the moisture conditions during each season. This makes it possible to determine seasonal surplus or deficiencies, which over the annual average can show whether a climate is dry or wet in a quantitative manner. The potential evapotranspiration is also an indicator of thermal efficiency. There is a direct relationship between incoming energy arriving at the earth's surface and the effect it has on temperature and moisture. This classification scheme allows a climate to be examined in terms of moisture and heat balance in a quantitative manner. This quantitative examination is an absolute necessity if the classification is to be used to differentiate pavement performance in a meaningful manner. The classification scheme recommended in this report is based on the use of potential evapotranspiration.

There are several methods to calculate the potential evapotranspiration occurring in a region. The more accurate schemes utilize energy relationships requiring knowledge of a variety of climatic elements such as saturation vapor pressure and temperature, radiation balances, heat flux, gas constants and other relationships. These values, however, are not readily available for a wide variety of areas and the increased complexity involved in these calculations makes them too cumbersome to use on a regular basis. The empirical method prepared by Thornthwaite (8) and modified by Thornthwaite and Mather lacks accuracy and a theoretical basis, but it follows measured variations rather well (9) and gives consistent data. More importantly it gives a numerical value that is indicative of the moisture state and the heat state, as well as indicating climatic variation extremely well.

The monthly potential evapotranspiration, $E_o$, is calculated from

$$E_o = 1.6(10\ T/I)^a \quad \text{(cm/mo)} \tag{2-4}$$

T is the monthly temperature $^oC$

$$I = \sum_{1}^{12} (\frac{T}{5})^{1.514} \tag{2-5}$$

$$a = (0.675\ I^3 - 77.1\ I^2 + 47{,}920\ I + 492{,}390) \times 10^{-6} \tag{2-6}$$

The results are summed over twelve months to obtain the yearly value. The calculations for each month must be corrected for the number of days in the month and the length of day as influenced by the latitude. While the accuracy of this method is suspect, the classification procedure has been validated by many climatology researchers; and the climatic regions delineated by the Thornthwaite method are in agreement with climatic regions developed from the more complex Radiation techniques (9), and correspond well with the Koeppen's method.

Thornthwaite develops four climatic criteria:

1. Moisture adequacy
2. Thermal efficiency
3. Summer concentration of thermal efficiency
4. Seasonal distribution of moisture adequacy

Moisture adequacy is expressed by the moisture index, which is a comparison of precipitation and potential evapotranspiration,

$$I_m = 100(\frac{S - .6D}{E_o}) \tag{2-7}$$

where $I_m$ is the moisture index,

$S$ is the monthly surplus, and

$D$ is the monthly deficit

with some allowance made for storage of moisture in the soil before a surplus or deficit will occur.

Thermal efficiency is represented by the potential evapotranspiration. This value is actually an energy related parameter and its distribution throughout the year is indicated by the summer concentration of thermal efficiency. This is the percentage of the mean annual potential evapotranspiration that occurs during the three summer months, when it will be the greatest.

The seasonal distribution of moisture adequacy is used to indicate the concentration of moisture surplus or deficit during the wet or dry season. This represents the short term moisture state, while the moisture index represents the long term moisture state. The ratio of water deficit to the annual potential evapotranspiration in moist climates is the aridity index, $I_a$. The ratio of water surplus to annual potential evapotranspiration in dry climates gives the humidity index, $I_h$.

$$I_h = \frac{S}{E_o} \times 100 \tag{2-8}$$

$$I_a = \frac{D}{E_o} \times 100 \tag{2-9}$$

The terminology for the climatic regions is listed in Table 2-1 through Table 2-3 along with the numerical values that delineate the regions.

Thornthwaite constructed a series of maps of the United States to illustrate the distribution of these parameters. They have been utilized here (8). Figure 2-3 illustrates the distribution of potential evapotranspiration. This illustrates that the South and Southwest have the potential to put more moisture back into the atmosphere than Northern areas, if it is available.

The annual average rainfall, shown in Figure 2-4 is combined with the potential evapotranspiration to produce the moisture index by a procedure discussed later. Figure 2-5 shows the distribution of the moisture index across the United States. As expected, there is a moisture surplus in the East and a deficit in the West with a surplus along the coast and in the mountains where temperatures are milder. The mild temperatures produce lower potential evapotranspiration resulting in a moist climate. Thus, the high elevation portions of California with a low amount of total rainfall will still have a moist climate because more of the moisture remains in the soil for a longer time due to lower temperatures. The moisture index values represent the yearly moisture balance and as such they indicate the long term moisture condition in the soil or subgrade. Different areas containing similar pavements may be expected to produce different behavior due to soil-moisture interaction as will be discussed in the following section on engineering behavior.

Short term moisture can be as damaging as long term moisture excesses. However short term excesses are more likely to be overlooked in areas having an extremely dry climate. Figure 2-6 delineates areas that experience concentrations of moisture at one time or another during the year. A large water surplus or deficit is one that would move the climate classification one step wetter or drier than its actual value when the moisture is averaged out over the entire year. A moderate moisture variation would be sufficient to alter the climate by half of a step. From this figure it is evident that the west coast is an area that will experience large moisture variations and thus be subject to MAD at a different rate than surrounding areas that maintain a more constant moisture condition.

The potential evapotranspiration is essentially a measure of the energy reaching the Earth's surface. The higher the sun's heat value, the warmer the climate and the less likely low temperature damage is to occur. A potential evapotranspiration value of zero would indicate that the average annual temperature was below 0°C. Thus, various levels of temperature can be inferred from Figure 2-3 which showed the distribution of potential evapotranspiration across the United States.

A more critical comparison is obtained when the potential evapotranspiration occurring during the three Summer months is compared with that occurring during the total year. This is referred to as the Summer Concentration of Thermal Efficiency. This parameter is shown in Figure 2-7. The higher this value, the less potential evapotranspiration that occurs during the winter. This means the temperature will be lower for a longer time in this area. The larger this parameter, the more low temperature moisture damage, such as frost heave, is likely to occur.

Divisions for this parameter could be placed anywhere. Figure 2-7 was constructed by Thornthwaite in 1946. Although no rational explanation was given by Thornthwaite for selecting the boundaries he used, they are developed from a predictive relationship with potential evapotranspiration levels which are used to show breaks in the major climatological areas, Figure 2-3, which are set up to differentiate climate based on the vegetation the climate will support.

## Selected Indicators

Both the Thornthwaite and Koeppen methods for classifying climate that have been presented here provide a breakdown of climate on the basis of moisture and temperature. The Koeppen system, however, uses parameters that are selected from values that exist in areas of similar vegetation.

There is no procedure to obtain these values, a priori, for an area, and no method for breaking down the areas themselves.

The Thornthwaite classification system provides a better base for examining the climatic influences on pavement systems. While the calculation procedure for the potential evapotranspiration may not be exact, it provides a much more rational procedure than that of examining the vegetation and putting similar climatic zones where similar vegetation occurs. Because the Thornthwaite procedure does have more flexibility, and its accuracy can be improved or altered with newer methods to obtain the potential evapotranspiration, it appears to offer the best potential for relating to engineering properties and material behavior. The Thornthwaite procedure has been examined to evaluate its relationship with MAD. Based on this study, the relationship allows the various levels calculated for the Thornthwaite variables to directly indicate the potential for MAD that the various climatic regions may induce in a pavement system.

## Engineering Behavior and Climatic Zones

The importance of each climatic zone rests in the moisture level and moisture change it can produce in a pavement, and the temperature it produces that may interact with the given amount of moisture. It still must be shown that moisture accelerated damage (MAD) differs for each climatic zone.

The variation of moisture beneath pavement systems, as studied by many researchers, has been summarized by Dempsey (10). Examination of the many studies presents no insight into predicting moisture variation, and the conclusions often are conflicting. Variations in moisture content along a pavement as large as ± 4 percent may be an indication of material variability, rather than moisture. It is also a fact that different materials at the same moisture content will perform quite differently. This difference is primarily due to grain size and plasticity characteristics as will be discussed in the section on intrinsic properties.

The soil-moisutre property that best reflects the interaction of grain size and plasticity is the soil moisture tension, or soil suction, which will be discussed with intrinsic properties. Coleman and Russam (11) have related the suction in the subgrade to the Thornthwaite moisture index for different subgrade materials. This relationship is shown in Figure 2-8. As a long term average, the same soil material can be expected to develop different suction levels in different climatic zones. When different suction levels develop, different performance characteristics will develop. This relationship has been validated for numerous climatic regions in Australia (12), North Africa, and also for various portions of the United States as part of an expansive clay study being conducted by the Waterways Experiment Station (13). The data collected by Atchison and Richards fit the curves of Coleman and Russam quite well, as is shown in Figure 2-9. It should be noted that these equilibrium values are for water depths of 17 feet or greater; and that depths less than this will alter the equilibrium substantially, in the direction of poorer performance. The climatic relationships curves should be considered as indicators of the best situation for pavement performance, with the realization that actual conditions will probably be much worse.

The effect of soil suction on CBR of a silty sand is illustrated in Figure 2-10. There is a uniform change in the CBR value with change in suction, and at lower suction values you have lower strength, requiring thicker materials in different climates for similar performance. The resilient modulus can be interpreted easier than soil suction to indicate performance in that it represents the deformation of the pavement system. This deformation produces fatigue in the surface course. With more deformation, fatigue damage will occur more quickly. The variation in resilient modulus with suction for a till is shown in Figure 2-11 (14). A change in performance is quite evident for this parameter. The estimated moisture index values are shown for the corresponding suction values for a silt. It can be seen that performance begins to deteriorate at a moisture index of -20 (Equation 2-7, Figure 2-11) with rapid deterioration beginning at -10.

Moisture index values are included for each material in the previous figures. These values indicate the extent that climate induced moisture conditions can vary performance. The suction values induced by the climate vary with each material due to the plasticity and grain size characteristics. It is evident that between a moisture index of 0 and -10 the performance really begins to deteriorate. Below the 0 moisture index the deterioration is constantly poor, the degree depending on the material type.

While fatigue cracking may be critical for flexible pavements as an indicator of MAD, rigid pavements are more susceptible to the problem of voids being created under the pavement. This results in cracked slabs, faulted joints, and loss of support. Moisture has long been recognized as a critical factor in these distress types. A study by Edris and Lytton (15) clearly shows the influence of climatic type on permanent deformation response. Residual strain as a function of suction is shown in Figure 2-12. There are dramatic breaks in the behavior of each of the three materials. An increasing residual strain means that permanent compaction under each wheel load is increasing which will produce larger voids under the pavement.

The relationship between the moisture index and the strength parameter indicate that a definite area exists wherein performance may be unpredictable because the materials can exist at moisture conditions at or near the critical points. In this area, any problem that adds moisture to the system, such as faulty joint sealing, could severely alter the performance.

The behavior indicated in Figure 2-11 and Figure 2-12 may be separated into behavioral groupings based on the climate, that classify as good, marginal, and poor performance area as indicated in Figure 2-13, based on long term performance. The relationship to the Thornthwaite moisture index is as follows:

I. Poor performance: This area, comparatively speaking, will have an extremely high potential for excess moisture occurrence. The moisture index is usually above 10.

II. Marginal: This area will have unpredictable performance. The moisture index is between -10 and + 10.

III. Good performance: The moisture index is usually -10 or smaller.

If seasonal moisture imbalances exist, the potential for MAD will be greater than if the moisture balance were as uniform as the surrounding area. Having a very dry period cannot undo the damage caused in the very wet period. This is particularly important in dry climates where there is a distinct wet season. Thornthwaite, by definition, set up a large water surplus or deficiency as the amount that would make the overall climate effect one grade wetter or drier than its annual average value. A moderate water surplus or deficiency will change the influence one half grade. Whether the winter is abnormally wet or the summer is abnormally dry, there exists a season of abnormal moisture that could place the areas in the next poorer moisture classification. In areas where the moisture index is in the -10 to 10 range, this abnormal moisture will definitely accelerate distress during the wet season, while performance in the dry season will be good, as will overall performance. The pavement will, however, deteriorate more rapidly than a similar pavement in the same climatic zone with no seasonal abnormality.

Temperature effects on performance are slightly more difficult to quantify as they relate to MAD problems. The majority of studies have shown that temperature can adversely affect performance, which in turn accelerates moisture damage. High temperatures can degrade repeated load performance of subgrade materials as illustrated in Figure 2-14 (15). The effect of temperature on the performance of asphalt concrete have been well documented, from loss of stability at high temperatures to low temperature cracking. Studies examining the interaction of temperature and moisture have concentrated primarily on the low temperature problems of frost heave. The result has been a lack of recognition for areas with moderate and high temperature problems that could directly, or indirectly, influence moisture related performance.

Freeze index values, degree days, and frost penetration values are several of the parameters used to describe the low temperature environment. The summer concentration of thermal efficiency, as previously mentioned, indicates the relative amount of energy reaching the pavement in the summer months as compared to the rest of the year. Thus, it indicates the relative warmth and coldness of the climate. A value of 25 percent would be found at the equator, and 100 percent would be found at the North Pole. With this continuous gradation it is possible to delineate both hot and cold pavement conditions on the same basis.

An exact relationship between the concentration of summer thermal efficiency cannot be made at present. Following studies into pavement performance in the different zones and an examination of the climatic variables, the number of temperature zones can be selected. The calculations to determine which zone a particular pavement falls into will remain the same, however, and it will be a matter of shifting the boundaries to the proper position. The boundaries will most probably reflect three types of temperature influence.

A. Low temperature activity

B. Freeze-Thaw activity

C. High temperature activity

Tentative boundaries for these are given in Figure 2-15, selected from Figure 2-7, previously shown. The zones illustrated delineate areas of similar pavement behavior, as influenced by the temperature, as derived from the Thornthwaite climatic classification scheme.

The interaction of moisture and temperature can be studied by combining Figure 2-13 and Figure 2-15, as in the map of nine climatic zones shown in Figure 2-16. These nine zones clearly indicate where potential MAD is most likely and what temperature effects will be most likely to accelerate the MAD. This permits a comparison of pavement performance in the different zones. Similar pavement systems should give similar behavior in similar zones. The nine zones may be described as follows:

1. I-A, Low temperature - high moisture
2. I-B, Freeze-thaw temperatures - high moisture
3. I-C, High temperatures - high moisture
4. II-A, Low temperature - variable moisture
5. II-B, Freeze-thaw temperature - variable moisture
6. II-C, High temperature - variable moisture
7. III-A, Low temperature - low moisture
8. III-B, Freeze-thaw temperature - low moisture
9. III-C, High temperature - low moisture

If there is a question as to which zone a pavement is in, the numerical calculations given in the example below should be performed to accurately place the pavement in a particular zone.

## Calculations to Evaluate Extrinsic Factors

### Potential Evapotranspiration

The data quantities that are necessary include the following:

1. Monthly average temperature
2. Monthly average rainfall
3. Latitude

First calculate the heat index from equation (2-5).

$$I = \sum_{1}^{12} \left(\frac{T}{5}\right)^{1.514}$$

T = monthly average temperature in °C

I = heat index, summed over 12 months

Second, calculate the constant, a, from equation 2-6.

$$a = (0.675I^3 - 77.1I^2 + 47{,}920\ I + 492{,}390) \times 10^{-6} \qquad (2\text{-}6)$$

Third, calculate the monthly potential evapotranspiration from equation 2-4.

$$PE = 1.6(10\ T/I)^a \qquad \text{(cm/month)} \qquad (2\text{-}4)$$

The yearly value is obtained by summing the 12 monthly values. Fourth, multiply each monthly value by the corresponding correction value for the latitude of the location being investigated. The correction values are given in Table 2-4. Figure 2-17 presents a tabular form for calculations.

These values are combined with monthly precipitation values in a table, and the moisture values are calculated. A table for Dalhart, Texas is given in Table 2-5. The moisture change indicates how much moisture goes into or comes out of storage. The actual evapotranspiration can never exceed the potential evapotranspiration; and it can never exceed the precipitation plus the amount of moisture in storage. The storage is assumed to have a maximum value of 4 inches (8), with any amount in excess of this becoming surplus. When the storage is at zero and the potential evapotranspiration is greater than the precipitation, this value is a deficit.

The moisture index is calculated from equation 2-7.

$$I_m = (S/PE)100 \qquad (2\text{-}7)$$

The humidity index for Dalhart is calculated from equation 2-8.

$$I_h = (S/PE)100 \qquad (2\text{-}8)$$

$$= (0/28.7)100 = 0\%$$

$I_a$ is not calculated for a dry climate. The zero value indicates there is little or no water surplus during the wet portion of the year, thus the average values calculated will accurately represent the expected performance. For a moist climate, the aridity index would be calculated.

The thermal efficiency is the value of the potential evapotranspiration. For Dalhart it is 72.9 cm (28.6 in.) which places it in a $B_2$ mesothermal climate. The concentration of Summer thermal efficiency is

$$\text{C.S.T.E.} = \frac{\text{PE(June + July + August)}}{\text{PE total}}\ 100$$

$$= \frac{(5.0 + 6.0 + 5.4)}{28.7}\ 100 = 57.14\%$$

Classification

The classification for extrinsic influence on performance is as follows.

Moisture Index

| Description | $I_m$ | Zone | Behavior |
|---|---|---|---|
| Wet | 10 or above | I | Poor |
| Moist | 10 to -10 | II | Transitional or Variable |
| Dry | -10 or below | III | Good |

Moisture Concentration

Moist Climates ($I_m$ above 0)

| $I_a$ | | Description |
|---|---|---|
| 0 to 10 | r: | no deficit |
| 10 to 20 | s: | moderate deficit |
| about 20 | $s_2$: | large deficit |

Dry Climates ($I_m$ below 0)

| $I_h$ | | Description |
|---|---|---|
| 0 to 16.7 | d: | little surplus |
| 16.7 to 33.3 | s: | moderate surplus |
| about 33.3 | $s_2$: | large surplus |

In areas with an r or d value for moisture concentration the moisture will be evenly distributed throughout the year. A value of s indicates that moisture will fall slightly more in one portion of the year than the others. A value of $s_2$ indicates that one part of the year will receive a substantial increase in moisture over the rest of the year.

A moisture deficit indicated by $I_a$ above will decrease the moisture index. When being related to pavement performance a deficit of moisture will not increase performance, but the larger amount of moisture present during the remainder of the year will decrease the performance, as compared to similar climatic areas without an aridity index value. This is illustrated in Table 2.2.

The same relationship holds for a moisture excess in a dry region. The concentration of moisture during a portion of the year will accelerate deterioration over another area with a similar climatic rating but no appreciable excess moisture during one particular time period of the year.

## SUMMARY

This chapter presented a procedure to delineate climate zones using climatic factors to indicate the presence of both heat and moisture. The moisture presence indicated by the moisture index value was related to performance indicators such as resilient modulus and CBR. This relationship showed that definite climatic zones could be established in which the moisture conditions present could be expected to develop a definite level of performance, good, fair, or poor. These three zones were combined with the temperature regions to produce a climatic map made up of zones of similar performance for pavements made up of similar materials.

Table 2-1. Seasonal Moisture Concentrations (8).

| Type | Moisture Index |
|---|---|
| A Perhumid | 100 and above |
| $B_4$ Humid | 80 to 100 |
| $B_3$ Humid | 60 to 80 |
| $B_2$ Humid | 40 to 60 |
| $B_1$ Humid | 20 to 40 |
| $C_2$ Moist subhumid | 0 to 20 |
| $C_1$ Dry subhumid | -33.3 to 0 |
| D Semiarid | -66.7 to -33.3 |
| E Arid | -100 to -66.7 |

Table 2-2. Seasonal Moisture Concentrations (8).

| Moist Climates (A, B, $C_2$) | | Aridity Index |
|---|---|---|
| r | little or no water deficit | 0 to 10 |
| s | moderate summer deficit | 10 to 20 |
| w | moderate winter deficit | 10 to 20 |
| $s_2$ | large summer deficit | above 20 |
| $w_2$ | large winter deficit | above 20 |
| **Dry Climates ($C_1$, D, E)** | | **Humidity Index** |
| d | little or no water surplus | 0 to 16.7 |
| s | moderate winter surplus | 16.7 to 33.3 |
| w | moderate summer surplus | 16.7 to 33.3 |
| $s_2$ | large winter surplus | above 33.3 |
| $w_2$ | large summer surplus | above 33.3 |

Table 2-3. Thermal Efficiency and its Summer Concentration (8).

| Thermal Efficiency | | Summer Concentration | |
|---|---|---|---|
| TYPE | INDEX (cm) | TYPE | CONCENTRATION (%) |
| $A'$ Megathermal | 114 and above | $a'$ | below 48.0 |
| $B'_4$ Mesothermal | 99.7 to 114.0 | $b'$ | 48.0 to 51.9 |
| $B'_3$ Mesothermal | 85.5 to 99.7 | $b'_3$ | 51.9 to 61.6 |
| $B'_2$ Mesothermal | 71.2 to 85.5 | $b'_2$ | 56.3 to 61.6 |
| $C'_2$ Microthermal | 42.7 to 57.0 | $c'_2$ | 68.0 to 76.3 |
| $C'_1$ Microthermal | 28.5 to 42.7 | $c'_1$ | 76.3 to 88.0 |
| $D'$ Tundra | 14.2 to 28.5 | $d'$ | above 88.0 |
| $E'$ Frost | below 14.2 | | |

Table 2-4. Mean Possible Duration of Sunlight in the Northern Hemisphere Expressed in Units of 30 Days of 12 Hours Each (8).

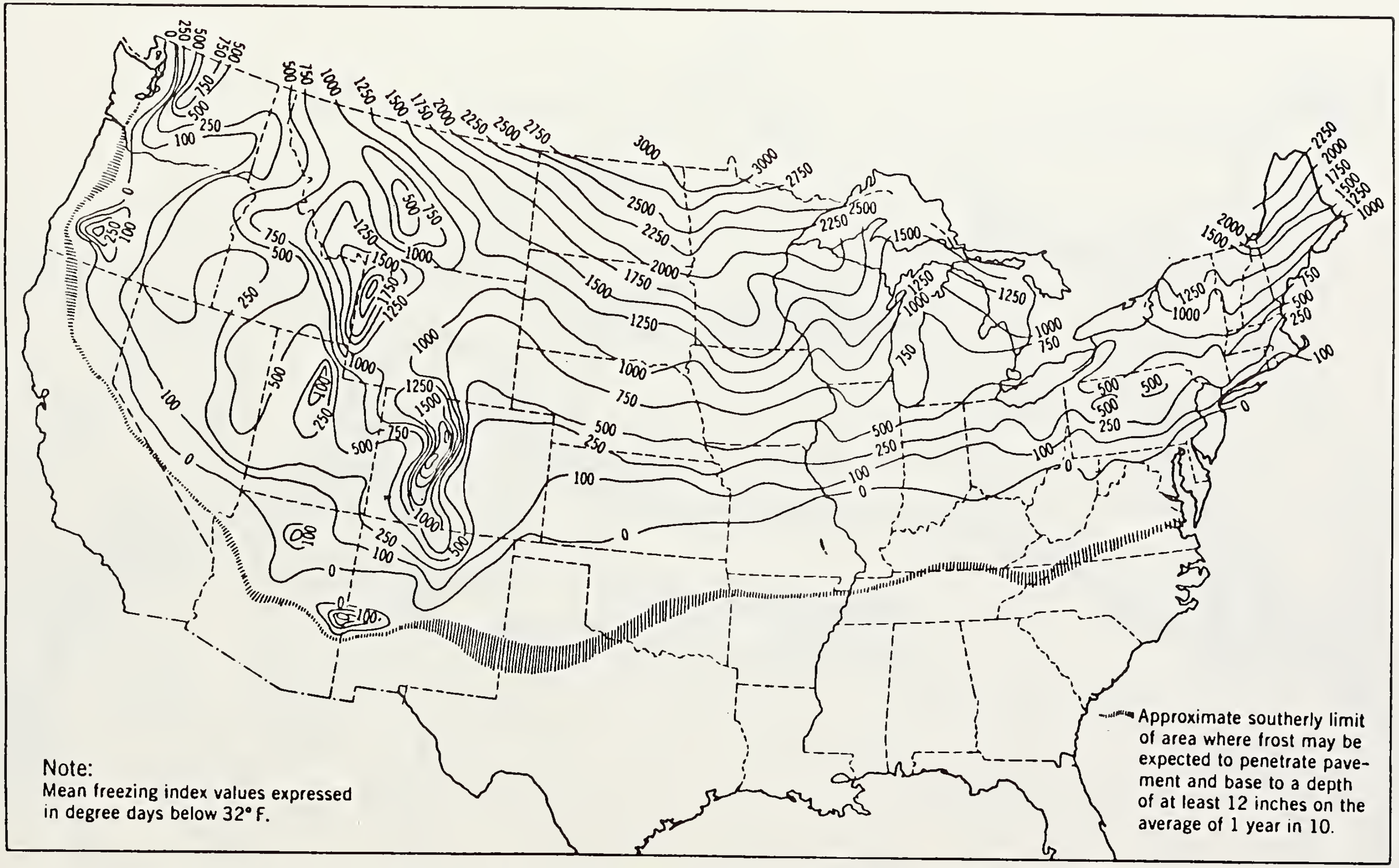
| Lat. | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | .95 | .90 | 1.03 | 1.05 | 1.13 | 1.11 | 1.14 | 1.11 | 1.02 | 1.00 | .93 | .94 |
| 25 | .93 | .89 | 1.03 | 1.06 | 1.15 | 1.14 | 1.17 | 1.12 | 1.02 | .99 | .91 | .91 |
| 26 | .92 | .88 | 1.03 | 1.06 | 1.15 | 1.15 | 1.17 | 1.12 | 1.02 | .99 | .91 | .91 |
| 27 | .92 | .88 | 1.03 | 1.07 | 1.16 | 1.15 | 1.18 | 1.13 | 1.02 | .99 | .90 | .90 |
| 28 | .91 | .88 | 1.03 | 1.07 | 1.16 | 1.16 | 1.18 | 1.13 | 1.02 | .98 | .90 | .90 |
| 29 | .91 | .87 | 1.03 | 1.07 | 1.17 | 1.16 | 1.19 | 1.13 | 1.03 | .98 | .90 | .89 |
| 30 | .90 | .87 | 1.03 | 1.08 | 1.18 | 1.17 | 1.20 | 1.14 | 1.03 | .98 | .89 | .88 |
| 31 | .90 | .87 | 1.03 | 1.08 | 1.18 | 1.18 | 1.20 | 1.14 | 1.03 | .98 | .89 | .88 |
| 32 | .89 | .86 | 1.03 | 1.08 | 1.19 | 1.19 | 1.21 | 1.15 | 1.03 | .98 | .88 | .87 |
| 33 | .88 | .86 | 1.03 | 1.09 | 1.19 | 1.20 | 1.22 | 1.15 | 1.03 | .97 | .88 | .86 |
| 34 | .88 | .85 | 1.03 | 1.09 | 1.20 | 1.20 | 1.22 | 1.16 | 1.03 | .97 | .87 | .86 |
| 35 | .87 | .85 | 1.03 | 1.09 | 1.21 | 1.21 | 1.23 | 1.16 | 1.03 | .97 | .86 | .85 |
| 36 | .87 | .85 | 1.03 | 1.10 | 1.21 | 1.22 | 1.24 | 1.16 | 1.03 | .97 | .86 | .84 |
| 37 | .86 | .84 | 1.03 | 1.10 | 1.22 | 1.23 | 1.25 | 1.17 | 1.03 | .97 | .85 | .83 |
| 38 | .85 | .84 | 1.03 | 1.10 | 1.23 | 1.24 | 1.25 | 1.17 | 1.04 | .96 | .84 | .83 |
| 39 | .85 | .84 | 1.03 | 1.11 | 1.23 | 1.24 | 1.26 | 1.18 | 1.04 | .96 | .84 | .82 |
| 40 | .84 | .83 | 1.03 | 1.11 | 1.24 | 1.25 | 1.27 | 1.18 | 1.04 | .96 | .83 | .81 |
| 41 | .83 | .83 | 1.03 | 1.11 | 1.25 | 1.26 | 1.27 | 1.19 | 1.04 | .96 | .82 | .80 |
| 42 | .82 | .83 | 1.03 | 1.12 | 1.26 | 1.27 | 1.28 | 1.19 | 1.04 | .95 | .82 | .79 |
| 43 | .81 | .82 | 1.02 | 1.12 | 1.26 | 1.28 | 1.29 | 1.20 | 1.04 | .95 | .81 | .77 |
| 44 | .81 | .82 | 1.02 | 1.13 | 1.27 | 1.29 | 1.30 | 1.20 | 1.04 | .95 | .80 | .76 |
| 45 | .80 | .81 | 1.02 | 1.13 | 1.28 | 1.29 | 1.31 | 1.21 | 1.04 | .94 | .79 | .75 |
| 46 | .79 | .81 | 1.02 | 1.13 | 1.29 | 1.31 | 1.32 | 1.22 | 1.04 | .94 | .79 | .74 |
| 47 | .77 | .80 | 1.02 | 1.14 | 1.30 | 1.32 | 1.33 | 1.22 | 1.04 | .93 | .78 | .73 |
| 48 | .76 | .80 | 1.02 | 1.14 | 1.31 | 1.33 | 1.34 | 1.23 | 1.05 | .93 | .77 | .72 |
| 49 | .75 | .79 | 1.02 | 1.14 | 1.32 | 1.34 | 1.35 | 1.24 | 1.05 | .93 | .76 | .71 |
| 50 | .74 | .78 | 1.02 | 1.15 | 1.33 | 1.36 | 1.37 | 1.25 | 1.06 | .92 | .76 | .70 |

Table 2-5. Comparative Moisture Data for Dalhart, Texas After Thornthwaite (8).

| | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Potential Evapotrans | 0 | .1 | .8 | 1.8 | 3.4 | 5.0 | 6.0 | 5.4 | 3.8 | 1.9 | .6 | 0 |
| Precipitation | 0.2 | .3 | .8 | 1.8 | 2.7 | 3.1 | 2.5 | 2.8 | 1.4 | 1.8 | .7 | .5 |
| Moisture Change | +0.2 | +.2 | 0 | 0 | -.7 | -.3 | 0 | 0 | 0 | 0 | .1 | .5 |
| Storage | .8 | 1.0 | 1.0 | 1.0 | .3 | 0 | 0 | 0 | 0 | 0 | .1 | .6 |
| Actual Evapotrans | 0 | .1 | .8 | 1.8 | 3.4 | 3.4 | 2.5 | 2.8 | 1.4 | 1.8 | .6 | 0 |
| Water Deficit | 0 | 0 | 0 | 0 | +.0 | 1.6 | 3.5 | 2.2 | 2.4 | .1 | 0 | 0 |
| Water Surplus | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

$$I_m = \frac{100(\text{Surplus}) - 60(\text{Deficit})}{\text{PE}} = \frac{-60(9.8)}{28.7} = -20.5$$

Figure 2-1. Koeppen's Climatic Differentiation Based Primarily on Temperature.



Note:
Mean freezing index values expressed in degree days below 32° F.

Approximate southerly limit of area where frost may be expected to penetrate pavement and base to a depth of at least 12 inches on the average of 1 year in 10.

Figure 2-2. Distribution of mean freezing-index values in continental United States. (From Corps of Engineers EM 1110-345-306.)

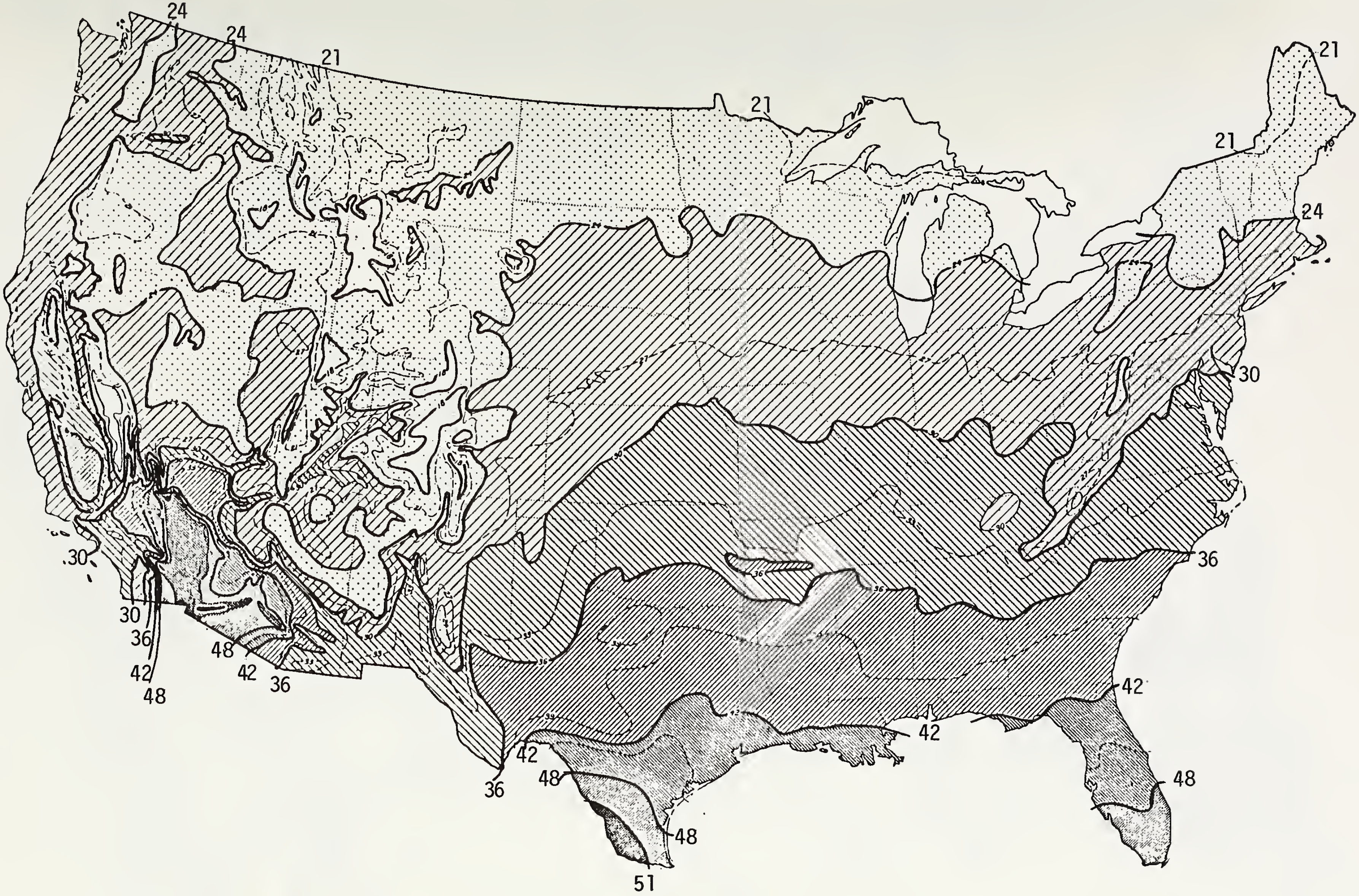


Figure 2-3. Potential Evapotranspiration, After Thornthwaite (8).

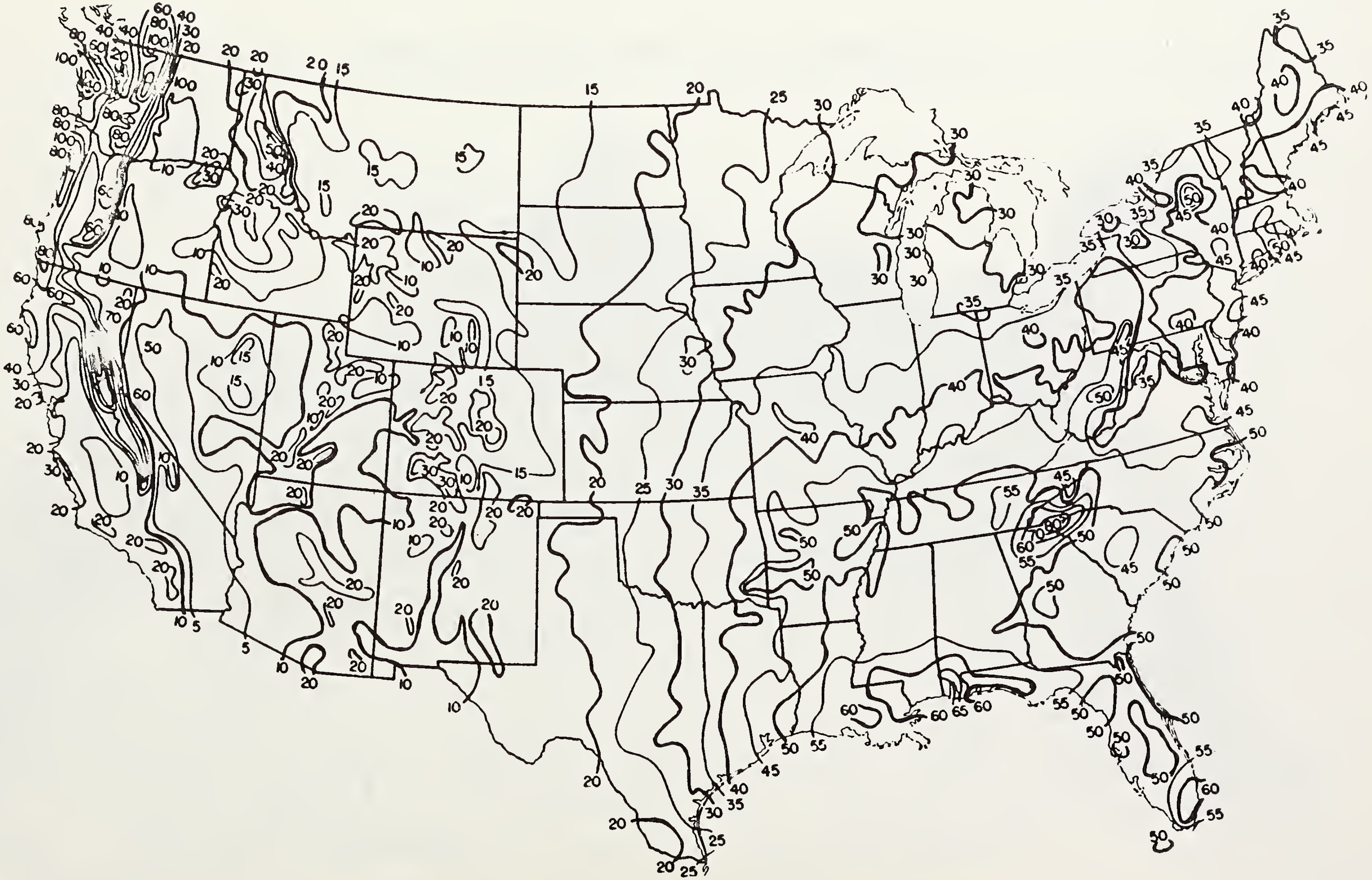


Figure 2-4. Annual Average Rainfall (16).

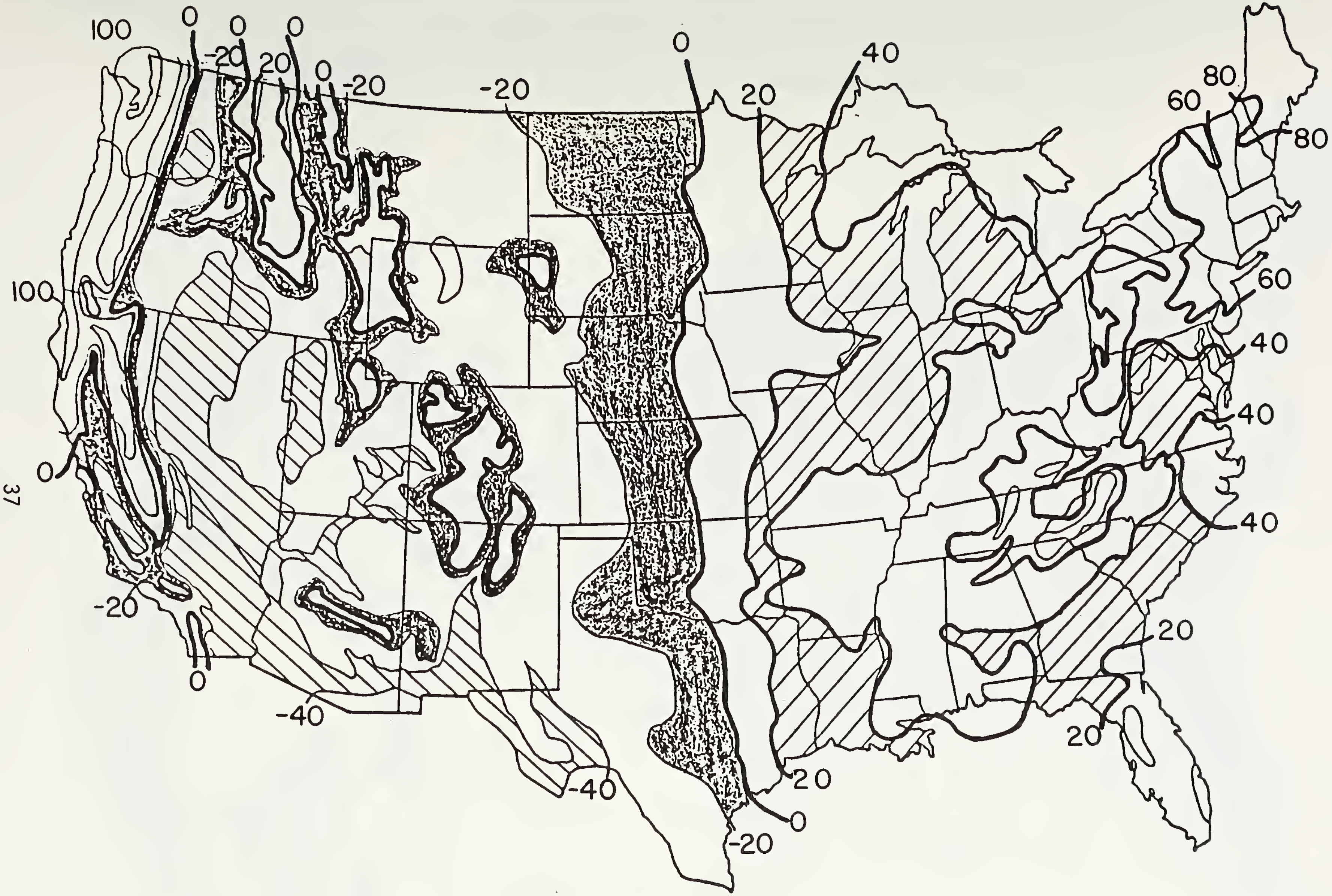


Figure 2-5. Distribution of Thornthwaite Moisture Index in the United States after Thornthwaite (8).

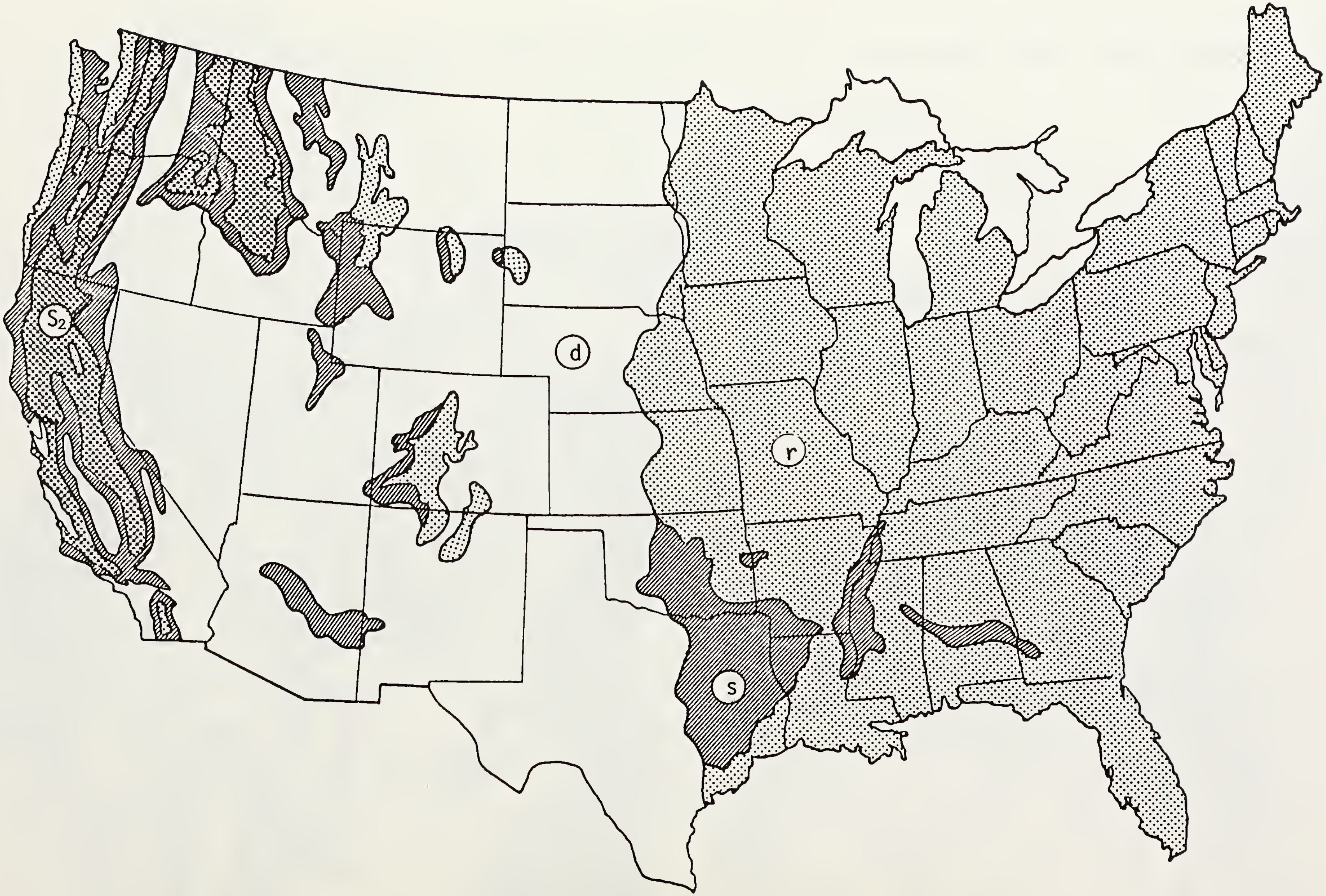


Figure 2-6. Distribution of Seasonal Moisture Variation Across the United States, after Thornthwaite (8).

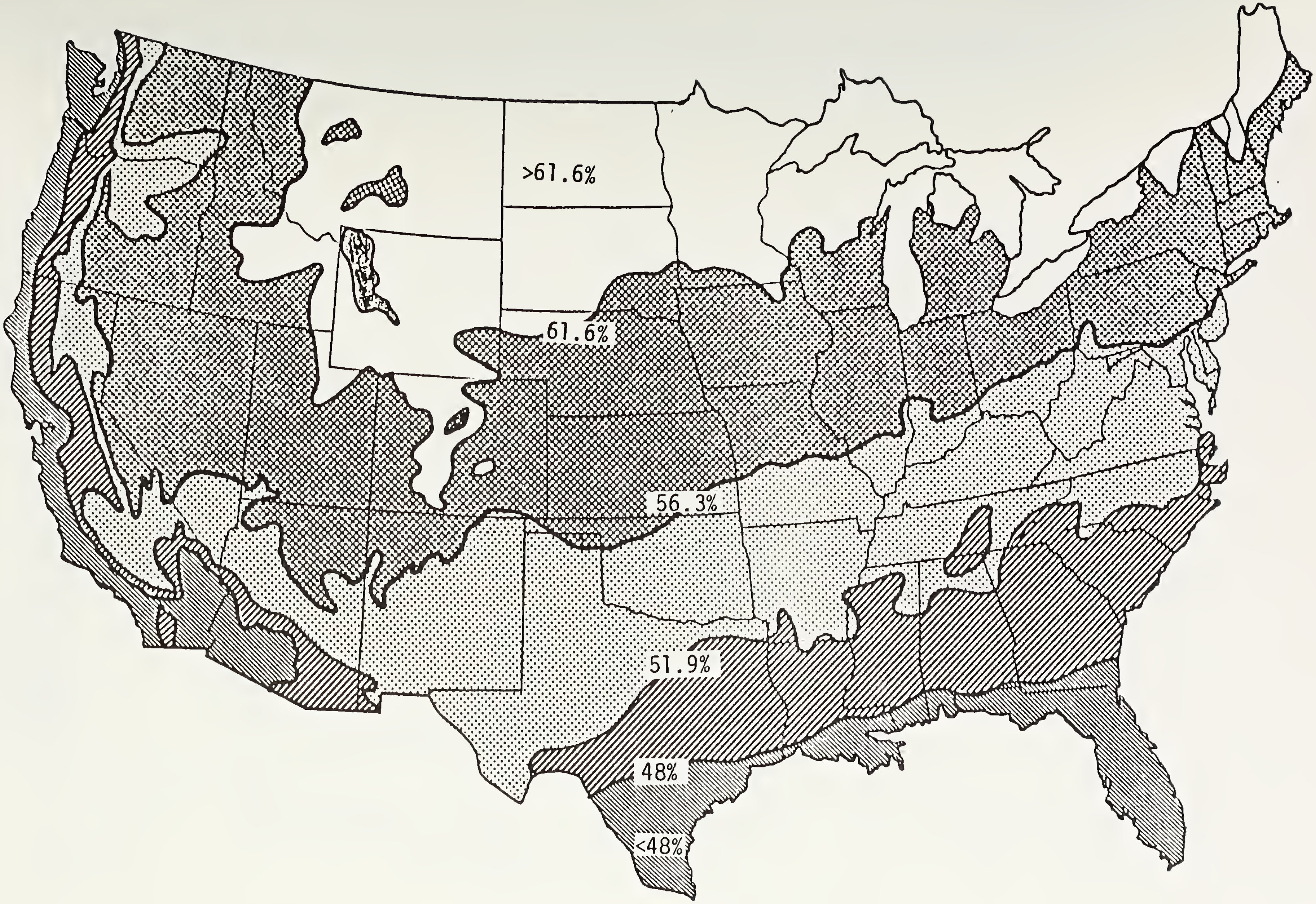


Figure 2-7. Distribution of the Summer Concentration of Thermal Efficiency, after Thornthwaite (8).

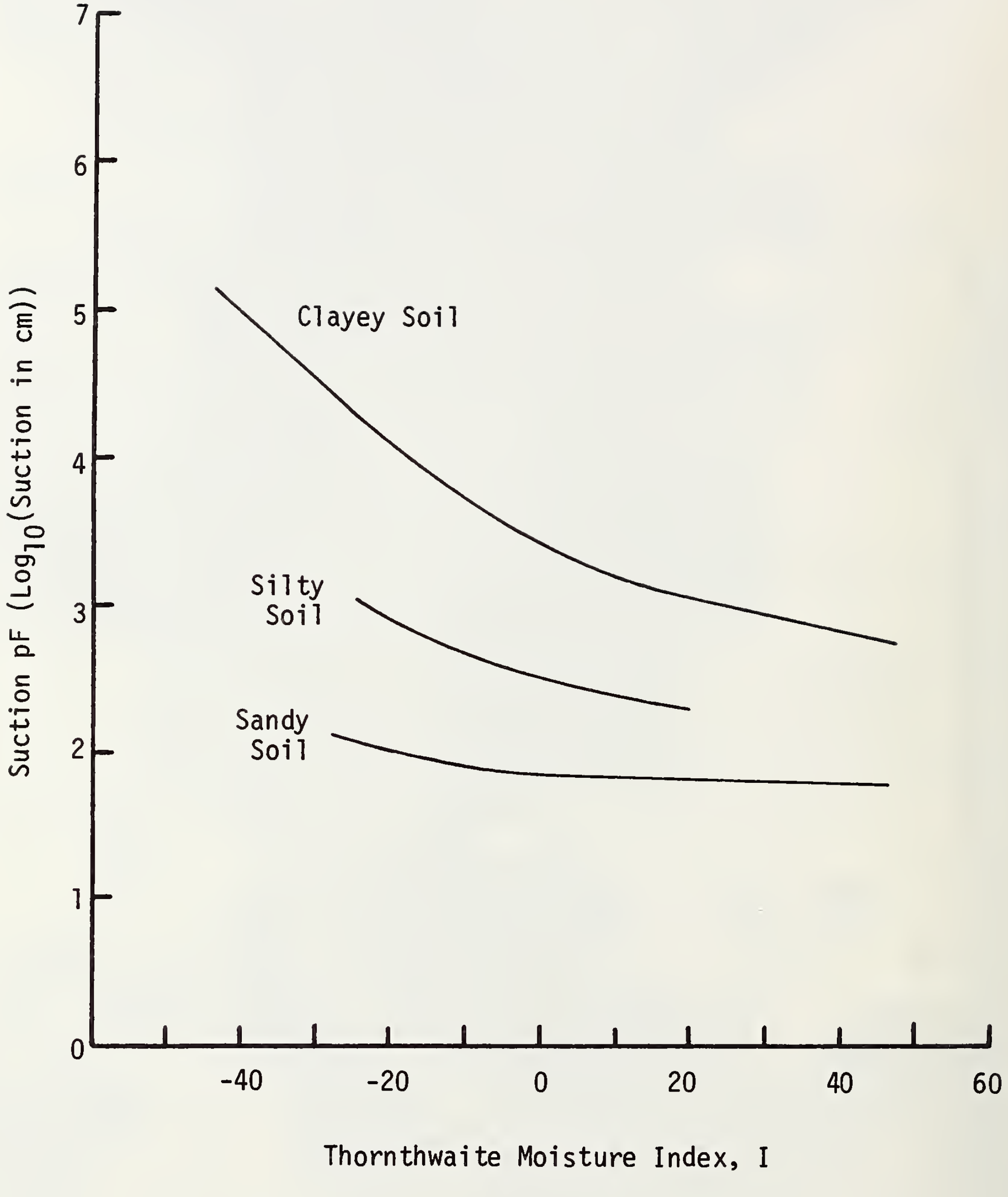


Figure 2-8. Equilibrium Suction in Subgrade as Influenced by the Climate, Indicated by the Thornthwaite Moisture Index (11).

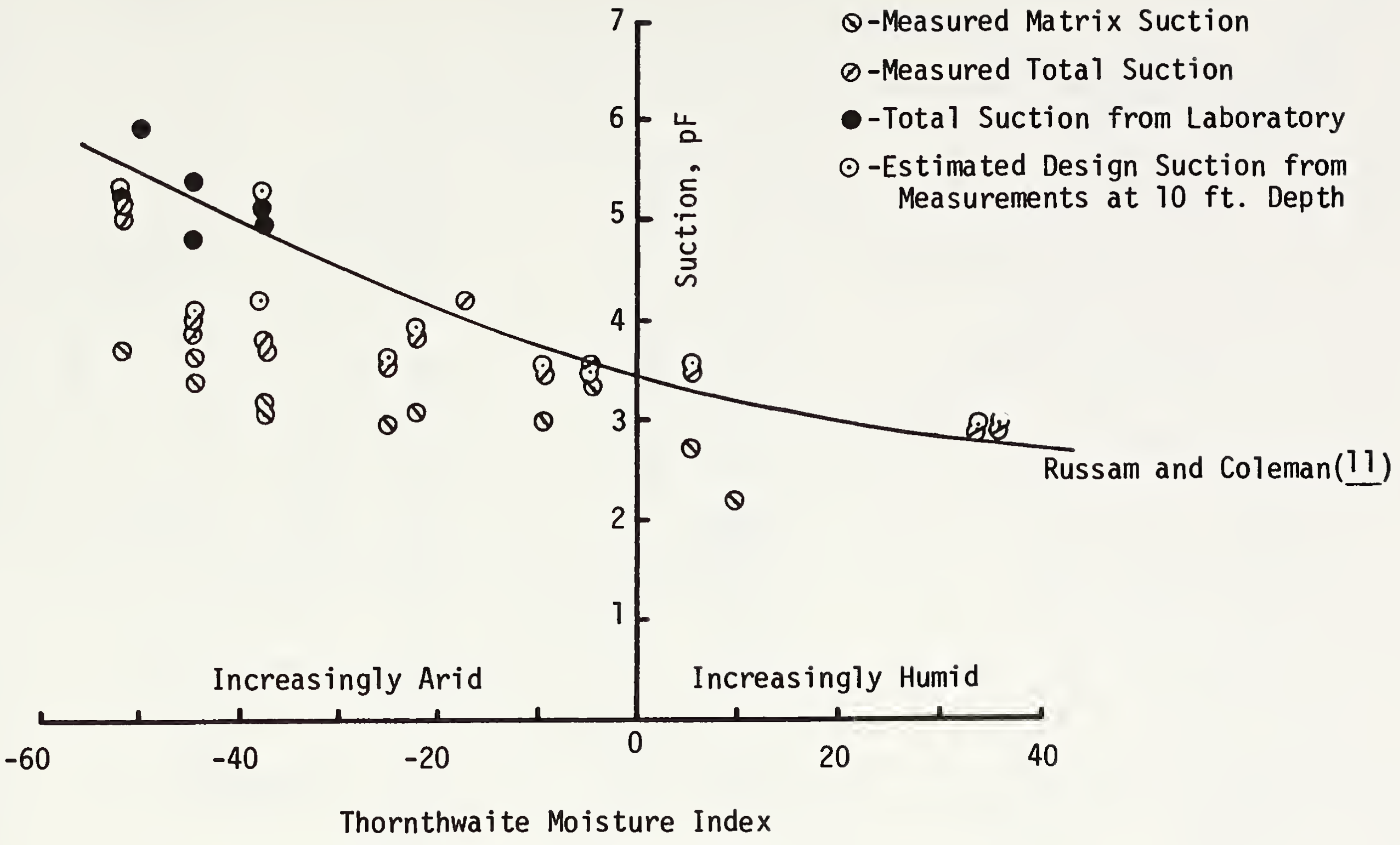


Figure 2-9. Equilibrium Subgrade Suction Values from Seventeen Sites in Australia with the Climatic Relationship Established by Russam and Coleman (12).

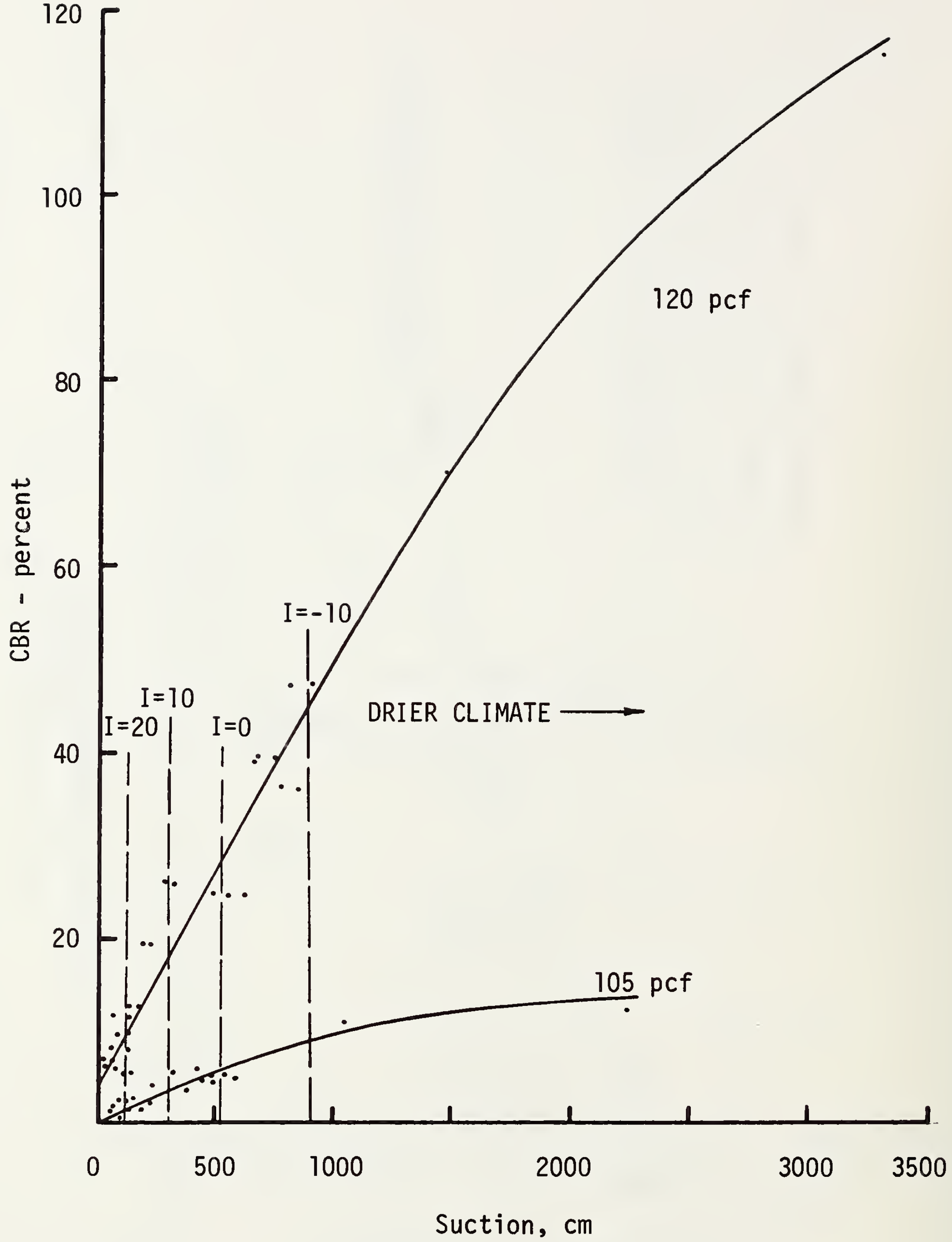


Figure 2-10. Effect of Suction on the CBR of a Silty Sand with Climatic Regions Indicated with the Expected Moisture Index for the Soil (14).

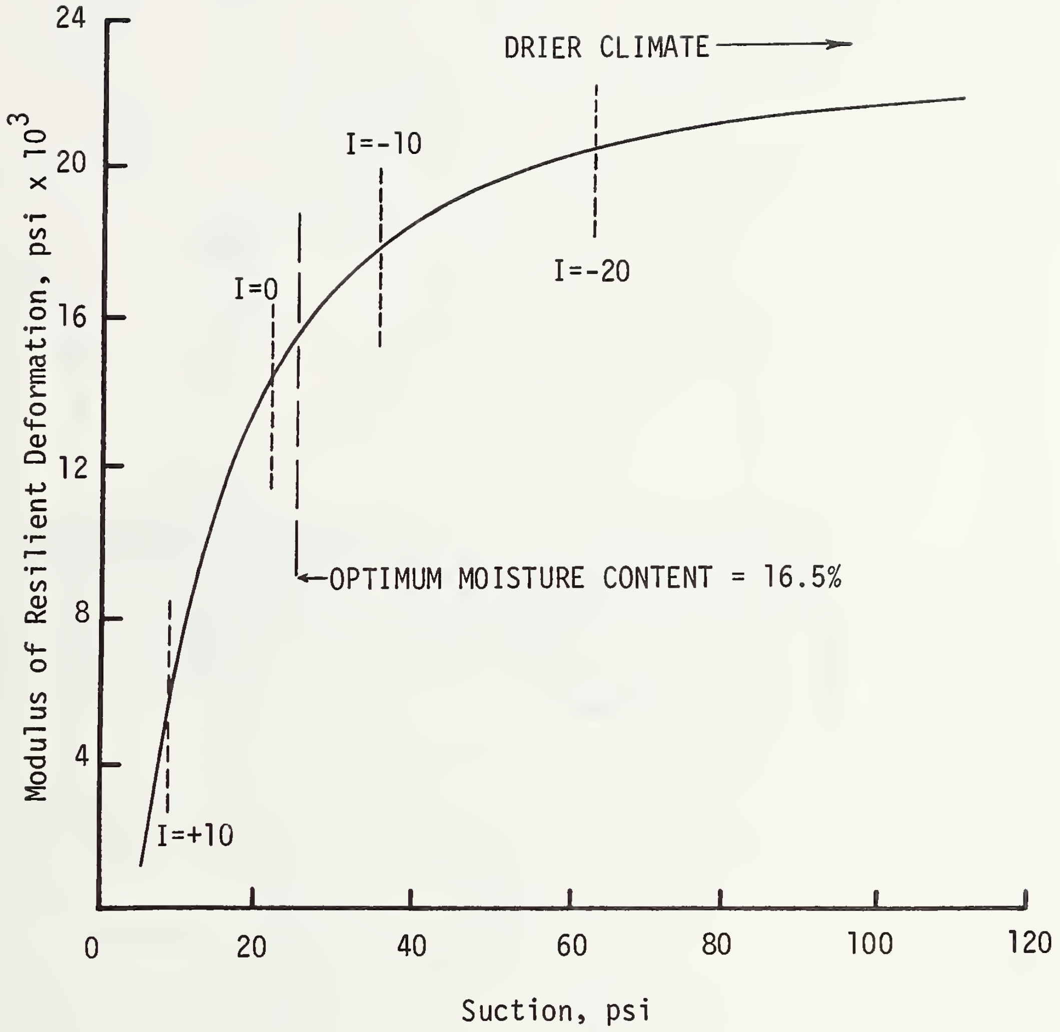


Figure 2-11. Effect of Soil Suction on the Resilient Modulus of a Canadian Till with the Expected Moisture Index for the Soil Indicated (14).

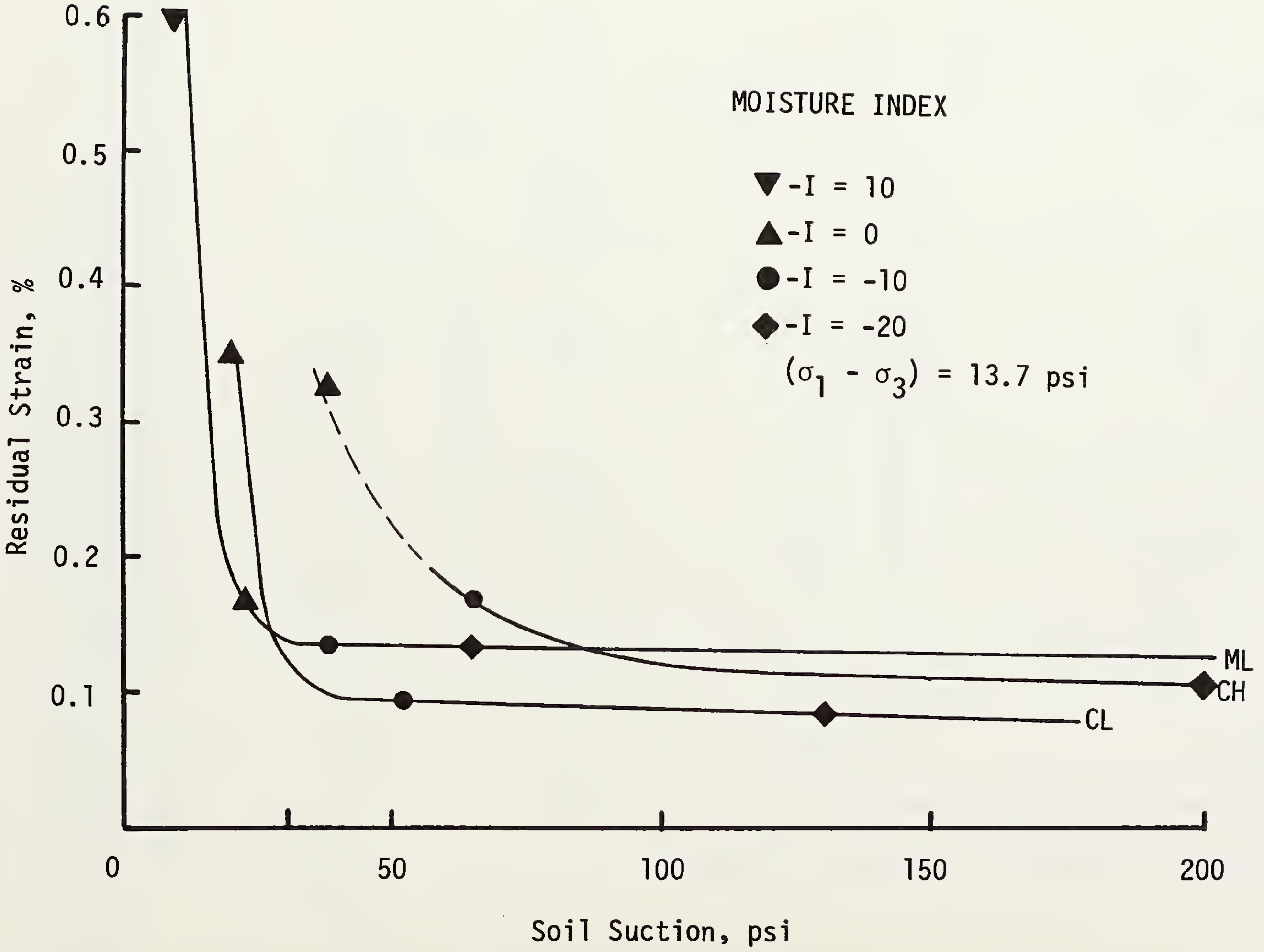


Figure 2-12. Residual Strain of Soils at 10,000 Load Cycles as a Function of the Initial Soil Suction With Climatic Induced Suction Levels Indicated by the Moisture Index (15).

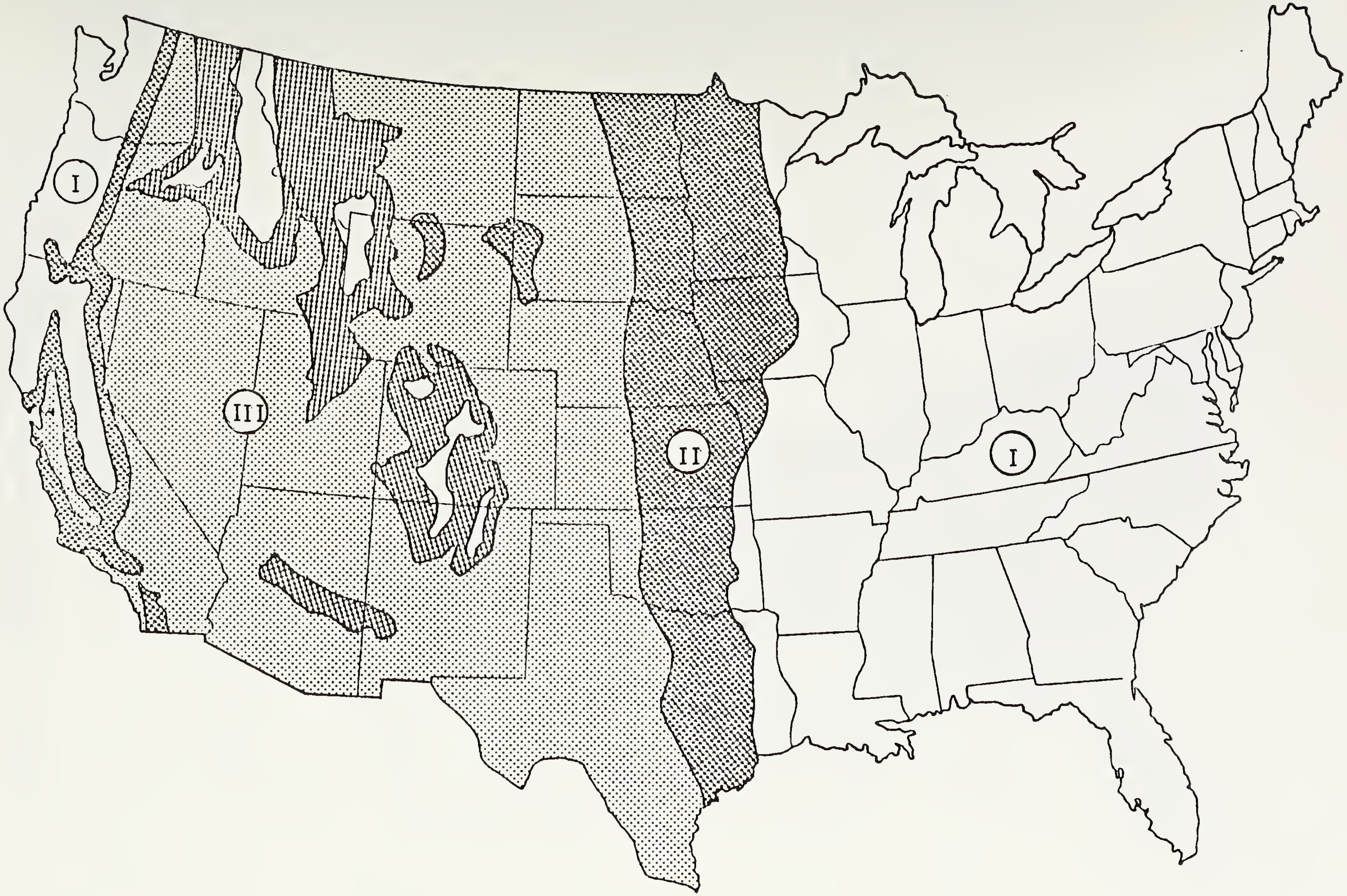


Figure 2-13. Moisture Regions Based on the Relationship of the Moisture Index With Repeated Load Performance.

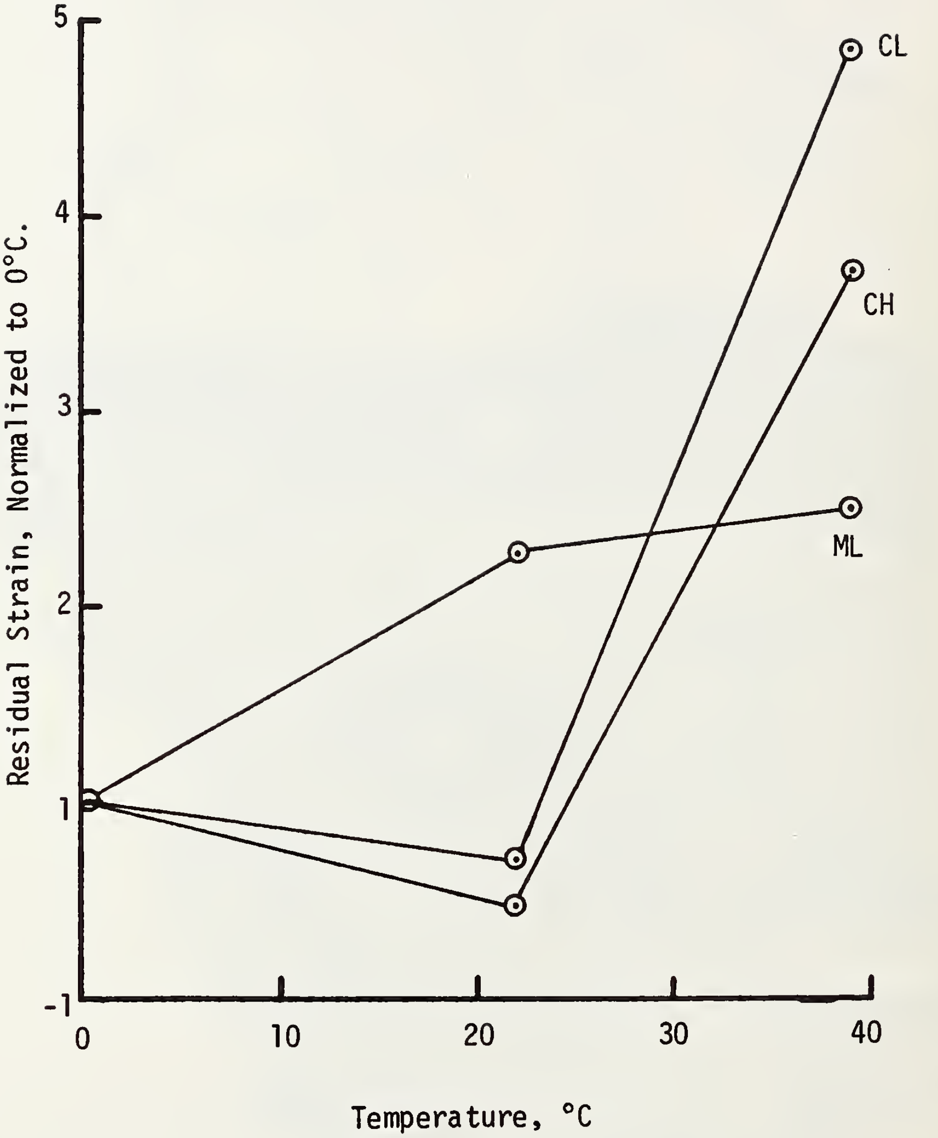


Figure 2-14. Change in Residual Strain Due to Change in Ambient Temperature (15).

Figure 2-15. Temperature Influence Regions Based on the Summer Concentration of Thermal Efficiency.

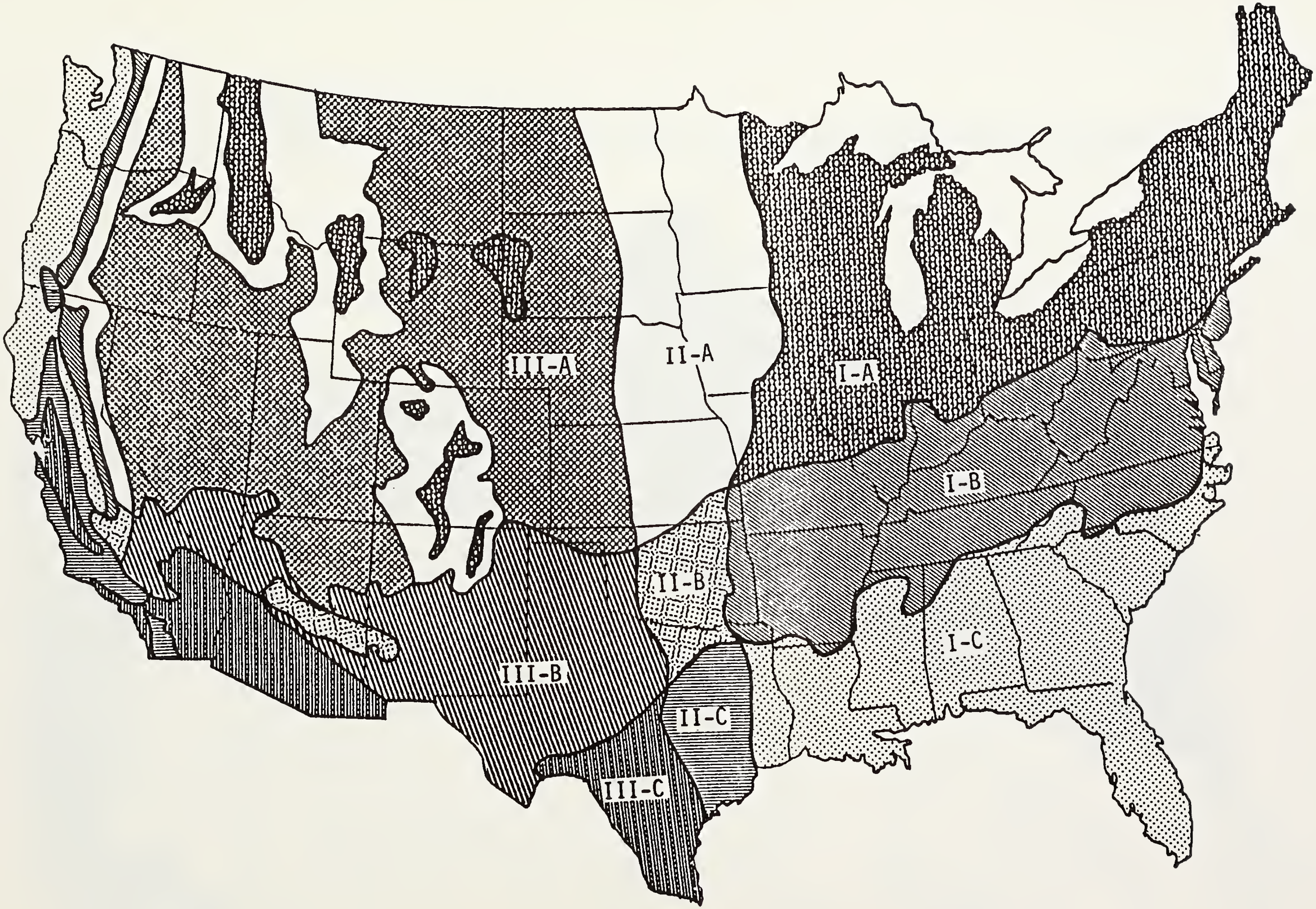


Figure 2-16. Climatic Zones Based on Thornthwaite Potential Evapotranspiration and Moisture Index and their Interaction with Performance, with Similar Performance Expected in Similar Climatic Regions.

| (1) Month | (2) Monthly Temperature °C | (3) $\left(\frac{(2)}{5.0}\right)^{1.514}$ | (4) $\frac{(2) \times 10.0}{I}$ | (5) $1.6(4)^{a}$ | (6) Correction Factor for Latitude | (7) (5)(6) |
|---|---|---|---|---|---|---|
| J | | | | | | |
| F | | | | | | |
| M | | | | | | |
| A | | | | | | |
| M | | | | | | |
| J | | | | | | |
| J | | | | | | |
| A | | | | | | |
| S | | | | | | |
| O | | | | | | |
| N | | | | | | |
| D | | | | | | |

$I = \sum =$ ______ x 47,920 = ______ (x) $\sum =$ ______ = annual potential evapotranspiration, cm

$I^2 =$ ______ x 77.1 = ______ (b)

$I^3 =$ ______ x 0.675 ______ (c)

(x) - (b) + (c) = ______

+ 492,390 = ______ x $10^{-6}$ = a

Figure 2-17. Tabular Setup for Calculating the Potential Evapotranspiration.

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# CHAPTER 3

# INTRINSIC FACTORS

The previous section examined the extrinsic, or external factors that influence the development of moisture accelerated distress, termed MAD. The presence of extrinsic factors, however, does not automatically imply that the pavement will experience MAD. If the intrinsic, or internal, factors in the pavement structure are such that the pavement is highly moisture resistant, or removes water very efficiently, then the pavement may not develop moisture related problems. However, the existence of external factors that indicate a high potential for MAD, and therefore the intrinsic factors that relate to moisture become extremely important.

Intrinsic properties are those that relate to drainage and exist in the pavement at the present time, or that would be built into the pavement once a certain structure was constructed. With a given set of extrinsic factors, the intrinsic properties will alter the potential for MAD. Intrinsic properties include the following:

1. Type of pavement. This will influence the amount of water made available through cracks or joints in the surface.
2. Properties of roadbed materials relating to moisture behavior.
    a. Drainability
    b. Permeabilities
    c. Physical geometry
    d. Soil type
3. Topography
4. Water table
5. Existing drainage facilities

When moisture is present in a pavement, in a predetermined amount, the variation in MAD caused by this moisture will depend entirely on the intrinsic factors and their ability, or inability, to remove moisture from the pavement system. It is necessary to examine the role each of the above factors play in altering moisture flow; and to show whether certain combinations should be avoided.

### Type of Pavement

The type of pavement will provide different potentials for moisture to enter the subsurface layers. The condition of the surface, the amount of cracking, will also show a great influence on the amount of moisture entering the pavement system. Cracking is a surface indicator and will be discussed in a later section.

A continuously reinforced concrete pavement will have a large number of cracks. They may be closely spaced and tight for the majority, and admit relatively little water into the pavement system. Jointed concrete pavement is more likely to provide a surface with high potential for water entry into the pavement system. At the pavement edge however the potential will be the same. Whether the joints are reinforced or not, the sealant must maintain its integrity to keep water out of the pavement system. At the present time there are few, if any, joint sealants that will keep the transverse joints watertight beyond one winter's thermal activity (1).

The shoulder joint is also a critical area for the infiltration of moisture into moisture sensitive areas of the pavement. It represents the longest continuous point of infiltration; and it falls at a critical point in the loading area of the pavement. Support at the pavement edge, and its variation, is critical to the performance at the joint. Loss of support due to moisture intrusion can lead to pumping and failure at the edge of the pavement.

A concrete pavement with a bituminous shoulder provides a material inconsistency that makes it nearly impossible to seal the joint for any useful time to prevent moisture intrusion. The difference in thermal properties of the asphalt and portland cement concrete makes it very difficult to obtain a sealant that can perform properly and bond to both materials. A concrete pavement with a concrete shoulder will still present a joint where water may enter the pavement system. This joint, however, can be designed or maintained to provide a tighter seal by tying the two concrete slabs together or by paving full width. Full width paving is also beneficial for bituminous pavements to eliminate points of moisture infiltration.

## Drainage

If subdrainage is provided in the pavement structure, the influence of moisture will be lessened somewhat if the drain has been designed properly. If the drain is several years old its efficiency is not likely to be the same as when it was first constructed; and water could be held in the pavement. If the drain system has not been maintained properly, water might even be backed up into the pavement system. Clogged pipe outlets, fouled french drain outlets, and ponding of water in the side ditches are only a few of the easily recognized items that indicate a moisture problem in the pavement may be developing. The point to be made is that the drain system should be thoroughly inspected before it is decided that the existing drainage system is functional at a level to aid in draining the pavement.

## Properties of Roadbed Material

The properties of the roadbed material influence how long the water that infiltrates through the surface will remain in the pavement system. The longer that moisture remains in the pavement system, the higher the potential for moisture damage in the pavement to be accelerated by the loadings. A number of studies have illustrated that the higher the level of saturation, the quicker the deterioration process (2, 3). Examples from these studies have been shown previously. The ability of different materials to retain water has been studied extensively for agricultural uses of the soil. Only very recently has this approach been used to study moisture variation in soils in pavement systems (4, 5).

Drainage systems in pavements are gravity drain arrangements that can only utilize the elevation head to drain the soil layers of the pavement. During saturated flow, the amount of water entering the pavement through the cracks is limited by the amount of water leaving the pavement system and flowing into the drains if drains are present. Saturated flow is limited by the permeability of the materials in the roadbed system, these values are easily determinable in the laboratory, or in-situ with special equipment (6). Thus, flow nets or computer techniques are good ways for predicting the maximum flow through the pavement system.

The controlling factor that dictates the required permeability of the pavement system to carry away the water, is the infiltration rate of water through the pavement surface. This depends on, primarily, the amount and type of cracking or joints that are present, or that could be expected to develop over a period of time. It has been estimated, (1) that infiltration is:

$$Q = 0.1\ [N + 1 + (W/\ell)] \tag{3-1}$$

where

$Q$ = amount if infiltration ($ft^3$/hour/linear foot of pavement)

$0.1$ = infiltration rate ($ft^3$/hour/ft of crack)

$N$ = number of lanes

$W$ = pavement width, (ft)

$\ell$ = pcc slab length or average distance between transverse cracks (ft)

This equation does not include the edge joint and assumes only one infiltration rate for all severity levels of cracking. This amount will, however, vary with crack width as is shown in Figure 3-1. The infiltration rate of 0.1 $ft^3$/hr/ft corresponds to .001 gal/min/in. as indicated in the figure. This indicates an average crack width of .023 inches has been used in the above equation. This width should not be considered typical, as crack width will vary even during one day. This is shown in Table 3-1 where the opening at a joint is shown as a function of spacing and subbase type, which shows the granular subbase to have a higher coefficient expansion than the stabilized material. Although the opening figures are for rather severe circumstances, the implication is clear that much wider crack openings may be expected than are used in the above equation. The amount of moisture entering the pavement will also depend on the intensity of the rainfall. Up to a fixed intensity, the cracks and joints could handle all the rain falling on the pavement. Beyond this intensity various percentages of the rainfall falling on the pavement surface would run off into the side ditches. This infiltration depends on several surface properties shown in Table 3-2.

The cracks, joints, and general surface conditions are only the first things that must be considered. If the permeability of the roadbed material is low enough to limit the quantity of flow below the level that surface conditions would allow; then the flow into the pavement system will be reduced to that which the roadbed materials allow. This was pointed out by Barksdale and Hicks (1) when they cautioned that the pavement surface condition may not be indicative of the surface infiltration rate, but that conditions existing beneath the pavement may control the amount of water entering the structural section.

The surface of asphaltic concrete pavements will have some permeability and admit a certain amount of water to the roadbed material. Some typical permeabilities are shown in Table 3-3 for old and new pavements. The lower permeabilities of old pavements illustrates the surface sealing effect produced by traffic. When the pavement has a permeability of 1.0 in/hr, this can result in an infiltration rate of 2 $ft^3$/hr/ft of pavement, considerably higher than that of most cracked pavements; as this rate of infiltration would require a crack spacing somewhat less than 2 ft by equation 3-1. These data illustrate quite clearly that the surface of a pavement can readily admit a rather large amount of water into the pavement structure. However, the factor controlling the quantity of water that actually enters the pavement structure is most likely the base course, its permeability, and how well it is drained.

Figures 3-2 and 3-3 illustrate the effect of grain-size distribution on the permeability of granular material and the wide variation in permeability that is possible by altering the gradation. Base courses can be designed to flow a given amount of surface infiltration by altering the gradation. Knowing the base course permeabilities and surface infiltration, the engineer can design the proper drainage system to assure that the water flowing into the pavement system is removed (12). Figure 3-4 further illustrates the effect of small changes in the gradation on permeability. This difference is what one may expect to occur over time as aggregate degrades during service. As a caution, the use of a gradation curve to estimate permeability represents the best condition possible for the material being used and is not conservative.

During the time a granular material is saturated, load associated damage will accumulate at an accelerated rate, compared to when the material is drier. In most pavements flow of surface infiltration will be restricted primarily to the base course because the base course will typically have a much larger permeability than the subgrade. The subgrade will, however, absorb moisture from the base course because it is in contact with the base. Although the rate of absorption may be slow, a subgrade under a poorly drained base course may contain an excess of moisture for an appreciable time.

To reduce the length of time the subgrade will be absorbing moisture, the base course and all other materials in contact with the subgrade should drain water quickly to a level where the subgrade will not attract water from them. Grain size distributions parameters effect both the coefficient of permeability, and the water holding capacity. The water holding capacity is sometimes referred to as specific yield (a material property), or suction (an energy term which may be related to material properties).

## Specific Yield

The specific yield of a granular material is often called the effective porosity of the material and is a function of capillary and gravity forces. It is the ratio of the volume of water that will drain under the influence of gravity from a saturated sample, to the total volume of that sample.

$$S.Y. = (V_{WD}/V_t)100 = n_e$$

where

$S.Y.$ = specific yield, percent

$V_{WD}$ = volume of water drained from the saturated sample

$V_T$ = total volume of the sample

In more fundamental terms it may be written as follows:

$$n_e = 1 - \frac{\gamma d}{G_s\gamma_\omega}(1 + G_sW_e)$$

where

$n_e$ = effective porosity

$\gamma_d$ = dry density of the specimen

$G_s$ = specific gravity of the solids

$\gamma_\omega$ = unit weight of water

$W_e$ = effective water content of the sample after drainage, dry weight basis

The use of this term is open to question as regards practical application because the time allowed for drainage is not specified. This time is actually a very important material parameter that is undergoing study at the University of Illinois to allow seasonal and even daily calculations of the amount of water present in a layered pavement system of specified physical and material properties. A coarse grained soil will drain to equilibrium quicker than a fine grained soil, even though it must drain to a lower water content. The water in a sample will drain until the remaining water in the menisci of the soil particles is held in equilibrium with the force of gravity. A smaller grain size distribution will provide smaller capillary menisci that will hold the water tighter; and upon drainage the volume of water leaving this sample, compared to the total volume, will be smaller.

This has been shown in a number of studies that will be discussed presently. Table 3-4 shows the results of a simple study conducted in the FHWA labs (16) illustrating a very marked dependence of specific yield on grain size. The study calculated the saturation of the samples after draining rather than specific yield, but the results are easily compared. The sand is a class-x concrete sand often used in drainage systems as a backfill. Upon gravity drainage, the sand is still greater than 90 percent saturated. The combinations of gravel and sand all drain to a much lower level of saturation. This is the basic principle behind the studies discussed here as they relate to the ability of a material to drain moisture and maintain a given saturation level.

Preuss and Todd (17), found that the $D_{50}$, median, grain size was best suited as a measure of representative grain diameter; the uniformity coefficient used to describe the samples was defined as $U = D_{60}/D_{10}$ where $U$ = uniformity coefficient; $D_{60}$ = that particle diameter such that 60% is finer than this diameter; $D_{10}$ = that particle diameter such that 10% is finer than this diameter. The results of this study indicated that the maximum value of specific yield occurred for a $D_{50}$ between 0.4 and 0.5mm, and that the specific yield decreased for values of $D_{50}$ outside this range. They also concluded that in general the specific yield decreased as the magnitude of the uniformity coefficient increased.

Barber and Sawyer (13), presented observed values of specific yield in sand graded from the No. 10 to the No. 200 sieve. The specific yield from saturation to drained moisture ranged from .017 for 10% clay passing the No. 200 sieve to .138 for 5% silica passing the No. 200 sieve. The specific yield was found to decrease for a given fraction passing the No. 200 sieve in the following descending order: Silica, Limestone, Manor Loam, Keyport Silt Load, Tuxedo Clay.

Strohm, Nettles and Calhoun (14), investigated the effects of various parameters on the effective porosity (i.e., specific yield). A range of effective porosity values for a given density and gradation was found. The effective porosity was found to decrease with increased density and increased fines. The effective porosity can approach zero in a highly compacted material containing as little as 5% fines.

Moulton (15), observed that most of the properties influencing the coefficient of permeability also influence capillarity and the specific yield. A statistical correlation between specific yield or effective porosity and coefficient of permeability for soils of various gradations and densities was performed. Data for high and low values were lacking and scattered, respectively. Middle range values were considered reasonably reliable.

It appears that reasonably accurate prediction or estimation of permeabilities of granular base pavement materials may be made from the effective grain size, porosity and percent passing the No. 200 sieve.

It also appears that reasonable values of specific yield or effective porosity may be predicted or estimated from the permeability.

To develop a reliable model for prediction of permeability and specific yield, it is recommended that the data analyzed by Moulton be added to so that the conditions may be confirmed and/or refined at the lower and higher ranges of the permeability and specific yield values.

The discussion of specific yield raises the question of moisture balance when two different soils are in contact and one has been saturated, as is the case in any typical drainage system. Moisture flow is an energy balance phenomenon. This relationship of energies is quite clearly illustrated by Strohm, Nettles, and Calhoun in their 1967 study (14). When a container of soil is raised above a pool of water and connected to the pool by a full standpipe of water, the water in the standpipe will be exerting a downward pull on the water in the soil sample. This downward force is resisted by the capillary force of the water in the soil menisci. The higher the column, the larger the downward force and the more water that will be pulled out of the soil sample.

The height of this column may be expressed in a number of ways. The two most common are:

1. Height of column in cm.
2. The pressure exerted at the bottom of the standpipe when the soil is removed (bars, atmospheres, or psi).

Because this downward force puts the water in the soil into tension, the quantity above is often referred to as soil moisture tension, or suction.

This variation of moisture tension and moisture content of the soil is the basis for studying moisture movement in unsaturated materials.

Sample curves for some typical soils are shown in Figure 3-6. These can be compared with the curves in Figure 3-7 which are taken from the work by Barber and Sawyer (13). These curves clearly indicate that finer grained material will have a much higher potential for attracting water than coarser grained material. Thus, when a base course becomes saturated, the moisture will be attracted by the finer grained clay subgrade. The longer the base course remains at a high level of saturation, the more moisture the subgrade will attract.

This is the basis behind the Corps of Engineer's requirement that within ten days the base course must drain 50 percent of all drainable water, i. e., 50 percent of the specific yield (19). The relationship to determine this time was first presented by Casagrande (18) as:

$$T = US - 0.48S^2 \,\mathrm{Log}(1 + 4.8\, U/S) \qquad 0 \leq U \leq 0.5 \tag{3-3}$$

and

$$\begin{aligned} T = {} & 0.5\, S - 0.48S^2 \,\mathrm{Log}(1 + 2.4/S) + \\ & 1.15\, S \,\mathrm{Log}(S - US + 12)/(1 - U)(S + 2.4) \qquad 0.5 \leq U \leq 1 \end{aligned} \tag{3-3}$$

where

$T = KHt/yD^2$, a time factor

k = coefficient of permeability, in feet per day

H = depth of base in feet

t = time in days

y - specific yield

D = width of base, drainage length, in feet

$Le = D\,(g\ell/gt)^2 + 1$

$ge = g\ell^2 + gt^2$

$S$ = slope factor = $H/Lege$

$Le$ = effective drainage length

$ge$ = effective slope of pavement

The curves presented in Figure 3-8 allow graphical selection of the time factor, from which t may be obtained. For U = 50, this relation may be closely approximated by:

$$t = (H/K)(0.44\ D^2/(.074\ H + Ds)) \tag{3-4}$$

where the terms are as previously defined.

The two material properties that are necessary are the saturated permeability and the specific yield of the base course material. The permeability can be roughly estimated from the nomograph in Figure 3-12. While this is only approximate, it will give a typical value that is likely to be representative, due to inhomogeneity of the base course material.

The limiting upper value for the specific yield is the volume of the voids. Due to capillary forces only a given percentage will actually drain under the influence of gravity. Table 3-5 has been assembled from available studies. The values represent percentages of the voids that will drain under gravity for reported materials. The following example will illustrate how this table can be used to obtain estimates of the specific yield (effective porosity).

Material: Combination of Sand (25%) and Gravel (75%)

See Figure 3-10.

$\gamma d = 114.09$ pcf

$G_s = 2.684$

The calculations are as follows:

$$\gamma_d = W_s/V_T = 114.09 \text{ pcf} = 1.825 \text{ gm/cc}$$

assuming $V_T = 1$ cc, $W_s = 1.825$ gm

$$V_s = W_s/G_s = 0.680$$

$$V_v = 1.0 - V_s - 0.320$$

$$N_{e_{maximum}} = \frac{V_v}{V_T} = \frac{.320}{1.0} = .320$$

See Figure 3-11 for explanations of the terminology used. From Table 3-5 the water loss percentage can be estimated. The gradation being studied contains less than 0.5 percent fines and is borderline between gravel or sand in the table (66 percent greater than #4).

An intermediate value would lean towards the influence of finer sized material and the water loss estimate would be between 57-70 percent. Assuming 60 percent water loss the specific yield (effective porosity) would be:

$$(N_{e_{max}})(\text{water loss})$$

$$= (.320)(.60) = 0.192 = N_e$$

The actual specific yield (effective porosity) is 0.175. The permeability can be estimated at 100 ft/day from Figure 3-12.

Assuming the following pavement section:

H = 9 inches - 0.75 ft

D = 13 ft

S = 1% - 0.01 ft/ft, no longitudinal slope.

the time for this base course to drain to a specified level of drainage may be calculated using equation 3-3, or from the graphical procedure given in Figure 3-8.

The drainage time curves for this material are presented in Figure 3-13. The change in drainage time produced by variation in the specific yield are shown by comparing the curves produced by using the actual and estimated values. The results are comparable. Although these curves utilize material properties the percentage of drainage is not a material property that can be used to indicate moisture related performance. Utilizing the same soil properties that were used to calculate the maximum specific yield, the saturation corresponding to the various levels of drainage can be obtained.

The importance of predicting saturation level rather than a percentage of water drained is clearly illustrated in studies that have investigated the resilient and permanent deformation characteristics of granular materials. Figure 3-14 illustrates the repeated load performance of the AASHTO granular materials (<u>20</u>). The resilient deformation, in the upper portion of the figure illustrates a linear increase in resilient deformation with increasing level of saturation. Increased resilient deformation may accelerate fatigue damage which is perhaps more important in flexible pavements than rigid.

Permanent deformation, however, is critical to both pavement types. In flexible pavements, permanent deformation is manifested as rutting. In rigid pavements the voids caused by permanent deformation under joints and cracks is critical to the performance of the joint or crack. Permanent deformation of coarse grained materials increases dramatically when the level of saturation is over 85 percent. The sooner saturation is reduced to the 85 percent level, the better the performance will be compared to a pavement that remains at a higher level of saturation. This concept has been addressed by Cedergren (10), although no numerical limits have been specified. The Corps of Engineer's procedure for airfield pavements is that 50 percent drainage be attained in 10 days. A criteria utilizing performance such as the 85 percent saturation limit would be more meaningful to relate to expected performance. Experience indicates that a pavement that drains in less than 8-10 hours exhibits better performance than one taking longer (1). Although an acceptable level of saturation is not clearly defined, the 85 percent level is an acceptable upper limit from the performance standpoint.

The calculations for drainage time to a given level of saturation assume a saturated base. The question that must be addressed is whether the base or subbase will have free access to the water in a rain or will it be kept relatively dry if the crack restricts entry of water to the granular materials. As mentioned previously an uncracked asphalt concrete can admit up to 2 $ft^3$/hr/linear ft of pavement. Water admitted by cracks depends on crack spacing and opening width.

A linear foot of base course constructed from the sand-gravel combination used in the preceding example to calculate the rate of drainage will contain 15,552 cubic inches. For the material to change from 40 to 50 percent drained the material will gain 10 percent of its specific yield. For this material ($N_e = .175$) the volume of water moved in 1.35 hours is 272 cubic inches. This produces a flow rate of 201 cubic inches/hr/ft of pavement, or 0.12 cubic ft/hr/ft of pavement. Thus, the pavement surface will readily admit more than enough water to utilize the ability of the granular material to carry away the water. Table 3-6 illustrates how this flow rate varies with the drainage state (saturation level). A wet material can drain large amounts of water while a partially dry material will drain less water in a given time period. This comparison illustrates the basic problem with drainage of unsaturated materials, in that they become more difficult to drain as they dry out. For the material examined here that is not a problem as the 85 percent saturation level is reached rather quickly in less than one hour. For a material with more fines it would still not be a problem as lower levels of saturation may never be reached.

The main point that should be made is that the base can carry away less water than the surface will admit to the base. Thus, most rainfalls will soon saturate the base course or subbase, and the surplus will run off the pavement for all but the smallest of cracks with the longest spacing. Thus, for nearly all pavements, the principles presented for calculating the time to drain to given levels of saturation will hold as they will become saturated easily.

Strohm, Nettles and Calhoun (14) examined four materials where the amount of fines and the top size were varied. The gradation curves are given in Figure 3-15. They determined whether the materials were acceptable or not according to Corps of Engineer's procedure for air field pavements. The following calculations illustrate the acceptability based on performance standards.

1. $\gamma_d$ = 136 pcf, no fines, gravel

   $G_s$ = 2.72

   $\gamma_c$ = 2.176 gm/cc, assume $V_T$ = 1 cc   $W_s$ = 2.176 gm

   $V_s$ = .800 cc

   $V_v$ = .2 cc

   Assuming 80% water loss, $N_e$ = (.8)(.2) = .16 (actual = .13)

2. $\gamma_d$ = 126 pcf no fines, lower max size, $\therefore$ slightly less water loss

   $G_s$ = 2.67

   $\gamma_d$ = 2.016,   $V_T$ = 1 cc   $W_s$ = 2.016 gm

   $V_s$ = .755 cc

   $V_v$ = .245 cc

   Assuming 75% loss $N_e$ - (.75)(.245) = .181 (actual = .15)

3. $\gamma_d$ = 133 pcf, 5% fines, sand with silt fines

   $G_s$ = 2.67

   $\gamma_d$ = 2.128 gm/cc,   $V_T$ = 1 cc   $W_s$ = 2.128 gm

   $V_s$ = .797 cc

   $V_v$ = .203 cc

   Assuming 35% loss $N_e$ = (.35)(.203) = .071 (actual = .06)

4. $\gamma_d$ = 136 10% fines, sand, smaller size $\therefore$ smaller loss

   $G_s$ = 2.67

   $\gamma_d$ = 2.176,   $V_T$ = 1 cc   $W_s$ = 2.716 gm

   $V_s$ = .815

   $V_v$ = .185

   10% silt fines - (.18)(.185) = .033 (actual = .03)

For the standard cross-section of a 12 foot lane on a one percent slope, with a 9 inch thick base the saturation-time curves are shown in Figure 3-16.

This figure presents lines for the estimated and actual permeability and effective porosity values. The differences are not significant.

The study by Strohm, Nettles and Calhoun determined the materials 1 and 2 were satisfactory while 3 and 4 were unsatisfactory for use in an airfield pavement. Utilizing the procedures developed in this chapter materials 1 and 2 are satisfactory, material 4 is unsatisfactory and material 3 is marginal since it comes close to the 85 percent saturation level at 10 hours drainage time. Excessive load associated damage may be expected for materials 3 and 4 as compared to 1 and 2.

Figure 3-17 illustrates the proposed delineation of base or subbase performance based on drainability. The three classes are:

1. Acceptable
2. Marginal
3. Unacceptable

While this section ignores the influence of subgrade and water table, they do influence the drainability. A pervious subgrade will aid the granular layer to drain more rapidly, as will a low water table. Rather than measure permeabilities and water table depths, the next section will describe a procedure to determine the drainability of the subgrade and its influence on pavement performance.

## Subgrade Drainage

The previous section examined a procedure to investigate moisture conditions in the granular material as they influence performance under loading. The moisture conditions in the subgrade can also drastically alter performance. Earlier this was indicated in the section on "extrinsic factors" where climate is related to relative amounts of moisture in the subgrade. The soil type, water table depth, and topography all influence moisture entering the pavement structure. The present system used for agricultural identification of soils utilizes all of the elements mentioned, i.e., topography, soil type, texture, and water table depth, in determining soil relationships. Each soil will also have a drainage classification that reflects the interaction of these properties. A soil classified as well drained when it is found at the top of a grade may be poorly drained when it is situated in a depression or when the water table is at a relatively shallow depth.

The drainage condition is given in county soil maps along with complete descriptions of the soil and its expected behavior. Hole (21) first applied numerical values to these descriptive drainage terms. These numerical values were termed the Natural Drainage Index of the soil. In this system, a value of +10 is given to a soil classified as very poorly drained, an organic, or bog soil. A value of -10 is given to a soil classified as very excessively drained. Intermediate classifications are given in Table 3-7.

The performance of pavements and the relationship of this performance to the Natural Drainage Index is important to this study. Haas examined the performance of two concrete pavements for frost action and related them to the Natural Drainage Index (22). Figure 3-18 illustrates the correlation between transverse (cracks per station) and longitudinal (percent of total length) cracks and the Natural Drainage Index for a concrete pavement with no transverse joints except for construction joints. Each point represents the average of the pavement over that soil type. The percentage of that soil type in the pavement section is indicated in parenthesis.

The second pavement examined is a jointed pavement with 50 foot joint spacing. In Figure 3-19 the transverse (cracks per 50 ft slab) and longitudinal (percent of total length) cracks are again plotted as a function of the Natural Drainage Index. The percentage of each soil type present in the pavement is again indicated in parenthesis. These two comparisons clearly illustrate a relationship between longitudinal cracking and the Natural Drainage Index. A relationship with performance and the drainability, or even negative, for a concrete pavement indicates that the Natural Drainage Index is a suitable indicator of pavement areas that may be expected to develop moisture related distress at an accelerated rate (MAD). At comparable given ages, and loading histories, the pavement sections overlying positive NDI soils would be expected to develop more distress than pavements overlying the negative valued NDI soils.

For classification purposes in this MAD Identification System the NDI values were divided into three general categories because the actual numerical indicators provide little further information concerning performance beyond general indications. The three categories used are as follows:

$$\text{NDI} > 2$$

$$-2 < \text{NDI} < 2$$

$$\text{NDI} < -2$$

The soils classified as $NDI > 2$ will be the poor draining soils, the soils with an NDI between -2 and +2 will be intermediate and the soils with $NDI < -2$ will be the best drained. Each soil class can be expected to give varied performance directly related to the moisture characteristics of the subgrade. Thus they will be indicative of the potential for Moisture Accelerated Distress.

If a soil is classified as $NDI > 2$ it will not assist in draining the granular layer above it and may actually decrease its effectiveness by intrusion and by providing a source of water near the pavement. A soil classified as $-2 < NDI < 2$ will not assist drainage of the granular layer, but it will not produce accelerated deterioration. A soil classified as $NDI < -2$ will improve the performance of the granular layer and will make a marginal material acceptable.

## A Procedure for Examining Intrinsic Factors

### Specific Yield

To estimate specific yield of a soil, the grain size distribution, density, specific gravity, and plasticity of fines must be known. First, calculate the volume of voids, $V_v$ as follows:

dry density, $\gamma_d = 114.$ pcf

specific gravity, $G_s = 2.684 = W_s/(V_s \cdot \gamma_w)$

dry unit density, $\gamma_d = 1.825$ gm/cc $= W_s/V_T$

Assume a total volume, $V_T = 1.0$ cc

therefore $W_S$ (weight of solids) = 1.825

$V_s$ (volume of solids) = 0.680 cc

Volume of voids = 1.0 - .680 = 0.320 cc

for 100 percent saturation $V_w = 0.320$ cc $= V_v$

The specific yield represents the amount of water filling voids that will drain under the influence of gravity. The amount and type of fines is important and Table 3-5 can be used to determine the amount of water lost. If the fines are nonplastic they can be considered inert. If the liquid limit and plasticity index plot below the "A" line on the plasticity chart used in the Unified Classification System the fines can be termed silt. If the liquid limit and plasticity index plot above the "A" line the fines can be termed clay. A sand with 5 percent silt fines will lose 35 percent of its saturation water. A sand with 5% clay fines may only lose <u>15</u> percent of its saturation water, from Table 3-5.

The specific yield (effective porosity) for our example material is the water loss percentage times the volume of the voids, $V_v$.

$$N_e = (.60)(.320) = .192$$

## Permeability

To estimate the permeability of the granular material, the percent fines the effective particle size, $D_{10}$, and the density may be used with a nomograph developed by Moulton (15) presented in Figure 3-12. For our sand-gravel combination ($D_{10}$ = .3 mm, $\gamma_d$ = 114 pcf, 0.5 percent fines) k = 100 ft/day.

## Drainage Times

Drainage times represent the time required for a flooded granular layer to drain a percentage of its specific yield. The following factors are necessary to calculate drainage times:

1. Coefficient of permeability, k, ft/day
2. Specific yield, $N_e$
3. Width of granular layer, D, ft
4. Transverse slope, gt, longitudinal grade, $g\ell$
5. Thickness of granular layer, H, ft
6. Slope factor, S

All of these factors are readily obtained from the estimation procedures just given, and from the physical geometry of the pavement section.

Figure 3-8 may be used to obtain a time factor, T, for the percent of drainage, U. U represents the percent of specific yield that has drained; and will be a fraction between 0 and 1. The time factor was explained in equation (3-3) and is repeated here:

$$T = kHt/N_eD^2 \qquad (3\text{-}5)$$

An example is as follows:

The graph in Figure 3-8 is entered with a particular degree of drainage, U, (.1, .2, .3, etc.) and a horizontal line is extended to intercept the curve representing the slope factor for this pavement. A vertical line down to the horizontal axis locates the time factor, T. All quantities in equation (3-5) are known except t, which is time in days for this material to drain the specified percentage of water, U. This gives the time for various percentages of available water to be lost.

## Saturation Levels

The saturation at any level of drainage can be calculated from the data used to obtain the specific yield, and the percent of water drained, U, as follows:

At a saturation level of 100%, assuming a total volume of 1.0 cc as was done earlier, the volume of water was found to be $V_w = .320$ cc.

The specific yield was estimated at $N_e = .192$. This represents the maximum amount of water that can be drained from the 1 cc sample. At a degree of drainage of U = .1 (10 percent), one-tenth of the specific yield will be drained off, reducing the water in the sample and the saturation.

$$V_w = 0.320 \text{ cc}, \ W_w = 0.320 \text{ gm}$$

$$N_e = .192$$

at U = .1, the volume of water lost is

$$(.192)(.1) = .0192 \text{ cc} = .0192 \text{ gm}$$

The new volume of water present is .320 - .0192 = .3008 cc

$$\text{Saturation} = (V_w/V_v)100$$

$$= (.3008)/.320) = 94\%$$

Thus, at $U = .1$, t can be calculated, and the saturation level can be calculated. If the calculations are repeated for $U = 0.5$, 50 percent drainage, the saturation level will be found to be 70 percent.

The form in Table 3-8 can be utilized to perform these calculations in an orderly manner. The same form in Table 3-9 has been filled out for the example calculation. The suitability of the material for drainage under a pavement may be examined by plotting the saturation and time data on Figure 3-17.

## SUMMARY

It is necessary to have county soil maps for the area of pavement being investigated. These maps delineate the soil areas over which the pavement passes. Most of these maps are of such quality that distances along the pavement to each soil change can be estimated. The percentage of each soil (NDI) present in the pavement system can then be determined and potential areas of poor performance can be catalogued for further study and for localized drainage or maintenance considerations which will be discussed in Chapter 4.

The drainage terminology and the numerical values for the Natural Drainage Index (NDI) are given in Table 3-7 along with the breakdown given in this chapter indicating the influence of the drainage of the subgrade layer on the overall performance of the pavement and the interaction with the drainage of the granular layers above the subgrade. Any subgrades classified as NDI $< -2$ will improve drainage in the granular layer and will perform excellently. When a soil with NDI $< -2$ combines with a marginal or acceptable granular material, drainage is not likely to improve performance since moisture removal is already excellent. Daylighted shoulders would work well with these materials only if they are maintained properly. Moisture damage present in these materials may mean contamination due to migration of fines, poor maintenance of any drainage appurtenances, or both. When an NDI $< -2$ subgrade occurs with an unacceptable granular layer the performance of the granular layer is not improved and the base may exhibit moisture problems. With this combination the granular layer will impede moisture flow and maintenance activities should be directed toward rapid removal of water from the granular layer, or preventing moisture from entering it.

A soil with NDI between -2 and +2 presents a lower drainage capacity due to a finer texture (more fines) and a slightly higher water table. This subgrade will not assist the granular layer in drainage; but it will not exhibit poor moisture performance either. This subgrade represents the average conditions typically found and subdrainage may help performance by improving drainage in the granular layers. Without edge drainage a marginal or unacceptable granular material will retain moisture and exhibit lower performance than when combined with a better subgrade. Water should be prevented from entering the pavement system and its rapid removal is essential. The drainage times were calculated assuming an edge drain was present. To maintain minimal performance the drainage should be there.

A subgrade classified as NDI> 2 is a very poorly drained material. It will not aid the granular material in draining moisture. Even more serious, however, this subgrade will exhibit very poor load related performance. The subgrade will have a high water table and will retain moisture that enters the granular layers. An acceptable or marginal granular material must have adequate edge drainage or joint sealing to prevent continual contact between the subgrade and the excess moisture that could exist in the granular layers. A granular layer that classifies as unacceptable will not benefit from subgrade drainage. Moisture should be prevented from entering the pavement system when these materials are present in any large quantity. See Table 3-10 for a summary of these recommendations.

Table 3-1. Computed Maximum Joint Opening Using Eq. 5.2 for a Temperature Drop of 60°F and Drying Shrinkage (8).

| Joint Spacing-ft. | Joint Opening - ins. | | | |
|---|---|---|---|---|
| | Stabilized Subbase | | Granular Subbase | |
| | Temp. | Temp. & Shrinkage | Temp. | Temp & Shrinkage |
| 15 | .040 | .050 | .050 | .060 |
| 20 | .050 | .070 | .060 | .080 |
| 30 | .080 | .100 | .100 | .120 |
| 40 | .100 | .130 | .130 | .170 |
| 50 | .130 | .170 | .160 | .210 |
| 100 | .260 | .340 | .320 | .420 |

$\alpha = 5.5 \times 10^{-6}/°F$

$\Delta T = 60°F$

$\varepsilon = 1.0 \times 10^{-4}$

Table 3-2. Infiltration into Surface Cracks of Portland Cement Concrete Pavements* (Precipitation Intensity 2 inches/hour)(9).

| Crack Width (inches) | Pavement Slope (percent) | Percentage of Runoff Entering Crack |
|---|---|---|
| 0.035 | 1.25 | 70 |
| 0.035 | 2.50 | 76 |
| 0.035 | 2.75 | 79 |
| 0.050 | 2.50 | 89 |
| 0.050 | 3.75 | 87 |
| 0.125 | 2.50 | 97 |
| 0.125 | 3.75 | 95 |

*Research by the University of Maryland (laboratory test data)

Table 3-3. Permeability of Asphalt Concrete Pavements (9).

New Pavements

| Source of Information | k (in./hr) |
|---|---|
| Kari & Santucci (US 101)[x] | 75 |
| Kari & Santucci (US 101 - left wheel path)[x] | 23 |
| Kari & Santucci (US 101 - between left & right wheel path)[x] | 45 |
| Kari & Santucci (US 101 - right wheel path)[x] | 30 |
| Cedergren | 50 |
| Reichert (Lessines, Belgium) | 78 |
| California Division of Highway Specifications | 20 |

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[x] Air Permeability

Old Pavements

| Source of Information | k (in./hr) |
|---|---|
| Baxter & Sawyer (laboratory tests) | 0.0001 |
| Tomita (USNCEL, laboratory tests) | 3.00 |
| Breen (University of Connecticut - traffic lane) | 0.75 |
| Breen (University of Connecticut - shoulder) | 2.25 |
| Reichert (Lessines, Belgium) | 3.50 |
| South Africa (cracked surfaces) | 1.00 |

Table 3-4. Water Retention Test (FHWA)(16).

| Material | Density (PCF) | Initial Saturation (%) | Saturation After Drainage (%) |
|---|---|---|---|
| Pea Gravel | 100.7 | 99.4 | 8.2 |
| Sand | 103.3 | 98.0 | 90.7 |
| Sand | 101.7 | 100.0 | 94.8 |
| 25% Sand + 75% Pea Gravel | 113.2 | 98.6 | 46.9 |
| 25% Sand + 75% Pea Gravel | 100.2 | 100.0 | 46.3 |

Table 3-5. Estimated Values of Water Loss for Calculating Specific Yield.

| 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.

Table 3-6. Variation in Flow Rate for the FHWA Combination Material.

| U, % | Time, hr | Flow Rate ft$^3$/hr/ft | S, % |
|---|---|---|---|
| .1 | | | 94.5 |
| | 0.60 | .26 | |
| .2 | | | 89.1 |
| | 0.89 | .18 | |
| .3 | | | 83.6 |
| | 1.22 | .13 | |
| .4 | | | 78.1 |
| | 1.35 | .12 | |
| .5 | | | 72.6 |
| | 1.90 | .083 | |
| .6 | | | 67.2 |
| | 2.66 | .059 | |
| .7 | | | 61.7 |
| | 5.35 | .029 | |
| .8 | | | 56.2 |
| | 9.50 | .017 | |
| .9 | | | 50.8 |

Table 3-7. Breakdown of Natural Drainage Index for Soils in Wisconsin. (22)

| Assigned Index Values - Natural Drainage Index | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| -10 | -2 | 1 | 2.5 | 4 | 5.5 | 7 | 8.5 | 10 |
| VERY EXCESSIVE | RANGE | | | | | | VERY POOR | |
| LITHOSOLS and REGOSOLS | | ZONAL SOILS | | | | | BOG SOILS | |
| Main Horizons - Wisconsin | | | | | | | | |
| A | A | A | A | Ag | Ag | Ag | Ag | 1 |
| C | B | B | B | Bg | G | G | G | 2 |
| | $B_3$ | | | | | | | G |
| | C | C | Cg | Cg | Cg | Cg | Cg | |

Table 3-8. Form to Calculate Drainage Times

Pavement Section ____________________

Percent Fines ____________ Type of Fines ____________

$D_{10}$ ____________ mm Density, $\gamma_{dry}$ = ____________ pcf

$G_s$ = ____________

k ____________ ft/day

H ________ ft., D ________ ft., gt ____________ ft/ft.

$g\ell$ ________ ft/ft., $L_e = D\sqrt{(g\ell/gt)^2+1}$ = ____________, $g_e = \sqrt{g_\ell^2 + gt^2}$ = ________

S = H/Lege = slope factor = ____________.

A = $\gamma d/62.5$ = ________ gm/cc, $V_T \equiv 1.0$ cc

$W_s$ = A = ____________ gm

$X = \frac{N_e D^2}{H k}$ = ________

$V_s = W_s/G_s$; $W_s$ = ________ ÷ $G_s$ = ____________ cc

$V_v = 1.0 - V_s = 1.0$ = ________ = B = ____________ cc = $n_e$ max

Estimated Water loss from Table 3-5 C = ____________ %

Specific Yield = $N_e$ = B x (C/100) = ________ x ________/(100) = ________

| (1) | (2) | (t days) | (t hours) | (3) | (4) | (5) | |
|---|---|---|---|---|---|---|---|
| U | T | (2)(X) | t x 24 | $N_e$ x U | B - (3) | $\frac{(4)}{B}$ | S = (5)100 |
| .1 | | | | | | | |
| .2 | | | | | | | |
| .3 | | | | | | | |
| .4 | | | | | | | |
| .5 | | | | | | | |
| .6 | | | | | | | |
| .7 | | | | | | | |
| .8 | | | | | | | |
| .9 | | | | | | | |

# Table 3-9. Form to Calculate Drainage Times

Pavement Section . Sample Soil

Percent Fines 0.5% Type of Fines Inert

$D_{10}$ 0.3 mm Density, $\gamma_{dry}$ = 114.09 pcf

$G_s$ = 2.684

k 100 ft/day

H 9" = 0.75 ft., D 13 ft., gt .01 ft/ft.

$g\ell$ 0.0 ft/ft., $Le = D\sqrt{(g\ell/gt)^2+1}$ = 13, $ge = \sqrt{g_\ell^2 + gt^2}$ = .01

S = H/Lege = slope factor = 5.77.

$A = {}^{\gamma d}/62.5$ = 1.825 gm/cc, $V_T \equiv 1.0$ cc

$W_s$ = A = 1.825 gm $X = \frac{N_e D^2}{H k}$ = 0.433

$V_s = W_s/G_s$; $W_s$ = 1.825 ÷ $G_s$ = 0.680 cc

$V_v = 1.0 - V_s = 1.0 =$ .320 = B = .320 cc = $n_e$ max

Estimated Water loss from Table 3-5 C = 60 %

Specific Yield = $N_e$ = B x (C/100) = .320 x 60 /(100) = .192

| (1)<br>U | (2)<br>T | (t days)<br>(2)(X) | (t hours)<br>t x 24 | (3)<br>$N_e$ x U | (4)<br>B - (3) | (5)<br>$\frac{(4)}{B}$ | S = (5)100 |
|---|---|---|---|---|---|---|---|
| .1 | .023 | .009 | .24 | .019 | .301 | .94 | 94 |
| .2 | .087 | .038 | .91 | .038 | .282 | .88 | 88 |
| .3 | .180 | .078 | 1.87 | .058 | .262 | .82 | 82 |
| .4 | .31 | .134 | 3.22 | .077 | .243 | .76 | 76 |
| .5 | .45 | .195 | 4.68 | .096 | .229 | .70 | 70 |
| .6 | .65 | .281 | 6.74 | .115 | .205 | .64 | 64 |
| .7 | .93 | .402 | 9.65 | .134 | .186 | .58 | 58 |
| .8 | 1.75 | .757 | 18.17 | .154 | .166 | .52 | 52 |
| .9 | 2.50 | 1.082 | 25.97 | .173 | .147 | .46 | 46 |

Table 3-10. Summary of Material Combinations and Resulting Problems.

| GRANULAR CLASSIFICATION<br>SUBGRADE SOIL NDI | ACCEPTABLE | MARGINAL | UNACCEPTABLE |
|---|---|---|---|
| < -2 | All materials are free draining, excellent performance. Provide positive outlet, recommended. | Subgrade assists drainage of granular layers. Positive outlet is critical to performance. | Maintain surface integrity. Draining granular layer will provide marginal benefits at best. |
| < -2, < 2 | Good granular layer drainage. Subgrade may be a problem. Provide positive outlet for granular layer. | Drainage may be beneficial, in these materials, in upgrading performance. | Drainage recommendations not beneficial except to remove subsurface water. |
| > 2 | Removal of subsurface water is required. Must provide positive outlet for granular layers. | Drainage of surface filtration and subsurface water must be done. | Do not try to drain surface infiltration. Maintaining surface integrity is critical Rework materials. |

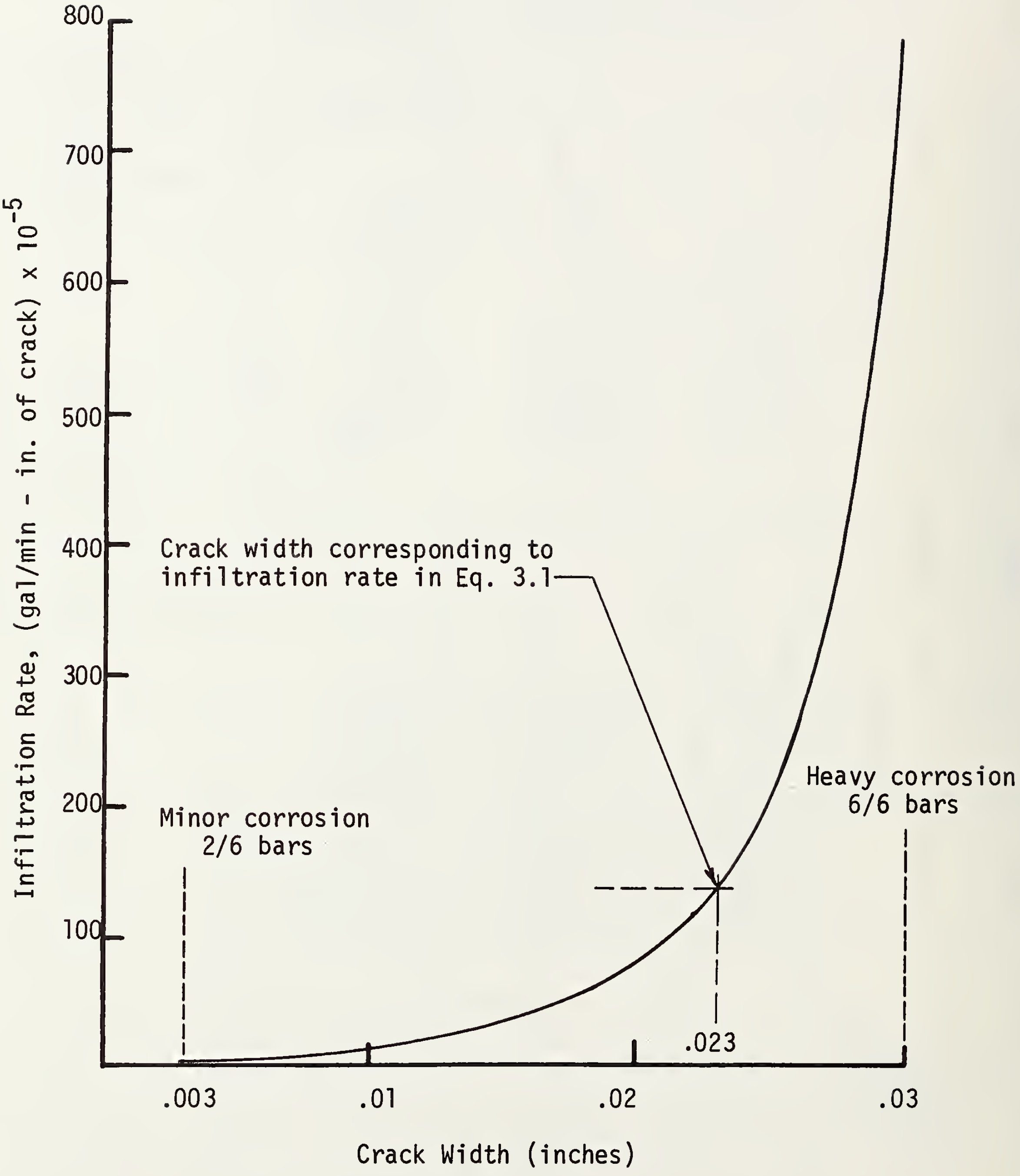


Figure 3-1. Permeability of Cracks with Varying Separation Indicating Corrosion Potention on Steel (11).

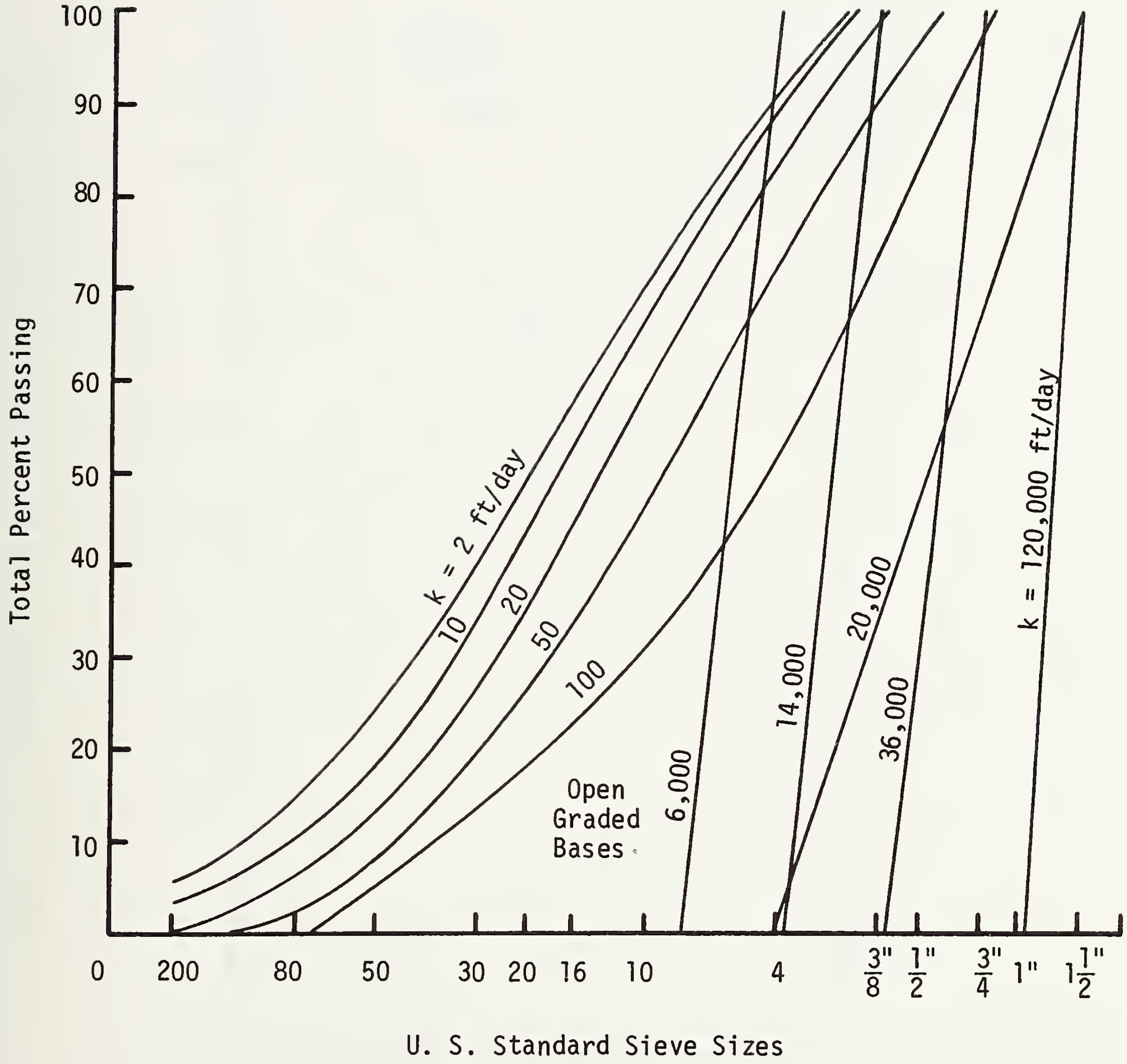


Figure 3-2. Typical Gradations and Permeabilities of Open Graded Bases and Filter Materials (12).

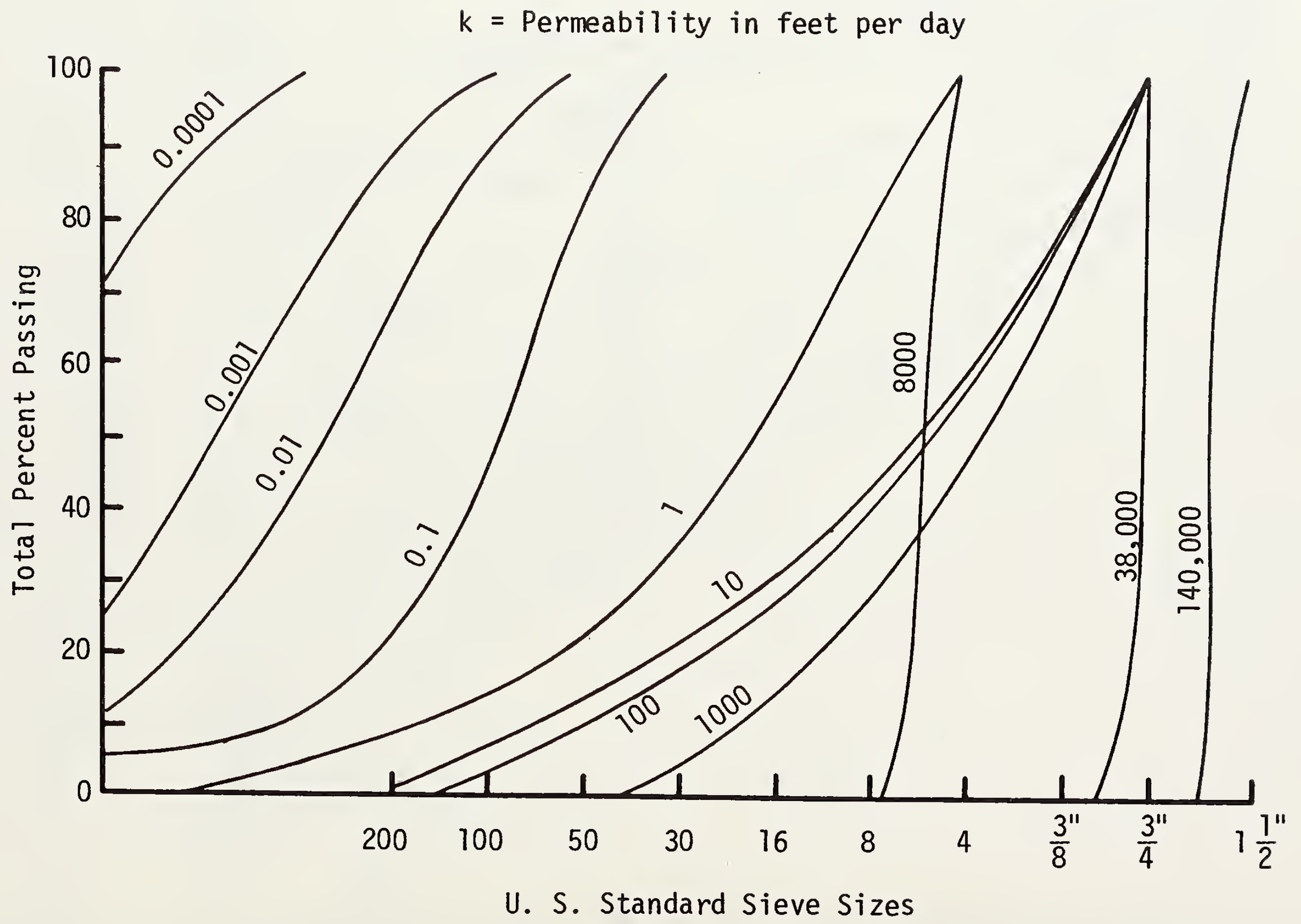


Figure 3-3. Permeabilities for Some Typical Gradations (13).

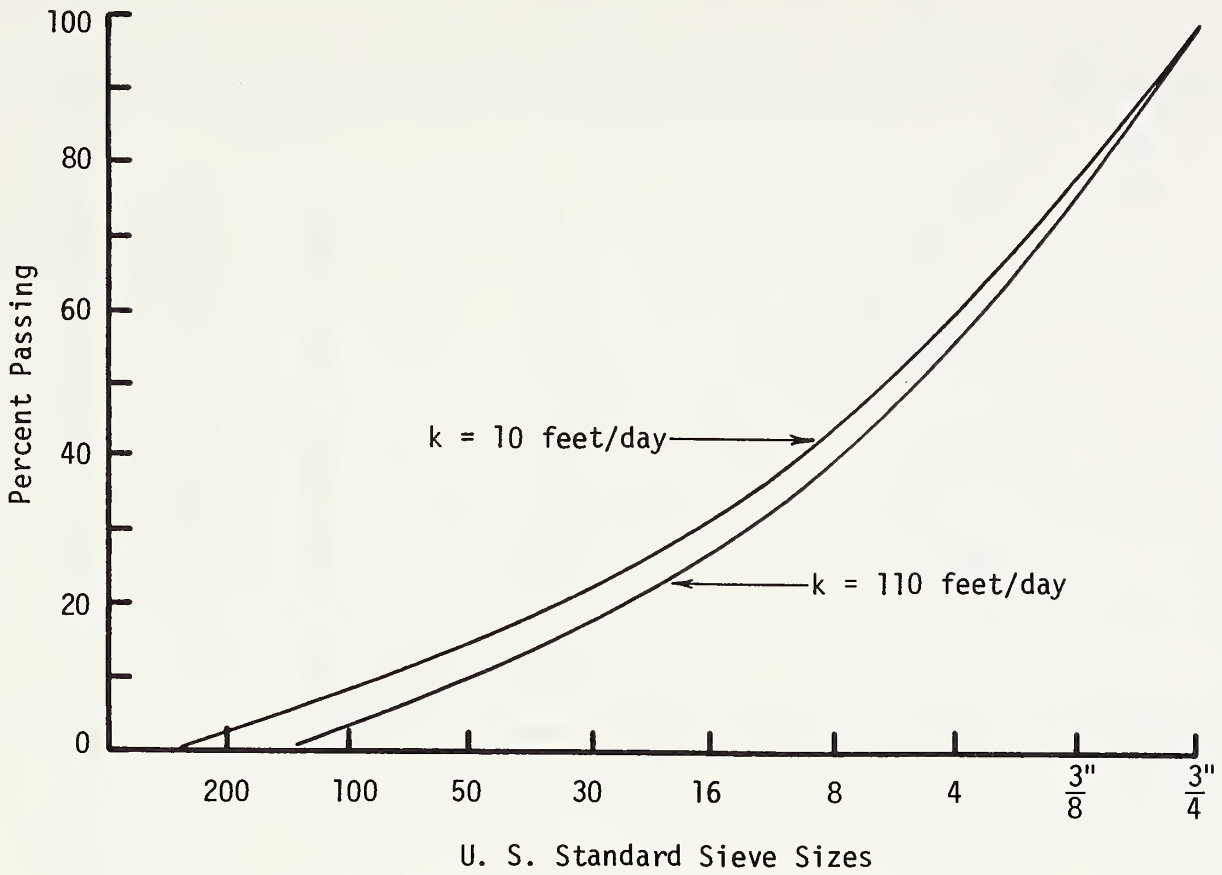


Figure 3-4. Change in Permeability With a Minor Gradation Change (13).

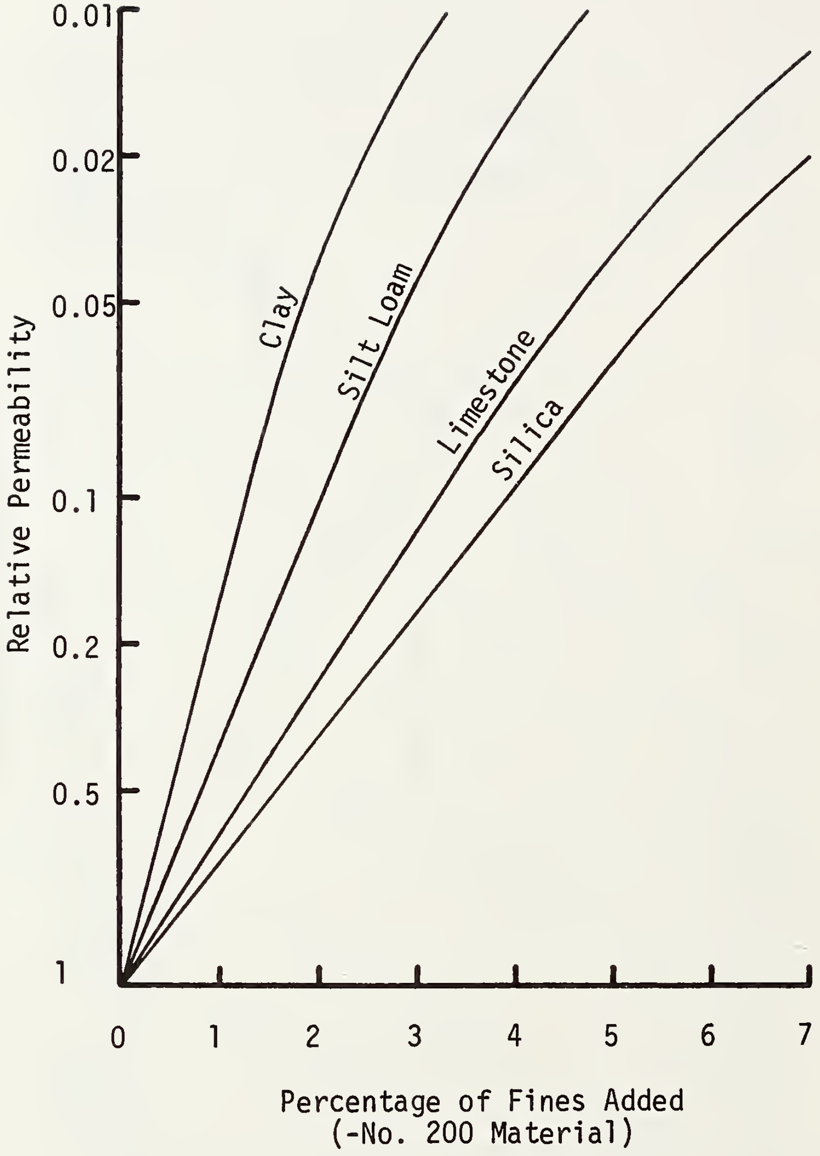


Figure 3-5. Effect of Amount and Type of Fines on the Permeability (20).

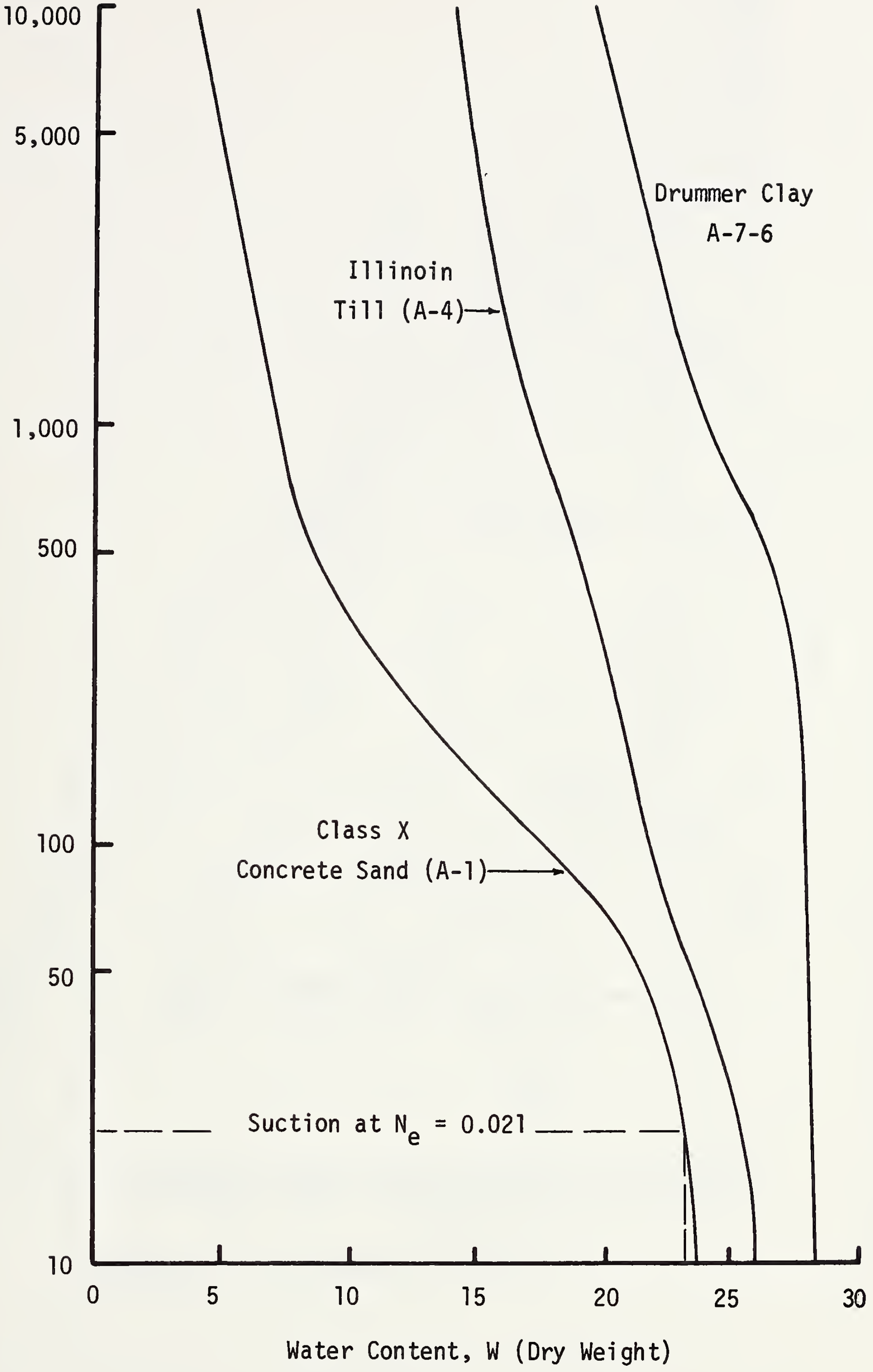


Figure 3-6. Soil Water Content - Suction Characteristic Relationships for Various Soils (4).

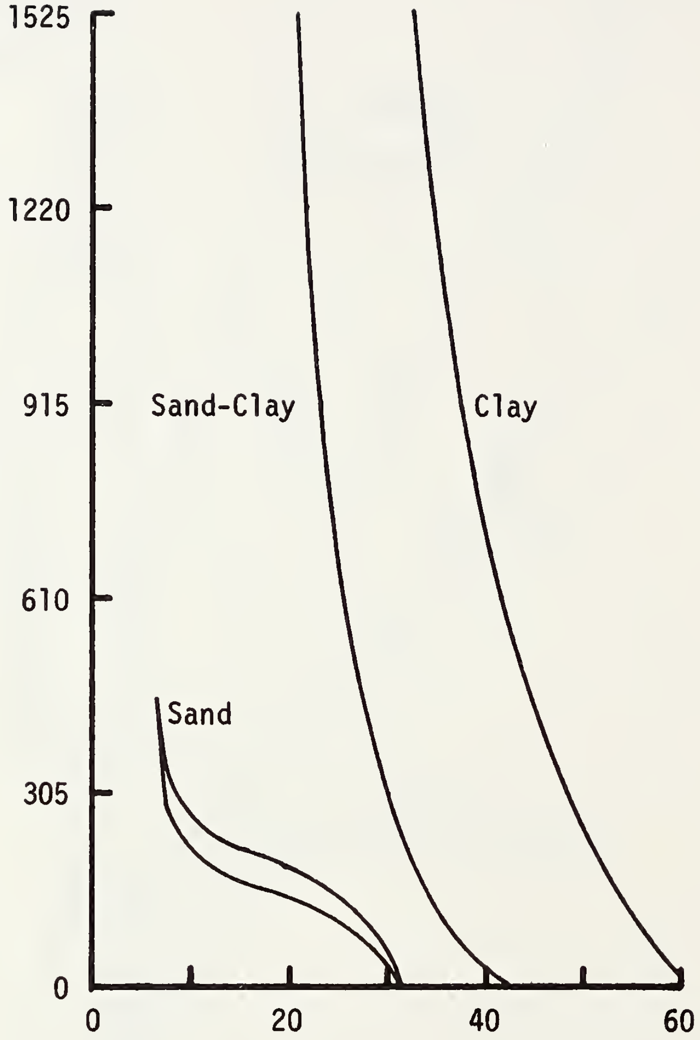


Figure 3-7. Characteristic Curves for Several Soils (20).

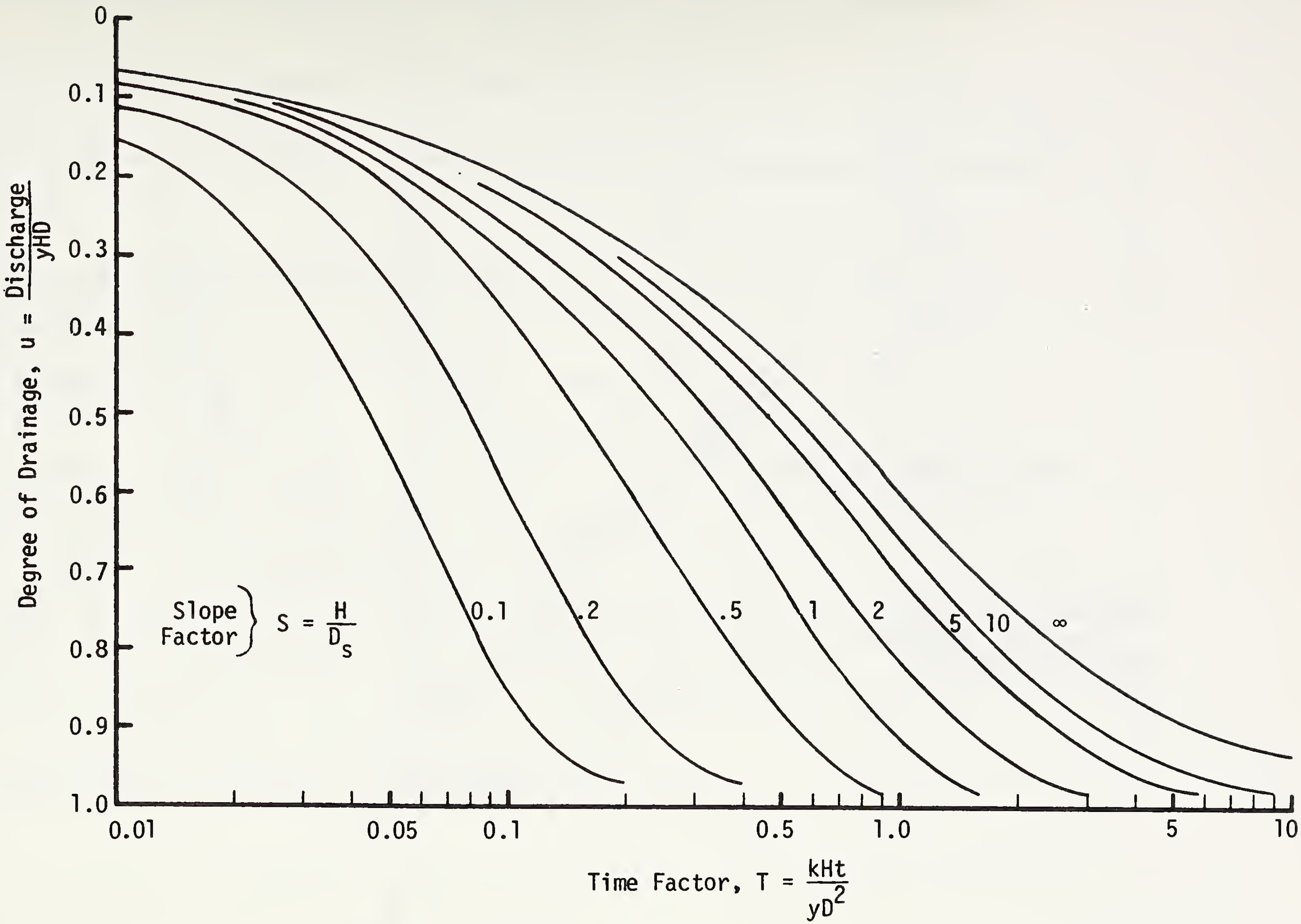


Figure 3-8. Graphical Procedure for Calculating the Rate of Drainage of a Flooded Base Course (18).

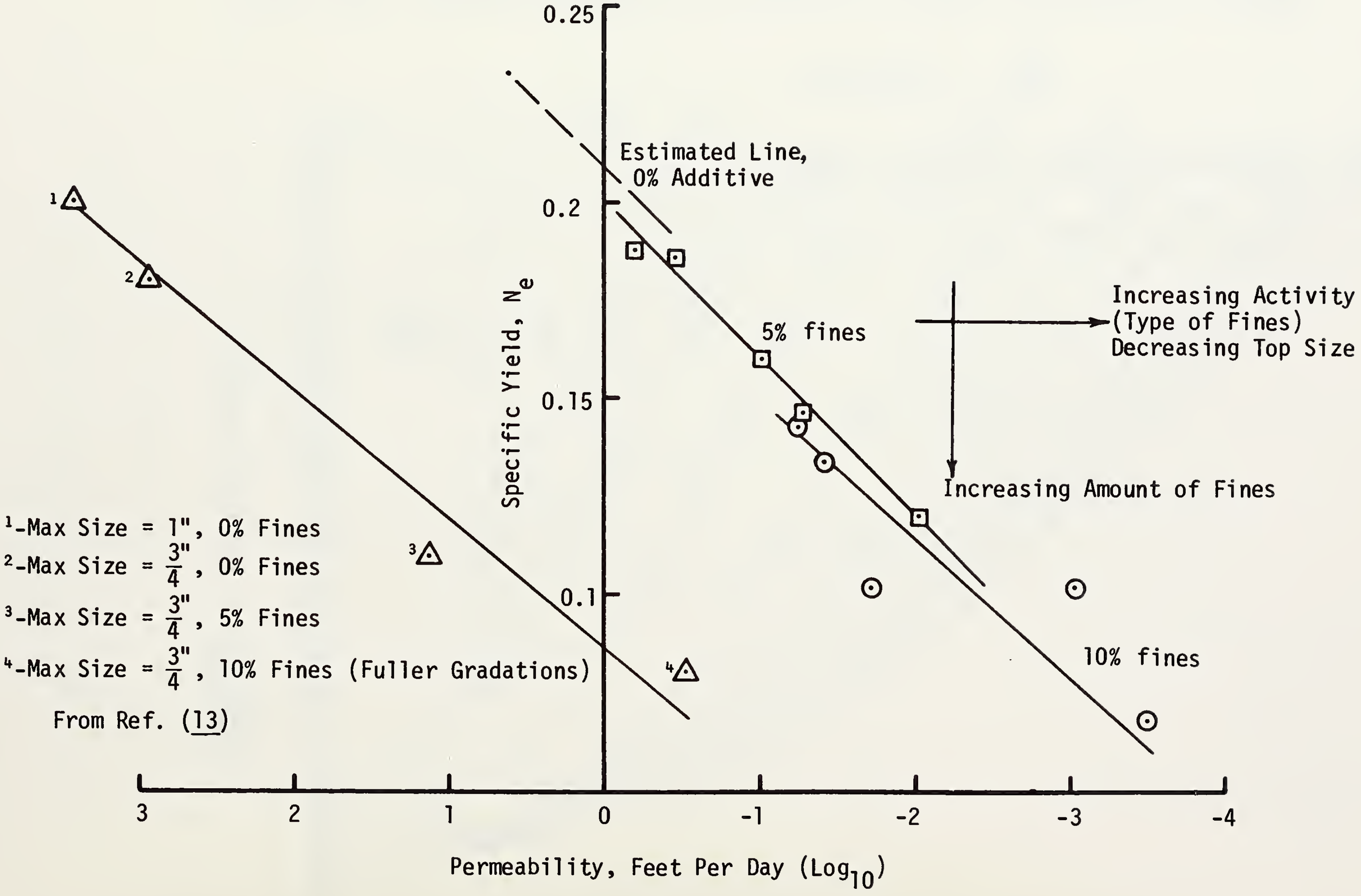


Figure 3-9. Relationship Between Permeability and Specific Yield Illustrating the Influence of Fines and Density (13, 14).

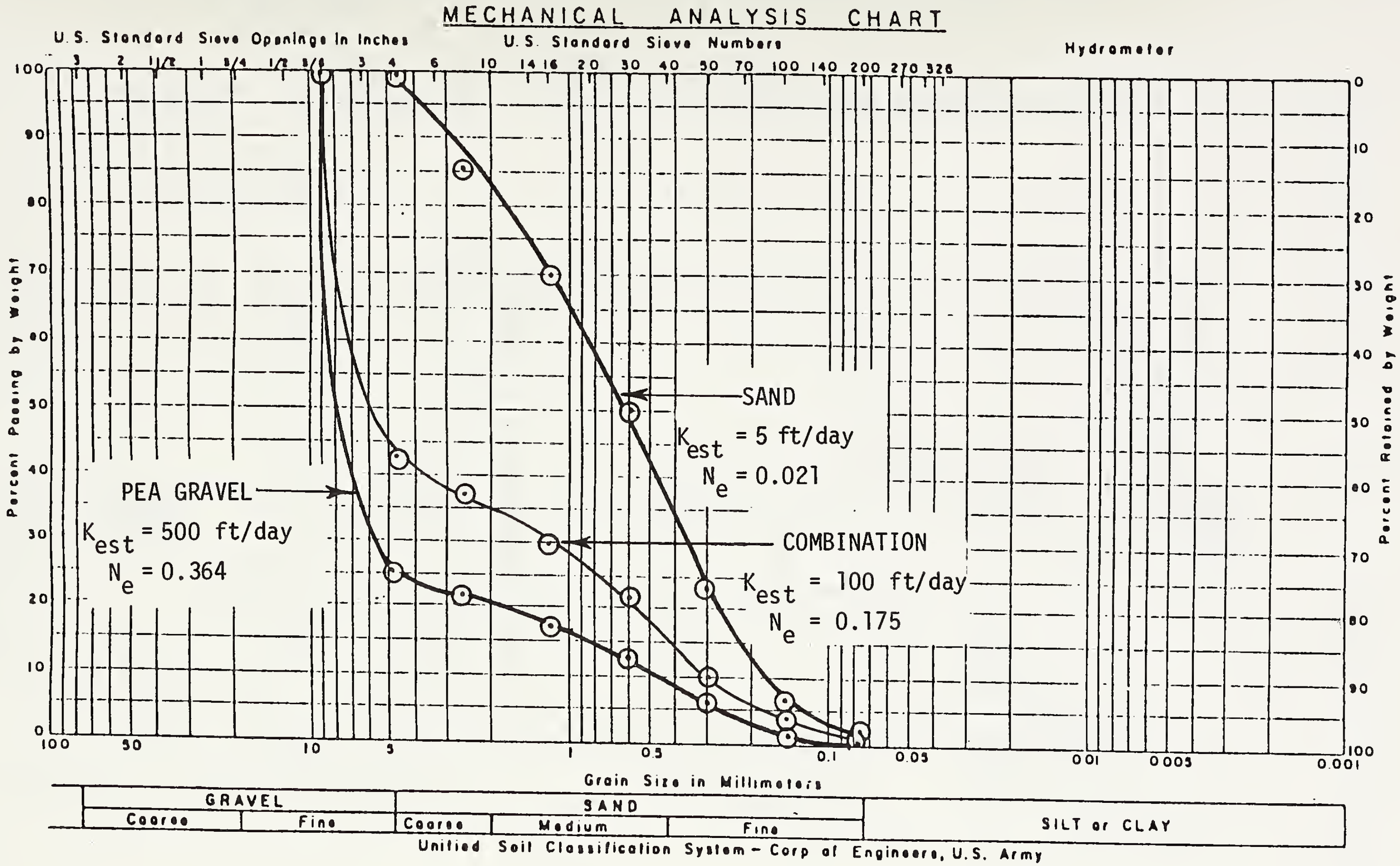


Figure 3-10. Grain Size Distribution Curves for the Two Materials Used in the FHWA Study (16).

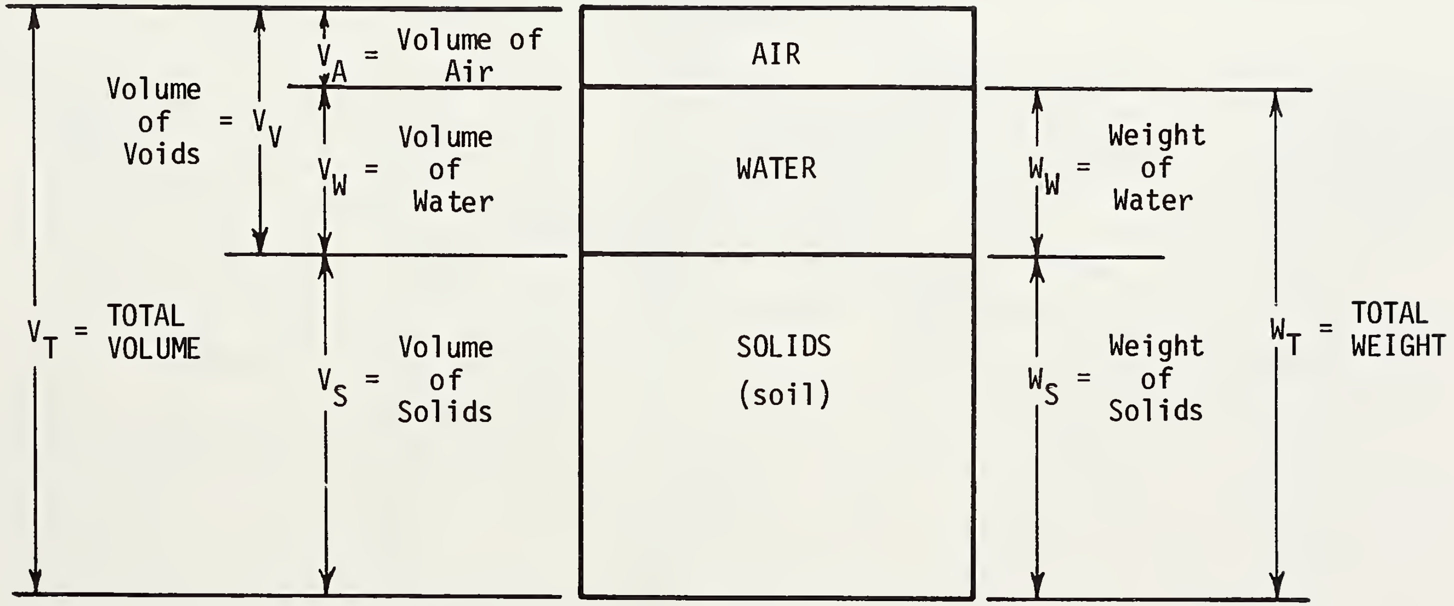
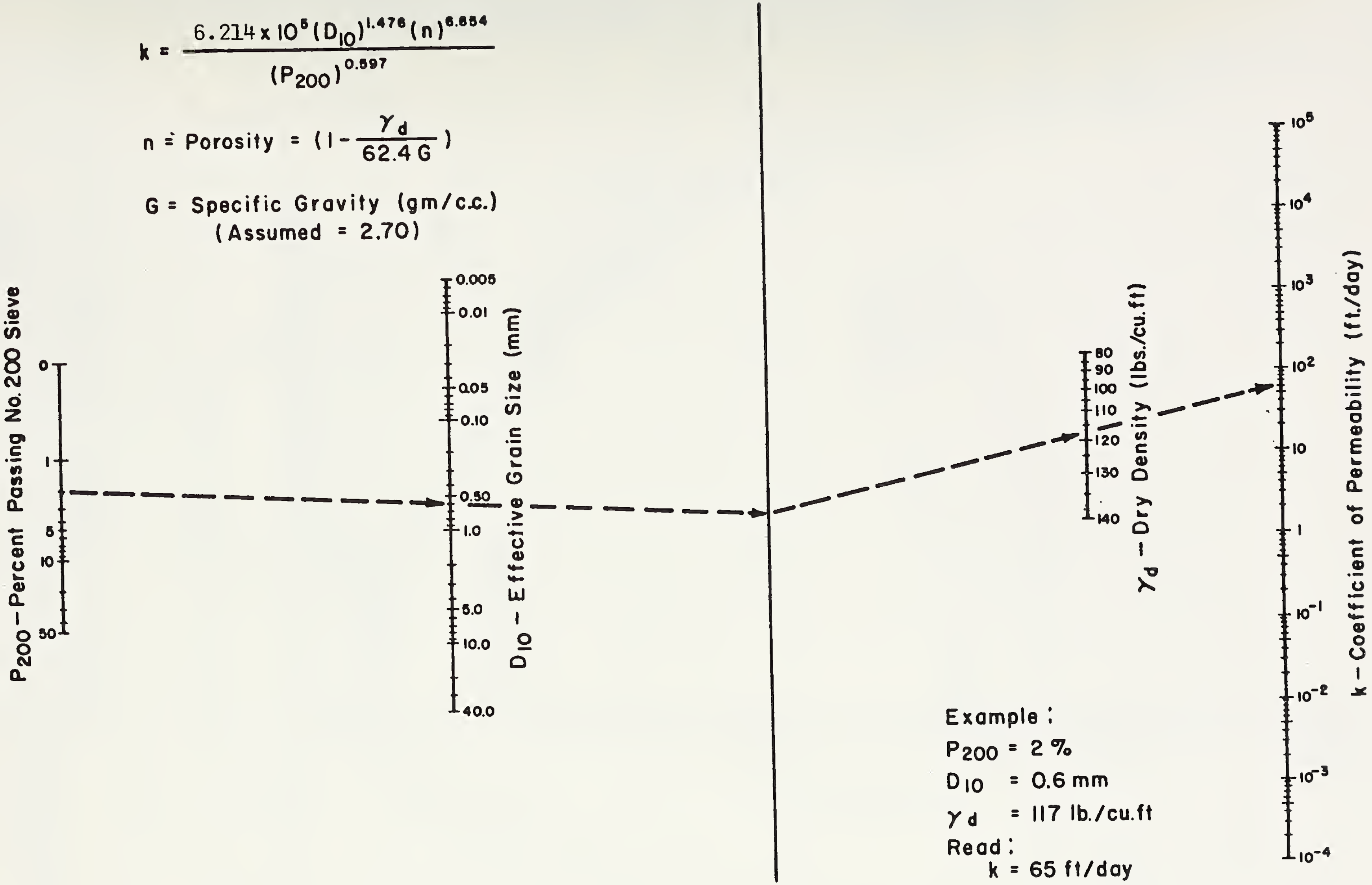


Figure 3-11. Definition of the Weight Volume Quantities Needed to Calculate Specific Yield (Effective Porosity).



$$k = \frac{6.214 \times 10^5 (D_{10})^{1.476} (n)^{6.654}}{(P_{200})^{0.597}}$$

$n \doteq$ Porosity $= (1 - \frac{\gamma_d}{62.4\,G})$

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

Example :
$P_{200} = 2\%$
$D_{10} = 0.6$ mm
$\gamma_d = 117$ lb./cu.ft
Read :
k = 65 ft/day

Figure 3-12. Procedure for Estimating the Coefficient of Permeability of Granular Drainage and Filter Materials (15).

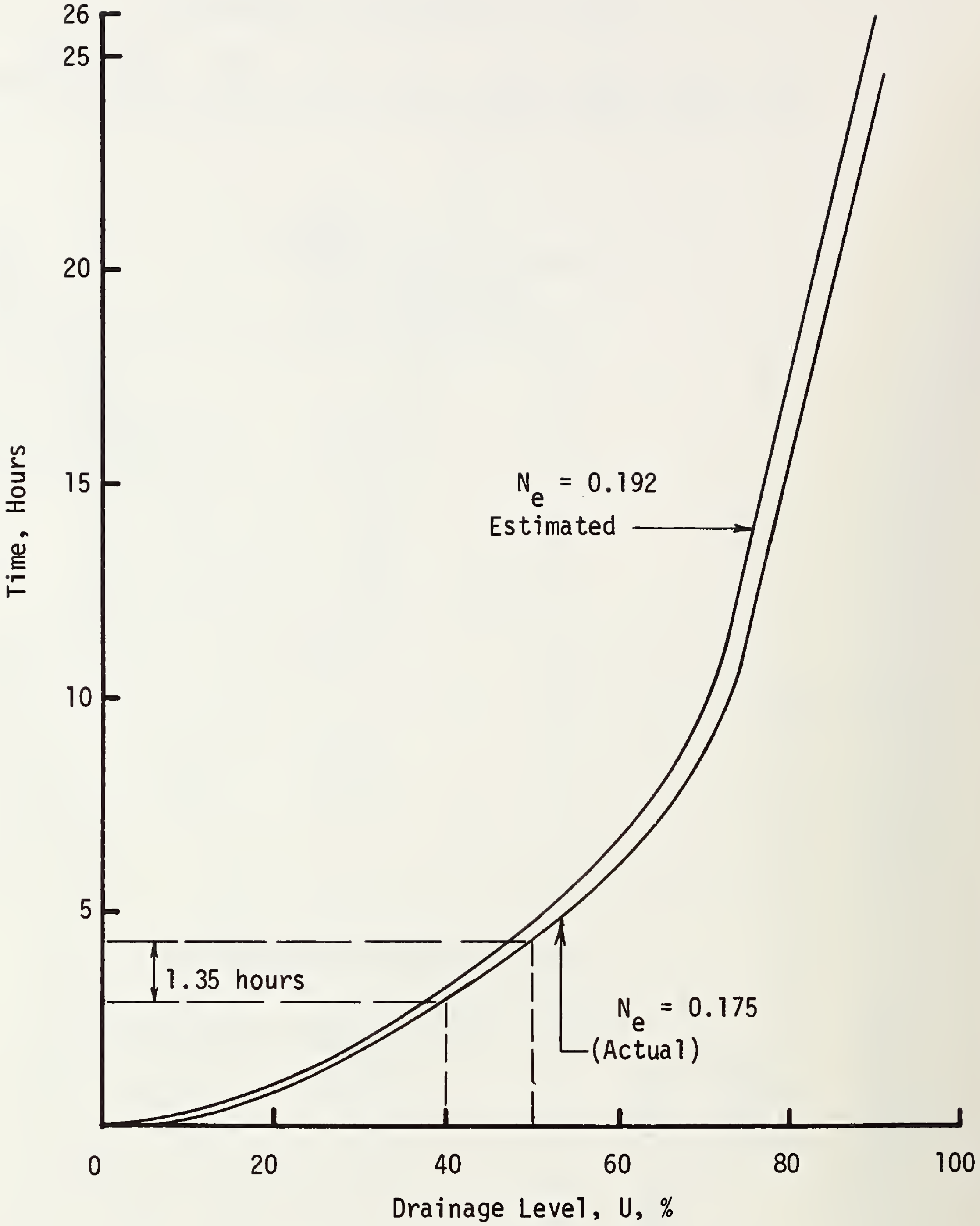


Figure 3-13. Drainage Curve for FHWA Sand-Gravel Mixture (16) Placed as a Base Course.

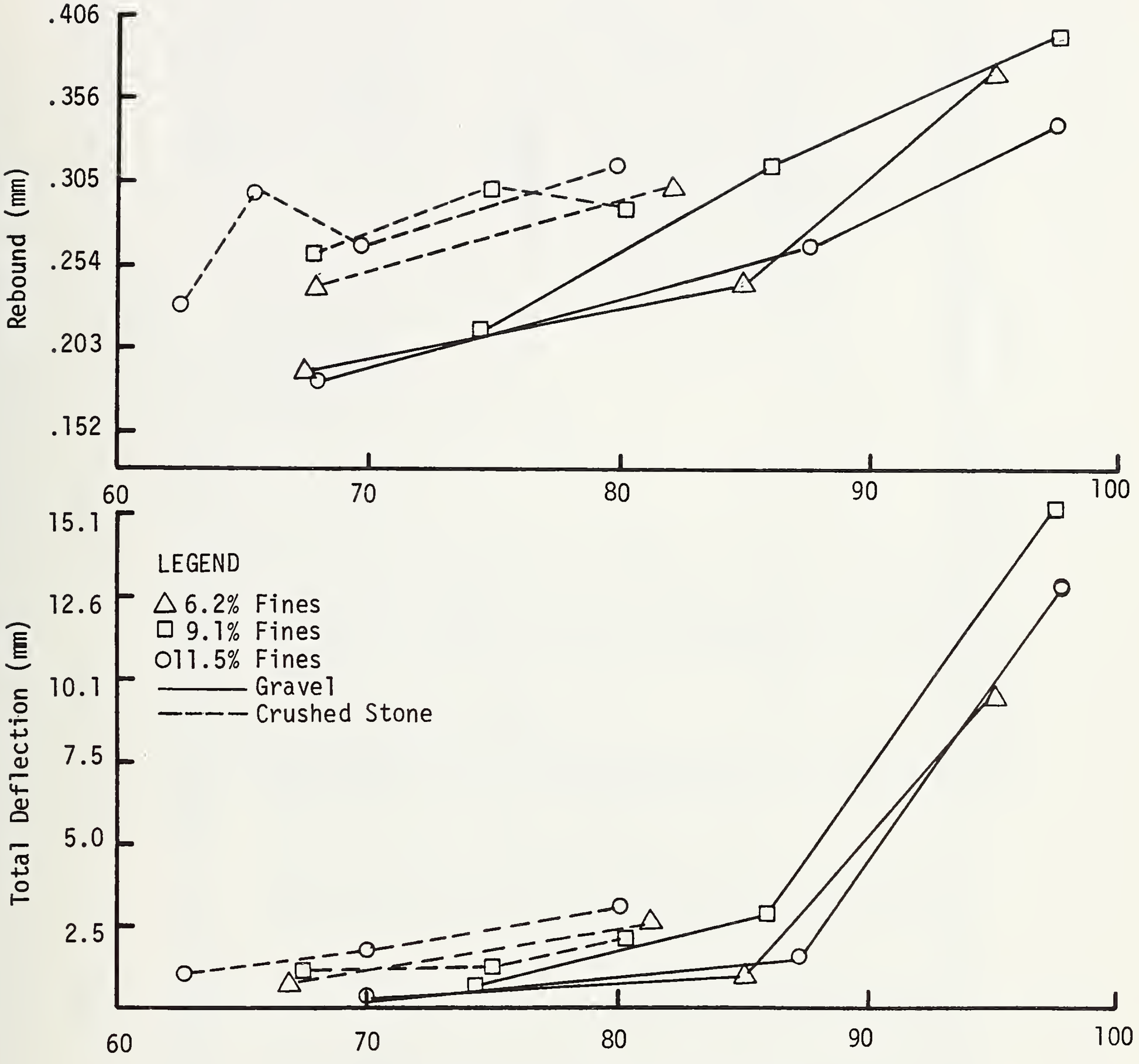


Figure 3-14. Effect of the Degree of Saturation on the Repeated-Load Deformation Properties of the AASHO Granular Materials (20).

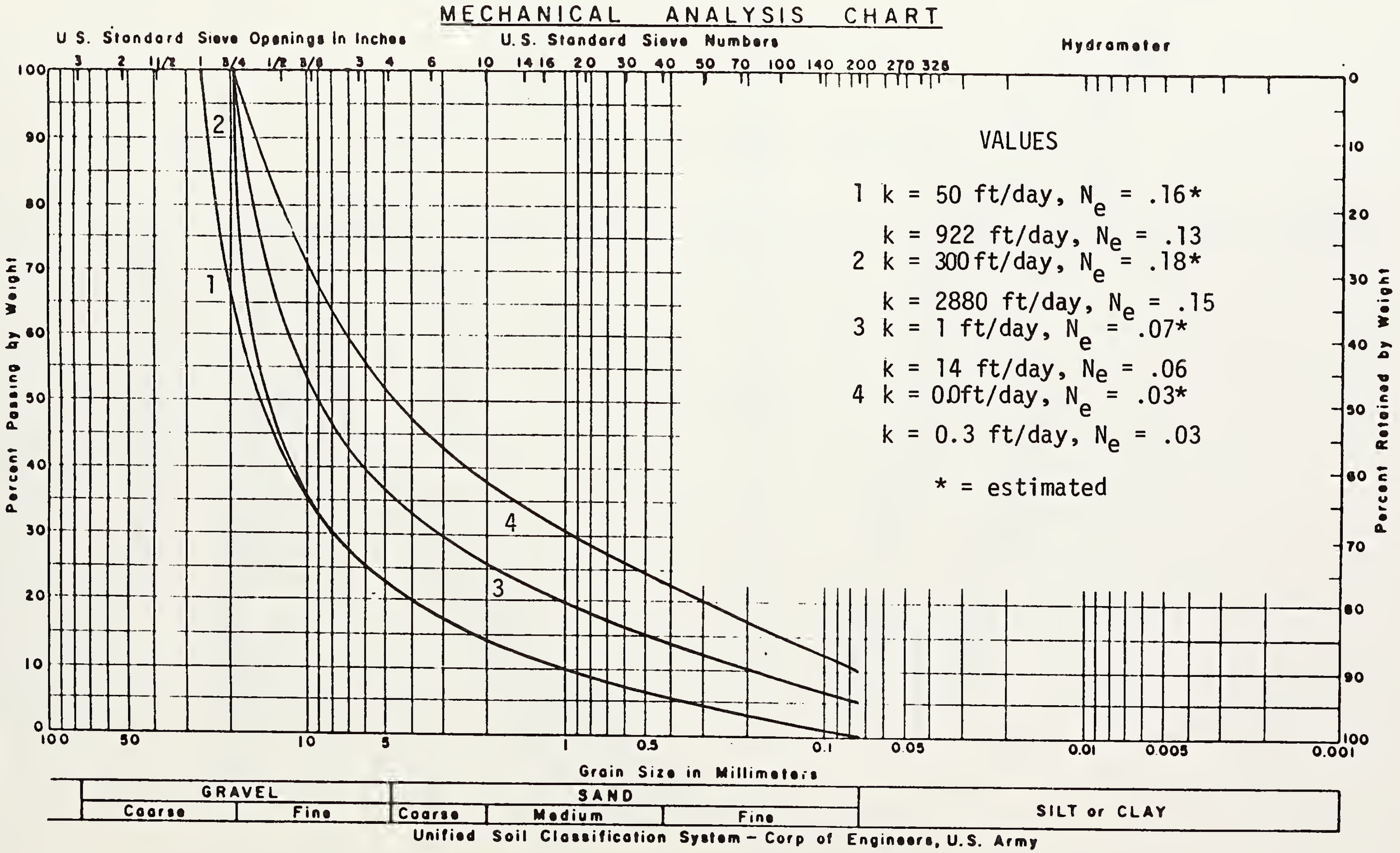


Figure 3-15. Gradation Curves for Representative Base Course Materials (13).

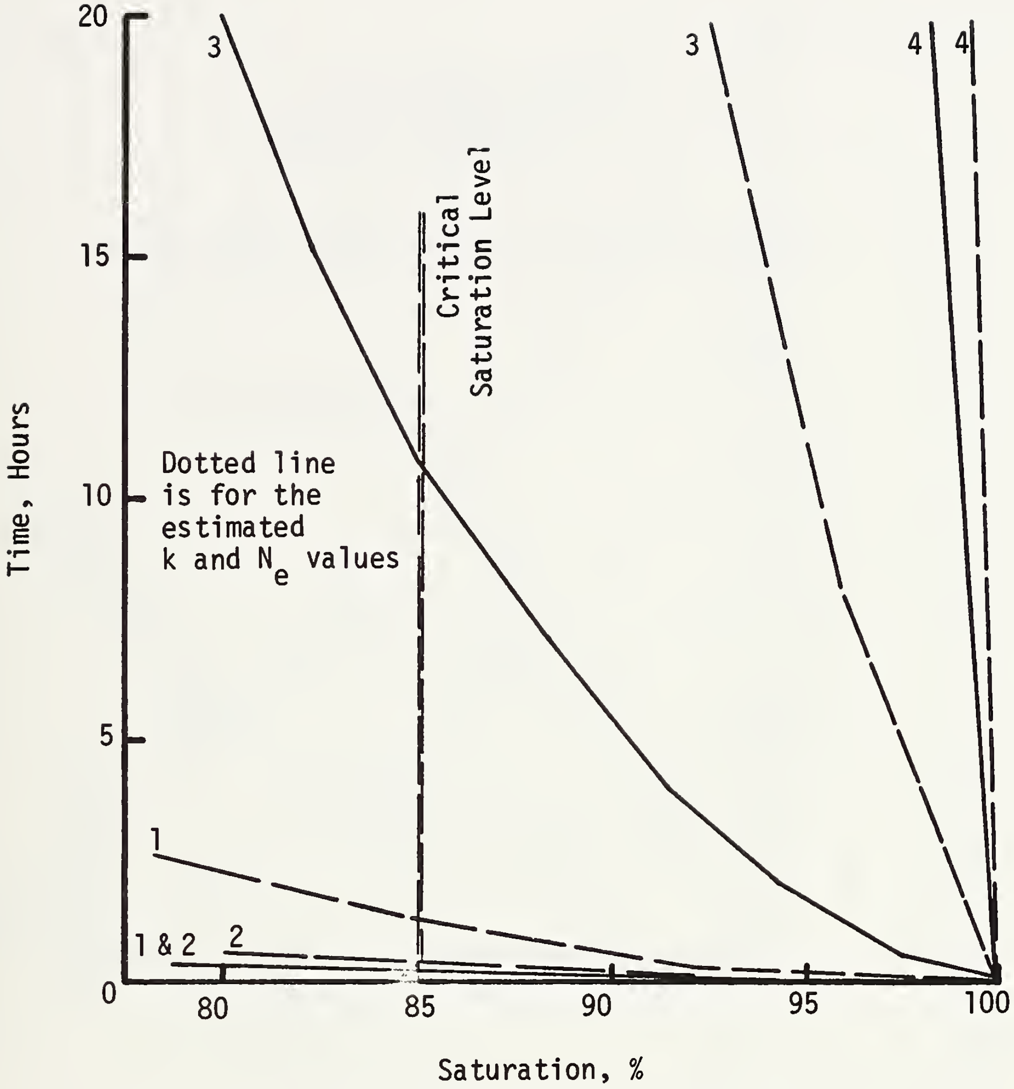


Figure 3-16. Drainage Curves for the Four Representative Base Course Materials Using Estimated and Measured Values of k and $N_e$.

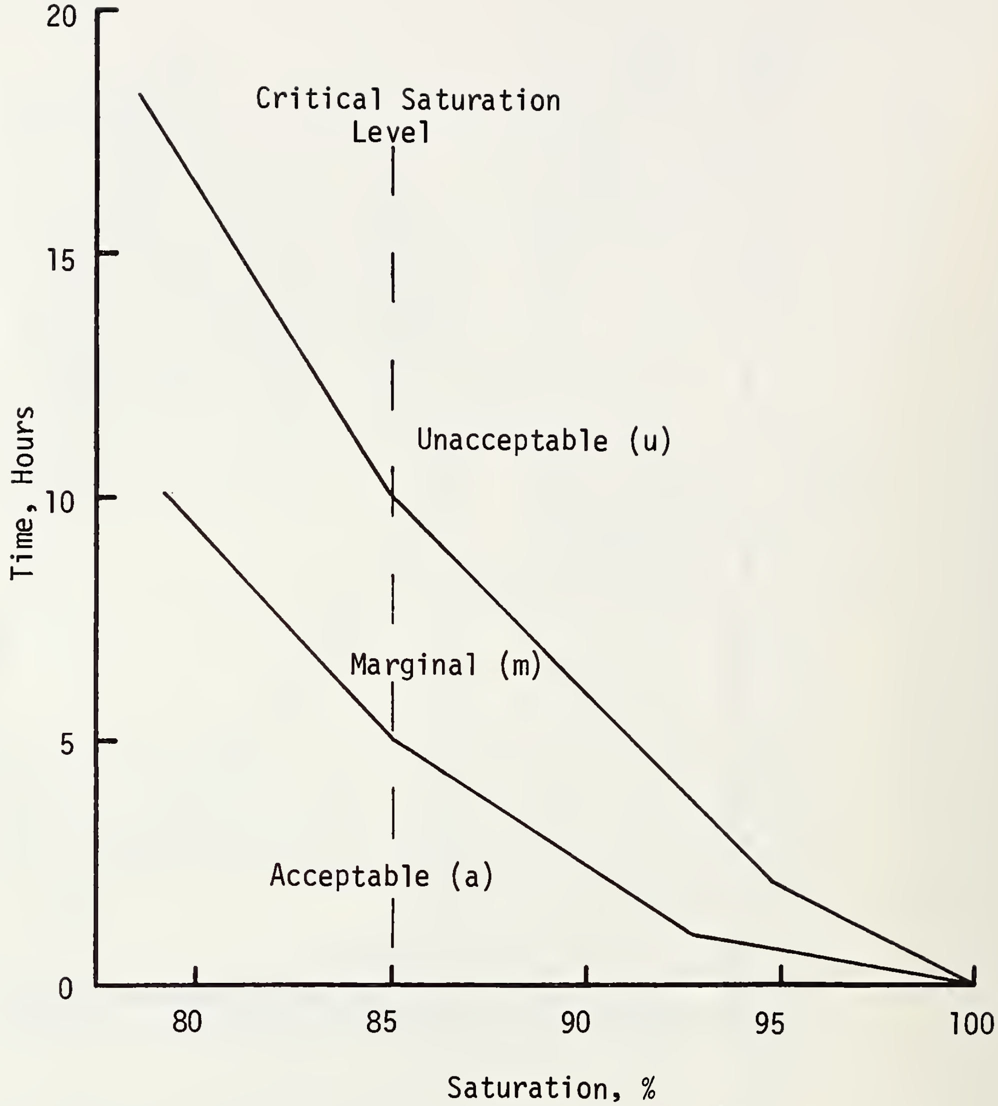


Figure 3-17. Drainability Classification of Base or Subbase, Indicating Load Related Performance.

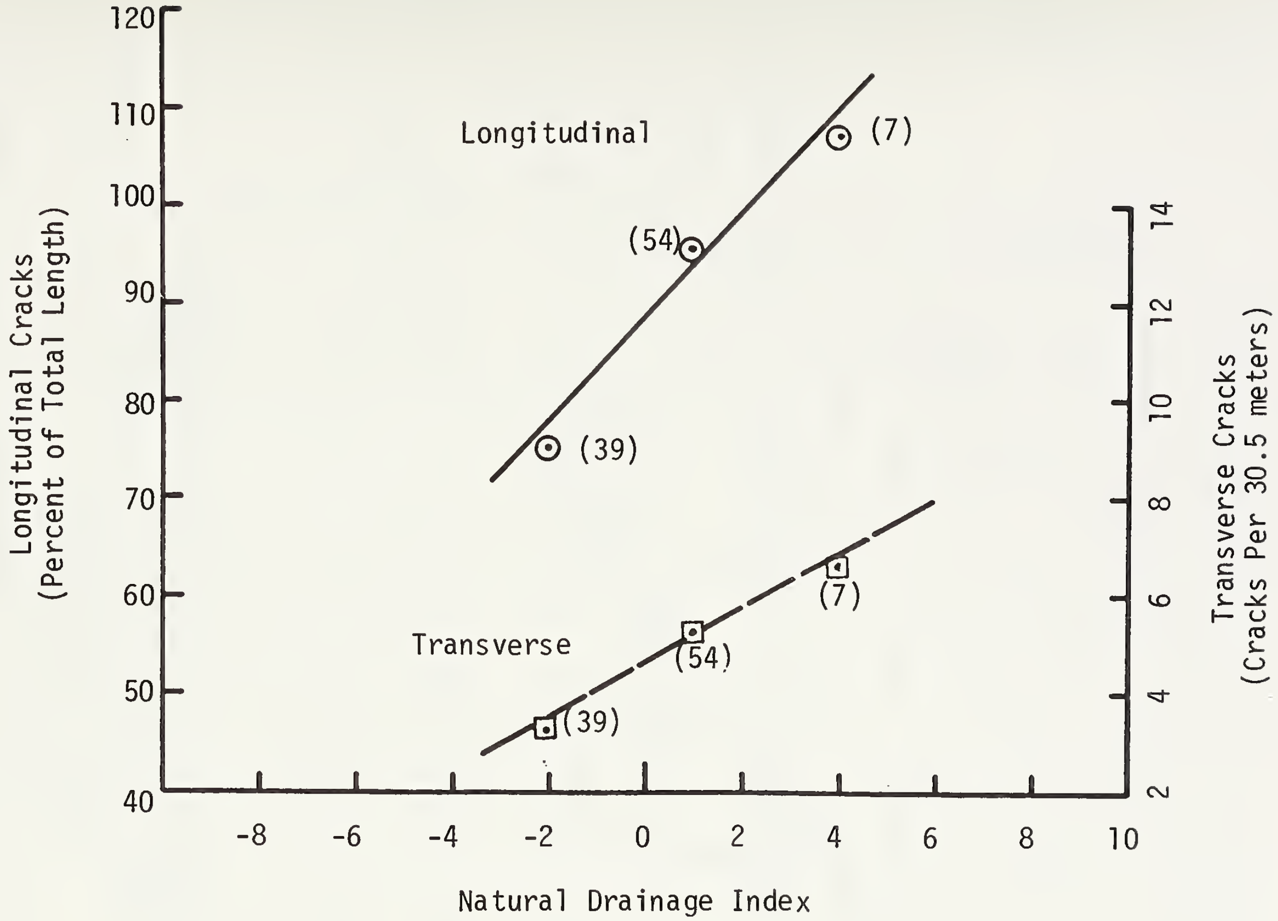


Figure 3-18. Relationship Between Cracking and Soil Type as Indicated By the Natural Drainage Index for a PCC Pavement With Construction Joints, (22).

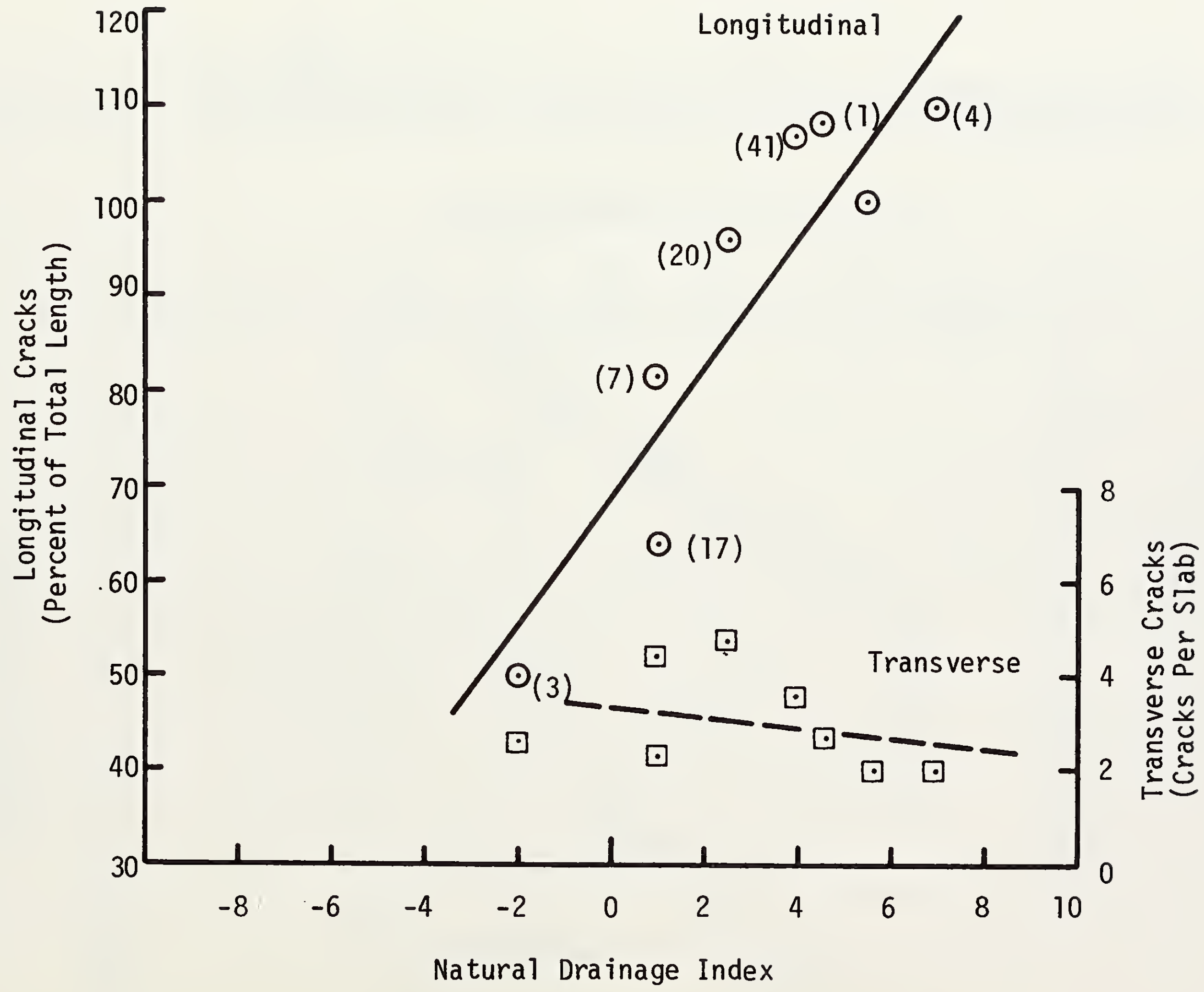


Figure 3-19. Relationship Between Cracking and Soil Type as Indicated by the Natural Drainage Type for a PCC Pavement With 15 meter (50 ft) Joint Spacing, (22).

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# CHAPTER 4

# USING THE MAD INDEX

The procedures described in the previous chapters allow the engineer to examine the components of the pavement structure for drainage capability and make definite statements concerning moisture problems for the individual components. To obtain an indication of the influence of moisture on the total pavement structure, the individual observations must be combined in an orderly, logical procedure. These combinations make it possible to rank individual pavements in relation to this potential for moisture accelerated distress, from low potential to high potential. Hopefully, the actual amount of damage resulting from moisture problems will correspond with the estimate, however, it will depend on the age and traffic on the pavement, and whether actual conditions have been accurately assessed. As a check, the actual damage must be determined from the pavement condition index survey, discussed separately.

In the subsequent portions of this chapter the procedure for ranking the total of 81 possible combinations for various climates and pavement materials will be presented. Descriptions of the combinations and narrative texts explaining the expected behavior are included. These rankings and descriptions indicate the potential for that pavement section to develop moisture damage. Maintenance recommendations are to be made when the actual distress and age of the pavement are considered.

The recommendations are based on the MAD Index. This numerical value of the MAD Index is developed from the various combinations and indicates the extent to which moisture accelerated distress can be expected to occur.

The categories for moisture damage are listed in Table 4.1. These categories are set up to include general indicators of potential pavement performance. To place a pavement into the approximate category it is necessary to first consider the extrinsic, or climatic factors. Tables 4.2 through 4.4 describe those extrinsic factors described earlier in Chapter 2, i.e., moisture, moisture concentration, and temperature, respectively. Typical MAD Index regions have been given the following description:

I - Moderate Potential for MAD; Numerical Value = 47

II - Normal Potential for MAD; Numerical Value = 67

III - Low Potential for MAD; Numerical Value = 85

Seasonal moisture concentration will alter the classification in the following manner:

S indicates a moderate concentration and decreases the numerical rating by 7 points.

$S_2$ indicates a large concentration and decreases the rating by 14 points.

r and d represent fairly even seasonal moisture and do not affect the rating.

These areas of moisture concentration during the year occur in several localized areas and have not been included in the general discussion that follows. When encountered in the analysis, they should be included in your consideration of climatic rating.

Temperature regions have been included to illustrate their interaction with moisture as follows:

C - High Temperature - No moisture interaction, no change in numerical rating.

B - Freeze-Thaw activity, may produce interaction, slight frost problem, decrease rating by 7 points

A - Frost area - severe moisture interaction, decrease numerical rating by 14 points.

The numerical values for intrinsic factors (granular base, subgrade) must be included in the next MAD Index. Table 4.5 reiterates the performance of the three classes of granular material as described in Chapter 2.

An acceptable granular layer will improve the ability of a pavement to resist moisture deterioration. This is true of all climatic areas and moisture conditions and material combinations. A marginal material will improve this ability only if it is drained and a good subgrade is present. If neither drainage nor good subgrade are present, moisture deterioration can be expected to develop over an extended time period. An unsatisfactory granular layer will produce excessive moisture damage in all climatic zones, compared to the other two levels of granular layer suitability. A procedure to include the influence of the quality of granular layers is as follows:

(a): An acceptable granular layer will add seven (7) points to the MAD Index arrived at by considering extrinsic factors.

(m): A marginal granular layer will not change the MAD Index

(u): An unacceptable granular layer will deduct seven (7) points from the MAD Index value derived from climatic classification.

The drainability of the subgrade very dramatically influences the performance of the pavement. Table 4.6 contains the descriptions of three drainability (NDI) classes established for the subgrade. The following values are suggested to include the effect of the drainability of the subgrade:

$NDI < -2$ - This represents the worst possible subgrade and the MAD Index is reduced by 15 points.

$-2 < NDI < 2$ - Intermediate amounts of damage can be attributed to this subgrade, the MAD Index is reduced by 7 points.

$NDI > 2$ - This is a very well drained subgrade and it will assist a marginal (m) granular layer. When found with an (m) material (see above) the MAD Index may be increased by 4 points. With other granular materials the MAD Index is unchanged.

A uniform application of the procedure and values presented result in the combinations illustrated in Table 4.7. While they are arbitrary rankings, they are based on a logical consideration of moisture, and performance, and indicate, in general, which combinations are most likely to develop moisture related damage. This information can be used advantageously in two ways:

1. For new pavements the rankings indicate the potential for moisture damage to occur in that particular pavement compared to constructing it of slightly different materials.
2. For existing pavements in various stages of disrepair this procedure provides a means of ranking the predicted performance of each pavement in terms of its materials, temperature region, and moisture condition. If the actual distress, accounting for traffic variations,

does not match the ranking, then material degradation, or other problems not recognized or accounted for should be determined by a more detailed investigation of the pavement structure.

The MAD Index, related to the numerical ranking procedure developed here is intended to be an indicator of relative pavement performance directly dependent on moisture and its interaction with materials and temperature. A condition survey of existing pavements is also necessary to infer suitable maintenance activities for the pavements. The development and consideration of the MAD Index, the pavement condition index, and the past useage of the pavement together will provide data for considering maintenance recommendations. The existing combinations of base and subgrade in each zone will also produce special maintenance considerations. The combinations of the MAD Index and the PCI are described in a very general manner in the following section.

## Distress and the MAD INDEX

Several of the more common distress types for flexible and rigid pavements are listed in Figure 4.3 and 4.4, respectively. Corresponding influences of moisture, load, and the components effected are indicated. The wide variability emphasizes that care must be exercised in identifying potential distress using the MAD Index.

The MAD Index will provide an indication of the extent to which moisture problems may develop. The surface condition of the pavement is the visible evidence showing the extent, to which moisture may have exerted a damaging influence on the pavement. An assessment of the type, amount, and severity of distress is necessary to accurately describe the overall condition of the pavement. The presence of particular distress types, or their absence, can indicate the presence or absence of moisture accelerated distress.

When distress is present it can be considered using the MAD Index to determine how critical the need for maintenance. For example, the following situations could arise for a given pavement:

1. If only minor distress exists, the rate of deterioration will usually be dependent on the level of moisture predicted by the extrinsic and intrinsic evaluations. The higher the predicted moisture, the quicker deterioration will occur and the sooner maintenance or rehabilitation will be needed.
2. If significant distress exists, it may or may not indicate moisture damage, depending on the type of distress present. Moisture related distress indicates maintenance or rehabilitation is needed:
   a. immediately if in a wet area,
   b. soon if in a seasonally wet area,
   c. in the future if in a dry area.

## PCI Concept

Reiterating, to arrive at an appropriate maintenance action and timing decision, pavement distress must be known by type, severity, and quantity. To aid the engineer in making this identification of distress, identification manuals for streets, airfields, and highways were recently developed (1, 2, 3). This development required extensive field surveys in many parts of the U. S., and discussions with many engineers working in pavement evaluation, maintenance, and rehabilitation. Trial use sessions have been held with field maintenance personnel to assure that the definitions are practical and easy to use.

A composite pavement distress index was developed by Shahin, et al (3, 4), that combines the type, severity and quantity of distress. They can be combined into a Pavement Condition Index (or PCI) for any given pavement section as follows:

$$PCI = 100 - \sum_{i=1}^{p} \sum_{j=1}^{m_i} a(T_i, S_j, D_{ij}) F(t,q) \qquad (4\text{-}1)$$

where: $a(\quad)$ = deduct value depending on distress type $T_i$, level of severity $S_j$, and density (or quantity) of distress $D_{ij}$

$i$ = counter for distress types

$j$ = counter for severity levels

$p$ = total number of distress types for pavement type under consideration

$m_i$ = number of severity levels for the $i^{th}$ type of distress

$F(t, q)$ = an adjustment function for multiple distresses that vary with total summed deduct value (t) and number of deducts (q).

Deduct value curves for each distress type and severity level were determined based upon the composite judgment of a large group of experienced pavement engineers (3). Thus, the calculated PCI of a given pavement section corresponds to the overall engineering judgment of a large group of experienced engineers as to the pavement's structural integrity (protection of the investment, maintenance needs), and surface operational condition (user related consideration). The steps necessary to determine the PCI for a given street are summarized in Figure 4.1. The procedure is very simple and straightforward, and has been officially adopted by the U.S. Air Force and Army, and is under trial implementation by other agencies. A suggested relationship of the PCI value to maintenance needs and timing is shown in Figure 4.2 for 3 levels of traffic (5).

Since the available PCI procedures are only applicable to city streets (2) and airfields (3), sets of deduct curves were developed for highspeed highways and are included in Volume II of this report. A distress identification manual was also developed specifically for highspeed highways.

## Moisture Distress Index

The PCI rating deduct values are used in a procedure to indicate the distress condition that is related to moisture damage. A moisture distress index is refined as the percent of deduct values that are caused or accelerated primarily by moisture. The magnitude of this moisture distress index indicates how far along moisture damage is. The MAD Index indicates whether further deterioration may be expected to develop as well as indicating whether or not excessive moisture related distress should be present in this pavement. The moisture distress index at present is subjective concerning which distress types should be considered in the moisture influence category. Recommendations must be made by engineer after examining the distress manual (4) and Figures 4-3 and 4-4.

## Using The MAD Index

The MAD Index is a qualitative indicator of relative moisture related performance that could be expected to occur in that section of pavement. The relative amounts of each Index value, or range of several values, present should be compiled as a percent of total project length. The locations of each of the levels of MAD Index should be noted on the plans to determine if the areas of low predicted performance are concentrated together or spread out. The County soil maps may be utilized for this purpose.

The above procedures will illustrate the quantity of each index combination and its relative location. If there are localized concentrations of poor materials, they can be individually treated. If poor materials are scattered throughout the project it may be more economical to treat entire sections for the worst conditions, rather than just the localized areas of expected poor performance. This decision will depend on the amount of the poor materials present.

The PCI distress survey must be correlated with the MAD Index. Areas of exceptionally high distress appearance should be noted and their position recorded on the same map where levels of MAD Index have been recorded. The areas of highest distress occurrence should occur over areas with the low MAD Index values. Likewise, low distress should be found over areas with high MAD Index values. Areas where discrepancies exist are areas that should be scheduled for sampling to determine why the measured performance is not in line with the predicted performance. Several circumstances can occur:

1. Predictions of low moisture related distress (High MAD Index) with poor actual measured performance. This situation should be investigated with field sampling to determine if any of the following unforeseen situations have occurred:
    a. Improper material placement
    b. Improper materials used and not noted in the MAD Index evaluation
    c. Excessive material degradation during service.
    d. Abnormally high water table.

e. Improperly maintained drainage

   i. side ditches clear and to grade

   ii. subdrainage flowing and outlets open

   iii. standing water and other indications of water concentration (vegetation such as willow and cattails).

2. Predictions of high moisture related distress (low MAD Index) with good actual measured performance. Again, it is desirable to determine why the difference exists. Usually, a visual examination with possible field sampling will explain the difference. On this section you will want to compare what you find with what you have found on other sections with similar MAD Index values that have not performed very well. The differences will indicate the ability of certain differences in maintenance or structure to improve the potential performance.

   a. Properly maintained drainage

      i. side ditches clear and to proper grade

      ii. subdrainage free flowing and outlets clear.

      iii. excessive vegetation, standing water, etc.

      iv. Topographic differences

      v. cut-fill section differences

Samples can be taken to investigate material differences.

It must be noted that comparisons of distress existing in different areas cannot be made unless the structural designs are the same. Pavement type, layer thicknesses, and layer arrangements must be similar. The traffic levels must also be comparable.

These structural quantities must be similar if the comparisons are to be indicative of the influences of the materials and the climate. For normal rehabilitation planning where a specific pavement is being evaluated this should be true and different portions of the pavement may be compared.

When pavement structures and traffic permit comparisons, areas where problems exist and where potential problems can be expected can be identified. When the MAD Index is added to these considerations, it can be a useful tool. The individual material combinations can also be examined to obtain insight into the moisture related behavior directly related to the drainage necessities of the pavement. The relative drainabilities of the subgrade and base course add further information about the advantage of installing drainage or the effectiveness of the existing facilities if they are functioning properly.

It should be remembered that the calculations for the drainage time to 85 percent saturation for the granular layers assumed the presence of a free draining edge on the downslope side of the layer. That is, there must be positive outlets before the potential drainage can occur. These calculations represent the optimum conditions for a material, and are on the non-conservative side.

Some general comments can be made concerning the possible combinations of subgrade and granular materials that go into the makeup of the MAD Index.

- 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.

Combining Intrinsic and Extrinsic Data - The descriptions provided for the subgrade and granular materials assume a steady concentration of excess moisture is being provided to the pavement structure. This moisture state exists most of the time in Region I and represents the most severe situation.

In Region II the moisture is seasonal and performance is better, even for similar materials. Drainage recommendations for specific material combinations will remain the same as there will be moisture present during part of the year and the material must remove this water. In Region III there will be very little excess moisture during any portion of the year and drainage considerations should be minimal. An important exception is where a seasonal surplus value exists for the moisture index. Pavements in $S_2$ regions will benefit from edge drainage to accomodate this seasonal excess of water.

To be technically correct, the comparison between distress and MAD Index should be done with the distress types that are directly influenced by moisture. A brief examination of the Pavement Distress Identification Manual (4) will show that nearly all distress types are susceptible to some degree of moisture acceleration in the distress development. Certain pavements and situations may be more susceptible than others. The MAD Index analysis as developed in this report enablesthe engineer to determine which pavements have the highest potential for Moisture Accelerated Distress.

Table 4-1. Potential For Moisture Accelerated Problems in a Pavement, as indicated by the MAD Index value.

| | |
|---|---|
| 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. |

Table 4-2. Regional Moisture Descriptions.

| Region | Description |
|---|---|
| I | Due to the climatic influences the subgrade will remain wet for the majority of the year and very 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. |

Table 4-3. Seasonal Moisture Concentration.

| 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. |
| $S_2$ | 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. |

Table 4-4. Regional Temperature Descriptions.

| 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 with 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 or B) and damage may range from minimal thermal fatigue in the North to high temperature stability problems in the south. |

Table 4-5. Effect of Granular Layer.

| | | |
|---|---|---|
| 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. |

Table 4-6. Subgrade Classifications.

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.

$$NDI > 2$$

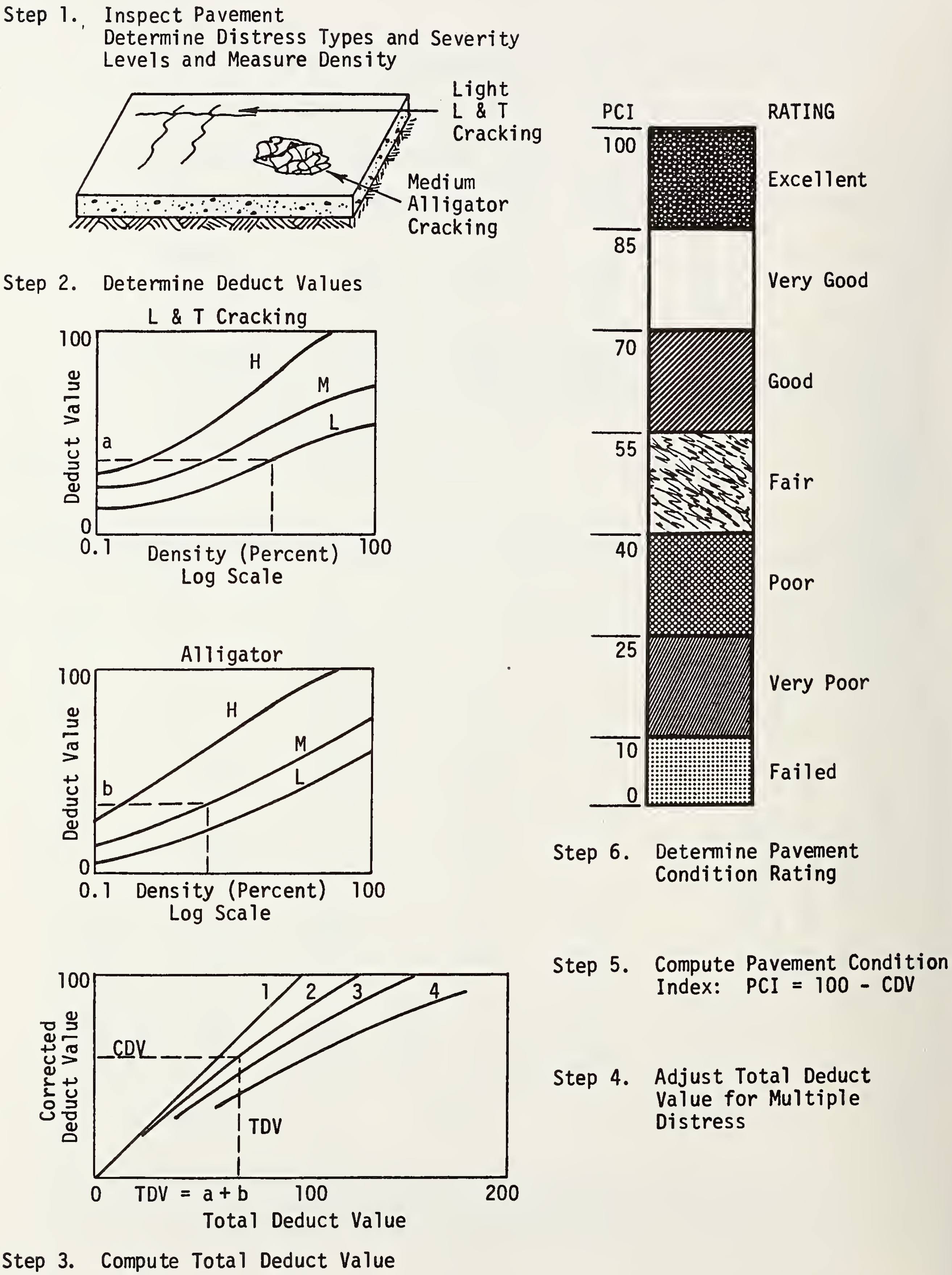
Table 4-7 Ranking of Material Combinations

Moisture Region
Temperature Region
Granular Material acceptability
Subgrade Drainability

| MAD Index | Damage Potential | Combinations | | | | |
|---|---|---|---|---|---|---|
| 100 | NEGLIGIBLE | | | | | |
| 99 | | | | | | |
| 98 | | | | | | |
| 97 | | | | | | |
| 96 | | | | | | |
| 95 | | | | | | |
| 94 | | | | | | |
| 93 | | | | | | |
| 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 Bai | | | |
| 69 | NORMAL | | | | | |
| 68 | | | | | | |
| 67 | | II Caj | II Bak | | | |
| 66 | | | | | | |
| 65 | | | | | | |
| 64 | | III Buk | III Amj | 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 Bai | 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 Bmi | II Aui | | | |
| 44 | | I Bmk | | | | | |
| 43 | | | | | | | |
| 42 | | | | | | | |
| 41 | | | | | | | |
| 40 | | I Cmj | I Bai | I Cuk | I Aak | | |
| 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 4-1. Procedure to Perform Pavement Rating. (2, 3)



Step 1. Inspect Pavement
Determine Distress Types and Severity
Levels and Measure Density

Step 2. Determine Deduct Values

Step 3. Compute Total Deduct Value

Step 4. Adjust Total Deduct Value for Multiple Distress

Step 5. Compute Pavement Condition Index: PCI = 100 - CDV

Step 6. Determine Pavement Condition Rating

Figure 4-2. Rehabilitation and Maintenance Needs (5).

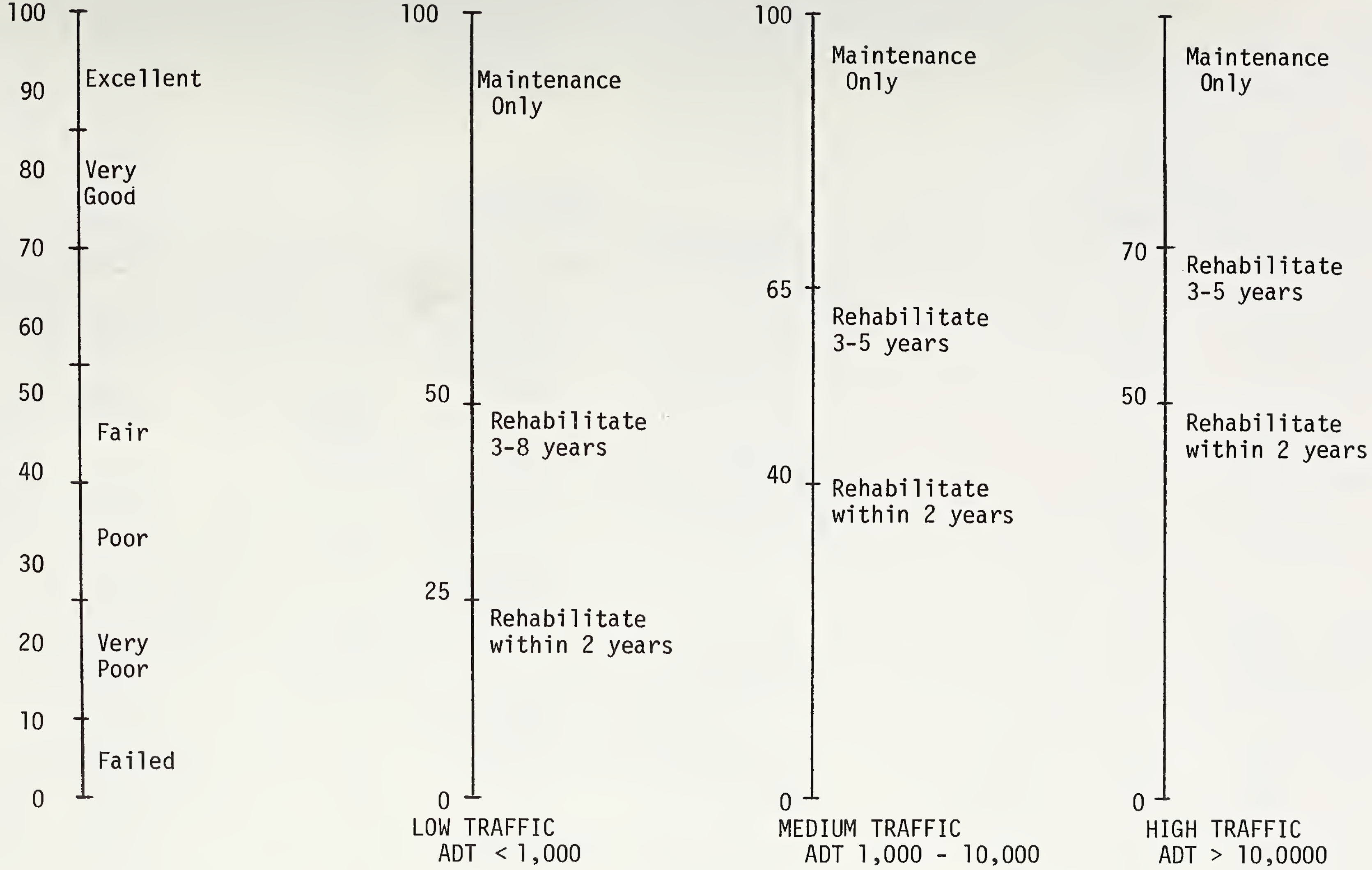


Figure 4-3. DISTRESS MANIFESTATIONS FOR FLEXIBLE PAVEMENTS

| TYPE | DISTRESS MANIFESTATION | MOISTURE PROBLEM | CLIMATIC PROBLEM | MATERIAL PROBLEM | LOAD ASSOCIATED | STRUCTURAL DEFECT BEGINS IN |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | ASPHALT | BASE | SUBGRADE |
| SURFACE DEFECT | ABRASION | NO | NO | AGGREGATE | NO | YES | NO | NO |
|  | BLEEDING | NO | ACCENTUATED BY HIGH TEMP. | BITUMEN | NO | YES | NO | NO |
|  | RAVELLING | NO | NO | AGGREGATE | SLIGHTLY | YES | NO | NO |
|  | WEATHERING | NO | HUMIDITY AND LIGHT-DRIED BITUMEN | BITUMEN | NO | YES | NO | NO |
| SURFACE DEFORMATION | BUMP OR DISTORTION | EXCESS MOISTURE | FROST HEAVE | STRENGTH-MOISTURE | YES | NO | YES | YES |
|  | CORRUGATION OR RIPPLING | SLIGHT | CLIMATIC & SUCTION RELATIONS | UNSTABLE MIX | YES | YES | YES | YES |
|  | SHOVING | NO |  | UNSTABLE MIX LOSS OF BOND | YES | YES | NO | NO |
|  | RUTTING | EXCESS IN GRANULAR LAYERS | SUCTION & MATERIAL | COMPACTION PROPERTIES | YES | YES | YES | YES |
|  | WAVES | EXCESS | SUCTION & MATERIALS | EXP. CLAY FROST. SUSC. | NO | NOT INITIALLY | NO | YES |
|  | DEPRESSION | EXCESS | SUCTION & MATERIALS | SETTLEMENT, FILL MATERIAL | YES | NO | NO | YES |
|  | POTHOLES | EXCESS | FROST HEAVE | STRENGTH-MOISTURE | YES | NO | YES | YES |
| CRACKING | LONGITUDINAL | YES | SPRING-THAW STRENGTH LOSS |  | YES | FAULTY CONSTRUCTION | YES | YES |
|  | ALLIGATOR | YES DRAINAGE |  | POSSIBLE MIX PROBLEMS | YES | YES MIX | YES | YES |
|  | TRANSVERSE | YES | LOW-TEMP, F-T CYCLES | THERMAL PROPERTIES | NO | YES, TEMP SUSCEPTIBLE | YES | YES |
|  | SHRINKAGE | YES | SUCTION, MOISTURE LOSS | MOISTURE SENSITIVE | NO | YES, HARDENING | YES | YES |
|  | SLIPPAGE | YES | NO | LOSS OF BOND | YES | YES-BOND | NO | NO |

Figure 4-4. DISTRESS MANIFESTATIONS FOR RIGID PAVEMENTS

| TYPE | DISTRESS MANIFESTATION | MOISTURE PROBLEM | CLIMATIC PROBLEM | MATERIAL PROBLEM | LOAD ASSOCIATED | STRUCTURAL DEFECT BEGINS IN | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | SURFACE | BASE | SUBGRADE |
| SURFACE DEFECTS | SPALLING | POSSIBLE | NO | CHEMICAL INFLUENCE | NO | YES - FINISHING | NO | NO |
| | SCALING | YES | F-T CYCLING | | NO | YES | NO | NO |
| | D-CRACKING | YES | F-T CYCLING | AGGREGATE | NO | YES | NO | NO |
| | CRAZING | NO | NO | RICH MORTAR | NO | YES - WEAK SURFACE | NO | NO |
| SURFACE DEFORMATION | BLOW-UP | NO | TEMPERATURE | THERMAL PROPERTIES | NO | YES | NO | NO |
| | PUMPING | YES | MOISTURE | FINES IN BASE MOISTURE SENSITIVE | YES | NO | YES | YES |
| | FAULTING | YES | MOISTURE-SUCTION | SETTLEMENT DEFORMATION | YES | NO | YES | YES |
| | CURLING | POSSIBLE | MOISTURE AND TEMP | | NO | YES | NO | NO |
| CRACKING | CORNER | YES | YES | FOLLOWS PUMPING | YES | NO | YES | YES |
| | DIAGONAL<br>TRANSVERSE<br>LONGITUDINAL | YES | POSSIBLE | CRACKING FOLLOWS MOISTURE BUILDUP | YES | NO | YES | YES |
| | PUNCH OUT | YES | YES | DEFORMATION FOLLOWING CRACKING | YES | NO | YES | YES |
| | JOINT | PRODUCES DAMAGE LATER | POSSIBLE | PROPER FILLER AND CLEAN JOINTS | NO | JOINT | NO | NO |

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# FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

## *FCP Category Descriptions*

### 1. Improved Highway Design and Operation for Safety

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

### 2. Reduction of Traffic Congestion, and Improved Operational Efficiency

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

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

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

### 4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

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

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

### 6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

### 7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

### 0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

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* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.