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Guide for Mechanistic-Empirical Design

OF NEW AND REHABILITATED PAVEMENT STRUCTURES

FINAL REPORT

PART 2. DESIGN INPUTS

CHAPTER 3. ENVIRONMENTAL EFFECTS

NCHRP

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DISCLAIMER

PART 2—DESIGN INPUTS

CHAPTER 3
ENVIRONMENTAL EFFECTS

2.3.1 INTRODUCTION

2.3.1.1 Importance of Climate in Mechanistic-Empirical Design

Environmental conditions have a significant effect on the performance of both flexible and rigid pavements. External factors such as precipitation, temperature, freeze-thaw cycles, and depth to water table play a key role in defining the bounds of the impact the environment can have on the pavement performance. Internal factors such as the susceptibility of the pavement materials to moisture and freeze-thaw damage, drainability of the paving layers, infiltration potential of the pavement, and so on define the extent to which the pavement will react to the applied external environmental conditions.

In a pavement structure, moisture and temperature are the two environmentally driven variables that can significantly affect the pavement layer and subgrade properties and, hence, its load carrying capacity. Some of the effects of environment on pavement materials are listed below:

- Asphalt bound materials exhibit varying modulus values depending on temperature. Modulus values can vary from 2 to 3 million psi or more during cold winter months to about 100,000 psi or less during hot summer months.
- Cementitious material properties such as flexural strength and moduli are not significantly affected by normal temperature changes. However, temperature and moisture gradients particularly in the top portland cement concrete (PCC) layer can significantly affect stresses and deflections and consequently pavement damage and distresses.
- At freezing temperatures, water in soil freezes and its resilient modulus could rise to values 20 to 120 times higher than the value of the modulus before freezing. Unbound materials are not affected by temperature unless ice forms below 32^{o}F.
- The freezing process may be accompanied by the formation of ice lenses that create zones of greatly reduced strength in the pavement when thawing occurs.
- All other conditions being equal, the higher the moisture content the lower the modulus of unbound materials; however, moisture has two separate effects:
    - First, it can affect the state of stress, through suction or pore water pressure. Coarse grained and fine-grained materials can exhibit more than a fivefold increase in modulus due to the soils drying out. The moduli of cohesive soils are affected by clay-water-electrolyte interaction, which are fairly complex.
    - Second, it can affect the structure of the soil through destruction of the cementation between soil particles.
- Bound materials are not directly affected by the presence of moisture. However, excessive moisture can lead to stripping in asphalt mixtures or can have long-term effects on the structural integrity of cement bound materials.

- Cement bound materials may also be damaged during freeze-thaw and wet-dry cycles reflected in modulus reduction and increased deflections. Freeze-thaw effects are experienced in the underlying layers but eventually lead to distresses in the pavement surface.

All the distresses considered in the Guide are affected by the environmental factors to some degree. Therefore, diurnal and seasonal fluctuations in the moisture and temperature profiles in the pavement structure brought about by changes in ground water table, precipitation/infiltration, freeze-thaw cycles, and other external factors are modeled in a very comprehensive manner in this mechanistic-empirical design procedure.

2.3.1.2 Consideration of Climatic Effects in Design

The Enhanced Integrated Climatic Model

Changing temperature and moisture profiles in the pavement structure and subgrade over the design life of a pavement are fully considered in the Design Guide approach through a sophisticated climatic modeling tool called the Enhanced Integrated Climatic Model (EICM). The EICM is a one-dimensional coupled heat and moisture flow program that simulates changes in the behavior and characteristics of pavement and subgrade materials in conjunction with climatic conditions over several years of operation. The EICM consists of three major components:

- The Climatic-Materials-Structural Model (CMS Model) developed at the University of Illinois (*1)*.
- The CRREL Frost Heave and Thaw Settlement Model (CRREL Model) developed at the United States Army Cold Regions Research and Engineering Laboratory (CRREL) (*2*).
- The Infiltration and Drainage Model (ID Model) developed at Texas A&M University (*3*).

The original version of the EICM, referred to simply as the Integrated Climatic Model, was developed for the Federal Highway Administration (FHWA) at Texas A&M University, Texas Transportation Institute in 1989 (*3*). This version coupled the ID Model to the previously developed CMS and CRREL Models, to develop an integrated environmental predictive methodology. The original version was then modified and released in 1997 by Larson and Dempsey as ICM version 2.0 (*4*). Additional modifications were performed in 1999, leading to ICM version 2.1. Further improvements were made as part of the Design Guide development to further improve the moisture prediction capabilities of ICM version 2.1. This version of the program will be referred to henceforth as EICM. Overall, the EICM computes and predicts the following information throughout the entire pavement/subgrade profile: temperature, resilient modulus adjustment factors, pore water pressure, water content, frost and thaw depths, frost heave, and drainage performance. The model can be applied to either asphalt concrete (AC) or PCC pavements.

In developing the EICM, data from the Long Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) test sections were used (*5, 6, 7, 8)*. A detailed discussion on the specific improvements can be obtained in Appendix DD and in References *5* through *8*.

In short, the major tasks (relevant to the Design Guide) undertaken in developing EICM are:

- Replacement of the soil-water characteristic curve (SWCC) Gardner equation with the equations proposed by Fredlund and Xing (*9*) to obtain a better functional fit.
- Development of improved estimates of SWCCs, saturated hydraulic conductivity (k_{sat}), and specific gravity of solids (G_s) given known soil index properties such as grain-size distribution (percent passing number 200 sieve, P_{200}, and effective grain size with 60 percent passing by weight, D_{60}) and Plasticity Index (*PI*).
- Incorporation into the EICM of an unsaturated hydraulic conductivity prediction based on the SWCC proposed by Fredlund, et al. in 1994 *(10)*.
- Addition of a climatic database containing hourly data from 800 weather stations from across the United States for sunshine, rainfall, wind speed, air temperature, and relative humidity. The data source was the National Climatic Data Center (NCDC).

The SWCC is defined as the variation of water storage capacity within the macro- and micro-pores of a soil, with respect to suction *(11)*. This relationship is generally plotted as the variation of the water content (gravimetric, volumetric, or degree of saturation) with soil suction. Several mathematical equations have been proposed to represent the SWCC. The ICM version 2.1 made use of the equation proposed by Gardner in 1958 that has been shown, in many cases, to misrepresent the SWCC due to excessive constraints to the relationship. Several studies have been conducted on comparing the different equations available to represent the SWCC *(12, 13)*. Those studies have generally shown that the equations proposed by Fredlund and Xing in 1994 *(9)* showed good agreement with an extended database. For this reason, the Fredlund and Xing equation is used in the Design Guide procedure.

Another important improvement of practical relevance was the introduction of algorithms to estimate the specific gravity of the solids (G_s) and the saturated hydraulic conductivity (k_{sat}). These estimations can be used in cases where G_s and k_{sat} cannot be estimated from field or laboratory testing (i.e., they can be used at input Level 2). The G_s and the k_{sat} are both estimated based on P200, PI, and D_{60} values.

The next major modification was the incorporation of an algorithm to predict the unsaturated hydraulic conductivity. The ICM version 2.1 made use of the Gardner's parameters for the representation of the unsaturated hydraulic conductivity function, which is the relationship between hydraulic conductivity and soil matric suction. As part of the modifications performed to the ICM version 2.1, the unsaturated hydraulic conductivity default parameters were replaced by the equation proposed by Fredlund et al. in 1994 *(10)*. The proposed hydraulic conductivity function is an integral form of the water content versus suction relationship and makes use of the SWCC fitting parameters proposed by the same researchers.

The last major modification to the ICM version 2.1 was the incorporation of data from over 800 weather stations across the United States. The information was obtained from the NCDC and contains hourly variations of several variables used to establish the temperature, moisture, and frost regimes within a pavement structure virtually anywhere in the country. This enhancement considerably enhances the quality of the design procedure.

Incorporation of EICM into the Design Guide

The EICM software has been made an integral part of the Design Guide procedure. It is fully linked to the software accompanying the Design Guide and internally performs all the necessary computations. The user inputs to the EICM are entered through interfaces provided as part of the Design Guide software. The EICM processes these inputs and feeds the processed outputs to the three major components of the Design Guide's mechanistic-empirical design framework—materials, structural responses, and performance prediction. Thus, climate is fully incorporated into the Design Guide methodology, which will provide improved capabilities in pavement design.

The tasks listed in the following paragraph summarize the role of the EICM module in the overall design process. For flexible pavement analysis and design, the tasks incorporated to account for the environmental effects include the following:

Task 1 Records the user supplied resilient modulus, M_R, of all unbound layer materials at an initial or reference condition. Generally, this will be at or near the optimum water content and maximum dry density. PART 2, Chapter 2 discusses how M_R can be estimated at the various hierarchical input levels.

Task 2 Evaluates the expected changes in moisture content, from the initial or reference condition, as the subgrade and unbound materials reach equilibrium moisture condition. Also evaluates the seasonal changes in moisture contents.

Task 3 Evaluates the effect of changes in soil moisture content with respect to the reference condition on the user entered resilient modulus, M_R.

Task 4 Evaluates the effect of freezing on the layer M_R.

Task 5 Evaluates the effect of thawing and recovery from the frozen M_R condition.

Task 6 Utilization of time—varying M_R values in the computation of critical pavement response parameters and damage at various points within the pavement system.

Task 7 Evaluate changes in temperature as a function of time for all asphalt bound layers.

The input in Task 1, M_{Ropt}, (M_R at optimum compaction conditions and the chosen reference value), is a materials-related entry provided by the user (described in PART 2, Chapter 2). This value is determined using either the Finite Element Analysis (FEA) procedure or the Linear

Elastic Analysis (LEA) procedure consistent with the Design Guide, depending on whether stress-dependent moduli or linear elastic analysis is utilized.

Tasks 2 through 7 are performed internally by the EICM embedded into the Design Guide software and the outputs are made available to both the flexible and rigid pavement design modules.

For rigid pavements, the following additional tasks are performed by the EICM:

Task 8 Generate temperature profiles in the PCC and underlying layers for the trial design section for each hour of each day for the selected location using the weather station information (used for thermal gradients in PCC, joint and crack openings and closings, and AC base temperatures for modulus estimation).

Task 9 Convert the non-linear temperature profile to an effective linear temperature gradient that is used to model slab curvature and thermal stresses.

Task 10 Generate a probability distribution file of effective linear temperature gradients that can be expected to occur for each month of the year for the trial design cross section.

Task 11 Determine the freezing index and the number of freeze-thaw cycles for the selected location.

Task 12 Provide mean monthly relative humidity values for use in estimating the moisture warping of the PCC slabs on a monthly basis.

One of the important outputs required from the EICM for the flexible and rigid pavement design is a set of adjustment factors for unbound material layers that account for the effects of environmental parameters and conditions such as moisture content changes, freezing, thawing, and recovery from thawing. This factor, denoted F_{env}, varies with position within the pavement structure and with time throughout the analysis period. The F_{env} factor is a coefficient that is multiplied by the M_{Ropt} to obtain M_R as a function of position and time.

Three additional outputs of importance from the EICM are the in-situ temperatures at the midpoints of each bound sublayer (with statistics that quantify the variability), the temperature profiles within the AC and/or PCC layer for every hour, and the average moisture content for each sublayer in the pavement structure. These outputs are described in the next subsection.

2.3.1.3 Major Outputs of the EICM

Following is a summary of the major outputs of the EICM and the ways they are used in Design Guide methodology. The output of the EICM can be described on two levels—internal and external. Both forms of outputs of the EICM are transparent to the user with the difference being that the internal outputs are not passed on to other components of the Design Guide software (e.g., structural response calculation module or the performance prediction module), while the external outputs are. However, the user has full control over the inputs that drive both these outputs (e.g., water table depths, climatic information for the project site).

Internal Output of the EICM

The computational engine of the EICM determines values of volumetric water content, θ_w, and temperature at each node over time based on certain user inputs discussed later in this Chapter. The values of θ_w are divided by the saturated volumetric water contents, θ_{sat}, to get values of degree of saturation, S. With no oscillations in the input groundwater table and no cracks in the AC layer, values of S are essentially values at a state of equilibrium, S_{equil}, unless freezing or thaw recovery is in progress.

Values of S_{equil}, together with values of degree of saturation at optimum conditions, S_{opt}, are then used to compute the unbound layer modulus adjustment factor for unfrozen conditions, F_U, at each node. The output temperatures are used to signal freezing at a node and an adjustment factor for frozen condition, F_F, is computed at each freezing node. Thawing normally follows freezing, as signaled by the rise in temperature above the freezing point. During the recovery period, material type/properties are used to compute the recovery ratio, *RR*, at recovering nodes. These *RR* values, together with reduction factors due to thawing, *RF*, are used to compute and adjustment factor for recovering conditions, F_R, at each recovering node.

External Output of the EICM

The following outputs are generated by EICM for use by other components of the Design Guide software:

- Unbound material M_R adjustment factor as function of position and time—values of composite environmental effects adjustment factor, F_{env}, are computed for every sublayer from the values of F_F, F_R, or F_U at each node. The sublayering is internally defined by the EICM and is a function of the frost penetration depth, among other factors. These F_{env} factors are sent forward either to the FEA or to the LEA structural analysis modules of the Design Guide software, where they are multiplied by M_{Ropt} to obtain M_R as function of position and time.
- Temperatures at the surface and at the midpoint of each asphalt bound sublayer—these values are subjected to statistical characterization for every analysis period (1 month or 2-week period). The mean, standard deviation, and quintile points are sent forward for use in the fatigue and permanent deformation prediction models.
- Values of hourly temperature at the surface and at a set depth increment (every inch) within the bound layers for use in the thermal cracking model.
- Volumetric moisture content—an average value for each sublayer is reported for use in the permanent deformation model for the unbound materials.
- Temperature profile in the PCC—hourly values are generated for use in the cracking and faulting models for jointed plain concrete pavement (JPCP) and the punchout model for continuously reinforced concrete pavement (CRCP).
- Number of freeze thaw cycles and freezing index are computed for use in JPCP performance prediction.

- Relative humidity values for each month are generated for use in the JPCP and CRCP modeling of moisture gradients through the slab.

The external EICM outputs feed directly into the materials characterization, structural response computation, and performance prediction modules of the Design Guide software.

2.3.1.4 Chapter Organization

A majority of this chapter is devoted to guiding the user through the process of generating the inputs needed for the EICM at the various hierarchical levels. Although the algorithms used for computing modulus adjustment factors, F_{env}, are internal to the EICM, considerable discussion is provided towards the end of the chapter to explain how these computations are made. Discussion on how EICM determines the temperature and moisture distribution within the pavement system is also included in this chapter.

2.3.2 CLIMATIC AND MATERIAL INPUTS REQUIRED TO MODEL THERMAL AND MOISTURE CONDITIONS

A relatively large number of input parameters are needed to produce the desired outputs from the EICM for pavement design. As with other inputs discussed so far in PART 2 of the Guide, even inputs to the climatic model can be provided at any of the hierarchical levels (1, 2, or 3) to provide flexibility in implementation of the Design Guide. The inputs required by the climatic model fall under the following broad categories:

- General information.
- Weather-related information.
- Ground water related information.
- Drainage and surface properties.
- Pavement structure and materials.

The ensuing discussion presents the specific inputs required under each of the above mentioned categories and the recommended procedures to obtain them at the various hierarchical input levels. The relevance of each of these inputs to pavement design is also noted, where applicable. The discussion presented covers both new and rehabilitation design.

Note that there is some overlap between the inputs discussed in this chapter and those discussed in PART 2, Chapters 1 and 2 as well as PART 3, Chapters 3, 4, 6, and 7. This is anticipated since the influence of climate on pavement performance is intimately linked with the materials, layer structure, and design features being considered in the trial design. The interaction between climate, materials, and pavement design is fully explored in the Design Guide.

2.3.2.1 General Information

Under this category, the following inputs specifically relate to the climatic model:

- *Base/Subgrade Construction Completion Month and Year*—This input is required for new flexible pavement design only. It is required to initialize the moisture model in the EICM. The moisture calculations in the unbound materials start from this point in time and as the moisture contents in these layers change from the optimum values input by the user to an equilibrium value, the layer moduli are adjusted accordingly. When taken in conjunction with the traffic open month, this input is also used to control the length of the analysis period. For example, if the time difference between the construction month and the traffic open month is 2 years and the anticipated design life is 20 years, the analysis period is set to 22 years. If this input is completely unknown, the designer should use the month that most highway construction occurs in the area.
- *Existing Pavement Construction Month and Year*—This input is required only for rehabilitation design using both AC and PCC overlays. If the underlying pavement is a flexible pavement, this parameter helps identify the extent to which the pavement is aged at the time of rehabilitation. If the underlying pavement is a rigid pavement, this parameter is used to estimate the strength and modulus of the PCC layer at the time of rehabilitation. If this input is completely unknown, the designer should use the month that most highway construction occurs in the area.
- *Pavement Construction Month and Year*—This parameter is required for both new and rehabilitation design. For flexible pavement design, this parameter helps determine the stiffness and strength characteristics of the asphalt layer and for rigid pavement design it is used to estimate the "zero-stress" temperature in the PCC at construction. The zero-stress temperature affects JPCP faulting and CRCP punchout predictions (see PART 3, Chapter 4 for more discussion on this input). Further, in CRCP design, this input is used to compute relative humidities, which have an impact on initial crack spacing and width. If this input is completely unknown, the designer should use the month that most highway construction occurs in the area.
- *Traffic Opening Month and Year*—The expected month in which the pavement will be opened to traffic after construction. This value defines the climatic conditions at the time of opening to traffic, which relates to the temperature gradients and the layer moduli, including that of the subgrade. If completely unknown, the designer should use the most likely month after the estimated construction month.
- *Type of Design*—New or Rehabilitation and AC or PCC. This input determines the types of climatic user inputs required for the analysis, climatic model initialization parameters, pavement sublayering schemes, types of outputs required from climatic analysis, and so on.

2.3.2.2 Weather-Related Data

To accomplish the climatic analysis required for incremental damage accumulation, the Design Guide approach requires information on the following five weather-related parameters on an hourly basis over the entire design life for the project being designed:

- Hourly air temperature.
- Hourly precipitation.
- Hourly wind speed.
- Hourly percentage sunshine (used to define cloud cover).
- Hourly relative humidity.

The air temperature is required by the heat balance equation in the EICM for calculations of long wave radiation emitted by the air and for the convective heat transfer from surface to air. Both computations are explained in detail later in this chapter. In addition to the heat calculations, the temperature data is used to define the frozen/thawing periods within the analysis time frame and to determine the number of freeze-thaw cycles.

Heat fluxes resulting from precipitation and infiltration into the pavement structure have not been considered in formulating the surface heat flux boundary conditions. The role of the precipitation under these circumstances in not entirely clear, and methods to incorporate it in the energy balance have not been attempted. However, precipitation is needed to compute infiltration for rehabilitated pavements and aging processes. Furthermore, the precipitation that falls during a month when the mean temperature is less than the freezing temperature of water is assumed to fall as snow.

Wind speed is required in the computations of the convention heat transfer coefficient at the pavement surface. The percentage sunshine is needed for the calculations of heat balance at the surface of the pavement. Both calculations are described in detail later on in this chapter.

Hourly relative humidities have a big impact on drying shrinkage of JPCP and CRCP and also in determining the crack spacing and initial crack width in CRCP. The role ambient relative humidity plays in determining these parameters is described in more detail in PART 3, Chapter 4, as well as in the related appendices.

Determination of Weather-Related Parameters

In the Design Guide approach, the weather-related information is primarily obtained from weather stations located near the project site. The software accompanying the Design Guide has an available database from nearly 800 weather stations throughout the United States. Several of the major weather stations have approximately 60 to 66 months of climatic data at each time step (1 hour) needed by the EICM. Other weather stations could have less than this amount of data, however, the Design Guide software requires at least 24 months of actual weather station data for computational purposes.

The climatic database can be tapped into by simply specifying the latitude, longitude, and elevation of the project site. Once the coordinates and elevation are specified, the Design Guide software will highlight the six closest weather stations to the site from which the user may select any number of stations to create a virtual project weather station. Because there could be some missing data in each actual weather station data file, it is recommended that as many stations be combined as possible to allow data smoothing and ensure adequate information (recall that a minimum of 24 months of climatic data is required) . The EICM will show the distance between the site and each highlighted weather station and the amount of information (number of months) available for each one of these stations. After the appropriate number of representative weather stations is chosen, interpolation of climatic data from these stations is done and the interpolated data is made available for storage as a virtual weather station. The climatic data from virtual weather stations created in this manner will be made use of by the Design Guide software to assess temporal changes in material behavior, computing structural responses due to environmental loads, and to predict pavement distress.

The configuration of weather-related information required for design is the same at all the three hierarchical input levels. Interpolation of climatic information from as many applicable weather stations as possible for a given project site is recommended to smooth erroneous data or to fill in missing information.

2.3.2.3 Groundwater Table Depth

The groundwater table depth is intended to be either the best estimate of the annual average depth or the seasonal average depth (a value for each of the four seasons of the year). At input Level 1, it could be determined from profile characterization borings prior to design. At input Level 3, an estimate of the annual average value or the seasonal averages can be provided. A potential source to obtain Level 3 estimates is the county soil reports produced by the National Resources Conservation Service (*14*).

It is important to recognize that this parameter plays a significant role in the overall accuracy of the foundation/pavement moisture contents and, hence, equilibrium modulus values. Every attempt should be made to characterize it as accurately as possible.

2.3.2.4 Drainage and Surface Properties

Surface Shortwave Absorptivity

This input pertains to the AC and PCC surface layers. The surface short wave absorptivity of a given layer depends on its composition, color, and texture. This quantity directly correlates with the amount of available solar energy that is absorbed by the pavement surface. Generally speaking, lighter and more reflective surfaces tend to have lower short wave absorptivity and vice versa.

The following are the recommended ways to the estimate this parameter at each of the hierarchical input levels:

- Level 1 – At this level it is recommended that this parameter be estimated through laboratory testing. However, although there are procedures in existence to measure shortwave absorptivity, there are no current AASHTO certified standards for paving materials.
- Level 2 – Not applicable.
- Level 3 – At Level 3, default values can be assumed for various pavement materials as follows:
    - Weathered asphalt (gray) 0.80 – 0.90
    - Fresh asphalt (black) 0.90 – 0.98
    - Aged PCC layer 0.70 – 0.90

Infiltration

This parameter defines the net infiltration potential of the pavement over its design life. In the Design Guide approach, infiltration can assume four values – none, minor (10 percent of the precipitation enters the pavement), moderate (50 percent of the precipitation enters the pavement), and extreme (100 percent of the precipitation enters the pavement). Based on this input, the EICM determines the amount of water available on top of the first unbound layer.

Most designs and maintenance activities, especially on higher functional class pavements, should strive to achieve zero infiltration or reduce it to a minimum value. This can be done by proper design of surface drainage elements (cross-slopes, side ditches, etc.), adopting construction practices that reduce infiltration (e.g., eliminating cold lane/shoulder joints, tied joints in the case of PCC pavements, etc.), proactive routine maintenance activities (e.g., crack and joint sealing, surface treatments, etc.), and providing adequate subsurface drainage in the form of drainage layers or edgedrains. Using moisture insensitive materials can also mitigate the impact of any moisture that infiltrates the pavement. PART 3, Chapter 1 provides more discussion on how to reduce pavement infiltration.

The amount of infiltration into the pavement at any given point in time due to a certain rain event is a function of the pavement condition, shoulder type, and drainage features the intercept the moisture. For simplicity, the general guidelines for estimating infiltration are based only on the shoulder type and if edgedrains are present or not. The shoulder type is relevant since the lane-shoulder joint represents the largest single source of moisture entry into the pavement structure. The presence of edgedrains is relevant since they shorten the drainage path and provide a positive drainage outlet. Note that if a drainage layer is present in addition to edgedrains, its impact on protecting the underlying layers from getting saturated is automatically accounted for within the EICM through a direct modeling of how this layer impacts the modulus of unbound layers and subgrade.

The following recommendations are made for selecting the *Infiltration* input parameter:

- Minor – This option is valid when tied and sealed concrete shoulders (in rigid pavements), widened PCC lanes, or full width AC paving (monolithic main lane and shoulder) are used or when an aggressive policy is pursued to keep the lane-shoulder joint sealed. This option is also applicable when edgedrains are used.
- Moderate – This option is valid for all other shoulder types, PCC restoration, and AC overlays over old and cracked existing pavements where reflection cracking will likely occur.
- Extreme – Generally not used for new or reconstructed pavement design.

These recommendations are valid at all the hierarchical input levels.

Drainage Path Length

The drainage path length is the resultant length of the drainage path, i.e., the distance measured along the resultant of the cross and longitudinal slopes of the pavement. It is measured from highest point in the pavement cross-section to the point where drainage occurs. This input is used in the EICM's infiltration and drainage model to compute the time required to drain an unbound base or subbase layer from an initially wet condition.

The DRIP microcomputer program (explained in Appendix TT and available as part of the Design Guide software) can be used to compute this parameter based on pavement cross and longitudinal slopes, lane widths, edgedrain trench widths (if applicable), and cross-section geometry (crowned or superelevated).

Pavement Cross-Slope

The cross slope is the slope of the pavement surface perpendicular to the direction of traffic. This input is used in computing the time required to drain a pavement base or subbase layer from an initially wet condition.

2.3.2.5 Pavement Structure Materials Inputs

Layer Thicknesses

The layer thickness of each material in the pavement structure should correspond to layers that are more or less homogeneous. EICM internally subdivides these layers for more accurate calculations of moisture and temperature profiles. The procedure always requires two unbound layers under the last stabilized layer for computational purposes (e.g., one layer could be compacted subgrade and the other the natural subgrade, or one layer could be compacted granular fill and the other natural subgrade). If the trial design does not facilitate this, the subgrade layer is subdivided into two layers internally by the Design Guide software. Further, all layer subdivisions are handled internally and automatically. The user should not subdivide the pavement layers into sublayers. A description of sublayering and its relevance in computing seasonal pavement moduli is provided in PART 3, Chapter 3.

Asphalt Material Properties

Several asphalt properties are required for the design of flexible pavements and AC overlays. Among these properties are those that control the heat flow through the pavement system and thereby influence the temperature and moisture regimes within it. Asphalt material properties that enter the EICM calculations include:

- Surface shortwave absorptivity.
- Thermal conductivity, *K*.
- Heat or thermal capacity, *Q*.

Shortwave absorptivity has been discussed earlier in this chapter. Therefore, the discussion under this section is restricted to thermal conductivity and heat capacity.

Thermal conductivity, *K*, is the quantity of heat that flows normally across a surface of unit area per unit of time and per unit of temperature gradient. The moisture content has an influence upon the thermal conductivity of asphalt concrete. If the moisture content is small, the differences between the unfrozen, freezing and frozen thermal conductivity are small. Only when the moisture content is high (e.g., greater than 10%) does the thermal conductivity vary substantially. The EICM does not vary the thermal conductivity with varying moisture content of the asphalt layers as it does with the unbound layers.

The heat or thermal capacity is the actual amount of heat energy *Q* necessary to change the temperature of a unit mass by one degree.

Table 2.3.1 outlines the recommended approaches to characterizing *K* and *Q* at the various hierarchical input levels for both new flexible pavement design and design of pavements with asphalt concrete overlays.

Table 2.3.1. Characterization of asphalt concrete materials inputs required for EICM calculations.

Material Property	**Input Level**	**Description**
Thermal Conductivity, K	1	A direct measurement is recommended at this level (ASTM E1952).
	2	Not applicable.
	3	User selects design values based upon agency historical data or from typical values shown below: • Typical values for asphalt concrete range from 0.44 to 0.81 Btu/(ft)(hr)(^{o}F).
Heat Capacity, Q	1	A direct measurement is recommended at this level (ASTM D2766).
	2	Not applicable.
	3	User selects design values based upon agency historical data or from typical values shown below: • Typical values for asphalt concrete range from 0.22 to 0.40 Btu/(lb)(^{o}F).

PCC Material Properties

Just as with asphalt materials, thermal conductivity, heat capacity, and surface shortwave absorptivity are also need for PCC materials in order for EICM to estimate the temperature and moisture regimes in a rigid pavement system. The characterization of shortwave absorptivity has already been discussed in an earlier section. Table 2.3.2 outlines the recommended approaches to characterizing thermal conductivity and the heat capacity of PCC materials used in the design of new PCC pavements, PCC overlays of existing AC pavements, and AC overlays of existing PCC pavements.

Table 2.3.2. Characterization of PCC material inputs required for EICM calculations.

Material Property	Input Level	Description
Thermal Conductivity, *K*	1	A direct measurement is recommended at this level (ASTM E1952).
	2	Not applicable.
	3	User selects design values based upon agency historical data or from typical values shown below: • Typical values for PCC range from 1.0 to 1.5 Btu/(ft)(hr)(^{o}F).
Heat Capacity, *Q*	1	A direct measurement is recommended at this level (ASTM D2766).
	2	Not applicable.
	3	User selects design values based upon agency historical data or from typical values shown below: • Typical values for PCC range from 0.2 to 0.28 Btu/(lb)(^{o}F) with the lower end of the range being more common.

Compacted Unbound Material Properties

Determination of Mass-Volume Parameters

The parameters of interest in this category are the maximum dry density ($\gamma_{d\,max}$), specific gravity (G_s), and the optimum gravimetric moisture content (w_{opt}) of the compacted unbound material in question. From these three inputs, all other mass-volume parameters can be computed, including the initial degree of saturation, S_{opt}, optimum volumetric water content, θ_{opt}, and saturated volumetric water content, θ_{sat}. These computations are done internally in the Design Guide software and are part of the EICM's internal outputs discussed earlier.

Table 2.3.3 describes the procedures to obtain the input parameters under this category for compacted unbound materials. At Level 1, it is required that the $\gamma_{d\,max}$, w_{opt}, and G_s be carefully measured in the laboratory in accordance with standard test protocols for each unbound layer. If the user chooses not to measure $\gamma_{d\,max}$, w_{opt}, and G_s, then it is suggested that Level 2 inputs be adopted. At input Level 2, the user enters gradation and engineering index properties of the unbound material such as the effective grain size corresponding to 60 percent passing by weight, D_{60}, the percent passing the No. 200 sieve, P_{200}, and the plasticity index, *PI*. From these

Table 2.3.3. Materials inputs required for unbound compacted material for EICM calculations—Mass-Volume Parameters.

Material Property	**Input Level**	**Description**
Specific Gravity (oven-dry), G_s	1	A direct measurement using AASHTO T100 (performed in conjunction with consolidation tests – AASHTO T180 for bases or AASHTO T 99 for other layers).
	2	Determined from P_{200}[1] and PI[2] of the layer as below: 1. Determine P_{200} and PI. 2. Calculate G_s (8): $G_s = 0.041(P_{200} * PI)^{0.29} + 2.65$
	3	Not applicable.
Optimum gravimetric water content, w_{opt}, and maximum dry unit weight of solids, γ_{dmax}	1	Typically, AASHTO T180 compaction test for base layers and AASHTO T99 compaction test for other layers.
	2	Determined from D_{60}[1], P_{200}[1] and PI[2] of the layer as illustrated below: 1. Read PI, P_{200}, and D_{60}. Identify the layer as a compacted base course, compacted subgrade, or natural in-situ subgrade. 2. Calculate S_{opt} (8): $S_{opt} = 6.752\ (P_{200} * PI)^{0.147} + 78$ 3. Compute w_{opt} (8): If $P_{200} * PI > 0$ $w_{opt} = 1.3\ (P_{200} * PI)^{0.73} + 11$ If $P_{200} * PI = 0$ $w_{opt\ (T99)} = 8.6425\ (D_{60})^{-0.1038}$ If layer is not a base course $w_{opt} = w_{opt\ (T99)}$ If layer is a base course $\Delta w_{opt} = 0.0156[w_{opt(T99)}]^2 - 0.1465 w_{opt(T99)} + 0.9$ $w_{opt} = w_{opt\ (T99)} - \Delta w_{opt}$ 4. To obtain G_s refer to the level 2 procedure for this input provided in this table above. 5. Compute $\gamma_{d\,max}$ for compacted materials, $\gamma_{d\,max\,comp}$ 6. $\gamma_{d\,max\,comp} = \dfrac{G_s \gamma_{water}}{1 + \dfrac{w_{opt} G_s}{S_{opt}}}$ 7. Compute $\gamma_{d\,max}$ If layer is a compacted material $\gamma_{d\,\max} = \gamma_{d\,\max\,\mathrm{comp}}$ If layer is a natural in-situ material $\gamma_d = 0.90 \gamma_{d\,\max\,\mathrm{comp}}$ 8. EICM uses γ_d for $\gamma_{d\,max}$
	3	Not applicable.

[1] P_{200} and D_{60} can be obtained from a grain-size distribution test (AASHTO T 27).

[2] PI can be determined from an Atterberg limit test (AASHTO T 90).

parameters, the EICM will compute γ_{dmax} S_{opt}, w_{opt}, and G_s using internally coded correlations. Although these correlations will not produce values of S_{opt} that are as precise as values derived from carefully measured $\gamma_{d\,max}$, w_{opt}, and G_s, they will produce values which are reasonable. Furthermore, the correlations have been adjusted until the other mass-volume parameters such as $\gamma_{d\,max}$ and G_s are internally consistent and reasonable. Level 3 inputs are not applicable for this input category.

Estimation of S_{opt}, θ_{opt}, θ_{sat}. These parameters are calculated internally in EICM from $\gamma_{d\,max}$, w_{opt}, and G_s using the equations given below:

$$\theta_{opt} = \frac{w_{opt}\gamma_{d\,\max}}{\gamma_{water}} \tag{2.3.1}$$

$$S_{opt} = \frac{\theta_{opt}}{1 - \dfrac{\gamma_{d\,max}}{\gamma_{water} G_s}} \tag{2.3.2}$$

and

$$\theta_{sat} = \frac{\theta_{opt}}{S_{opt}} \tag{2.3.3}$$

where,

γ_{water} = Unit weight of water (in consistent units).

Equilibrium Gravimetric Moisture Content

Equilibrium gravimetric moisture content is a required input for rehabilitation design. However, it is not required for new pavement design. It is recommended that this parameter be estimated from direct testing of bulk samples retrieved from the site or through other appropriate means.

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity, k_{sat}, is required to determine the transient moisture profiles in compacted unbound materials and to compute their drainage characteristics. Table 2.3.4 describes how this parameter can be estimated at the various hierarchical input levels.

Dry Thermal Conductivity and Dry Heat Capacity

Table 2.3.5 outlines the recommended approaches to characterizing "dry" thermal conductivity (K) and the heat capacity (Q) of unbound materials. The EICM automatically adjusts the initial values for K and Q according to the current moisture content of the soil.

Table 2.3.4. Materials inputs required for unbound compacted material for EICM calculations—Saturated Hydraulic Conductivity, k_{sat}.

Material Property	**Input Level**	**Description**
Saturated hydraulic conductivity, k_{sat}	1	A direct measurement using a permeability test (AASHTO T215) is recommended at this level.
	2	Determined from P_{200}[1], D_{60}[1], and PI[2] of the layer as below: 1. Determine $P_{200}PI = P_{200} * PI$ 2. If $0 \le P_{200}PI < 1$ $k_{sat} = 118.11 \times 10^{\left[-1.1275(\log D_{60}+2)^2 + 7.2816(\log D_{60}+2) - 11.2891\right]}$ (ft/hr) Valid for $D_{60} < 0.75$ in If $D_{60} > 0.75$ in, set $D_{60} = 0.75$ mm 3. If $P_{200}PI \ge 1$ $k_{sat} = 118.11 \times 10^{\left[0.0004(P_{200}PI)^2 - 0.0929(P_{200}PI) - 6.56\right]}$ (ft/hr)
	3	Not applicable.

[1] P_{200} and D_{60} can be obtained from a grain-size distribution test (AASHTO T 27).

[2] PI can be determined from an Atterberg limit test (AASHTO T 90).

Table 2.3.5. Materials inputs required for unbound compacted material for EICM calculations—Dry Thermal Conductivity (*K*) and Heat Capacity (*Q*).

Material Property	**Input Level**	**Description**
Dry Thermal Conductivity, K	1	A direct measurement is recommended at this level (ASTM E1952).
	2	Not applicable.
	3	*Soil Type* *Range* *Recommended* *Btu/(ft)(hr)(^{o}F)* A-1-a 0.22 – 0.44 0.30 A-1-b 0.22 – 0.44 0.27 A-2-4 0.22 – 0.24 0.23 A-2-5 0.22 – 0.24 0.23 A-2-6 0.20 – 0.23 0.22 A-2-7 0.16 – 0.23 0.20 A-3 0.25 – 0.40 0.30 A-4 0.17 – 0.23 0.22 A-5 0.17 – 0.23 0.19 A-6 0.16 – 0.22 0.18 A-7-5 0.09 – 0.17 0.13 A-7-6 0.09 – 0.17 0.12
Dry Heat Capacity, Q	1	A direct measurement is recommended at this level (ASTM D2766).
	2	Not applicable.
	3	User selects design values based upon agency historical data or from typical values shown below: • Typical values range from 0.17 to 0.20 Btu/(lb)(^{o}F).

Soil Water Characteristic Curve Parameters

The SWCC defines the relationship between water content and suction for a given soil (*15*). Table 2.3.6 outlines the recommended approach to characterizing the parameters of the SWCC at each of the three hierarchical input levels. As part of the Design Guide development, a lot of effort was expended to obtain the fitting parameters of the Fredlund and Xing equation from soil index properties *(13)*. As can be observed from table 2.3.6, when the soil has a *PI* greater than zero, the SWCC parameters are correlated with the product of P_{200} (decimal) and *PI,* referred to as $P_{200}PI$. For those cases where the *PI* is zero, the parameters are correlated with the D_{60}. Figures 2.3.1 and 2.3.2 show examples of the goodness of the fit of these correlations. The data points shown in these figures represent the actual, measured SWCCs (after some smoothing). The goodness of the fit can be judged by observing the extent to which the "predicted" band is centered on and envelops the experimental data. For each figure, the experimental data subset represents the same range in $P_{200}PI$ (or D_{60}), as does the predicted band given by the solid curves. Figure 2.3.3 summarizes the results obtained for both groups of soils.

Table 2.3.6. Options for estimating SWCC parameters.

Input Level	**Procedure to Determine SWCC Parameters**	**Required Testing**
1	1) Direct measurement of suction (h) in psi, and volumetric water content (θ_w) pairs of values. 2) Direct measurement of optimum gravimetric water content, w_{opt} and maximum dry unit weight, $\gamma_{d\,max}$. 3) Direct measurement of the specific gravity of the solids, G_s. 4) Compute θ_{opt} as shown in equation 2.3.1. 5) Compute the S_{opt} as shown in equation 2.3.2. 6) Compute θ_{sat} as shown in equation 2.3.3. 7) Based on a non-linear regression analysis, compute the SWCC model parameters a_f, b_f, c_f, and h_r using the equation proposed by Fredlund and Xing, and the (h, θ_w) pairs of values obtained in step 1. $$\theta_w = C(h)\times\left[\frac{\theta_{sat}}{\left[\ln\left[EXP(1)+\left(\frac{h}{a_f}\right)^{b_f}\right]\right]^{c_f}}\right]$$ $$C(h)=\left[1-\frac{ln\left(1+\frac{h}{h_r}\right)}{ln\left(1+\frac{1.45\times10^5}{h_r}\right)}\right]$$ 8) Input a_f (psi), b_f, c_f, and h_r (psi) into the Design Guide software. 9) EICM will generate the function at any water content (SWCC).	Pressure plate, filter paper, and/or Tempe cell testing. AASHTO T180 or AASHTO T99 for $\gamma_{d\,max}$. AASHTO T100 for G_s.

Table 2.3.6. Options for estimating SWCC parameters (continued).

Input Level	**Procedure to Determine SWCC Parameters**	**Required Testing**
2	1) Direct measurement of optimum gravimetric water content, w_{opt} and maximum dry unit weight, $\gamma_{d\,max}$. 2) Direct measurement of the specific gravity of the solids, G_s. 3) Direct measurement of P_{200}, D_{60}, and PI. 3) The EICM will then internally do the following: a) Calculate $P_{200} * PI$. b) Calculate θ_{opt}, S_{opt}, and θ_{sat} as described for level 1. c) Based on a non-linear regression analysis, the EICM will compute the SWCC model parameters a_f, b_f, c_f, and h_r by using correlations with $P_{200}*PI$ and D_{60} *(13)*. i. If $P_{200}PI > 0$ $a_f = \frac{0.00364(P_{200}PI)^{3.35} + 4(P_{200}PI) + 11}{6.895}$, psi $\frac{b_f}{c_f} = -2.313(P_{200}PI)^{0.14} + 5$ $c_f = 0.0514(P_{200}PI)^{0.465} + 0.5$ $\frac{h_r}{a_f} = 32.44e^{0.0186(P_{200}PI)}$ ii. If $P_{200}PI = 0$ $a_f = \frac{0.8627(D_{60})^{-0.751}}{6.895}$, psi $\bar{b}_f = 7.5$ $c_f = 0.1772\ln(D_{60}) + 0.7734$ $\frac{h_r}{a_f} = \frac{1}{D_{60} + 9.7e^{-4}}$ d) The SWCC will then be established internally using the Fredlund and Xing equation as shown for Level 1.	AASHTO T180 or AASHTO T99 for $\gamma_{d\,max}$. AASHTO T100 for G_s. AASHTO T27 for P_{200} and D_{60}. AASHTO T90 for PI.
3	Direct measurement and input of P_{200}, PI, and D_{60}, after which EICM uses correlations with $P_{200}PI$ and D_{60} to automatically generate the SWCC parameters for each soil, as follows: 1) Identify the layer as a base course or other layer 2) Compute G_s as outlined in table 2.3.3 for Level 2. 3) Compute $P_{200} * PI$ 4) Compute S_{opt}, w_{opt}, and $\gamma_{d\,max}$ as shown for level 2. 6) Based on a non-linear regression analysis, the EICM will compute the SWCC model parameters a_f, b_f, c_f, and h_r by using correlations with $P_{200}PI$ and D_{60}, as shown for Level 2. 7) The SWCC will then be internally established using the Fredlund and Xing equation as shown for Level 1.	T27 for P_{200} and D_{60}. T90 for PI.

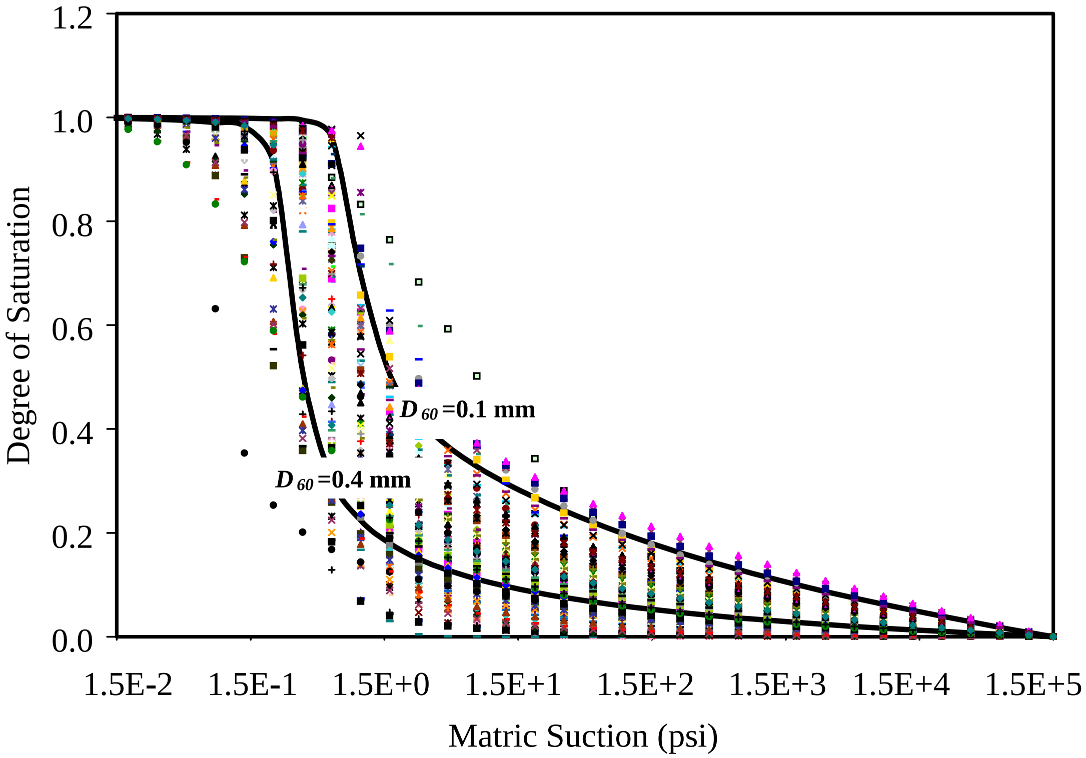


Figure 2.3.1. Range of SWCCs for soils with D_{60} between 0.004 and 0.016 inches.

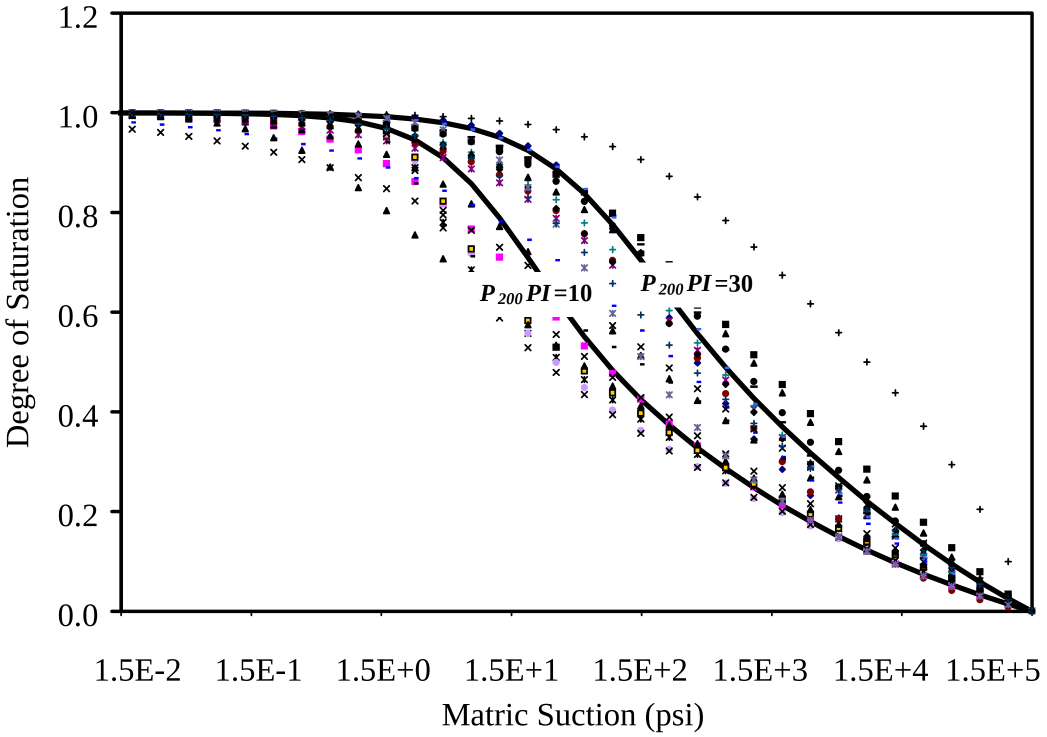


Figure 2.3.2. Range of SWCCs for soils with $P_{200}PI$ between 10 and 30.

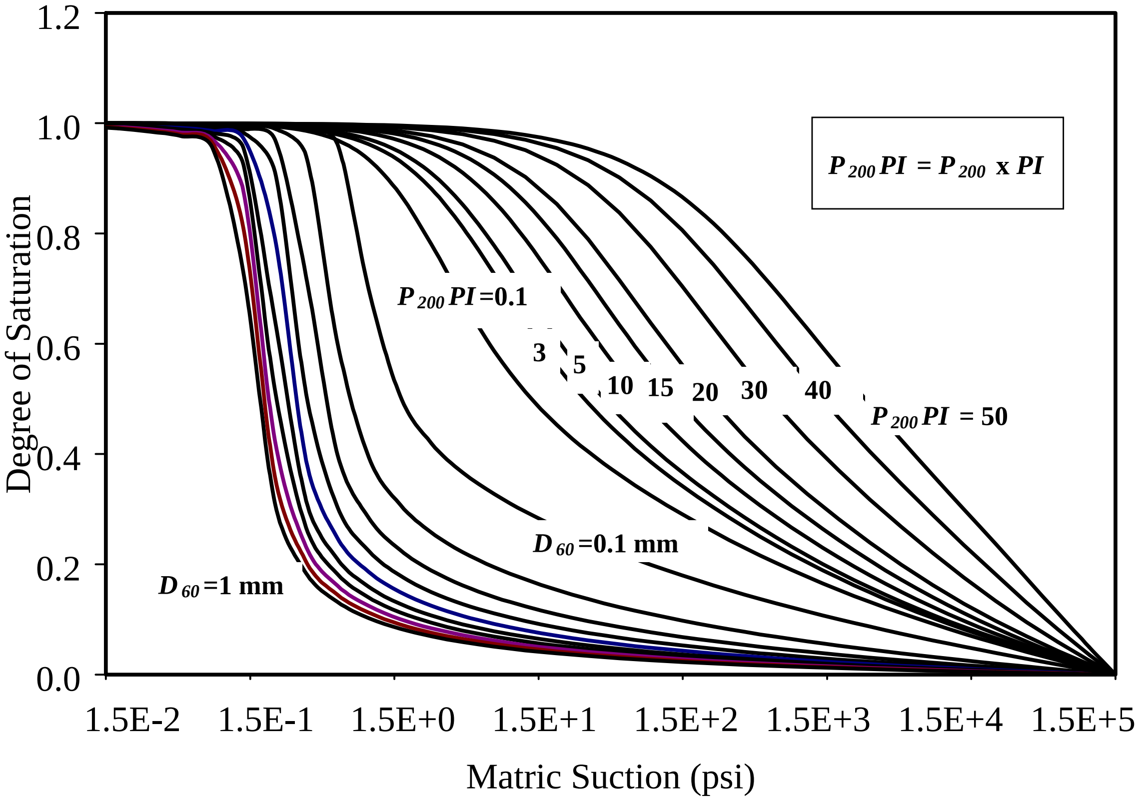


Figure 2.3.3. Predicted SWCC based on D_{60} and $P_{200}PI$.

Uncompacted/Natural Unbound Material Properties

Table 2.3.7 describes the input parameters for natural, in-situ layers, which lie below the compacted layers. Although the material properties of these lower layers are important to the overall load-response behavior of the pavement, a lower level of effort is generally sufficient to characterize them when compared to the properties of the overlying compacted materials. Therefore, Level 1 inputs are generally not required for in-situ materials. It is recommended that only PI, P_{200}, P_4, and D_{60} be measured for the in-situ layers (where P_4 is the percent passing the number 4 sieve; all other parameters have been defined previously). These values will be used with internally coded correlations in the Design Guide software (similar to those presented for compacted materials) to generate all additional input data needed.

Table 2.3.7. Inputs required for unbound natural, in-situ materials for EICM calculations.

Required Properties	Options for Determination
Specific Gravity, G_s	Direct measurement (Level 1) not required. Refer to table 2.3.3 to estimate this parameter from gradation parameters (Level 2).
Saturated Hydraulic Conductivity, k_{sat}	Direct measurement (Level 1) not required. Refer to table 2.3.4 to estimate this parameter from gradation parameters (Level 2).
Maximum Dry Unit Weight, γ_{dmax}	Direct measurement (Level 1) not required. Refer to table 2.3.3 to estimate this parameter from gradation parameters (Level 2).
Dry Thermal Conductivity, K Heat Capacity, Q	Direct measurements or default values can be combined and used. Refer to table 2.3.5 for a range of reasonable values.
Plasticity Index, PI	Direct measurement required in accordance with AASHTO T 90.
P_{200}, P_4, D_{60}	Direct measurement required in accordance with AASHTO T 27.
Optimum Gravimetric Water, w_{opt}	Not required. Refer to table 2.3.3.
Equilibrium Gravimetric Water Content	Direct measurement required for rehabilitated pavement analyses. This parameter is NOT required for new pavement design.

2.3.3 EICM CALCULATIONS – COMPOSITE ENVIRONMENTAL EFFECTS ADJUSTMENT FACTOR, F_{env}, FOR ADJUSTING M_R

2.3.3.1 Relevance of F_{env} to Design

To evaluate the resilient modulus of unbound materials used in the Design Guide, several factors influencing the modulus need to be considered:

- Stress state.
- Moisture/density variations.
- Freeze/thaw effects.

The values of the resilient moduli at any location and time within a given pavement structure are calculated as a function of the above factors.

The effect of stress state on M_R of unbound layers is considered in the Design Guide approach through the use of the universal constitutive equation that relates the resilient modulus to the bulk stress, the octahedral shear stress, and atmospheric pressure at any given location within the pavement. In the Design Guide approach, stress-sensitivity of unbound layers is only accounted for if the inputs are provided at Level 1 and that too only for flexible pavement design. In the Design Guide software execution, the FEA module is used for structural computations in place of the LEA module when Level 1modulus inputs are provided for unbound materials. At input Levels 2 and 3, stress sensitivity is not considered. At Level 2, the user enters an estimate of M_R at a reference moisture condition which is determined at or near the optimum moisture content and maximum dry density. At this input level, it is also possible to enter other parameters such as CBR, R-values, structural layer coefficient (a_i), and so on at a reference moisture condition from which an estimate of M_R can be obtained using standard correlations. At input Level 3, an estimate of the M_R is sufficient. More details on the configuring the resilient modulus input for unbound materials can be obtained in PART 2, Chapter 2.

Although the stress sensitivity is only considered if Level 1 inputs are used, the impact of temporal variations in moisture and temperature on M_R are fully considered at all levels through the composite environmental adjustment factor, F_{env}. The EICM deals with all environmental factors and provides soil moisture, suction, and temperature as a function of time, at any location in the unbound layers from which F_{env} can be determined. The resilient modulus M_R at any time or position is then expressed as follows:

$$M_R = F_{env} \cdot M_{Ropt} \tag{2.3.4}$$

The factor F_{env} is an adjustment factor and M_{Ropt} is the resilient modulus at optimum conditions (maximum dry density and optimum moisture content) and at any state of stress. It is obvious in equation 2.3.4 that the variation of the modulus with stress and the variation of the modulus with environmental factors (moisture, density, and freeze/thaw conditions) are assumed independent. Although this is not necessarily the case, recent studies support the use of this assumption in predicting resilient modulus without significant loss in accuracy of prediction. The adjustment factor F_{env}, being solely a function of the environmental factors, can then be computed inside the EICM, without actually knowing M_{Ropt}.

2.3.3.2 Environmental Effects on M_R of Unbound Pavement Materials

As has been stated earlier in this chapter, in a pavement structure, moisture and temperature are the two environmentally driven variables that can significantly affect the resilient modulus of unbound materials.

- All other conditions being equal, the higher the moisture content the lower the modulus; however, moisture has two separate effects:
    - It can affect the state of stress, through suction or pore water pressure.
    - It can affect the structure of the soil, through destruction of the cementation between soil particles *(16)*.
- At freezing temperatures, water in soil freezes and the resilient modulus rises to values 20 to 120 times higher than the value of the modulus before freezing; the process may be accompanied by the formation of ice lenses that create zones of greatly reduced strength in the pavement when thawing occurs.

The development of predictive equations and techniques that address the influence of changes in moisture and freeze/thaw cycles on the resilient modulus of unbound materials is described in the following two subsections.

<u>Resilient Modulus as Function of Soil Moisture</u>

An intensive literature review study was completed with the objective of summarizing existing models that incorporated the variation of resilient modulus with moisture (*5*). Using these published models from the literature (*17*, *18*, *19*, *20*), it was possible to develop (select) a model that would analytically predict changes in modulus due to changes in moisture. This model is presented in equation 2.3.5.

$$log \frac{M_R}{M_{Ropt}} = a + \frac{b-a}{1 + EXP\left(ln \frac{-b}{a} + k_m \cdot \left(S - S_{opt} \right) \right)} \qquad (2.3.5)$$

where,

M_R/M_{Ropt} = Resilient modulus ratio; M_R is the resilient modulus at a given time and M_{Ropt} is the resilient modulus at a reference condition.
a = Minimum of log(M_R/M_{Ropt}).
b = Maximum of log(M_R/M_{Ropt}).
k_m = Regression parameter.
$(S - S_{opt})$ = Variation in degree of saturation expressed in decimal.

Equation 2.3.5 approaches a linear form for degrees of saturation, S, within +/- 30% of S_{opt} but flattens out for degrees of saturation lower than 30% below the optimum. This extrapolation is in general agreement with known behavior of unsaturated materials in that, when a material becomes sufficiently dry, further drying increments produce less increase in stiffness and strength (*21*).

Using the available literature data and adopting a maximum modulus ratio of 2.5 for fine-grained materials and 2 for coarse-grained materials, the values of a, b, and k_m for coarse-grained and fine-grained materials are given in table 2.3.8. The predictions of this revised model are shown in figures 2.3.4 and 2.3.5, for fine-grained and coarse-grained materials, on semi-log scales. This model is implemented within the EICM version linked to the Design Guide software.

Table 2.3.8. Values of a, b, and k_m for coarse-grained and fine-grained materials.

Parameter	**Coarse-Grained Materials**	**Fine-Grained Materials**	**Comments**
a	- 0.3123	-0.5934	Regression parameter.
b	0.3	0.4	Conservatively assumed, corresponding to modulus ratios of 2 and 2.5, respectively.
k_m	6.8157	6.1324	Regression parameter.

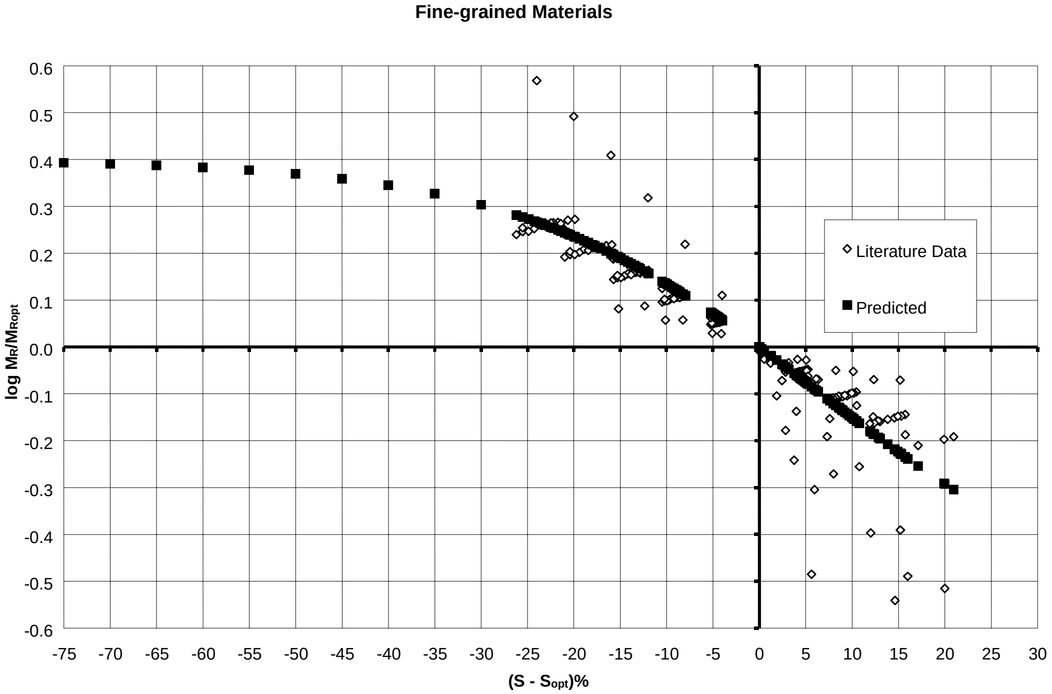


Figure 2.3.4. Resilient modulus - moisture model for fine-grained materials (semi-log scale).

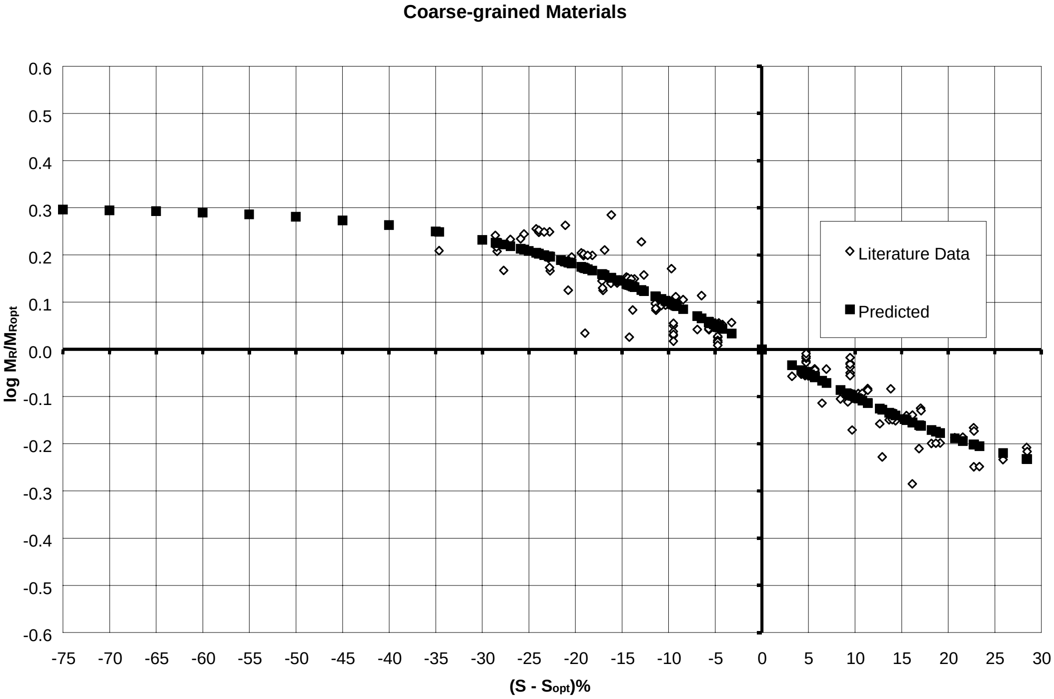


Figure 2.3.5. Resilient modulus - moisture model for coarse-grained materials (semi-log scale).

The Choice of Optimum Conditions as the Reference and Initial Conditions for M_R

As stated in PART 2, Chapter 2 and throughout this chapter, the required user input for stiffness of unbound materials is the M_R value estimated at or near optimum moisture and maximum dry density. The purpose of this section is to present the rationale behind the choice of optimum as the reference condition for the evaluation of M_R and as the initial condition for compacted unbound layers for input to the Design Guide software. The reference condition will be considered first.

- From literature it was found that the majority of resilient modulus tests have been performed on specimens at optimum conditions ($\gamma_d = \gamma_{dmax}$, $w = w_{opt}$ and $S = S_{opt}$) than any other condition *(6)*. Therefore, if optimum is made the reference condition, the database for the M_{Ropt} value will grow rapidly and the ability to make reasonable estimates of M_{Ropt} without resilient modulus testing will grow with it.
- It is common practice to require that contractors compact bases to at least 95% of γ_{dmax} by T180 (Modified) and other layers to 95% of γ_{dmax} by T99 (Standard). Given that contractors will typically target compaction somewhat above the minimum required, field compaction of $\gamma_d = \gamma_{dmax}$ is a reasonable approximation used in the Design Guide as the reference condition. Moisture content is rarely controlled strictly by specification, but good construction practice will force contractors to wet the material near optimum to facilitate compaction. Thus $w = w_{opt}$ and $S = S_{opt}$ are also reasonable assumptions for reference conditions, although the actual moisture content for field compaction may vary from somewhat higher to somewhat lower than optimum.

The choice of optimum as both reference condition and initial condition is both reasonable and practical. The actual compaction density and moisture can of course be measured at several specific points in the pavement structure, but not before construction. However, design of the pavement is performed well before construction. Furthermore, even if the precise γ_d and w were known at the design stage, the probability of having a database of M_R values at this condition is not high.

The implications of the choice of optimum as reference and initial condition can be examined by discussing figure 2.3.6. If compaction at S_{opt} is assumed, then it is likewise assumed that S changes (increases or decreases) to an equilibrium value, S_{equil} with time as shown by the solid curve in figure 2.3.6a or in figure 2.3.6b. In either case, S_{equil} is computed by the EICM, using the given depth to the groundwater table, y_{GWT}, and the soil-water characteristic curve, SWCC. Thus the value of S_{equil} does not actually depend on the initial S. If the actual initial degree of saturation, S_0, is slightly higher than S_{opt} as shown in figure 2.3.6a or slightly lower than S_{opt} as shown in figure 2.3.6b, the dashed path is followed to S_{equil}. Given that optimum has been chosen as the reference condition, it is the change from S_{opt} to S_{equil} that is of primary interest. The process of making a best estimate of the M_R under equilibrium conditions is as follows:

1. Estimate or measure M_R at optimum conditions to get M_{Ropt}.
2. Estimate or measure S_{opt}.
3. Use the EICM to compute S_{equil}.

4. Use (S_{opt} - S_{equil}) to evaluate the change in M_R from the reference condition (M_{Ropt}) to the final, equilibrium condition (M_{Requil}).

By using the above algorithm, no significant error in M_{Requil} is incurred by using S_{opt} instead of the actual S_0. The only error that is incurred is that of using the solid curve instead of the dashed curve to compute intermediate M_R values before the time to equilibrium, t_{equil}, is reached. In other words, the most accurate procedure would be to continue to use S_{opt} as the reference, but to jump initially to S_0 and then follow the dashed curve to S_{equil}. However, this more accurate procedure is considered unjustified for several reasons. First, it entails the difficulties of a priori estimation of S_0, as discussed above. Second, when the relatively short duration of t_{equil} is considered, it is apparent that the differences between the dashed and solid curves in figure 2.3.6 produce no significant error in the cumulative damage estimate for the pavement structure. This is particularly true if the pavement structure is not loaded with vehicular traffic until after equilibrium conditions are reached. Results of prior analyses indicate that t_{equil} is hours or days for most coarse-grained materials and weeks to several months for the great majority of the fine-grained materials. This duration is obviously very short compared to a 20- or 25-year design life. Thus, what is most important is to obtain the best possible estimate of M_{Requil}, which is operative 98% or 99% of the design life in non-frozen zones) whereas, a minor error in M_R prior to reaching t_{equil} is of no consequence.

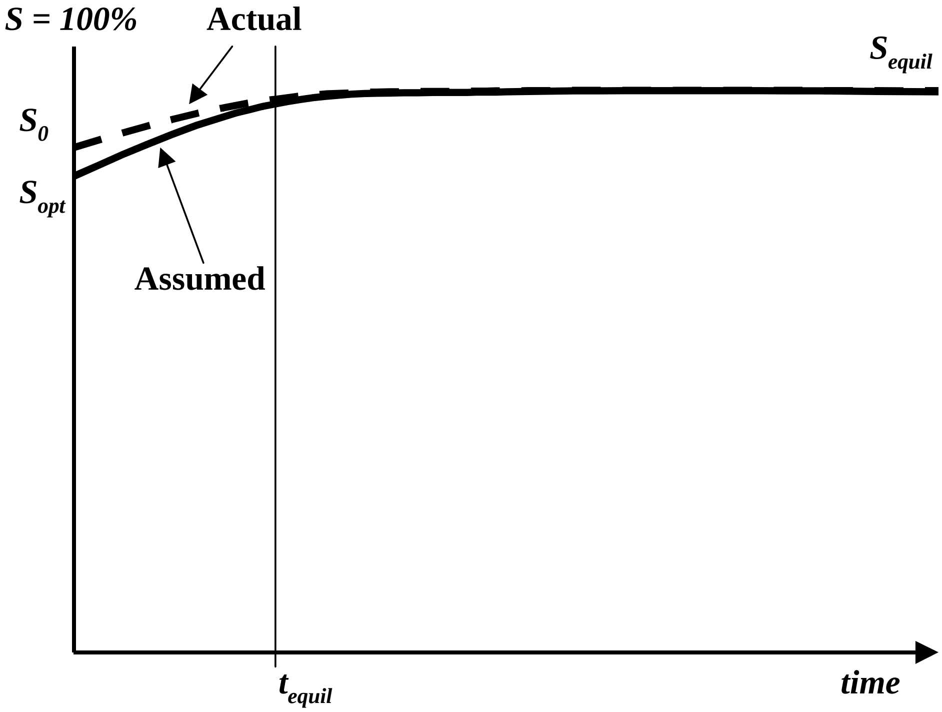
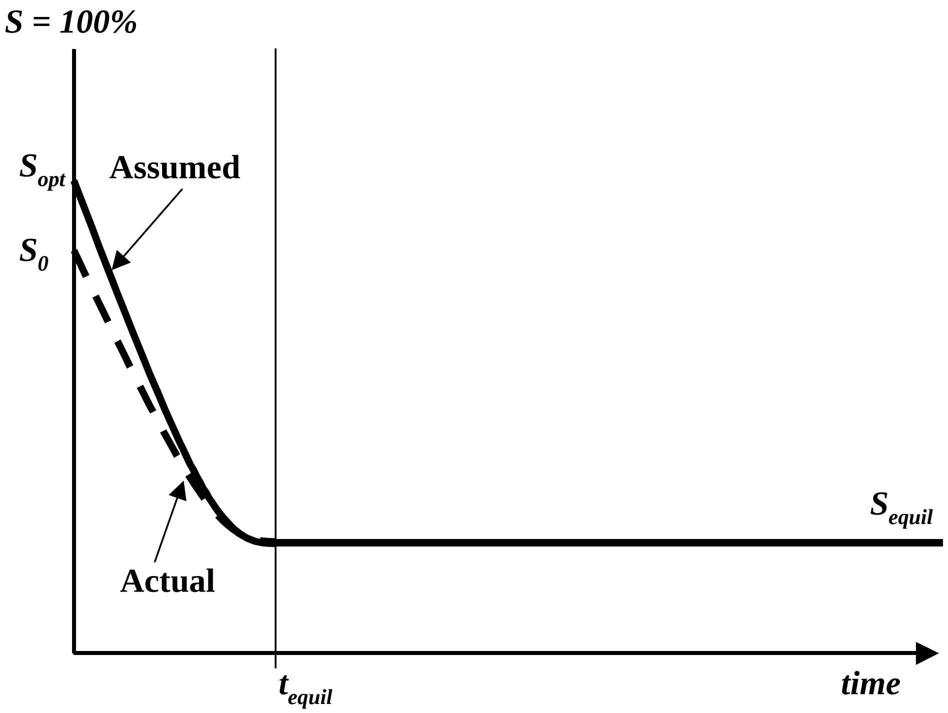


Figure 2.3.6a. Variation of degree of saturation with time.



ure 2.3.6b. Variation of degree of saturation with time.

Resilient Moduli for Frozen/Thawed Unbound Materials

To study the behavior of unbound materials under freezing/thawing conditions, a significant number of literature sources were consulted and salient values of moduli, M_R, and ratios of moduli were extracted *(7)*. The objective of the search was to obtain absolute values of moduli for frozen material, termed M_{Rfrz}, and the ratio of M_R just after thawing, termed M_{Rmin}, to the M_R of natural, unfrozen material, termed M_{Runfrz}. The ratio is used as a reduction factor, termed *RF*. Because some of the data from the literature produced *RF* values based on M_{Runfrz} as a reference and some were based on M_{Ropt} as a reference, it was decided to adopt the conservative interpretation of using the smaller of M_{Runfrz} and M_{Ropt} as a reference. These definitions are repeated in equation form below.

$M_{Rfrz} = M_{Rmax} = M_R$ for frozen material

M_{Runfrz} = the normal M_R for unfrozen material

$M_{Rmin} = M_R$ just after thawing

RF = modulus reduction factor = M_{Rmin}/smaller of (M_{Runfrz}, M_{Ropt}) (2.3.6)

The average values reported in the literature for M_{Rfrz} are as follows:

- $M_{Rfrz\_ave} \cong 3*10^6$ psi for coarse-grained materials.
- $M_{Rfrz\_ave} \cong 2*10^6$ psi for fine-grained silt and silty sands.

- $M_{Rfrz\_ave} \cong 1*10^6$ psi for clays.

If a single value were selected for all frozen soils, $2*10^6$ psi would be a reasonably unbiased estimate and $1*10^6$ psi would be a conservative estimate.

For thawed materials, the degree of M_R degradation upon thawing was found to be correlated with frost-susceptibility, or the ability of the soil to sustain ice lens formation under favorable conditions. Frost-susceptibility in turn can be estimated from the percent passing the No. 200 sieve, P_{200}, and the Plasticity Index, *PI*. In tables 2.3.9 and 2.3.10, *RF* values used in the Design Guide approach are given for coarse-grained and fine-grained materials as a function of P_{200} and *PI*.

Table 2.3.9. Recommended values of *RF* for coarse-grained materials ($P_{200} < 50\%$).

Distribution of Coarse Fraction*	**P_{200} (%)**	**$PI < 12\%$**	**$PI = 12\% - 35\%$**	**$PI > 35\%$**
Mostly Gravel $P_4 < 50\%$	< 6	0.85	-	-
	6 – 12	0.65	0.70	0.75
	> 12	0.60	0.65	0.70
Mostly Sand $P_4 > 50\%$	< 6	0.75	-	-
	6 – 12	0.60	0.65	0.70
	> 12	0.50	0.55	0.60

* If it is unknown whether a coarse-grained material is mostly gravel or mostly sand, assume sand.

Table 2.3.10. Recommended values of *RF* for fine-grained materials ($P_{200} > 50\%$).

P_{200} (%)	**$PI < 12\%$**	**$PI = 12\% - 35\%$**	**$PI > 35\%$**
50 - 85	0.45	0.55	0.60
> 85	0.40	0.50	0.55

Recovering materials experience a rise in modulus with time, from M_{Rmin} to M_{Runfrz}, that can be tracked using a recovery ratio (*RR*) that ranges from 0 to 1:

- $RR = 0$ for the "immediately after thawing" condition, when excess water makes the suction go to zero, $M_{Rrecov} = M_{Rmin}$.
- $RR = 1$ when the suction is equal to the suction dictated by the depth to the ground water table – i.e., equilibrium is achieved, $M_{Rrecov} = M_{Runfrz}$.

$$RR = \frac{\Delta t}{T_R} \tag{2.3.7}$$

where,

RR = Recovery ratio.
Δt = Number of hours elapsed since thawing started.
T_R = Recovery period: Number of hours required for the material to recover from the thawed condition to the normal, unfrozen condition.

For the Design Guide, the recovery period, T_R, is noted as a function of the material type/properties, as follows:

- T_R = 90 days for sands/gravels with $P_{200}PI < 0.1$.
- T_R = 120 days for silts/clays with $0.1 < P_{200}PI < 10$.
- T_R = 150 days for clays with $P_{200}PI > 10$.

In the ensuing section, the algorithm used in the Design Guide that outlines a methodology for obtaining the composite moduli for layers in which two or more states of the material coexist and/or the resilient modulus varies with depth and time is presented.

2.3.3.3 Computation of Environmental Adjustment Factor, F_{env}

The resilient modulus M_R at any time or position is determined as a product of the composite environmental adjustment factor, F_{env}, and the resilient modulus at optimum conditions M_{Ropt} (see equation 2.3.4). The computation of the F_{env} as a function of all the Design Guide inputs and EICM estimated parameters discussed so far will be presented in this section.

The environmental adjustment factor, F_{env} is a composite factor, which could in general represent a weighted average of the factors appropriate for various possible conditions:

- Frozen: frozen material – F_F (factor for frozen materials)
- Recovering: thawed material that is recovering to its state before freezing occurred – F_R (factor for recovering materials)
- Unfrozen/fully recovered/normal: for materials that were never frozen or are fully recovered – F_U (factor for unfrozen material)

The methodology to estimate F_{env} described below illustrates how the adjustment factors are calculated for all three cases, at two levels—at each nodal point and for each layer.

- *At each node*: In the EICM the pavement structure is characterized by an array of nodes at which the values of moisture, suction, and temperature are calculated at any time *t*. It is important to note that these nodes may not coincide the nodes of the finite element mesh used in the FEA module for structural computation.

- *For a given layer (base, subbase, subgrade)*: Note that frozen, thawed, and never frozen materials can coexist within a single layer. The following procedure describes a method of computing a composite adjustment factor that can handle all possible cases. The calculation of a composite adjustment factor is useful even when the material in a layer is all at the same state (unfrozen or recovering). This is because the adjustment factors vary from node to node (with moisture or suction) and an equivalent factor for the whole layer is needed for later computations.

It should be noted that all necessary computations to estimate F_{env} are made internally within the Design Guide software and are transparent to the user.

Adjustment Factors at Node Level

The computation of the adjustment factors for each specific case (frozen, recovering, unfrozen) at the node level follows:

F_F – Adjustment Factor for Frozen Materials

The value of F_F is computed at each node at which a freezing temperature occurs. Table 2.3.11 presents the procedure in the Design Guide to estimate this parameter.

Table 2.3.11. Summary of computations made by the EICM to determine adjustment factor for frozen material, F_F.

Step No.	**Description**
1	From user entered P_{200}, PI, and D_{60}, compute $P_{200} * PI$.
2	Obtain an estimated value of M_{Ropt_est} (user input). M_{Ropt} is either a direct user input or can be estimated from other engineering properties such as CBR, R-value, structural layer coefficients (a_i), Penetration Index, or from gradation parameters as explained in PART 2, Chapter 2.
3	Assign values for the Frozen Resilient Modulus, $M_{R\,frz}$ *(7):* a) If $P_{200} * PI = 0$ $M_{R\,frz} = 2.5 X 10^6$ *psi* b) If $P_{200} * PI > 0$ $M_{R\,frz} = 1 X 10^6$ *psi*
4	Compute the frozen adjustment factor, F_F *(7)*: $$F_F = \frac{M_{R\,frz}}{M_{R\,opt\_est}}$$

F_R – Adjustment Factor for Recovering Materials

The value of F_R is computed at each node at which freezing temperatures do not occur and the recovery ratio RR is < 1. Table 2.3.12 presents the procedure implemented in the Design Guide software to estimate this parameter.

F_U – Adjustment Factor for Unfrozen or Fully Recovered Materials

Table 2.3.13 presents the procedure implemented in the Design Guide software to estimate F_U.

Table 2.3.12. Summary of computations made by the EICM to determine adjustment factor for recovering material, F_F.

Step No.	Description
1	Obtain user input gradation parameters P_{200}, P_4, PI, and D_{60} as well as estimated depth to water table, y_{GWT}. Compute $P_{200} * PI$.
2	Compute Recovery Ratio, RR: $RR = \frac{\Delta t}{T_R}$ where, Δt = number of hours elapsed since thawing started T_R, the recovery period, is a function of the material properties: - T_R = 90 days for sands/gravels with $P_{200} * PI < 0.1$; - T_R = 120 days for silts/clays with $0.1 < P_{200} * PI < 10$; and, - T_R = 150 days for clays with $P_{200} * PI > 10$.
3	Compute S_{opt} as discussed in table 2.3.3 for Level 2 or as in equation 2.3.2 for Level 1.
4	Compute S_{equil} from the SWCC *(9)* : $S_{equil} = C(h) \times \frac{1}{\left[\ln\left[EXP(1) + \left(\frac{h}{a_f}\right)^{b_f}\right]\right]^{c_f}}$ $C(h) = 1 - \frac{ln\left(1 + \frac{h}{h_r}\right)}{ln\left(1 + \frac{1.45 \times 10^5}{h_r}\right)}$ where: $h = y_{GWT} * \gamma_{water}$, in psi a_f(psi), b_f, c_f, and h_r (psi) are calculated as in table 2.3.6.
5	Compute R_{equil} value as *(5)* : $log\ R_{equil} = log\frac{M_{Requil}}{M_{Ropt}} = a + \frac{b - a}{1 + EXP\left[ln\left(-\frac{b}{a}\right) + k_m\left(S_{equil} - S_{opt}\right)\right]}$ where: a, b, and k_m are constants from table 2.3.8.
6	Compute the RF value as a function of PI, P_4, and P_{200} from tables 2.3.9 and 2.3.10.
7	Compute the factor for recovering material, F_R *(7)*: If $(S_{equil} - S_{opt}) < 0$: $F_R = RF + R_{equi\ l} * RR - RR * RF$ If $(S_{equil} - S_{opt}) > 0$: $F_R = R_{equil}(RF + RR - RR * RF)$

Table 2.3.13. Summary of computations made by the EICM to determine adjustment factor for unfrozen or fully recovered material, F_U.

Step No.	Description
1	Compute S_{opt} as discussed in table 2.3.3 for Level 2 or as in equation 2.3.2 for Level 1.
2	Compute the adjustment factor for unfrozen or fully recovered material, F_U *(5)*: $$\log F_U = \log \frac{M_R}{M_{Ropt}} = a + \frac{b-a}{1 + EXP\left[\ln\left(-\frac{b}{a}\right) + k_m\left(S - S_{opt}\right)\right]}$$ where: a, b, and k_m are constants from table 2.3.8. S is the estimated degree of saturation at any node.

Composite Adjustment Factors, F_{env}, for Structural Layers

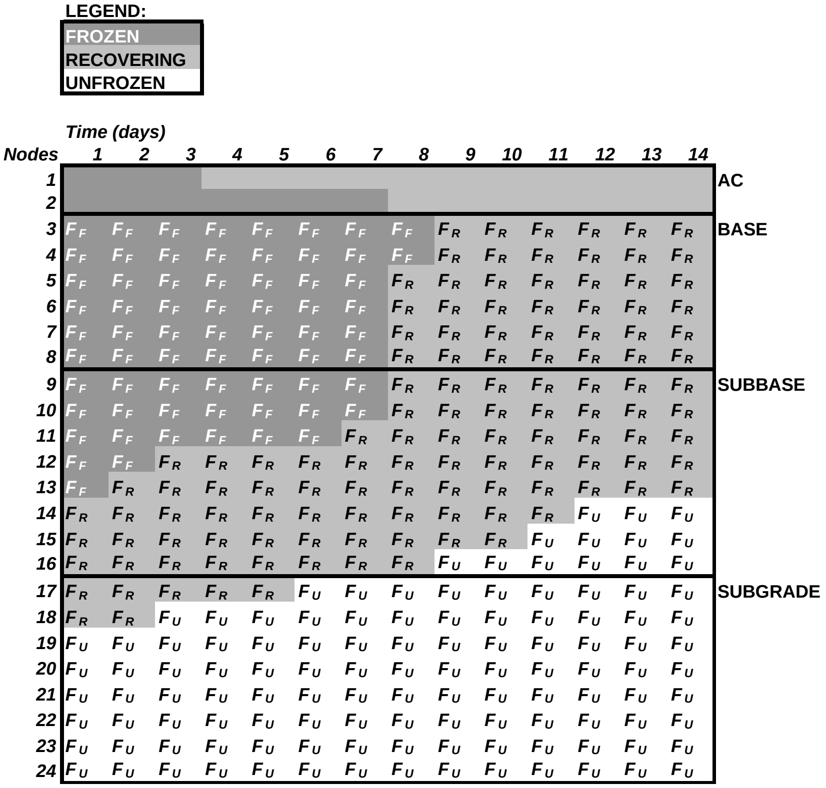
To help visualize possible changes in M_R caused by changes in the physical state with time, a time–depth diagram for a typical pavement structure is presented in figure 2.3.7. The three possible states of the material are identified: frozen (dark gray, denoted F_F), recovering (light gray, denoted F_R) and unfrozen or fully recovered (white, denoted F_U).

The solution to the problem of generating a composite adjustment factor, F_{env}, consists of building a matrix that will have as elements M_R adjustment factors at node i at time t, having the number of rows equal to the number of nodes and the number of columns equal to the number of time increments (one hour for each time increment) considered in the analysis period (2-week period or 1 month). The matrix corresponding to the time–depth diagram is shown in figure 2.3.8. The elements of the matrix are shown as F_F, F_R and F_U depending on the state of the material. In figure 2.3.8, example numerical values of F_F, F_R, and F_U are evaluated at each node/time and symbols are replaced with numbers.

Once the matrix of adjustment factors is established, it is subdivided as follows:

(a) In layers, corresponding to the structural layers (base, subbase, subgrade) defined by the user.
(b) In sublayers, defined by the EICM as needed by the subsequent modules. This sublayering is also a function of the frost penetration depth.
(c) For each analysis period (2 weeks or 1 month), a "sub-matrix" of M_R adjustment factors is assigned to each sublayer.

If the elements of the matrices were modulus values, corresponding to a temporary assumption that $M_{Ropt} = 1$, then a simple way to obtain an equivalent modulus is to consider an elastic spring series analogy. Consider the elements of column 1 (corresponding to Hour 1, for example) of a node/time matrix, as elastic moduli of a series of springs (one spring per node). If the stress



LEGEND:

FROZEN

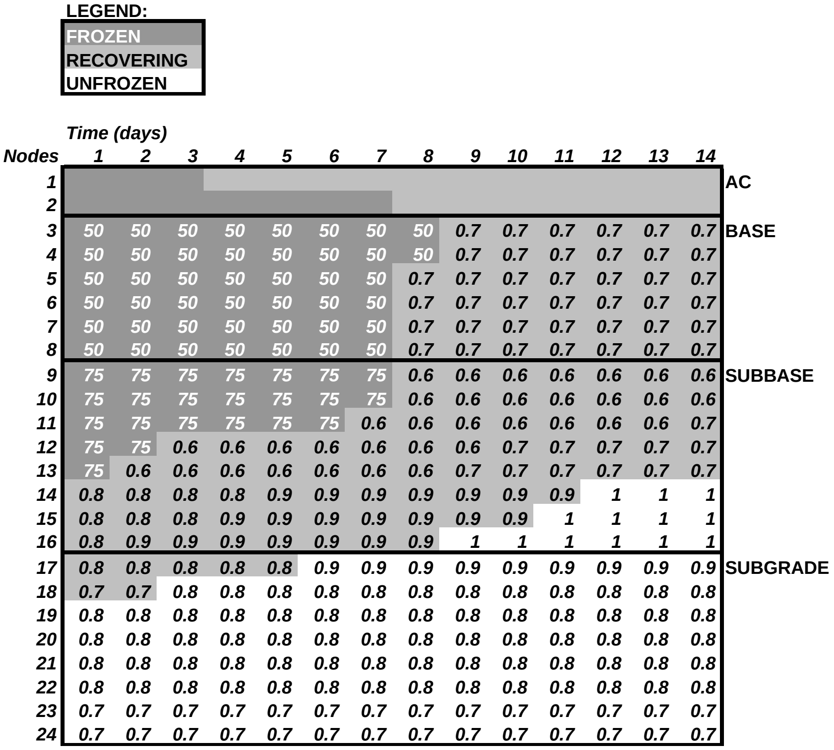
RECOVERING

UNFROZEN

Time (days)

Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
1															AC
2															
3	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	BASE
4	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	
5	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
6	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
7	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
8	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
9	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	SUBBASE
10	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
11	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
12	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
13	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
14	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_U	F_U	F_U	
15	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_U	F_U	F_U	F_U	
16	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_U	F_U	F_U	F_U	F_U	F_U	
17	F_R	F_R	F_R	F_R	F_R	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	SUBGRADE
18	F_R	F_R	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
19	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
20	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
21	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
22	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
23	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
24	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	

Figure 2.3.7. Time-depth diagram and matrix of adjustment coefficients.



LEGEND:

FROZEN

RECOVERING

UNFROZEN

Time (days)

Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
1															AC
2															
3	50	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	BASE
4	50	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	
5	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
6	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
7	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
8	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
9	75	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	SUBBASE
10	75	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	
11	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	
12	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	
13	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	
14	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	
15	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	1	
16	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	1	1	1	
17	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	SUBGRADE
18	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
19	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
20	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
21	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
22	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
23	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
24	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	

Figure 2.3.8. Matrix of adjustment coefficients.

applied to this model is σ, then the displacement in one spring at a given node and time increment can be computed as:

$$\delta_{node,t} = \frac{\sigma \cdot h_{node}}{M_{R\,node,t}} \tag{2.3.8}$$

where,

$node$ = Node number.
t = Time (corresponding to the column in the matrix being considered).
h_{node} = Length of the spring assigned to the node being considered.
$M_{Rnode,t}$ = Modulus for the node.

The total displacement for the given time is given by the sum of displacements from all nodes at the considered time *t*, which is a summation vertically, for example, for Hour 1:

$$\delta_{t=1} = \sigma \cdot \sum_{node=1}^{n} \frac{h_{node}}{M_{R\,node}} \tag{2.3.9}$$

where,

n = Number of nodes (rows in the matrix).

To get the average displacement over the whole analysis period (2 weeks or 1 month), equation 2.3.10 is used:

$$\delta_{average} = \sigma \cdot \frac{1}{t_{total}} \cdot \sum_{t=1}^{t_{total}} \left(\sum_{node=1}^{n} \left(\frac{h_{node}}{M_{R\,node,t}} \right) \right) \tag{2.3.10}$$

where:

t_{total} = Total number of *t* time increments over which the composite modulus is calculated (number of columns in the matrix). For use in the EICM, each time increment has been set to 1 hour.

Then the composite (equivalent) modulus can be obtained by finding a composite modulus, M_{Rcomp}, which produces the same $\delta_{average}$ over the total layer thickness for the same applied σ. Equating $\delta_{average}$ for the composite model to $\delta_{average}$ from equation 2.3.10 and canceling σ which appears on both sides:

$$\frac{h_{total}}{M_{Rcomp}} = \frac{1}{t_{total}} \cdot \sum_{t=1}^{t_{total}} \left(\sum_{node=1}^{n} \left(\frac{h_{node}}{M_{R_{node,t}}} \right) \right) \tag{2.3.11}$$

where,

h_{total} = Total height of the considered layer/sublayer, and:

$$h_{total} = \sum_{node=1}^{n} h_{node}$$

(2.3.12)

Because the resilient modulus at any node/time can be expressed as the product of an adjustment factor times the resilient modulus at optimum, equation 2.3.11 can be replaced with equation 2.3.13. A composite adjustment factor, F_{env}, for the considered sub-layer (sub-matrix) can be obtained from:

$$\frac{h_{total}}{F_{env} \cdot M_{Ropt}} = \frac{1}{t_{total}} \cdot \sum_{t=1}^{t_{total}} \left(\sum_{node=1}^{n} \left(\frac{h_{node}}{F_{node,t} \cdot M_{Ropt}} \right) \right)$$

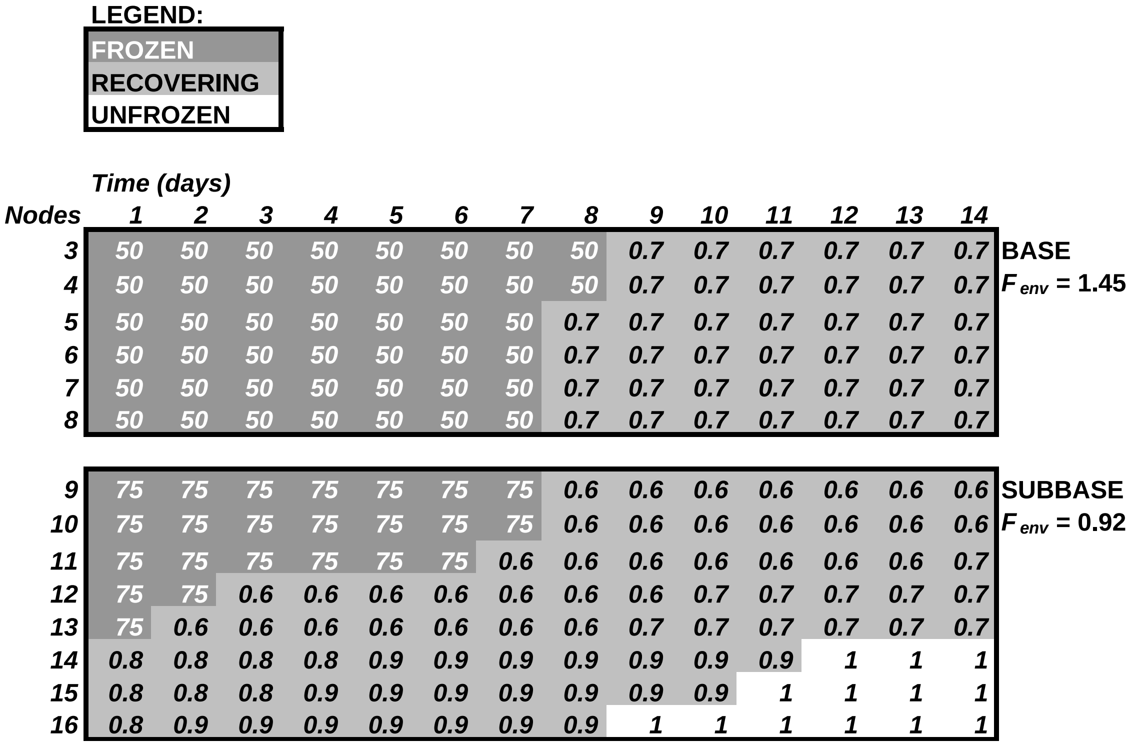
$$F_{env} = \frac{h_{total} \cdot t_{total}}{\sum_{t=1}^{t_{total}} \left(\sum_{node=1}^{n} \left(\frac{h_{node}}{F_{node,t}} \right) \right)}$$

(2.3.13)

where,

F_{env} = Composite adjustment factor for the considered sublayer.
$F_{node,t}$ = Adjustment factor at a given node and time increment (which could be F_F, F_R, or F_U, depending on the state of the material).

As an example, F_{env} is computed for the subbase and the subgrade layers in figure 2.3.9. For simplification, equal lengths are assigned to each node.



LEGEND:
FROZEN
RECOVERING
UNFROZEN

Time (days)

Nodes	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	
3	50	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	**BASE**
4	50	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	**F_{env} = 1.45**
5	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
6	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
7	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
8	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
9	75	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	**SUBBASE**
10	75	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	**F_{env} = 0.92**
11	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	
12	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	
13	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	
14	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	
15	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	1	
16	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	1	1	1	

Figure 2.3.9. Example computations of $F_{env.}$

It is important to note that the procedure should be applied for the entire design period (e.g., 20 years divided into months or 2-week periods) since the adjustment factors vary from node to node, even within a layer (or sublayer) in which all material is at the same state (frozen, unfrozen, or recovering).

F_{env} Implementation

The Design Guide has two options for structural analysis: LEA and FEA. Although EICM provides environmental data on an hourly basis, it is obviously impractical to perform the linear elastic or the finite element analysis on an hourly basis. To address this, the analysis period (design life) was divided into 1-month or 2-week periods, at the end of which stress-strain analyses are performed. This raises the problem of computing equivalent/weighed values for the input parameters of the structural model to be analyzed.

In the LEA module, one modulus value is used for a given structural layer (or sublayer). This value is obtained by multiplying the value of the reference modulus for that material with the value of F_{env} generated by EICM for that specific layer and analysis period as described in the previous section of this chapter (equation 2.3.4). The reference modulus for the considered structural layer is the resilient modulus of that material at optimum moisture content and maximum dry density (M_{Ropt}).

Although the resilient modulus of a material is strongly affected by the state of stress at which it is measured, the assumption of linear elasticity requires constant modulus values for each layer/sublayer. Ideally, the constant value to be used should yield analysis results comparable to those obtained by using stress dependent moduli and finite element analysis. The only way to guarantee that is to actually run a finite element analysis, which will make the linear elastic analysis unnecessary. Therefore, when actual test data is available or a predictive model capable of estimating resilient modulus as a function of stress is used, a state of stress representative for the whole layer (sublayer) should be estimated and the resilient modulus at that particular state of stress should be input as a constant value.

In the FEA module, a finite element analysis is performed for each time period (1-month or 2-week period) and the resilient modulus at each node of the finite element mesh is affected not only by environmental factors but also by the state of stress. Thus, the solution for equivalent modulus values at each node becomes problematic. While the composite environmental factor F_{env} is computed assuming a constant value of M_{Ropt}, in the finite element analysis M_{Ropt} is a function of the state of stress, as given in equation 2.3.14 (universal constitutive model):

$$M_{Ropt} = k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \tag{2.3.14}$$

where,

k_1, k_2, k_3 = Regression constants.

p_a = Atmospheric pressure.

θ = Bulk stress.

τ_{oct} = Octahedral shear stress.

To solve for the composite F_{env} by a procedure similar to that described at the beginning of this section (i.e., spring analogy), knowledge of the state of stress would be needed on an hourly basis, for each column of the time-depth matrix. This will involve running finite element analyses on an hourly basis that defeats the purpose of finding an equivalent, composite value for F_{env} and makes the analysis impractical in terms of computational time (720 analyses per 1-month time period, 1.7 million analyses per 20-year design period). To avoid this problem, it was considered acceptable to use the value of F_{env} as an adjustment factor for the modulus at each node of the finite element mesh, in spite of the initial assumption that M_{Ropt} is constant. Therefore, the equation used to compute the stress-dependent modulus in the finite element analysis is:

$$M_R = F_{env} \cdot k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a} \right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + 1 \right)^{k_3} \tag{2.3.15}$$

where,

M_R = stress dependent resilient modulus for the considered finite element

F_{env} = composite environmental adjusting factor for the layer/sublayer of which the finite element considered is part

More theoretically correct algorithms for including environmental effects in the finite element analysis are presented and discussed in Appendix DD.

2.3.4 EICM CALCULATIONS – DETERMINATION OF THE TEMPERATURE THROUGHOUT THE PAVEMENT SYSTEM

2.3.4.1 Introduction

It is a well-understood fact that the climatic factors such as temperature and moisture directly affect material behavior and pavement performance. However, the effect of moisture is more significant on unbound materials than on bound materials. On the other hand, temperature affects both the bound (asphalt and cement) and unbound layers significantly.

Because asphalt is a visco-elastic material, its properties depend greatly upon temperature. At very cold temperatures, its stiffness is close to that of PCC, whereas at very warm temperatures, its stiffness is closer to an unbound material.

The durability of PCC materials is affected greatly by the freeze-thaw environment it operates under. Temperature and moisture related curling and warping phenomena play a significant role in defining the PCC pavement fatigue behavior. Temperature and moisture also play a role in the opening and closing of joints in JPCP and cracks in CRCP, which affect performance.

In unbound materials, cooler temperatures result in frost formation and a subsequent increase in modulus. For the frozen conditions, the resilient modulus of subgrade soils is generally assumed to be 1 million psi for fine-grained materials and 2.5 million for coarse-grained materials. On the other hand, warmer temperatures cause thawing, resulting in increased moisture contents and a subsequent decrease in modulus values. During the thawing process, the resilient modulus of unbound materials may go well below the optimum value (0.5 to 0.85 times M_{Ropt}).

The CMS and CRREL models in the EICM are primarily responsible for most the temperature calculations. A brief overview of these models is presented in this subsection. The ensuing subsections discuss the temperature calculations in more details. Through this discussion, the relevance of climatic models to the overall pavement design process is brought to fore. Furthermore, the discussion also illustrates how the various climate and materials inputs discussed in this chapter and elsewhere in this Design Guide are used in the computation of temperature, moisture, and frost regimes throughout the pavement system.

CMS Model

The CMS model was originally developed at the University of Illinois *(1)*. It is a one-dimensional, forward finite difference heat transfer model to determine frost penetration and temperature distribution in the pavement system. The model considers radiation, convection, conduction, and the effect of latent heat. It does not consider transpiration, condensation, evaporation, or sublimation. These latter effects are neglected because of the uncertainty in their calculations and because their omission does not create significant errors in the heat balance at the surface of the pavement. Heat fluxes caused by precipitation and moisture infiltration are also neglected.

The inputs to the model include:

- Heat capacity of the pavement materials.
- Thermal conductivity of the pavement materials.
- Pavement surface absorptivity and emissivity.
- Air temperature.
- Wind speed.
- Incoming solar radiation.

Most of these parameters, with the exception of solar radiation, have been presented and discussed earlier in this chapter. Solar radiation will be discussed in a later section.

It is worthwhile to note that for pavement layers (AC or PCC), the EICM assumes that the user input heat capacity and thermal conductivity do not vary over time. However, for unbound layers (base courses and soils), as the moisture and frost contents change with time, so do the heat capacity and thermal conductivity. The user input dry heat capacity and dry thermal conductivity, along with the water and ice content predicted by the EICM, are used to calculate the wet heat capacity and wet thermal conductivity internally. In this manner the heat/temperature calculations of the EICM are coupled with the EICM's moisture predictions. The amount of water held in the soil matrix, whether this held water is in the form of liquid or ice, directly affects the thermal properties of that material.

The one-dimensional finite difference calculation performed by the CMS model has two boundaries, the upper boundary that is the pavement surface, and the lower boundary that is the constant deep ground temperature node. At the upper boundary, parameters such as air temperature, wind speed, amount of solar radiation, and pavement absorptivity and emissivity, determine the quantity of heat flowing into or out of the pavement. The lower boundary is a constant temperature node, capable of supplying an infinite amount of heat in order to keep the temperature at that node constant. By modeling the heat flow through the pavement, temperatures at various depths are easily calculated.

Once the thermal properties that define the heat flow through the pavement and unbound layers have been established and the boundary conditions have been identified, it is necessary to determine the amount of heat inflow/outflow at the pavement surface.

The two processes by which heat is added or subtracted from the pavement surface are convection and radiation, which are discussed below.

Convection Process

Convection is the process of transferring heat energy due to differences in the air temperature and the pavement surface temperature. If the pavement surface is warmer than air, heat is lost from the upper boundary. If the pavement surface is colder than the air, heat is added to the upper boundary. The amount of convection that occurs is directly related to this temperature difference and the measured wind speed. Higher wind speeds directly correlate with higher convection rates.

Radiation Process

The second method of heat flow at the surface is radiation. The primary source of radiation heat flow is short wave solar radiation from the sun. The amount of solar radiation impinging upon the pavement surface is dependent upon the following factors:

- The position of the sun in the sky.
- The amount of cloud cover.

The latitude of the site being modeled, and the time of the day and year determine the position of the sun in the sky. These calculations are done internally by the EICM, and require no user input other than latitude. The amount of cloud cover is a user input and can be obtained from the climatic database (refer to discussion in section 2.3.2.2). These two variables determine the amount of solar radiation that is impinging on the pavement surface. The amount of solar radiation actually absorbed by the pavement is determined by the user input surface shortwave absorptivity (see section 2.3.2.4 for discussion).

The other type of radiation induced heat flow is long wave radiation. Long wave radiation is thermal radiation that is emitted by the pavement according to black body radiation theory. Depending on the absolute temperature of a material in degrees Kelvin, a specific amount of heat energy is emitted in the form of long wave radiation. The EICM assumes a constant value for emissivity for pavements, dependent upon the temperature. A portion of this long wave radiation emitted by both the pavement and the surrounded landscape is re-absorbed by the pavement, after reflecting off of clouds. The method used to determine the amount of long wave radiation re-absorbed is similar to that employed for short wave radiation.

CRREL Model

The second model used in the Design Guide is the CRREL *(2)* model. It is a one-dimensional coupled heat and moisture flow in the subgrade soil at temperatures that are above, below and at the freezing temperature of water. In addition, the model predicts the depth of frost and thaw penetration. It also estimates the vertical heave due to frost formation and vertical settlement when the soil thaws. The CRREL model uses the temperature profiles through the asphalt layers as established by the CMS model to compute changes in the soil temperature profile, and thus frost penetration and thaw settlement.

2.3.4.2 Boundary Conditions for CMS Model

Heat Flux Boundary Condition

Temperatures throughout the pavement structure are dominated by atmospheric conditions at the surface. While it is easy to measure the air temperatures, there is not a direct correspondence between the air temperatures and pavement surface temperatures. To estimate the pavement temperature, the energy balance at the surface been used in the CMS model is described as *(22, 23)*:

$$Q_i - Q_r + Q_a - Q_e \pm Q_c \pm Q_h \pm Q_g = 0 \qquad (2.3.16)$$

where,

Q_i = Incoming short wave radiation.
Q_r = Reflected short wave radiation.
Q_a = Incoming long wave radiation.
Q_e = Outgoing long wave radiation.
Q_c = Convective heat transfer.
Q_h = Effects of transpiration, condensation, evaporation, and sublimation.
Q_g = Energy absorbed by the ground.

The variables in equation 2.3.16 are illustrated in figure 2.3.10 *(3)*. The net all-wave length radiation at the surface is Q_n.

$$Q_n = Q_s - Q_l \qquad (2.3.17)$$

where,

Q_s = Net short wave radiation
Q_l = Net long wave radiation

$$Q_s = Q_i - Q_r \qquad (2.3.18)$$

$$Q_l = Q_a - Q_e \qquad (2.3.19)$$

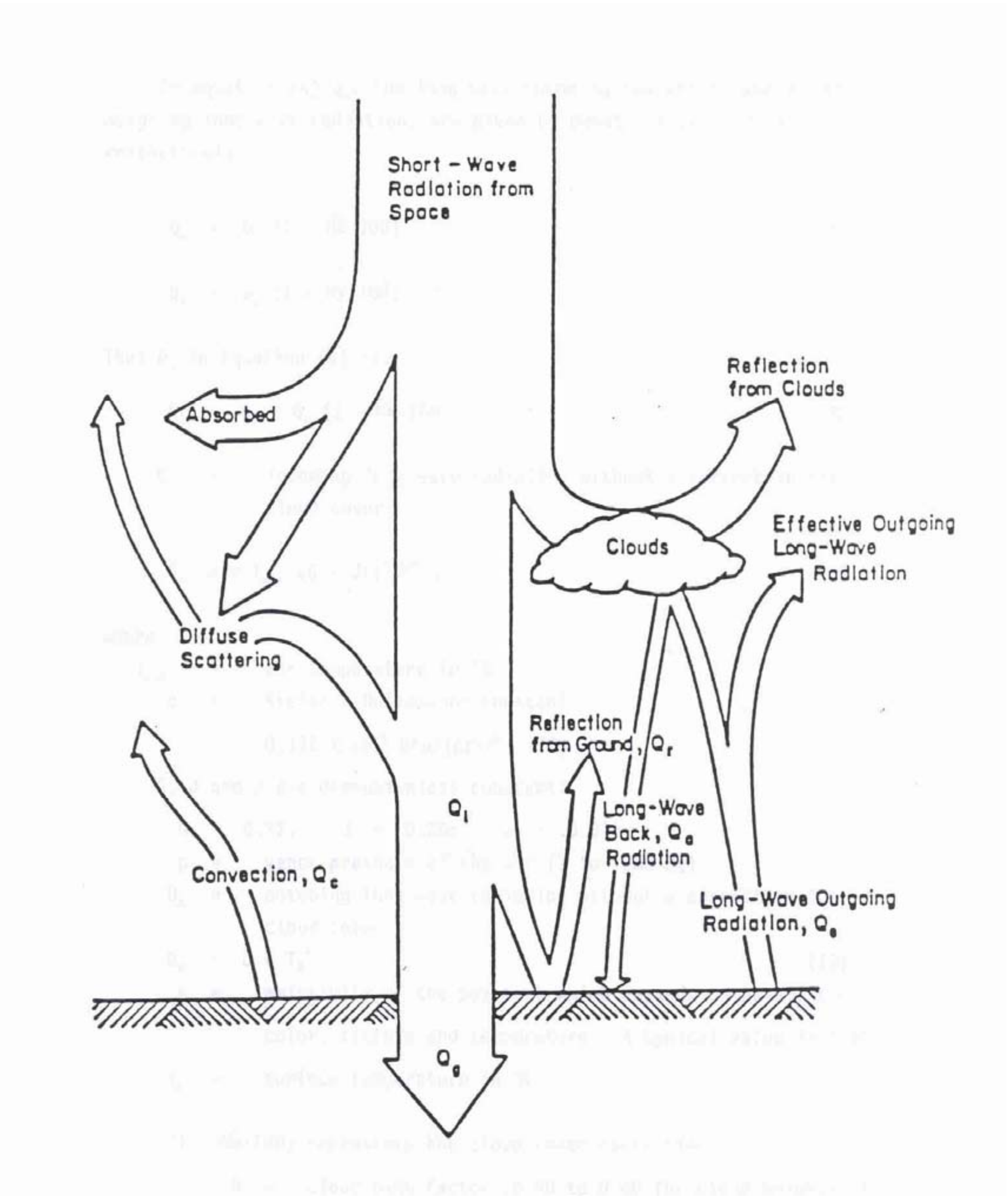


Figure 2.3.10. Heat transfer between pavement surface and air on a sunny day *(3)*.

Q_s has been given by Barker and Haines as *(24)*:

$$Q_s = a_s R * \left[A + B \frac{S_c}{100} \right] \tag{2.3.20}$$

where,

a_s = Surface short wave absorptivity of pavement surface.

R^* = Extraterrestrial radiation incident on a horizontal surface at the outer atmosphere. It depends on the latitude of the site and the solar declination of the sun, which is the position of the sun north or south of the equator and is a function of the time of year only.

A, B = Constants that account for diffuse scattering and adsorption by the atmosphere. The values of A and B for the Midwest have shown to be 0.202 and 0.539, respectively *(1)*.

S_c = Percentage of sunshine which accounts for the influence of cloud cover.

In equation 2.3.19, Q_a, the long wave incoming radiation, and Q_e, the outgoing long wave radiation, are given by equations 2.3.21 and 2.3.22.

$$Q_a = Q_z \left(1 - \frac{NW}{100}\right) \tag{2.3.21}$$

$$Q_e = Q_x \left(1 - \frac{NW}{100}\right) \tag{2.3.22}$$

Thus Q_l in equation 2.3.23 is:

$$Q_l = \left(Q_z - Q_x\right)\left(1 - \frac{NW}{100}\right) \tag{2.3.23}$$

In equation 2.3.23, Q_z is the incoming long wave radiation without a correction for cloud cover and $\left(1 - \frac{NW}{100}\right)$ represents the cloud cover correction:

$$Q_z = \sigma_{sb}\, T_{air} \left(G - \frac{J}{10^{\rho p}}\right) \tag{2.3.24}$$

where,

N = Cloud base factor (0.9 to 0.80 for cloud heights of 1,000 ft to 6,000 ft *(25)*.

W = 100-S_c (average cloud cover during day or night).

T_{air} = Air temperature in °R.

σ_{sb} = Stefan-Boltzmann constant, 0.172×10^{-8} Btu/(hr-ft^2-°R).

G = 0.77.

J = 0.28.

ρ = 0.074.

p = Vapor pressure of the air (1 to 10mm Hg).

Q_x = Outgoing long wave radiation without a correction for cloud cover

$$Q_x = \sigma_{sb}\, \varepsilon T_s^4 \tag{2.3.25}$$

ε = Emissivity of the pavement which depends on pavement color, texture and temperature. A typical value is 0.93.

T_s = Surface temperature in °R.

In equation 2.3.16, Q_c, the rate of heat transfer by convection, is given by:

$$Q_c = H(T_{air} - T_s) \qquad T_{air} \text{ and } T_s \text{ are in } {}^oF \qquad (2.3.26)$$

where,

H = Convection heat transfer coefficient

This parameter is difficult to determine because of the many variables that influence it. However it can also be expressed as follows *(1, 26)*:

$$H = 122.93\ [0.00144 T_m^{0.3} U^{0.7} + 0.00097(T_s - T_{air})^{0.3}] \qquad (2.3.27)$$

where,

T_s = Surface temperature, in ^{o}C.
T_{air} = Air temperature, in ^{o}C.
T_m = Average of surface and air temperature, in ^{o}K.
U = Average daily wind speed in m/sec.

The maximum value of the heat transfer coefficient is partly controlled by the stability criteria established for the finite difference approach in computations within the EICM. The suggested maximum value is 3.0 Btu/(hr-ft^2-^{o}F). The effects of transportation, condensation, evaporation and sublimation (Q_h) have been neglected in the formation because they are either too small to be significant or the effects cancel each other out in the energy balance.

In summary, the above calculations determine the surface temperature and thus control the temperature throughout the underlying materials. The depth of frost is established by comparing the computed temperatures with the freezing temperatures of the soil. The depth of frost penetration has been identified as the position of the 30^{o}F isotherm.

Finally, the finite difference approach is used to determine the nodal temperatures. Details of the finite difference grid and the formulation of the heat conduction equations are provided in Reference *1*.

Wind Speed

Wind speeds are required in the computations of the convention heat transfer coefficient described above. Daily speeds required for computations of the convention heat transfer coefficient are determined by linear interpolation between adjacent months.

Sunshine

Not all the first order weather stations that are used to complete the data for the EICM have recorded percentage of possible sunshine data. In such situations sunshine data from nearest station have occasionally been transferred to the location where data are missing. It is felt that these modifications should not significantly affect the calculation of heat balance at the surface of the pavement.

Air Temperature

The description presented earlier shows that heat balance equation requires air temperatures for calculation of long wave radiation emitted by the air and for the convective heat transfer from surface to air. While only maximum and minimum values are recorded by the weather stations, values for each time step are required for calculations in the EICM. Observations have shown that temperature variations over a 24-hr period can adequately modeled by a sine wave that has its minimum value of temperature slightly after sunrise and peaks in the early mid afternoon. While the times of sunrise may vary significantly with seasons, especially in the more northern latitudes, a suitable average is computed by the program.

Rainfall

Heat fluxes resulting from precipitation and infiltration into the pavement structure have not been considered in formulating the surface heat flux boundary conditions. The role of the precipitation under these circumstances in not entirely clear, and methods to incorporate it in the energy balance have not been attempted.

2.3.4.3 Temperature Distribution Profile

After the amount of heat inflow/outflow due to convection and radiation at the pavement surface is determined, this amount of heat is added/subtracted from the quantity of heat at the upper boundary. The EICM iterates a single time step, calculating a new temperature profile for the pavement system. This updated temperature profile is used for convection and radiation calculations at the next time step.

Temperature Data for Flexible Pavement Analysis

For the purpose of the Design Guide a base unit of one month is used for incremental damage computations. In situations where the pavement is exposed to freezing and thawing cycles, the base unit of 1 month is changed to 15 days' (half month) duration to account for rapid changes in the pavement material properties during frost/thaw period. It is important to realize that if only average monthly (or semi-monthly) temperatures are used in the analysis, the effect of extreme temperatures will not be reflected in the damage computations. The approach adopted in the Design Guide to circumvent this problem and to include the extreme temperatures during a given month (or during 15 days for freeze/thaw period) is discussed below.

The EICM provides 0.1 hours (6 minutes) temperature over the analysis period. This temperature for a given month (or 15-days) can be represented by a normal distribution with a certain mean value (μ) and the standard deviation (σ), $N(\mu,\sigma)$ as shown in figure 2.3.11.

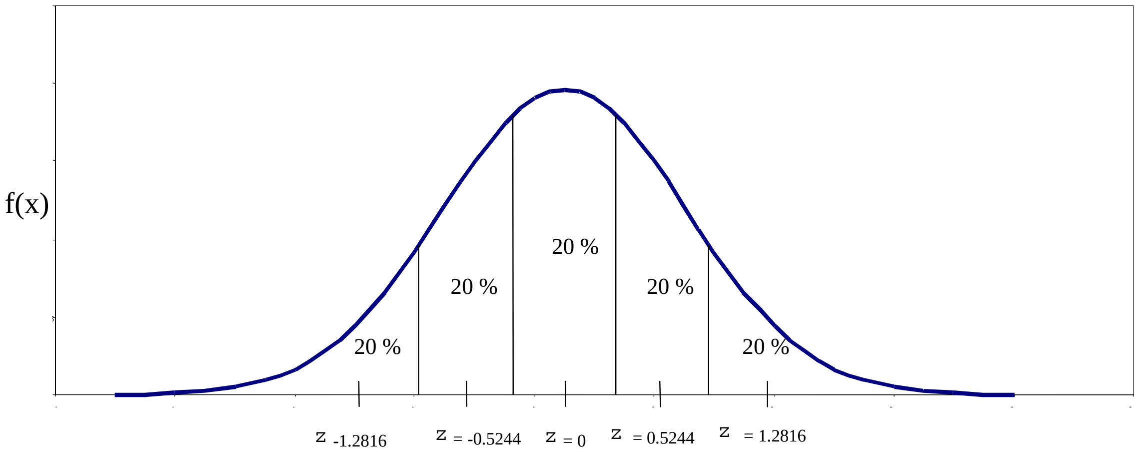


Figure 2.3.11. Temperature distribution for a given analysis period.

While the EICM calculates temperature on a relatively small time step of 0.1 hours, temperatures are output to the Design Guide summary files in two formats for flexible pavement analysis. One of them is used for rutting and fatigue analysis while the other is used for thermal fracture.

Rutting/Fatigue Temperature Data

Temperature is an important factor affecting the asphalt stiffness and consequently the dynamic modulus of asphalt concrete mixes. Because the modulus of the asphalt layers within the pavement structure affect the overall pavement response, it is important to properly account for the temperature as a function of time and depth.

The EICM model provides frequency distribution of the pavement temperature as a function of time and depth. The frequency distribution of temperature data obtained using EICM is assumed to be normally distributed, as depicted in figure 2.3.11. The frequency diagram obtained from the EICM represents the distribution at a specific depth and time. To account for different temperatures and frequency distributions along the AC depth, the asphalt layers are subdivided into sub-layers as discussed in PART 3, Chapter 3.

As shown in figure 2.3.11, a given month may have some extreme temperatures that could be significant for rutting and fatigue damage. Using the average value will not capture the damage caused by these extreme temperatures. To account for the extreme temperature, the temperatures over a given interval are divided into five different sub-seasons. For each sub-season the sub-layer temperature is defined by a temperature that represents 20% of the frequency distribution for pavement temperature, as shown in figure 2.3.11. This sub-season will also represent those conditions when 20% of the monthly traffic will occur. This is accomplished by computing pavement temperatures corresponding to standard normal deviates of -1.2816, -0.5244, 0, 0.5244 and 1.2816, as illustrated in figure 2.3.11. These values correspond to accumulated frequencies of 10, 30, 50, 70 and 90 % within a given month. As an example, if the mean monthly temperature (μ) reported is 50°F and has a standard deviation (σ) of 15°F, the quintile temperatures are as given in table 2.3.14.

Table 2.3.14. Quintile temperature distribution.

Sub-season	**z-value**	**Temperature, ^{o}F = $\mu + z\,(\sigma)$**
1	-1.2816	30.8
2	-0.5244	44.8
3	0	50.0
4	0.5244	55.2
5	1.2816	69.2

Table 2.3.14 shows that the approach used clearly takes into account the extreme temperatures in a given interval. Each sub-season shown above will account for 20% of the traffic in the corresponding interval. The EICM generates five quintile temperature values for each interval and at each selected depths (i.e., for rutting and fatigue, temperature values are required at the surface of the pavement structure and at mid-depth of all asphalt bound sub-layers). Since the first sub-layer for the asphalt is always 0.5 inches, the temperatures are provided at 0.25 inches from the surface. No temperature information is generated for any other type of layer, as it is not required for the analysis.

The surface temperature and the temperature at 0.25 inches are used to estimate the fatigue at the surface (top down cracking). The fatigue strains developed at the surface and 0.5 inch are superimposed by the thermal strain at these depths to estimate top-down fatigue. The approach is discussed in PART 3, Chapter 3 in detail.

In summary, the EICM provides the temperature values for all quintiles of the temperature distribution profile for use in fatigue cracking and permanent deformation models. These are provided as a function of time and depth. The depth locations at which temperature distributions need to be computed are defined by the thickness of asphalt sub-layers.

Thermal Fracture Temperature Data

Thermal fracture analysis requires hourly temperature data. Temperature values are required at the surface, at 0.5 inch, and at every inch within the asphalt layer. This defines the temperature–depth relationship within the asphalt layer. For the thermal fracture module, the last depth temperature should correspond to a depth that is even (2, 4, 6, 8 inches …etc). If the thickness of asphalt layer is 7 inches, hourly temperatures up to a depth of 8 inches are required. For an asphalt layer of 7 inches, the temperature at the 8-inch depth will correspond to that of the underlying layer. This temperature depends upon the material type of the underlying layer.

In addition to developing a temperature-depth profile for thermal fracture module to predict cracking, temperatures at the surface and at 0.5 inch are used for estimating tensile strains. The tensile strains at these two depths are superimposed with the strains developed due to traffic loading to estimate top-down cracking. The thermal fracture module only reports the tensile strains and a value of zero is reported for compressive strains. The details of top-down cracking are provided in PART 3, Chapter 3.

In summary, the EICM will generate a temperature file that defines the temperature–depth relationship for use in flexible pavement thermal cracking prediction. The file includes temperature values on an hourly basis for the entire analysis period. The temperatures are used by the thermal fracture model to predict cracking along with the tensile strains at the surface and 0.5-inch depth for top-down cracking.

Temperature Data for Rigid Pavement Analysis

For rigid pavement design, the main temperature data of interest is the temperature profile through the PCC layer. EICM is configured to produce hourly temperature profiles for a minimum of one full year. For most sites, EICM climatic database provides 5 years of hourly data. The data are used in the prediction of faulting and fatigue cracking in JPCP and punchouts in CRCP.

In the JPCP design module of the Design Guide software, the output from EICM is further processed to obtain monthly distributions of hourly temperature gradients through PCC. In this process the nonlinear temperature distribution is first converted to equivalent linear temperature gradient based on stress equivalence. The equivalent linear temperature gradient is the linear temperature gradient that would produce the same curling stress as that produced by the actual nonlinear temperature profile. Thus, the use of equivalent linear temperature gradients does not cause any loss of accuracy in damage calculations; the equivalent linear temperature gradients are used solely for the purposes of computational efficiency. If climatic data for multiple years are used, the results are averaged to obtain average monthly distribution of hourly temperature gradients.

In addition, parameters such as number of freeze-thaw cycles, mean annual precipitation, and mean annual freezing index are also computed from the temperature information for use in the various JPCP and CRCP structural distress models. Other uses of temperature data include the JPCP joint opening/closing model and the CRCP crack width model.

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