Environmental Factors in Flexible Pavement Design

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ABSTRACT

The principal objective of this research was to study the influence of the environment on the thickness of flexible pavements. Environmental variables considered include general soil conditions and temperature effects. As identified in previous studies, six climatic zones were recognized. Weather information and soil properties were collected for 175 typical stations covering the continental United States, excluding Alaska. Based on the criteria of rutting of 1.25 cm (0.5 in.) and thermal cracking of 115 m/1000 m² (35 ft/1,000 ft²), appropriate asphalt-cement grades were selected for each station. To consider the interaction of temperature and modulus with fatigue damage, the concept of effective modulus was introduced. The effective modulus calculated by using the appropriate asphalt grade was found to be nearly constant within a zone but varied considerably from one zone to another. A sensitivity analysis was performed on the AASHO flexible pavement design equation, the purpose of which was to determine the effect of the regional factor and the soil support value on the structural number. After these two items had been combined with the change in the layer coefficient due to modulus change, their overall effect on pavement thickness was evaluated. The ratio of the thickness required at a given station to that required at reference conditions [namely, asphalt effective modulus of 34.5 kPa (5 x 10^5 psi), regional factor of 1.0, and soil support value of 5.0] is defined as the depth factor. The depth factor ranged from as low as 0.45 in Florida, parts of Mississippi, Alabama, Georgia, and the Carolinas to as high as 1.60 in regions of Montana, North Dakota, and South Dakota. The higher the depth factor, the more severe the influence of environment on pavement performance. Examples to illustrate how the depth factor may be incorporated into the AASHO flexible design are given.

In the design of flexible pavements, traffic load and environment are the most influential factors in the determination of pavement thickness. Before the AASHO Road Test, most pavements were designed with regard to traffic alone, with little if any consideration for the environment. Since the introduction of the AASHO pavement design (1), however, more emphasis has been placed on environmental effects. For example, the AASHO flexible model, which is written symbolically as follows, presents in equational form the design relationship between the important variables:

$$\log W = 9.36 \log(SN + 1) - 0.20 + \log [(c_0 - p)/(c_0 - 1.5)] \div \left\{0.40 + [1{,}094/(SN + 1)^{5.19}]\right\} + 0.37756 (SSV - 3.0) - 0.97 \log(R_f) \quad (1)$$

where

- W = total number of 80-kN (18-kip) equivalent axle loads (EALs),
- SN = weighted structural number,
- c_0 = initial serviceability index,
- p = terminal serviceability index,
- SSV = soil support value, and
- R_f = regional factor.

Buick (2) studied the significance of these variables and showed that besides traffic, SSV and R_f are most important in the formulated thickness function.

Following the AASHO study (1) several attempts were made to investigate the climatic effect on pavements, first in four climatic zones, then later in six climatic zones (Figure 1). The effect of the surrounding environment on the pavement performance, however, has not yet been quantified to any degree.

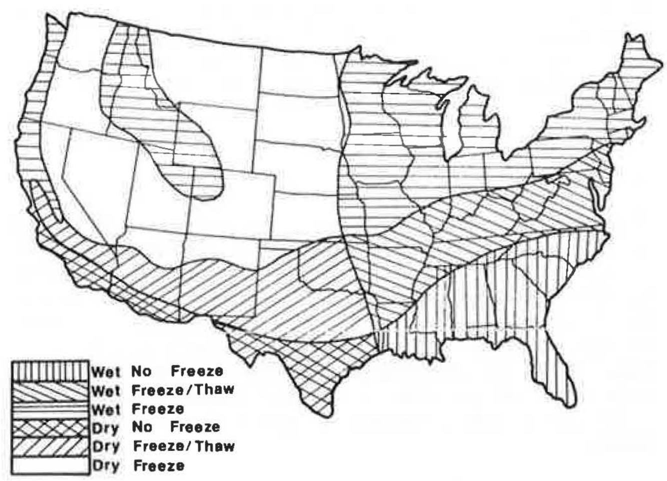

FIGURE 1 Climatic zones of the United States (3).

Environmental variables can include such inputs as general soil conditions, moisture, and air temperature variation around and within the pavement structure. In this study, the environmental variables are limited to soil and climatic conditions.

This investigation was motivated by the provisions of section 137(a) of the Surface Transportation Assistance Act of 1982, which, in part, calls for a study to make specific recommendations for changing the apportionment formulas to take into account weather-related factors. "The study shall analyze current conditions and factors including, but not limited to, volume and mix of traffic, weight and size of vehicles, environmental, geographical and meteorological conditions in various states...." Environmental and geographical effects on flexible pavements are analyzed in this paper.

The objective of this study was to show how the environmental factors affect the thickness requirement of flexible pavements. The AASHO Interim Guide equation for flexible pavement (Equation 1) provided the basic structural design model. Through a systematic sensitivity analysis of the AASHO equation with respect to the most significant environmental factors (such as modulus of asphalt concrete, SSV, and R_f), their impact on the equation was evaluated and quantified. In order to portray the severity of environment nationwide, the concept of a depth factor is introduced and discussed.

GENERAL FRAMEWORK

A combination of existing design procedure (1), weather information from the U.S. Weather Bureau (4), and a soil map for the contiguous United States (5) was used in developing the flexible-pavement thickness requirements for the entire United States. The AASHO flexible-pavement equation (Equation 1) forms the basis for structural design. This equation relates traffic repetitions and SN; SSV and R_f are secondary variables. One tacit assumption in the design equation is that asphalt concrete, regardless of location or climate or both, will have the same stiffness (modulus) as that encountered in the AASHO Road Test. That the AASHO design procedure does not take into account the variations in the asphalt-concrete modulus is considered a major drawback of the method. In order to overcome this deficiency, a weighted average modulus is introduced in the first part of the study. Because asphalt grade plays a crucial role in the modulus of the asphalt mixture, a rational method was developed to select the appropriate asphalt grade.

In the second part of the study, the overall effect of environment on pavement structural thickness is evaluated by performing (a) a sensitivity analysis of the AASHO equation with respect to the SSV and R_f and (b) a sensitivity analysis to illustrate the role of the effective modulus in the thickness design. The overall effect of environment on structural design is obtained by combining items (a) and (b) to give rise to what is defined in this paper as the depth factor.

CLIMATIC EFFECT ON ASPHALT LAYER

The effect of climate on the asphalt layer is well documented in that the asphalt modulus fluctuates substantially with ambient temperature. Therefore it is customary to specify softer-grade asphalt in colder climates to reduce thermal cracking and harder-grade asphalt in warmer climates to reduce rutting. There is as yet no complete procedure for selecting the asphalt grade appropriate to the climate except for a graphical solution proposed in premium pavement design to minimize low-temperature cracking (6). Not only low-temperature cracking but also excessive rutting must be taken into account in the asphalt selection process; accordingly, the graphical plot of Von Quintus et al. is modified as in Figure 2. In the development of this nomograph two criteria are specified: the thermal cracking is not to exceed 115 m/1000 m² (35 ft/1,000 ft²) and rutting is to be no more than 1.25 cm (0.5 in.).

Asphalt-Grade Selection to Minimize Thermal Cracking

Von Quintus et al. used the TC-1 program (7) in developing the asphalt-grade selection chart. We too have used this program because it provides the capability of estimating low-temperature cracking and material properties for asphalt-concrete surfaces. By using the program for asphalt of a given penetration index, the relation between low-temperature cracking and expected minimum pavement temperature can be obtained. Subsequently this relation was plotted in nomographical form as shown on the right-hand side of Figure 2.

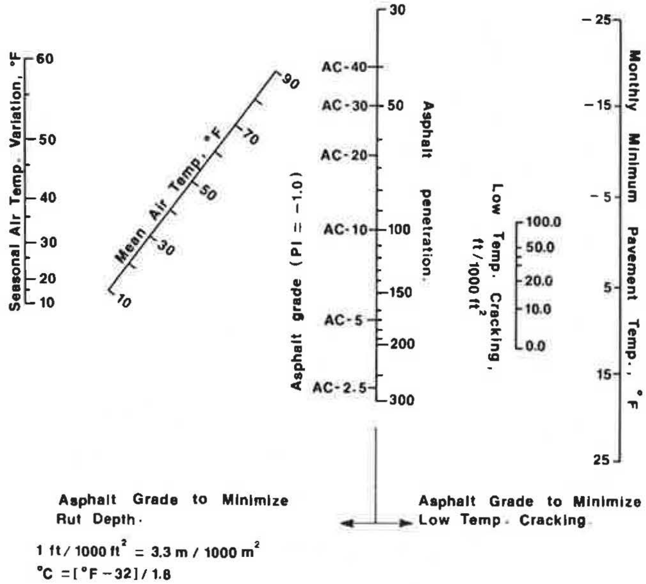

FIGURE 2 Asphalt-concrete grade selection to minimize rut depth and low-temperature cracking.

Asphalt-Grade Selection to Minimize Rutting

Climatologically representative stations were selected throughout the United States, and pertinent air temperature data were gathered for those stations from U.S. Weather Bureau records. AASHO flexible pavement designs were prepared for typical subgrade conditions. With the VESYS computer program, the asphalt penetration grade required for each station was determined, with the stipulated criterion that rutting be no more than 1.25 cm. In other words a relation was established between the mean air temperature in combination with seasonal variations and the asphalt grade, and it is nomographed on the left-hand side of Figure 2.

Asphalt Selection to Minimize Both Cracking and Rutting

Employing the nomographs in Figure 2, we want to determine the appropriate asphalt grades for the entire country. To accomplish this, such weather data as the mean air temperature and monthly mean air temperature variation at some 175 typical stations covering the entire United States were gathered from U.S. Weather Bureau records. These temperature data were used in a graph proposed by Von Quintus et al. (6) to estimate the expected minimum temperature of the pavement at each station. With the minimum pavement temperature and the criterion of thermal cracking no more than 115 m/1000 m² the minimum penetration and therefore the asphalt grade are obtained from Figure 2. The maximum allowable penetration to satisfy the rutting criterion is obtained by placing the appropriate ambient temperature information on the left-hand side of Figure 2. A grade of asphalt that will provide penetration no less than that required to prevent low-temperature cracking and no more than that required to prevent rutting is construed to be the right grade for that station. Plotting all of the 175 points on a map enabled the identification of five zones of asphalt-concrete-grade asphalt (see Figure 3). Note that for this study a penetration index (PI) of -1.0 is used.

When the asphalt grade is known for each region, it is desirable to calculate a representative modulus for each climatic zone; this topic is discussed in the next section.

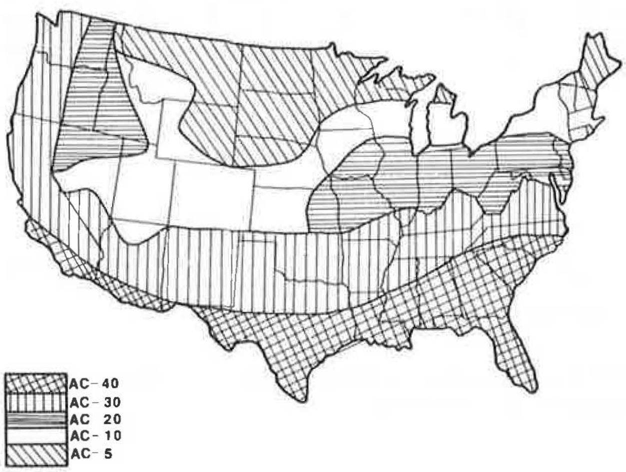

FIGURE 3 Recommended asphalt-concrete grades for the United States.

Effective Modulus Related to Climatic Zones

Variations in climate and ambient temperature produce significant changes in the modulus of asphalt-concrete materials. Von Quintus et al. (6) developed a procedure that includes a weighted mean asphalt-concrete modulus for each asphalt cement type and climate. The terms "effective modulus" or "weighted mean asphalt-concrete modulus" were developed to designate the effects of temperature variations on fatigue cracking. These effects cannot be adequately determined by simply averaging the asphalt-concrete modulus over all seasons because of the interaction of temperature and modulus with the fatigue damage produced in the pavement. The effective modulus is defined mathematically by the following equation (6):

$$E_e = \sum_{i=1}^{n} E_i \times FF(E_i) / \sum_{i=1}^{n} FF(E_i) \quad (2)$$

where E_e is the effective modulus and E_i is the modulus during the ith period (season). $FF(E_i)$ is termed the fatigue factor, defined as follows:

$$FF(E_i) = d_f(E_i)/d_f(34.5 \times 10^5 \text{ kPa}) \quad (3)$$

where $d_f(E_i)$ is the unit damage caused by a single application of 18-kip axle load at modulus E_i corresponding to temperature T_i. In Equation 2, n = 4 if the temperature variations are averaged, so that four seasonal temperatures are considered, or n = 12 if the variations are expressed on a month-by-month basis.

The fatigue factor is related to modulus E_i; this relationship is expressed by the following empirical equation:

$$\log FF(E_i) = -1.9427 \log E_i + 1.3553 \quad (4)$$

where E_i is the asphalt-concrete modulus (psi x 10^5). It should be noted from Equations 3 and 4 that $FF(34.5 \times 10^5$ kPa$) = 1.0$, because a modulus of 34.5×10^5 kPa was used as a reference.

After an asphalt grade has been selected and the seasonal pavement temperature estimated, one can evaluate the seasonal asphalt-concrete modulus for each station. If the seasonal effective modulus is substituted in Equation 4, the effective modulus for each station can be estimated by using Equation 2. Sample calculations of E_e are given elsewhere (6). Interestingly enough, the effective modulus, as listed in Table 1, exhibited little variation within a zone, even with the different asphalt grades specified in Figure 3. That fatigue sensitivity of asphalt also enters into the effective-modulus calculation partly accounts for the seemingly anomalous result. The mix properties for estimating the temperature-dependent modulus and in turn the effective modulus of Table 1 are listed as follows:

TABLE 1 Calculated Effective Modulus in Various Climatic Zones

Zone	Asphalt Grade	Effective Modulus (psi x 10^5)
Wet no-freeze	AC-40	8.40
Wet freeze and thaw	AC-30	5.30
Wet freeze	AC-20	4.42
	AC-10	4.43
	AC-5	4.27
Dry no-freeze	AC-40	4.90
Dry freeze and thaw	AC-30	3.30
Dry freeze	AC-5	2.50
	AC-10	2.40
	AC-30	2.90

Note: 1 psi = 6.895 kPa.

Property	Value
Percent asphalt by weight	5
Percent air voids	5
Percent passing No. 200 sieve	5
Loading frequency	10 Hz
PI	-1.0

The data in Table 1 clearly show that the pavement location and the prevailing climate indeed have a significant effect on the asphalt modulus. For example, the effective modulus in a wet no-freeze region may be three times as large as that in a dry freeze region. How this variation affects the thickness design is discussed in a later section.

ENVIRONMENTAL EFFECT ON PAVEMENT THICKNESS

Effect of SSV and R_f on SN

To quantify the effect of the environment on the pavement thickness, the researchers performed a sensitivity analysis of the AASHO design equation (Equation 1). This analysis clearly identified the individual and combined effects of the AASHO design parameters on SN. The design parameters considered were SSV and R_f in addition to the effective modulus. Excluded in this analysis were such other parameters as traffic and initial and final serviceability indices.

The combined effect of all of the variables on the weighted SN is best expressed by the following equation of total differential:

$$dSN = (\partial SN/\partial c_0)\,dc_0 + (\partial SN/\partial p)\,dp + (\partial SN/\partial W)\,dW + (\partial SN/\partial SSV)\,dSSV + (\partial SN/\partial R_f)\,dR_f \quad (5a)$$

If the initial and final serviceability indices are kept constant, $dp = 0$ and $dc_0 = 0$. In addition, because this study is concerned with environmental variables only, the wheel-load term also drops out. With these modifications, Equation 5a becomes as follows:

$$dSN = (\partial SN/\partial SSV)\,dSSV + (\partial SN/\partial R_f)\,dR_f \quad (5b)$$

The first-order partial derivatives of the weighted SN with respect to SSV and R_f were presented by Buick (2) as follows:

$$\partial SN/\partial SSV = 0.3775/(\partial\phi/\partial SN) \quad (6)$$

$$\partial SN/\partial R_f = (-0.4166/R_f)/(\partial\phi/\partial SN) \quad (7)$$

where $\partial\phi/\partial SN$ is defined by the function shown below:

$$\partial\phi/\partial SN = [4.065/(SN+1)] + \log[(c_0 - p)/(c_0 - 1.5)]\left\{5{,}677.9\,(SN+1)^{4.19}/[0.4(SN+1)^{5.19} + 1{,}094]^2\right\} \quad (8)$$

with $c_0 = 4.0$, $p = 2.5$, and $\log[(c_0 - p)/(c_0 - 1.5)] = -0.2218$.

Proportional change in SN may be expressed by using Equation 5b as follows:

$$\Delta SN/SN = [(\partial SN/\partial SSV)/SN]\,dSSV + [(\partial SN/\partial R_f)/SN]\,dR_f \quad (9)$$

When the value of $[(\partial SN/\partial SSV)/SN]$ was evaluated for $1 < SN < 6$, it was found to vary between 0.19 and 0.11; the average was 0.13. In other words SN increases by an average of 13 percent for a unit decrease of SSV. With an SSV of 5.0 as a base value and $[(\partial SN \div \partial SSV)/SN] = 0.13$, the values for $[(\partial SN \div \partial SSV)/SN]dSSV$ and the soil support value factor (FSSV) are given in Table 2.

With a similar approach, the values of $[(\partial SN/\partial R_f) \div SN]R_f$ are computed as listed in Table 3 for $R_f = 1.0$ as a reference. For the range of $1 < SN < 6$ the average value was found to be -0.16, which was used to compute the influence factor (FR_f), as defined in Equation 10.

TABLE 2 Soil Support Value Factor

SSV	dSSV	$[(\partial SN/\partial SSV)/SN]\,dSSV$	FSSV
2.0	+3.0	0.39	1.39
3.0	+2.0	0.26	1.26
4.0	+1.0	0.13	1.13
5.0[a]	0.0	0.00	1.00
6.0	-1.0	-0.13	0.87
7.0	-2.0	-0.26	0.74
8.0	-3.0	-0.39	0.61
9.0	-4.0	-0.52	0.48

Note: SSV = soil support value; dSSV = change in SSV from reference value; FSSV = soil support value factor.
[a]Reference soil support value.

TABLE 3 Values of $[(\partial SN/\partial R_f)/SN]\,R_f$ for Different Values of SN

SN	$\partial SN/\partial R_f$	$[(\partial SN/\partial R_f)/SN]\,R_f$
1.0	-0.21	-0.21
2.0	-0.33	-0.17
3.0	-0.49	-0.16
4.0	-0.62	-0.15
5.0	-0.70	-0.14
6.0	-0.77	-0.13

Influence factors for SSV and R_f, respectively, are defined as follows:

$$FSSV = 1 + [(\partial SN/\partial SSV)/SN]\,dSSV$$

$$FR_f = 1 + [(\partial SN/\partial R_f)/SN]\,dR_f \quad (10)$$

Equation 9 could be simplified to read as follows:

$$\Delta SN/SN = (FSSV + FR_f) - 2 \quad (11)$$

Equation 11 is an explicit expression for the change in SN as a function of FSSV and FR_f. The values of FSSV and FR_f are given in Tables 2 and 4, respectively.

TABLE 4 Influence Factor of R_f

R_f	dR_f	$[(\partial SN/\partial R_f)/SN]\,dR_f$	FR_f
1.0[a]	0.0	0.0	1.00
2.0	-1.0	+0.08	1.08
3.0	-2.0	+0.11	1.11

Note: dR_f = change in R_f from reference value; FR_f = influence factor of R_f.
[a]R_f reference value.

In order to assign FSSV for various sections of the United States, soil deposits were identified and strength characteristics of each soil were estimated. A map of this general nature has been compiled by Woods (5) as shown in Figure 4. The general

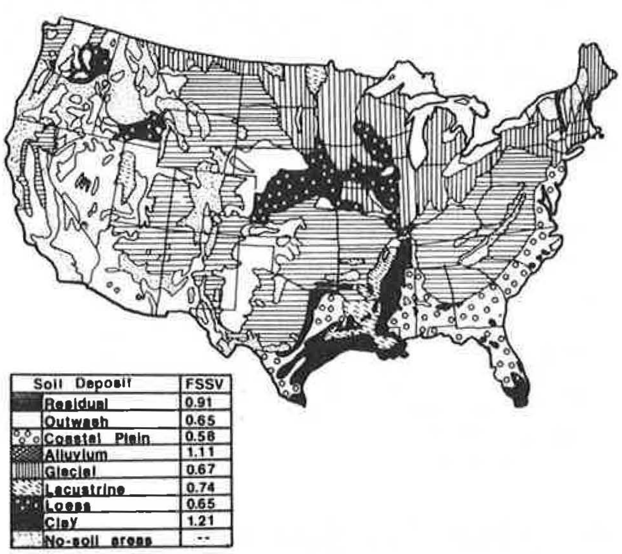

FIGURE 4 FSSV for soil deposits in the United States.

soil description given by Woods has made it possible to estimate such strength parameters as California bearing ratio (CBR) and from that the SSV (5,8). When the SSV values are known, data in Table 2 may be employed to derive FSSV for each soil deposit, as tabulated in the inset to Figure 4. The interpretation of this map is that under similar traffic conditions regions with higher FSSV values call for thicker pavements on account of the abundance of weaker subgrade soils. A similar interpretation could be offered for the FR_f. From the range of values of the latter (1.0 to 1.11), it could be concluded that R_f exerts a relatively small influence on the thickness of flexible pavements.

Effect of Asphalt-Concrete Modulus on SN

Yet another sensitivity analysis was performed to study how effective modulus influences pavement thickness. With the AASHO suggested values (1) of the asphalt layer coefficient for different asphalt-concrete moduli, a regression analysis was performed to relate mathematically a_1 (asphalt layer coefficient) to E_1 (asphalt modulus), which yielded the following equation:

$$a_1 = 0.22691 E_1^{0.4260} \quad R^2 = 0.993, SE = 0.051 \tag{12}$$

for $1.0 < E_1 < 10.0$ where E_1 is in units of 10^5 psi (1 psi = 6.895 kPa).

In order to study the effect of modulus on flexible pavement design, the modulus factor (MF) is defined as the ratio of layer coefficient evaluated at the reference modulus of 34.5×10^5 kPa to that at an arbitrary modulus. That is,

$$MF_B = a_{1*}/a_{1B} \tag{13a}$$

where a_{1*} and a_{1B} are layer coefficients evaluated at the reference value and at an arbitrary value, E_B. According to Equation 12, the layer coefficient bears an explicit relation to the asphalt modulus. Substitution for a_{1*} and a_{1B} from Equation 12 results in the following:

$$MF_B = 1.983/E_B^{0.426} \tag{13b}$$

Note that Equation 13b is valid for a reference modulus of 34.5×10^5 kPa. By using Equation 13b, MFs for typical values of modulus are listed in Table 5. The significance of MF is the same as that of FSSV or FR_f in that larger MF-values indicate thicker pavements. As can be seen from Table 5, larger MF-values result solely from lower effective moduli of asphalt.

TABLE 5 Values of MF for Different Moduli

Asphalt-Concrete Modulus E_1 (psi)	MF (E_1)	Asphalt-Concrete Modulus E_1 (psi)	MF (E_1)
200,000	1.48	600,000	0.92
300,000	1.24	700,000	0.86
400,000	1.10	800,000	0.82
500,000[a]	1.00	900,000	0.78

Note: 1 psi = 6.895 kPa.

[a]Asphalt-concrete reference modulus.

Combined Effects of Asphalt Modulus, SSV, and R_f on Asphalt-Concrete Thickness

Although an explicit expression to estimate pavement thickness considering all of the environmental factors is desired, for purposes of this study it suffices to determine the relative asphalt thickness with respect to a chosen set of reference values: effective modulus = 34.5×10^5 kPa, SSV = 5.0, and $R_f = 1.0$.

Considering the general case of an asphalt pavement, the change in asphalt thickness between stations B and * (with reference values) ($\Delta h_{B/*}$) can be estimated as follows:

$$\Delta h_{B/*} = (h_B - h_*)/h_* \tag{14}$$

where h_B and h_* are asphalt thickness at B and *.

For a full-depth pavement, Equation 14 may be written as follows:

$$\Delta h_{B/*} = [(SN_B/a_{1B}) - (SN_*/a_{1*})]/(SN_*/a_{1*}) \tag{15}$$

If the overall change in SN from station * to B is defined as ΔSN,

$$SN_B = SN_* + \Delta SN \tag{16}$$

If Equations 13a and 16 are substituted into Equation 15, the following is obtained:

$$\Delta h_{B/*} = MF\ [1 + (\Delta SN/SN_*)] - 1 \tag{17}$$

The depth factor (DF) is defined as the ratio of asphalt thickness at station B to that at station * with reference environmental conditions. That is,

$$DF_B = h_B/h_* \tag{18}$$

By using the simple relation $h_B = h_* + \Delta h_{B/*}$ as well as Equation 17 in Equation 18, the following is obtained:

$$DF_B = \{MF_B[1 + (\Delta SN/SN)]\} \tag{19}$$

Note that MF_B, the modulus factor corresponding to the effective modulus at B, has finally been calculated (see Table 5). In addition, with values of $\Delta SN/SN$ evaluated from Equation 11, the depth factor for a given station can be explicitly calculated. A map of the United States listing values of DF for the whole country is presented in Figure 5.

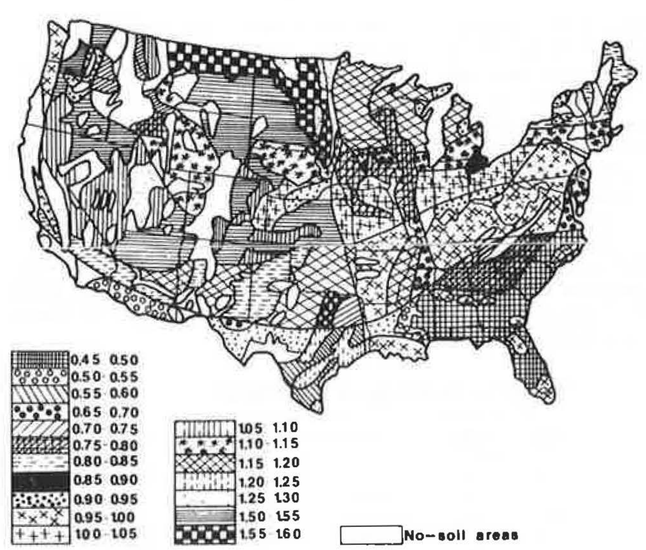

FIGURE 5 DF values for the United States.

It is significant that the DF boundaries coincide with those of the soil map of Figure 4 and the climatic zonal map of Figure 1; the climatic zones perhaps exert a greater influence than does soil on DF. The latter assertion can be substantiated by comparing DFs in Figure 5: DF varies from as low as 0.45 in Florida, parts of Mississippi, Alabama, Georgia, and the Carolinas, where the effective modulus is 58.0×10^5 kPa (8.4×10^5 psi), to as high as 1.60 in regions of Montana, North Dakota, and South Dakota, where, in fact, the effective modulus is the lowest, namely, 17.2×10^5 kPa (2.5×10^5 psi).

DF is a convenient index that portrays how severe the environment is with regard to pavement life.

Asphalt-concrete pavements need to be thicker in regions where the DF is greater than 1 than in regions where the DF is less than 1.

CONCLUDING REMARKS

In order to adequately account for the effects of the environment in the AASHO flexible pavement design, the influence of climatic variables in the design is evaluated by a sensitivity analysis. The effect of ambient temperature on asphalt-concrete stiffness is also incorporated into the final version of the environmental factor referred to in this report as DF. A DF map of the United States (Figure 5) is included for ready reference.

Higher DFs resulted from either poor subgrade soil or a relatively small effective modulus or both. DF is a convenient index for assessing the influence of environment on flexible pavement in that the higher the depth factor, the more severe the environment is for pavement performance. Therefore, federal agencies will find that DF can be an effective measure in allocating funds for construction and maintenance of highway systems throughout the country.

Because DF is a measure of environmental severity with regard to pavement performance, the AASHO design procedure could be updated by incorporating the DF concept. As pointed out earlier, it includes not only the effect of SSV and R_f on SN but also the climatic effect on the asphalt layer coefficient (a_1). Two examples are presented in the following to illustrate how DF could be incorporated into the AASHO design procedure. The data normally required for AASHO design, along with other special information for both examples, are listed in Table 6.

TABLE 6 Input Data for Pavement Design Examples

Item	Example 1	Example 2
Mean air temperature (°C)	7	20
Climatic zone	Dry freeze	Wet no-freeze
Asphalt-cement grade	AC-5	AC-40
Effective modulus E_e (kPa)	17.2×10^5	58.0×10^5
Effective asphalt layer coefficient a_{1e}	0.38	0.56
AASHO asphalt layer coefficient a_1	0.42	0.42
AASHO regional factor	3.0	1.0
AASHO mean SSV	6.5	9.0
Traffic (80-kN EALs)	3×10^6	6×10^6
Depth factor	1.23	0.47
Gravel base thickness h_2 (cm)	25.4	0.0

Note: 1 cm = 0.39 in.; 1 kPa = 0.145 psi; t°C = (t°F − 32)/1.8; 1kN = 0.2 kip.

Example 1: Huron, South Dakota

Thickness for Standard Conditions

Enter Figure 6 with W = 3 x 10⁶ 18-kip EALs and h_2 = 25.4 cm (10.0 in.) to obtain the asphalt layer thickness for reference conditions, h_{1R} = 14.2 cm (5.6 in.). Figure 6 was prepared by using the AASHO design charts with inputs of R_f = 1.0 and SSV = 5.0 along with E_e = 34.5 x 10⁵ kPa (reference values). Note that the asphalt layer thickness can also be computed by using Equation 20, which is the regression equation developed from the data in Figure 6:

$$h_{1R} = [4.62 \exp(-0.061 h_2)] \times W^{0.161 \exp(0.0354 h_2)}$$

$$R^2 = 0.970, \mathrm{SE} = 0.10 \quad (20)$$

where h_2 is the gravel base thickness in inches.

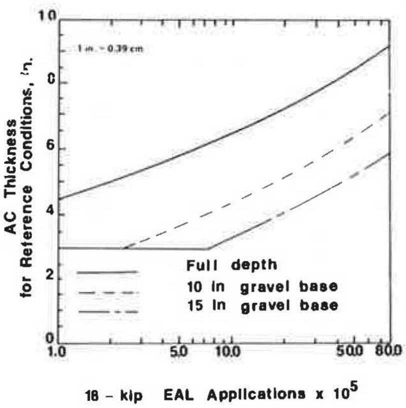

FIGURE 6 Asphalt-concrete thickness for the reference conditions versus traffic with and without gravel base.

Asphalt Thickness for Huron, South Dakota

Multiply h_{1R} by the depth factor to get the asphalt thickness; h_1 = 1.23 x 14.2 cm = 17.5 cm (6.9 in.). The required pavement thickness, therefore, is 17.5 cm of asphalt concrete and 25.4 cm of gravel base.

Example 2: Tallahassee, Florida

Thickness for Standard Conditions

With W = 6 x 10⁶ 18-kip EAL and no base specified, from Figure 6 or Equation 20, h_{1R} = 22.4 cm (8.8 in.).

Asphalt Thickness for Tallahassee, Florida

As in example 1, h_1 = 0.47 x 22.4 cm = 10.5 cm (4.2 in.). The required pavement thickness is 10.5 cm (4.2 in.) of full-depth asphalt concrete.

Comparison between the AASHO design and the AASHO modification with DF results in the data given in Table 7. From these examples two observations deserve mention:

1. If the AASHO design were to be followed along with the AASHO-recommended layer coefficient for asphalt concrete (a_1 = 0.42), the pavement in Huron, South Dakota, would have been underdesigned by approximately 1.78 cm (0.7 in.) and would have had a shorter life than that anticipated. This result would have been expected because DF is greater than 1.0. On the other hand, the pavement in Tallahassee, Florida, is overdesigned by nearly 3.8 cm (1.5 in.). A low DF of 0.47 reflects this.

TABLE 7 Comparison of Structural Designs

Location	Pavement Component	Pavement Thickness (cm) A	B	C
Huron, S.D. (DF = 1.23)	Asphalt concrete	15.7	17.3	17.5
	Gravel base	25.4	25.4	25.4
Tallahassee, Fla. (DF = 0.47)	Asphalt concrete	14.5	10.9	10.6
	Gravel base	0.0	0.0	0.0

Note: A = AASHO SN with a_1 = 0.42, p = 2.5; B = AASHO SN with variable a_{1e} [layer coefficient corresponding to the effective modulus (Equation 12)], p = 2.5; C = AASHO design with DF modification, p = 2.5. 1 cm = 0.39 in.

2. Had the effect of climate been included in the AASHO design by judiciously varying the effective asphalt layer coefficent as a function of effective modulus, a correct pavement design would have been obtained. The good agreement between the designs in the last two columns of Table 7 confirms this assertion.

These examples reaffirm the previous conclusions: namely, that the DF concept is a useful measure in assessing the relative effect of environment on pavement and that this concept could serve as a guide for personnel who allocate federal funds to projects in various parts of the country.

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Seasonal Load Limit Determined by the Criterion of Uniform Failure Rate

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ABSTRACT

Efficient performance of our highway system requires rational optimization of its use within the constraints of the adopted strategy. During the spring-thaw season in the northern part of the United States many highway agencies reduce the maximum load limits on some roads in an attempt to preserve the pavement serviceability. The selection of such a reduced load limit is not well defined now. A rational method has been developed that suggests that the load limit should be reduced in such a way to maintain a uniform rate of pavement deterioration throughout the year. The method considers various types of pavement failure such as fatigue cracking, rutting, and roughness and combines them by using the AASHO serviceability index. If the properties of the pavement materials are determined, mechanistic approaches can be used to predict the failure trend and to adjust the axle load limit to maintain the uniformity of this trend. A computer program LOADLMT has been developed in order to determine the optimum seasonal axle load limit on flexible pavements under various conditions. The use of the method was verified on a typical road under typical traffic distribution, material properties, and environmental conditions. The adoption of a seasonal load limit determined by this method indicates a large extension of the useful life of the road. The concept of this method is compared with other criteria currently used.

With the rapid aging of highway pavements, the public demand for higher levels of service, and the escalating rates for labor, equipment, and materials, highway operations should be performed according to a scientifically based procedure. A good understanding of the pavement behavior under various conditions and a rational optimization of such behavior within the constraints of the adopted strategy would result in efficient road performance.

The deterioration of pavement because of traffic and aging causes the serviceability of the road to decrease. The rate of decrease of serviceability varies depending on the amount of traffic, material properties, and environmental conditions. During