STRUCTURAL DESIGN OF INTERLOCKING CONCRETE PAVEMENTS

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ABSTRACT

Several methods for designing interlocking concrete pavements for roads and streets are presently available. All recognize the need to consider the subgrade soil, paving materials, environment and anticipated traffic. There are number of limitations associated with each, including inadequate characterization of the subgrade soil and paving materials, lack of pavement performance prediction capabilities, and inability to specify desired pavement failure and reliability level. This paper presents a method to overcome these limitations. The AASHTO flexible pavement design methodology was used as the fundamental framework for developing this procedure. Several modifications allow for the characterization of interlocking concrete pavers as well as for various levels of engineering analysis depending on the availability of information. The proposed design methodology is demonstrated through a numerical example.

Keywords: interlocking concrete pavements, concrete block pavements, concrete pavers, structural design model, pavement performance variables, concrete block pavement design curves.

INTRODUCTION

The concept of tightly fitted paving units or pavers set on a flexible granular base is as old as the roads of the Roman Empire. The modern version, interlocking concrete pavements (sometimes referred to as concrete pavers), originated in the Netherlands in the late 1940's as a replacement for clay brick streets. This technology quickly spread to Germany and western Europe as a practical and attractive pavement for both pedestrian and vehicular traffic.

Concrete pavers came to North America in the early 1970's and have been successfully used in many pavement applications. Their use has many advantages including their resistance to freeze-thaw cycles and deicing salts, ease of maintenance and repair, access to utilities, low maintenance costs, various shapes and colors.
A typical cross section is shown in Figure 1a.

In this pavement structure, both the base and subbase are comprised of unbound aggregate. Base and subbase layers stabilized with asphalt or cement can also be used, as shown in Figure 1b. Edge restraints are required along the edges of the pavement to prevent the outward migration of pavers from the force of traffic, which would result in the opening of joints and loss of interlock between the units. The example shown in Figure 1 is a schematic representation of any number of curb designs that are typically made of concrete.

Typical laying patterns are illustrated in Figure 2. Regardless of the pattern used, concrete pavers are first placed, mechanically or manually, on a bedding sand layer and vibrated with a high frequency plate vibrator. Sand is then spread and swept into the joints and the pavers are again vibrated until the joints are full of sand so that the interlocking of units (full shear transfer), critical to the performance of interlocking pavements, is obtained.

After the pavement has been in service for a short time, the joints between the pavers become sealed. Therefore, surface drainage must be provided in the normal way; i.e., surface gradient. If water gets trapped between the pavers and a stabilized layer, this water can be drained through the sand layer under the units at an appropriate drainage outlet such as a catch basin or manhole. Care must be exercised, however, to ensure that the sand does not wash away nor float up through the paver joints.

Although the use of concrete pavers in pavement design and construction is a rather new development, several design methods are presently available (5, 7 to 9, 16 to 18, 20, 23, 26). All of these methods recognize the need to consider the subgrade soil, characteristics of the pavement materials, environmental effects and the anticipated traffic over the design period. While they provide an excellent reference, limitations of these procedures include: (1) inadequate characterization of the subgrade soil and pavement materials, especially concrete pavers; (2) lack of pavement performance prediction capabilities; and, (3) inability to specify desired pavement failure and reliability levels.

In view of this, a study was undertaken to develop a more comprehensive design procedure for roads and streets. The analysis framework found within the newly revised (1986) American Association of State Highway and Transportation Officials (AASHTO) Flexible Pavement Design Method (1) was selected as the basis for this effort because: (1) of its broad experience base and general acceptance in North America, (2) it does not suffer from the limitations noted above, and more importantly, (3) the load distribution and failure modes of a interlocking concrete pavement are very similar to those of any other flexible pavement system; i.e., the main failure mode is increasing roughness due to repetitive shear deformations.

Modifications to the AASHTO method were necessary for application to the design of interlocking concrete pavements. In particular, a strength characterization model for concrete pavers was developed. Also, alternate procedures for characterizing the environment, traffic, subgrade and material strengths were developed to allow for various levels of engineering analysis, depending on the information available to the designer.

While the AASHTO framework was used, the reader should understand that the following methodology is not affiliated, endorsed nor approved by the AASHTO organization. In addition, this design procedure is only recommended for roads and streets with posted speed limits of 60 kph or less. The reader should also note that the AASHTO equations in this paper are based on English inch-pound units. Conversions of the equations to metric are necessary if the reader wishes to make calculations with S.I. units.

AASHTO DESIGN METHODOLOGY

The design procedure recommended by AASHTO is based upon the results of the extensive AASHO Road Test conducted in the late 1950's and early 1960's. This road test introduced the concept of functional failure of a roadway. Simply stated, the function of any road is to safely and smoothly carry traffic from one point to another. When these conditions are no longer met, functional failure has occurred.

In order to quantify such a functional description, two additional concepts were introduced: Serviceability and Performance. Serviceability is a measure of how well a road is serving its intended function, on the scale of 0 to 5 (5 being excellent), at a particular point in time. Performance, which is a time related function of serviceability, is the ability of a pavement to satisfactorily serve traffic over a period of time.

Using these concepts and incorporating the effects of the environment, traffic, subgrade soil and construction materials, pavement design formulas were developed. These formulas have been modified over the years to incorporate new advances in pavement technology. The most recent modifications were made in 1986, when the new AASHTO Guide was published. In this guide, the basic initial design equation for use with flexible pavements is given by:

$$\log_{10}(EALs*F_R) = 9.36*\log_{10}(SN+1)-0.20+\frac{\log_{10}((p_o-p_t)/(p_o-1.5))}{0.4+\frac{1094}{(SN+1)^{5.19}}} + (2.32*\log_{10}(M_R) - 8.07) \quad (1)$$

where EALs = cumulative number of 18-kip (80 kN) equivalent single axle load repetitions over the specified design life; F_R = reliability design factor; SN = structural number of the pavement; p_o = initial pavement serviceability; p_t = terminal pavement serviceability; and, M_r = resilient modulus of the subgrade soil (in psi).

Given the subgrade resilient modulus, the anticipated traffic, desired reliability level, and a specified initial and terminal serviceability level, the above equation can be used to determine the required structural number (a parameter characterizing the combination of layer thickness and material type).

DESIGN METHODOLOGY
Design Variables

Like other existing procedures, the design of concrete paver roads is based upon the evaluation of four primary factors and their interactive effect. They are: environment, traffic, subgrade soil and pavement materials. These design variables and their characterization are discussed below. While other approaches for establishing the design variables can be used, only those procedures intended for use in the absence of more detailed information are presented.

<u>**Environment**</u>

Pavement performance is significantly influenced by environmental factors. Moisture adversely affects the load bearing capacity of the pavement by reducing the strength of unbound granular materials and subgrade soils. Moisture causes differential heaving and swelling of certain soils, too. Temperature can also affect the load bearing capacity of pavements, particularly those that have asphalt stabilized layers. The combined effect of temperature and moisture can lead to the detrimental effects of frost action: (1) heave brought about by expansion of water during freezing and (2) reduced material strength caused by thawing.

These detrimental effects can be reduced, or even eliminated, by preventing moisture from entering the pavement system, removing or improving swelling or frost susceptible soils, or by selecting pavement materials that are not as susceptible to environmental problems. It is often not possible to achieve complete protection against the environment due to economic considerations. Consequently, the effects of the environment must be mitigated to the extent allowed by budget and available materials.

In the design methodology, like AASHTO, environmental effects are incorporated through the characterization of the subgrade soil and pavement materials. Subjective descriptions (see Table 1) of drainage quality and moisture conditions help determine design strength values for both subgrade soils and unbound granular materials. Also if freeze-thaw action is a consideration, the subgrade support value is reduced according to its frost susceptibility category. A more detailed discussion on these considerations is provided later in the paper.

Traffic

A key factor in the design of pavements is the anticipated traffic over its design life. In most design procedures, traffic related parameters such as vehicle mix, volumes, growth rate, directional split and lane distribution are used to arrive at a single value representation of traffic for direct input into the design procedure. Typically, traffic is represented in terms of the number of equivalent 18-kip (80 kN) single (highway standard) axle load repetitions or EALs.

For the design of a concrete paver road, the traffic mix analysis model is based upon the following equation:

$$EALs = 365 * ADT * \frac{EAL_o}{100} * \frac{DS}{100} * \frac{LF}{100} * \frac{\left[\left(1 + \frac{i}{100}\right)^n - 1\right]}{\frac{i}{100}} \qquad (2)$$

where ADT = average daily traffic in both directions, EAL_o = number of EAL repetitions per 100 vehicles at the start of the design period; DS = directional split, in percent; LF = lane distribution factor, in percent; i = traffic growth rate, in percent; and, n = pavement design life, in years.

Specific traffic information may not be available in many situations. The road class and vehicle classification systems shown in Tables 2 and 3, were developed to overcome this situation. These are for use in conjunction with Equation 2. As noted in these tables, there are eight functional road classes and six vehicle groups defined in the analysis. In Table 2, typical average daily traffic and lane distribution factors are provided as a function of the road class. Vehicle distributions, vehicle damage factors and EAL_o for typical urban and rural roads are given in Table 3. Additionally, a 20-year design life, 4% traffic growth rate and 50% directional split is recommended in the absence of any other information.

The designer can therefore use the typical values derived for each variable from actual local, provincial and national traffic data (2, 5, 14) or, at the other end of the spectrum, specify the appropriate value for each traffic factor based on survey results, local experience, etc.

The designer should also be cognizant of the variability associated with all pavement design factors, and hence, performance predictions (EALs to failure). In the design procedure, like AASHTO, this variability and the desired level of reliability are incorporated into the design process through a shift in the design traffic:

$$\text{Design EALs} = F_R * \text{EALs (from Eq. 2)} \tag{3}$$

where F_R = reliability design factor (greater than or equal to 1, depending on the reliability level). In turn, this factor is given by:

$$F_R = 10^{(zr * so)} \tag{4}$$

where z_r = standard normal deviate (a function of the reliability level) and s_o = overall standard deviation.

For rigid pavements, the standard deviation ranges from s_o = 0.3 to 0.4, while that of flexible pavements ranges from 0.4 to 0.5. Based upon these values, a standard deviation of s_o = 0.45 was assumed for interlocking concrete pavements. Typical F_R values are shown in Table 4 as function of the reliability level. Recommended reliability levels according to road class have been included in Table 2.

Note that while the F_R factor accounts for the variability of all performance related factors, it is only applied to traffic. Accordingly, average values should be used for all other design factors.

Subgrade Support

One of the most significant factors in the design of pavements is the evaluation of the subgrade soil strength. Many procedures for establishing this design factor are available: e.g., estimates made by the engineer based on experience; soil type to strength correlations; laboratory tests; in-situ evaluation methods such as dynamic deflection tests.

For the design of interlocking concrete pavements, alternate approaches based upon the USCS or AASHTO soil classification systems are provided for characterizing subgrade soils (5, 27). Both approaches make use of soil type to strength correlations for estimating subgrade strength in the absence of any other information.

For each soil classification system, typical resilient modulus (M_r) values have been assigned as a function of the soil type and are summarized in Tables 5 and 6, respectively. As shown, three modulus values are provided for each USCS or AASHTO soil type. These values are related to the environmental and drainage conditions discussed earlier (see Table 1). Guidelines for selecting the appropriate M_r value are summarized in Table 7.

Each soil type in Tables 5 and 6 has also been grouped into one of the five U.S. Army Corps of Engineers Frost Susceptible soil categories (5, 27). These categories with a brief description and reduced M_r values are presented in Table 8. The M_r values shown should only be used when frost action is a design consideration.

Pavement Materials

Structural Number and Layer Coefficients

The last set of design variables that must be established are related to the pavement structure. First, all paving materials available for construction must be identified. Next, the strength of each material must be established. Finally, all feasible material type and layer thickness combinations that provide sufficient structural capacity must be developed.

Because the design procedure is based on the AASHTO method, the required load bearing capacity of the pavement is represented by an index number termed the structural number (SN). Analytically, the SN value is represented by the following equation:

$$SN = a_1 * t_1 + a_2 * t_2 + ... + a_n * t_n = Ó\ a_i * t_i \qquad (5)$$

where a_i = layer coefficient for material in the i^{th} layer, and t_i = thickness of the i^{th} layer.

The layer coefficient (a_i), which expresses the relative ability of a material to function as a structural pavement component, is related to the type and properties of the material in question. Nomographs for selecting a_i as a function of the resilient (elastic) modulus or other material properties are provided in the AASHTO Guide. However, no such nomographs presently exist for concrete pavers. Consequently, a literature review was undertaken to gather information to characterize concrete pavers in terms of the layer coefficient.

Layer Coefficient - Concrete Pavers

Data reported in the literature (3 to 13, 15 to 26)indicates that the performance of interlocking concrete pavements is dependent on the interlocking of the individual units and, to a lesser degree, on the shape and thickness of the units. The interlocking of the paver is, in turn, influenced by the laying pattern and thickness of the bedding sand.

Paver shape has an effect its mechanical behavior; i.e., a uniform cross section will not crack as easily as those with variable cross sections. Unit thickness primarily affects the mechanical behavior but, an increase in thickness also produces an increase in structural capacity. The performance of the herringbone laying pattern is much superior compared to the stretcher or basketweave patterns which tend to creep in the direction of traffic movement and adversely affect the interlocking of the pavers. And, as the thickness of the bedding sand layer is recommeded to be between 25 - 40 mm after compaction. Very thin bedding sand layers will not produce the locking up action obtained by sand migration upward into the joints during the initial vibration phase in construction.

The literature also details several approaches for establishing the strength and behavior of interlocking concrete pavements. Of these, two approaches have produced results which, when compared with field deflection measurements, show good agreement: finite element mehtods(4, 8, 9, 11, 17) and multi-layer elastic solutions (3, 4, 6, 8, to 11, 17 to 19). The model used in the first approach is one of rigid bodies (paver units) with springs for the jointing and bedding sand. In the latter approach, both pavers and sand are modeled as a composite layer.

Findings by Houben, et.al. (8, 9) show that while the finite element method produces a better fit of field conditions, its complexity is a major limitation. As a consequence, most existing design procedures rely on elastic solutions to characterize the strength and behavior of interlocking concrete pavements. A comprehensive summary of these procedures and the research efforts that led to their development is presented in Reference (24).

Because of its simplicity and general acceptance, the multi-layer elastic approach was also used in the development of the proposed paver design procedure; i.e., model concrete pavers and bedding sand materials as a composite layer. Modulus values for this layer, developed by researchers in seveeral countries, are summarized in Table 9. While a wide range of values is reported, it is apparent that initial modulus values are significantly lower than those measured after many traffic repetitions, revealing a time/traffic dependence of the layer strength. This "progressive stiffening" affects performance and was incorporated into the design methodology.

Based on findings by the Australian Cement and Concrete Association (10), an initial composite modulus of 50,750 psi (350 MPa) was assumed. Also, a maximum composite modulus value of 450,000 psi (3100 MPa) was assumed to be reached, in a linear fashion, after 10,000 EALs. Using these moduli, layer coefficients were developed for the composite paver and sand layer based on the following AASHTO material characterization model:

$$a_{B/S} = 0.44 * \left(\frac{E_{B/S}}{450{,}000}\right)^{1/3} \tag{6}$$

where $a_{B/S}$ = layer coefficient of the composite layer and $E_{B/S}$ = modulus of the composite layer (in psi).

Figure 3 illustrates the recommended relationship between the layer coefficient and traffic based on the modulus characterization presented herein. To determine the appropriate value, the contribution of both the reduced and full strength periods must be accounted for by use of a weighted layer coefficient as follows:

$$a_{B/S} = 0.44 - 0.09 * \frac{t_s}{t_d} \tag{7a}$$

for t_s (settling period) $\leq t_d$ (design Life), or

$$a_{B/S} = 0.26 + 0.09 * \frac{t_s}{t_d} \tag{7b}$$

for $t_s > t_d$; t_s is calculated from Equation 2; i.e., solve for number of years (n) to reach 10,000 EALs.

These models are applicable to all paver shapes but assume that a herringbone laying pattern will be used along with a 1 inch (25 mm) thick bedding sand layer (minimal thickness). A minimum paver thickness of 3.15 inches (80 mm) is recommended for design EALs of 2,000,000 repetitions or less, 3.94 inches (100 mm) may be used for higher traffic levels. The 3.15 inch (80 mm) thick units may be used under loads exceeding 2,000,000 repititions but a thicker base will need to be used to compensate for this substitution. Also, because these models are based on a composite strength, the combined paver and bedding sand thicknesses must be used as input into Equation 4 to compute the pavement SN value.

Layer Coefficients - Other Pavement Materials

For other pavement materials, a_i correlations were derived from the AASHTO nomographs. Specifically, regression analyses between resilient modulus (or other material properties) and the a_i layer coefficient were performed for each material type. The best fitting equation was found to be of semi-logarithmic form:

$$ai = K_1 + K_2 * \log_{10}(\text{material property}) \tag{8}$$

where K_1 and K_2 are regression constants dependent upon material type and strength parameter.

The K_1, K_2 constants for each material type and strength parameter combination are summarized in Table 10. In the absence of material strength information, the default a_i values shown in Table 10 should be used. Also, recommended minimum layer thickness requirements are provided for each material type.

Unless reflected in the design strength value, the predicted a_i value for unbound granular base and subbase materials should be corrected for drainage and moisture conditions:

$$a_i \text{ (corrected)} = m_i * a_i \text{ (uncorrected)} \tag{9}$$

The m_i values recommended for use in the design procedure are summarized in Table 11.

Serviceability

The initial serviceability (p_o) represents the serviceability value of a pavement immediately after construction. Because sufficient data is not presently available to establish this value for interlocking concrete pavements, a p_o value of 4.0 is recommended. Alternatively, the terminal serviceability (p_t) represents the lowest serviceability value that will be tolerated before major rehabilitation of the pavement. For concrete pavers the recommended p_t value is 2.5 for all road classes.

Design Curves

Using Equation 1 and the variable definition procedures presented in this paper, a set of structural thickness design curves were developed for use interlocking concrete pavements. Figures 4, 5 and 6 represent the base thickness design curves for unbound granular, asphalt-treated and cement-treated materials, respectively. These thickness values are seen to be a function of the subgrade strength (M_R) and design traffic repetitions (expressed in EALs).

Use of these curves for the design of interlocking concrete pavements entails the following steps:

- Establish moisture and drainage conditions; use Table 1.
- Compute design EAL repetitions; use known or recommended (Tables 2, 3 and 4) traffic related values for input into Equations 2 and 3.
- Characterize subgrade strength; in the absence of any other information, use Tables 5 and 7 or 6 and 7 or, if frost is a consideration, use Table 8.
- Determine base thickness requirement; use subgrade M_R and design EALs as input into Figure 4, 5 or 6, depending on material in question.
- Characterize paving materials in terms of the AASHTO layer coefficient; if material properties are known, use a_i correlations presented in Table 10, otherwise use recommended default values.
- Correct base thickness requirement for a_i values other than the recommended default value:

$$t' = t * \frac{a(\text{actual})}{a(\text{default})} \tag{10}$$

where t' = corrected base thickness; t = base thickness from Figure 4, 5 or 6; a(actual) = layer coefficient derived from known material property; and, a(default) = default layer coefficient = 0.14, 0.30 and 0.20 for unbound granular, asphalt-treated and cement-treated materials, respectively.

Equation 10 can also be used to develop subbase thicknesses, as illustrated in the ensuing sample problem. Note however, that final layer thicknesses should not be less than the allowable value (see Table 10).

NUMERICAL EXAMPLE

Problem Statement

An two-lane urban, commercial street is to be designed using concrete pavers. Laboratory tests on the subgrade soil indicate that the pavement is to be constructed on a sandy silt; i.e. ML soil type according to the USCS classification system. From available climatic data, coupled with the subgrade soil type, it is anticipated that the pavement will be exposed to moisture levels approaching saturation more than 25% of the time, drainage quality will be fair, and frost is a design consideration. Detailed traffic data are not available.

Using the above information, complete interlocking concrete pavement designs are to be developed for the following base and subbase paving materials:

- Unbound granular or asphalt-treated base layer; modulus of 45,000 and 350,000 psi, (310 and 2410 MPa) respectively.
- Unbound granular subbase; modulus of 14,000 psi (95 MPa).

All designs are to include a base layer but not necessarily the granular subbase layer.

Solution and Results

Step 1: Establish moisture and drainage conditions. As stated earlier, the pavement will be exposed to moisture levels approaching saturation conditions more than 25% of the time and the quality of drainage is fair.

Step 2: Compute design EAL repetitions. Since detailed traffic information was not available, the values recommended in Table 2, 3 and 4 were used: ADT = 2,000; EAL_o = 3.841; DS = 50%; LF = 100%; i = 4%; n = 20 years; and, F_R = 2.010. Input of these values into Equations 2 and 3 yield a design traffic of 839,089 EALs.

Step 3: Characterize subgrade soil. Since only its USCS soil classification is known, Tables 5 and 7 were used to establish the design strength value. For a USCS ML soil and the given moisture and drainage conditions, the recommended subgrade modulus value is M_R = 7,500 psi (52 MPa). Because frost action is a consideration, the appropriate (reduced) design strength value is M_R = 4,500 psi (31 MPa).

Step 4: Determine base thickness requirements. Input of the design traffic (839,089 EALs) and subgrade strength (M_R = 4,500 psi/31 MPa) values into Figures 4 and 5 yields base thickness require- ments of 10.5 and 5.25 inches (265 and 130 mm) for the unbound aggregate and asphalt-treated materials, respectively.

Step 5: Determine AASHTO layer coefficients. Using the known material moduli as input into the a_i correlations presented in Table 10, the following layer coefficients were determined: 0.44 for the composite concrete paver and sand layer; 0.14 for the unbound granular base; 0.30 for the asphalt-treated base; and, 0.08 for the unbound granular base. Note that the a_i value for both the unbound granular base and subbase materials has been adjusted for moisture and drainage conditions; i.e., a multiplier factor of 0.8 (from Table 11) was used.

Step 6: Calculate corrected base thickness requirements. Since both granular and asphalt-treated base materials under consideration have layer coefficients equal to those used in the development of the design curves (i.e., Figures

4 through 6), no corrections were necessary. The final granular and asphalt-treated base thicknesses are 10.5 and 5.25 inches (265 and 130 mm), respectively.

As indicated earlier, these thicknesses can also be used to develop subbase thicknesses. Using Equation 10 and an a_i value of 0.08 for the granular subbase, the equivalent thickness required is approximately 19 inches (480 mm). Since all designs must include a base layer, only that thickness exceeding the minimum allowable value (4 inches/100 mm for granular bases and 3 inches/75mm for asphalt-treated bases) was converted into subbase quality material.

The final paver alternative cross sections are summarized in Figure 7. Because traffic does not exceed 2,000,000 EALs, 3.15 inch (80 mm) thick units and a one inch (25 mm) bedding sand layer are recommended (and reflected in the base/subbase thicknesses). Also, the alternatives shown are but a small subset of the possible material type-layer thickness combinations, which satisfy the design considerations and constraints. Cost-effectiveness analyses of these and other pavement cross section alternatives should be conducted in order to select the optimal design.

SUMMARY AND CONCLUSIONS

The 1986 AASHTO pavement design methodology was selected as the basis for developing a design procedure for the structural design of interlocking concrete pavements. In order to extend its use to pavers, a strength model to characterize the concrete pavers and bedding sand layer was developed based on findings reported in the literature. Also, multiple input options for the key pavement performance factors were developed in order to allow for various levels of engineering analysis.

A set of structural thickness design curves was also developed. These design curves provide the required granular, asphalt-treated or cement-treated base thickness as a function of the design subgrade strength and traffic repetitions. The use of these curves and the proposed design procedure were demonstrated through a numerical example. The design procedure is incorporated into a computer software program, called Pavechek, available from the Concrete Paver Institute.

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TABLE 1
SUBJECTIVE DESCRIPTION OF MOISTURE AND DRAINAGE CONDITIONS (1)

Parameter	Description	Available Options
Moisture	Percent of time that pavement is exposed to moisture levels approaching saturation	o less than 1 % o 1 to 5 % o 5 to 25 % o greater than 25 %
Drainage	Quality of drainage (time to remove water)	o excellent (2 hrs) o good (1 day) o fair (1 week) o poor (1 month) o very poor (water will not drain)

TABLE 2
ROAD CLASSIFICATION SYSTEM (2, 5, 14)

Road Class		Average Daily Traffic*	Lane Distribution Factor** (%)	Recommended Reliability Level (%)
Arterial or Major Streets				
	Urban	40,000	90	90
	Rural	15,000	90	85
Major Collectors				
	Urban	15,000	90	85
	Rural	6,000	90	80
Minor Collectors				
	Urban	6,000	100	80
	Rural	2,000	100	80
Commercial/Multi-Family Locals				
	Urban	2,000	100	75
	Rural	1,000	100	75

* in both directions

** use 100% for 1 or 2 lanes in both directions; 90% for 3 or 4 lanes; and, 80% for more than 4 lanes.

TABLE 3
VEHICLE CLASSIFICATION SYSTEM (2, 5, 14, 27)

Vehicle Type	Urban Roads Distribution (%)	Urban Roads Damage Factor*	Urban Roads EAL Reps.	Rural Roads Distribution (%)	Rural Roads Damage Factor*	Rural Roads EAL Reps.
Passenger Vehicles	77.0	0.0004	0.031	70.0	0.0004	0.028
Recreation Vehicles	0.5	0.09	0.045	1.5	0.06	0.090
Pickups	14.0	0.01	0.140	18.5	0.01	0.185
Single Unit Trucks	6.0	0.25	1.500	5.5	0.20	1.100
Buses	0.5	0.25	0.125	1.0	0.20	0.200
Tractor-Trailer Combinations	2.0	1.00	2.000	3.5	0.95	3.325
Number of EALs/100 vehicles:			3.841			4.928

* Damage Factor = Number of EALs/vehicle pass

TABLE 4
RELIABILITY DESIGN FACTOR, F_R (1, 27)

Reliability Level (%)	F_R
50	1.000
60	1.300
70	1.721
75	2.010
80	2.390
85	2.929
90	3.775
95	5.499
99	8.527

TABLE 5
SUBGRADE STRENGTH AS A FUNCTION OF USCS SOIL TYPE (5, 27)

USCS Soil Group	Option 1 M_r (ksi)	Option 2 M_r (ksi)	Option 3 M_r (ksi)	Frost Suscep.Group
GW, GP	20	20	20	NFS
GW-GM, GW-GC,	20	20	20	F1
GP-GM, GP-GC	20	20	20	F1
GM, GM-GC, GC	20	20	20	F3
SW, SP	20	20	20	NFS
SW-SM, SW-SC	20	20	20	F2
SP-SM	20	20	20	F2
SP-SC	17.5	20	20	F2
SM, SM-SC	20	20	20	F4
SC	15	20	20	F3
ML, ML-CL	7.5	15	20	F4
CL	7.5	15	20	F3
MH	6	9	12	F4
CH	4.5	6	7.5	F3

Note: refer to Table 7 for selection of appropriate option

TABLE 6
SUBGRADE STRENGTH AS A FUNCTION OF AASHTO SOIL TYPE
(5, 27)

AASHTO Soil Group	Option 1 M_r (ksi)	Option 2 M_r (ksi)	Option 3 M_r (ksi)	Frost Suscep. Group
A-1-a	20	20	20	NFS
A-1-b	20	20	20	F1
A-2-4, A-2-5	20	20	20	F4
A-2-6	7.5	15	20	F3
A-2-7	20	20	20	F3
A-3	15	20	20	F2
A-4	7.5	15	20	F4
A-5	4.5	6	9	F4
A-6	4.5	10.5	20	F3
A-7-5	4.5	6	7.5	F3
A-7-6	7.5	15	20	F3

Note: refer to Table 7 for selection of appropriate option

TABLE 7
ENVIRONMENT AND DRAINAGE OPTIONS FOR SUBGRADE CHARACTERIZATION (1)

	Strength Option			
	Percent of Time Pavement is Exposed to Moisture Levels Approaching Saturation			
Quality of Drainage	< 1%	1 to 5%	5 to 25%	> 25%
Excellent	3	3	3	2
Good	3	3	2	2
Fair	3	2	2	1
Poor	2	2	1	1
Very Poor	2	1	1	1

TABLE 8
FROST SUSCEPTIBLE SOIL CATEGORIES (5, 27)

Frost Suscept. Group	Description	M_r (psi)
NFS	Non-frost susceptible soils (less than 2% passing .02 mm sieve); no problem.	
F1	Gravelly soils (3 to 20% passing .02 mm sieve); slight problem.	12,000
F2	Sands (3 to 15% passing .02 mm sieve); slight to medium problem.	9,000
F3	Gravelly soils (greater than 20% passing .02 mm sieve); sandy soils except silty sands (greater than 20% passing .02 mm sieve); plastic clays (PI > 12); varved clays (with uniform condition); medium to high problem.	4,500
F4	Silts, including sandy silts and fine silty sands (greater than 15% passing .02 mm sieve); lean clays (PI < 12); varved clays (with non-uniform conditions); highest problem.	4,500

TABLE 9
SUMMARY OF LAYER MODULI FOR COMPOSITE PAVER AND SAND LAYER

Country	Modulus, psi psi/MPa	Reference
United Kingdom	130,500/900	(3)
	290,000/2000	
Japan	243,900/1680	(17)
	627,850/4330	
New Zealand	60,175/415	(19)
Australia	50,750/350*	(10)
	464,000/3200	
Netherlands	92,655/640	(9)
	402,085/2770	
United States (U.S.A.C.E.)	742,500/5120	(18)

* Initial modulus value

TABLE 10
STRUCTURAL LAYER COEFFICIENT CORRELATIONS

$$a_i = K_1 + K_2 * \log_{10} (\text{material strength})$$

Material	(Units)	Strength Parameter	Regression Constants K1		k2		Recommended Default a_i Value*	Maximum Allowable a_i Value	Minimum Allowable Thickness, in.
Asphalt Treated Base/Subbase	Modulus	(psi)	-1.453	0.316	0.30		0.40	3.0	
		Marshall Stability (lb)		-0.323	0.187				
Cement Treated Base/Subbase	Modulus	(psi)	-2.651	0.486	0.22		0.30	4.0	
		Unconfined Compressive Strength (psi)		-0.395	0.212				
Unbound Granular Base	Modulus	(psi)	-0.976	0.249	0.14***		0.25	4.0 or 6.0**	
		CBR (%)			-0.053	0.098			
		R-value		-0.514	0.338				
Unbound Granular Subbase	Modulus	(psi)	-0.839	0.227	0.11***		0.20	4.0 or 6.0**	
		CBR (%)			0.012	0.065			
		R-value		-0.205	0.176				

* for use in the absence of material strength information

** use 4.0" if EALs $\leq$ 500,000 repetitions; 6.0" if EALs > 500,000 repetitions

*** must be corrected for moisture and drainage conditions, unless reflected in design strength value used

TABLE 11
DRAINAGE COEFFICIENT FOR GRANULAR MATERIALS (1)

Quality of Drainage	Drainage Coefficient: Percent of Time Pavement is Exposed to Moisture Levels Approaching Saturation			
	< 1%	1 to 5%	5 to 25%	> 25%
Excellent	1.4	1.3	1.3	1.2
Good	1.3	1.2	1.1	1.0
Fair	1.2	1.1	0.9	0.8
Poor	1.1	0.9	0.7	0.6
Very Poor	1.0	0.9	0.6	0.4