suitable rehabilitation measure for plain jointed PCC pavements.

6. From the current condition of the test section, the 11.4-cm CRC section could perform acceptably for up to 10 years with some maintenance. This overlay design could be used successfully on sections that have moderate traffic levels if the existing pavement was properly prepared.

7. The minimum thickness for a concrete overlay on a road that has a large volume of heavy trucks should be 15.2 cm. Both the CRC and jointed PCC sections that used the 15.2-cm thickness are doing well after five years of heavy truck traffic. From the performance of the two PCC overlay sections on I-85, the joint spacing in a 15.2-cm jointed PCC overlay should be 4.6 m. All the joints in the original pavement should be matched in the overlay and intermediate joints added to obtain the desired joint spacing. The transverse cracking that occurs on the test sections is attributed to the movement of the dowel assemblies and other start-up problems at the time of construction of these short test sections. These problems are not expected to occur on a regular construction project.

8. The major problem with using concrete overlays is the necessity of closing the roadway and diverting the traffic for an extended period of time. Generally the traffic will have to be directed onto the adjacent travel direction, which requires temporary concrete median barriers and upgrading and widening of the shoulders to maintain two lanes of traffic in each direction on an undivided highway or construction of slip ramp on a divided highway. This additional expense must be considered in determining the cost of a concrete overlay. From the standpoint of accidents and traffic flow, the slip ramps used on the research-overlay project performed very satisfactorily. This performance was felt to be due to proper design of the slip ramp to minimize loss of speed by the driving public, to signing, and to delineation between opposing lanes of traffic.

9. The experience in Georgia to date on the overlay sections reported here and on other rehabilitation projects has shown that edge drains are not effective on a long-term basis for the prevention of pumping and faulting.

10. In the asphaltic concrete overlay sections, the placement of strips of heavy-duty waterproofing membrane (Bithuthene) over all joints and cracks in the existing PCC pavement has proved to date to be the most effective method of reducing the number and severity of reflection cracks from the existing joints into the overlay. Engineering fabrics (Mirafi and Petromat) and the stress-relieving interlayer (Arkansas base) were also effective. The edge-drain treatment was not effective; in fact, it was worse than no treatment (control sections).

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This paper does not constitute a standard, specification, or regulation.

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Design Procedure for Premium Composite Pavement

W. RONALD HUDSON AND FREDDY L. ROBERTS

A brief description of a method for designing premium composite pavements is given. A premium pavement is defined as a pavement structure that will perform free from structural maintenance for 20 years and will require only minimum maintenance for an additional 10-20 years. To satisfy this requirement, the procedure incorporates the best current design and construction practices for composite pavement. The method described provides highway engineers with a systematic technique for selecting a premium pavement design. The procedure is more complex than some empirically based systems but is relatively easy to use. The complete manual includes a number of charts, figures, and worksheets and a procedure for their use. On the basis of design data, a user can select a precalculated pavement cross section from a catalog of designs. An overview of the design system and a brief explanation of the procedure and of the factors considered in the development of the procedure are given. An explanation of the design inputs required for use of the procedure is also included. A discussion of the limiting criteria used in development of the design procedure for premium pavement is followed by special considerations required for the design of reinforcement in the concrete layers of composite pavements and discussion of the design methodology.

For several years, the Federal Highway Administration (FHWA) has pursued multiple research studies aimed at producing premium pavement structures for heavily traveled highways. The intention of these efforts has been to develop pavements and minimize maintenance, which disrupts traffic flow and creates hazards and high user costs. This research is aimed at the development of pavement structures that will be maintenance-free for a minimum of 20 years and will require only routine maintenance for 10-20 years thereafter. A composite pavement has, in this case, been defined by FHWA as a pavement made up of both rigid and flexible layers and that has an asphaltic surface layer. The rigid layer(s) may be portland cement concrete (PCC) or cement-treated soil or base.

The research reported here is drawn from a portion of an FHWA-sponsored research project on flexible and composite structures for zero maintenance. The overall goal of that project is to develop pavement design procedures that can be used to design the thickness, specify the materials, and specify the unique construction procedures required for premium flexible and composite zero-maintenance pavements.

In using the design method for composite pavements discussed here, we emphasize that sound engineering must also be used in selecting any pavement design strategy. The designer must recognize that it is difficult in a general design procedure to successfully couple the knowledge of performance of local materials and the service requirements for

Curling Stress

One item that should be considered in the performance of composite pavements is the thickness of asphalt concrete required to significantly reduce the curling stress in the concrete slab. Basically, the temperature differential of the concrete slab is computed as a function of asphalt concrete thickness. For the majority of the conditions investigated, 3 in of asphalt concrete was found to significantly reduce the temperature differential of the concrete slab and the resulting curling stress and is included as a minimum thickness in this procedure.

Low-Temperature Cracking

The low-temperature cracking criterion is initially used to define the material properties for the asphalt concrete or continuously reinforced concrete (CRC). Both programs TC-1 (6) and CRCP-2 (7) were used to define the materials necessary to achieve proper performance. Regression equations were developed for use in the design of the required percentage of steel for the CRC rigid base layers instead of the CRCP-2 program. Once the material properties have been defined, the thicknesses to resist fatigue cracking and rutting can be determined.

Fatigue Cracking

This step provides for the determination of the thickness of the rigid layers required to limit the amount of fatigue cracking. A series of plots was developed to allow for a graphical determination of the required low-modulus concrete thickness for composite pavements by using results from VESYS III (8) and SLAB49 (9).

Reflection Cracking

The computer program RFLCR-1 (10) was used to determine whether reflection cracking was predicted to occur in composite pavements. Based on numerous studies, it was concluded that an asphalt crack relief layer provided the best potential for minimizing the distress manifestation of reflection cracking.

Deflection and Subgrade Compressive Strain

By using the FHWA criteria (1) and the computer program VESYS III, surface deflection and subgrade compressive strain were computed for pavement cross sections that satisfy the previous criteria. If the pavement structure does not meet the criteria established, then stabilized materials are used to reduce these two pavement-response variables.

Frost Penetration

Once the pavement structural thicknesses have been determined, frost action must be considered. By using the procedure described by Barber (11), the frost penetration is predicted, if a frost-susceptible material exists. If the frost penetrates a frost-suspectible material, then additional thicknesses or an insulating material must be used to prevent frost heave or spring-thaw strength reductions. Detailed guidelines for determining the treatment method are supplied in the design manual (2), which includes a series of figures prepared to simplify this step of the procedure.

Summary

The procedure is an iterative one in which there is much interaction between user and model. For the procedure to design premium pavements accurately, the user must have adequate information concerning the materials in a specific environment. Without this information, no model or procedure can be expected to design for proper performance reliably. It is also noted that if the user elects to use the graphs presented later in this paper instead of each computer program, it must be ensured that the simplifying assumptions have been met.

DEVELOPMENT OF LIMITING CRITERIA

We next describe the selection of the limiting criteria for each of the significant distress checks made as a part of this design procedure.

Fatigue of PCC

One of the major distress mechanisms associated with rigid pavements is fatigue cracking, defined by Mills and Dawson as "the process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after sufficient number of fluctuations" (12). The use of cracking alone as a design criterion is inadequate, since the formation of a crack does not necessarily imply a functional failure, as has been reported by several investigators (10,13-16). These fatigue relationships were determined from data collected on reinforced and nonreinforced jointed concrete pavements for different levels of service [class 3 and 4 cracking and a present serviceability index (PSI) of 2.5]. In order to develop a fatigue failure criterion for zero-maintenance pavements, the specific effects of four factors on fatigue cracking of concrete layers were investigated. These factors were failure criterion, pavement type, concrete type, and laboratory data.

Failure Criterion

In establishing failure criteria, it becomes questionable whether fatigue relationships based on concrete surface layers are valid for composite pavements, since the concrete layer is no longer the riding surface. Hence fatigue criteria may be different if based on PSI values for composite pavements. Failure criteria based on cracking also may be different for composite pavements, but the difference should be much smaller, since cracking is primarily related to concrete stress and strength magnitudes, whereas PSI is related primarily to roughness. Since performance of a composite pavement is directly related to the cracking of the rigid base layer, cracking was selected as the failure criterion for the concrete layer.

Pavement Type

Several fatigue relationships based on the performance of reinforced and nonreinforced jointed concrete pavements were studied. In studies of the AASHO Road Test completed by Treybig and others (10) and by Yimprasert and McCullough (17), it was observed that essentially no difference existed in the sections that failed, although the nonreinforced sections had a greater probability of survival and shorter time span between the different levels of cracking. Therefore, from these analyses and since no other studies reported comparisons of fatigue cracking in reinforced and nonreinforced pavements, the same fatigue-cracking criteria were applied to all types of concrete pavement. Only a difference in loading conditions (edge, corner, or interior) based on pavement type was used to predict the applied flexural stress in the concrete layer.

Concrete Type

The fatigue relationships are generally based on the road-test concrete pavements but are based on different failure definitions, except for the curve developed by Treybig, McCullough, and Hudson (13), which is based on failures of a jointed concrete pavement at airfields. Therefore, it is unclear whether these same fatigue relationships can be applied to other concrete mixtures such as lean concrete or econocrete. Laboratory fatigue results by Raithby and Galloway (18) that illustrate the effect of curing time and mixture properties on the fatigue relationships show that all mixtures exhibit approximately the same relationship between the stress/strength ratio and cycles to failure. Laboratory fatigue results for specimens that range from PCC to lean concrete show that there is no distinct relationship for each type of concrete; i.e., the relationship for lean concrete falls between other relationships determined for PCC (18-21; unpublished report by C.E. Kesler on fatigue and fracture of concrete, University of Maryland). The loading frequency of concrete beams does not have a great effect on the fatigue life of concrete (18). Therefore, it has been assumed that one fatigue curve can be used to describe the cracking failure criteria for all types of concrete mixtures. However, this might not be true if the concrete were the surface layer and failure were based on PSI.

Laboratory Data

Results from laboratory studies compared with the fatigue characteristics determined from field pavement performance show a difference. For large stress/strength ratios, a larger number of load applications are expected before terminal serviceability is reached in the field than is observed in the laboratory. This is due to the interval between initial cracking and the severity level of cracking defined as pavement failure. For small stress/strength ratios, a smaller number of load applications are expected before terminal serviceability is reached in the field than is observed from laboratory results. This is probably the result of environmental factors, the dynamic effect of loads, and other damage factors that may have been underestimated in developing the field fatigue curves. Therefore, until more-reliable fatigue information can be obtained, the fatigue curves that describe field performance will be used to determine fatigue failure for low-modulus concrete.

To summarize, in this method the failure of the concrete layer for composite pavements was based on cracking severity determined from pavement performance data. By using this failure criterion, zero maintenance should not be required for the traffic specified in a 20-year period, during which time cracking will cause a pavement condition in which routine maintenance will be required to provide additional years of service.

Transverse Cracking

There are almost no data available to establish a failure criterion for transverse cracking (including low-temperature and reflection cracking). Based on observations of in-service pavements, Darter and Barenberg established a 10- to 30-ft crack spacing as a limiting value (22). Therefore, based on this information and the project staff's experience, an average crack spacing of 30 ft was selected as the failure criterion for transverse cracking in the surface layer.

For the concrete slab in composite pavements, the CRC layer's performance has also been observed to be related to crack spacing. Based on previous observations and performance studies, a crack spacing greater than 4 ft but less than 8 ft has been observed to provide adequate serviceability.

Deflection

Surface deflection has also been related to field performance by a large number of researchers. In fact, a large number of design and evaluation procedures are based on surface deflection. Therefore, surface deflection was selected as an additional limiting design criterion for zero-maintenance pavements. This allows the use or consideration of data from a large number of studies and observations of past pavement performance. Therefore, based on a review of existing data, Figure 3 (23) was selected to develop the pavement structural cross section to limit surface deflections.

Roughness

The other important performance parameter used in establishing limiting criteria for zero-maintenance pavements is roughness or PSI. Based on previous studies conducted on flexible and composite pavements, a PSI lower than 3.0 will require maintenance. Hence, a limiting PSI value of 3.0 was selected in establishing the pavement cross section to meet the zero-maintenance criteria.

SPECIAL CONSIDERATION OF REINFORCEMENT

Some reinforcement will be required for concrete layers used in construction of composite pavement. For jointed concrete subsurface layers, load-transfer devices are suggested for most situations to prevent potential faulting and subsequent reflection of cracks to the surface. In CRC subsurface layers, longitudinal steel runs continuously throughout the length of the pavement. In CRC subsurface layers, transverse reinforcement is provided for most pavements. Other uses of reinforcement occur at terminal anchorages, construction joints, and edges of pavements that have tied shoulders, as previously discussed. Space does not permit the treatment of reinforcement here (1,2).

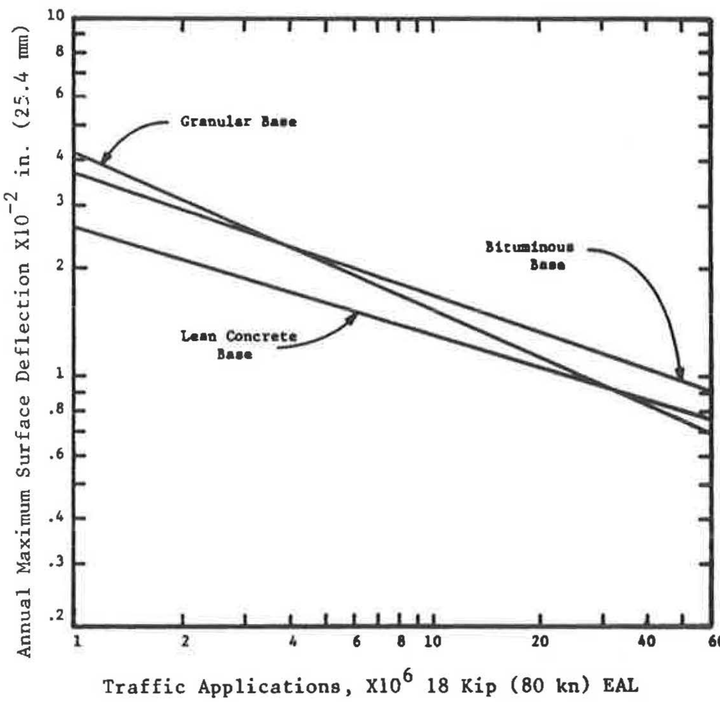
THICKNESS DESIGN PROCEDURE

The structural design charts have been prepared in a form in which combined traffic applications and PCC flexural strengths are used to determine layer thicknesses. A set of charts has been prepared that are used to determine the principal thicknesses for PCC layers. The charts determine the structural thickness required to satisfy the design criteria of fatigue cracking, rutting, and roughness. A second set of charts has been developed to determine the requirements for stabilized base thickness as a function of traffic and subgrade modulus and to indicate the additional thickness required to satisfy the deflection and subgrade vertical compressive strain criteria. A complete treatment of the procedure is contained in the FHWA report (1). Only certain sample charts are included in this paper.

Design Inputs

The designer must collect the basic information described in the following paragraphs.

Figure 3. Allowable maximum surface deflection used to develop structural cross section for each pavement type.



Environmental Factors

Temperatures are used to determine depth of frost penetration. The temperature values required are (a) mean annual air temperature, (b) warmest mean monthly air temperature, and (c) the coldest mean monthly air temperature. These air temperatures may be obtained from climatological records (24). They are used to reflect the effects of other environmental factors, such as solar radiation, daily temperature variations, and minimum design temperatures for specific areas in the United States. We have developed charts for obtaining the number of the environmental region as well as for predicting the annual minimum pavement temperature for each region (1,2).

Natural Soil Properties

The subgrade modulus is used as one of the principal design parameters. Since the modulus of most subgrade soils is dependent on the state of stress, the subgrade modulus should be based on in situ or expected field conditions, e.g., a moisture content and density that the soil is likely to reach under the pavement structure. This equilibrium moisture content is usually similar to that found at a depth of about 3 ft in the natural soil.

By using information on soil properties from classification tests, the engineer must determine whether stabilization of the existing subgrade is required. The type and amount of stabilizer should be substantiated by approved testing methods.

Traffic

Traffic is usually expressed in 18-kip equivalent single-axle loads as presented in the American Association of State Highway and Transportation Officials (AASHTO) Interim Guide (25) and as developed at the AASHO Road Test (26). In this design manual, total traffic is also expressed as the number of 18-kip equivalent axle loads that occur in the design lane during the minimum 20-year maintenance-free design life.

Thickness Determination

By using the total projected traffic, low-modulus PCC flexural strength (28 days), and the subgrade modulus, the thickness can be determined for each pavement type. For all pavement cross sections that require a stabilized base layer, an improved subgrade-layer thickness of 24 in is required. The minimum thickness recommended for the stabilized base layer is 6 in.

The minimum asphalt concrete thickness required over a CRC rigid base is 3 in, to minimize curling stress. The asphalt concrete material placed over a jointed concrete rigid base consists of 3 in of an asphalt crack relief layer and 2 in of dense graded asphalt concrete. With this surface thickness, the relationships shown in Figures 4 and 5 (1) are used to determine the thickness of low-modulus concrete required to resist fatigue cracking and retain an acceptable PSI level. The selection of a particular design chart is based on the 28-day concrete flexural strength determined by ASTM C-78 or AASHTO T-97.

Figures 6 and 7 (1) can be used to determine the thickness requirements for stabilized base layers of asphalt or cement in combination with the low-modulus concrete base for composite pavements.

Adjustment for Frost Susceptibility

The frost penetration below the pavement surface can be estimated for the pavement cross section by using the natural soil type and the environmental region in a relationship shown in Figure 8 (1) for region 2. If the subgrade soil is frost-susceptible, two design alternatives are possible. The engineer may elect either to totally protect the subgrade from frost penetration or to increase the structural thickness to account for reduced strength values that occur during spring thaw. Suggestions are provided in the manual (1,2) to assist the engineer in choosing between full and partial protection from frost penetration. Among the factors that affect this decision are soil classification, strength dur-

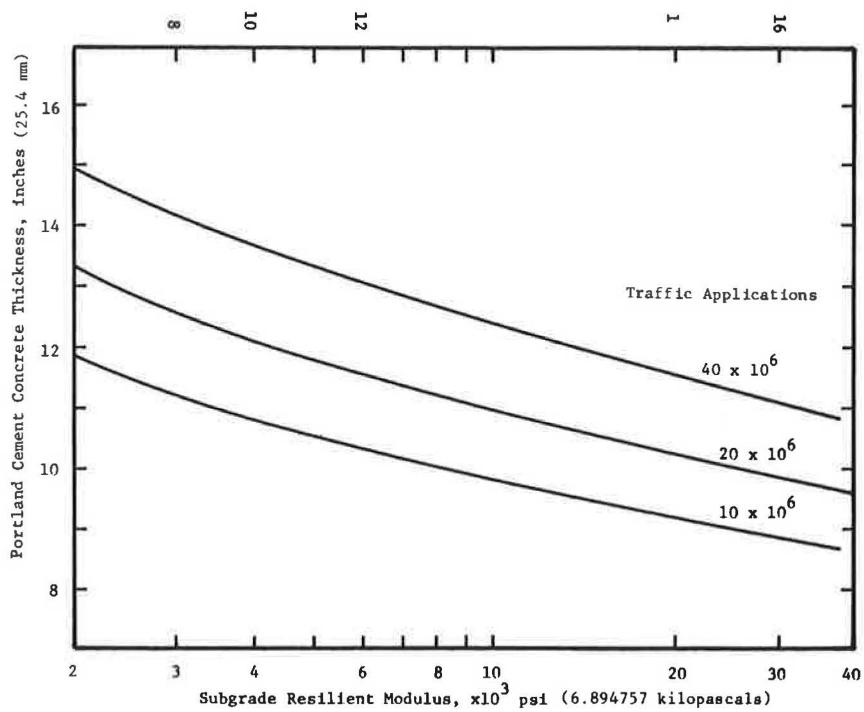


Figure 4. Low-modulus CRC thickness required by fatigue and roughness criteria for composite pavements with flexural strength of 500 lbf/in².

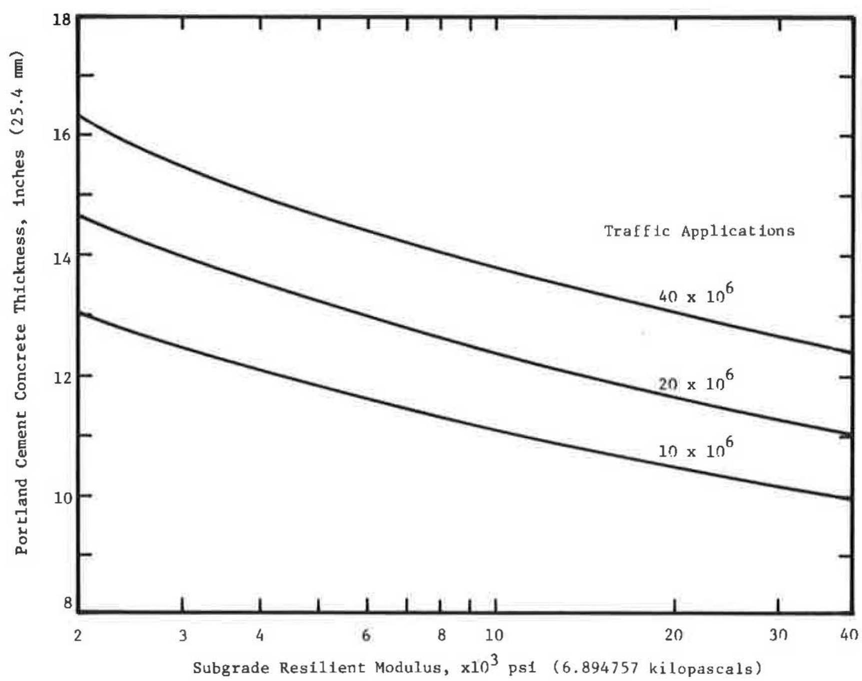


Figure 5. Low-modulus jointed concrete pavement thickness required by fatigue and roughness criteria for composite pavement with flexural strength of 500 lbf/in².

ing the thaw period, water-table location, pavement type, and soil modulus.

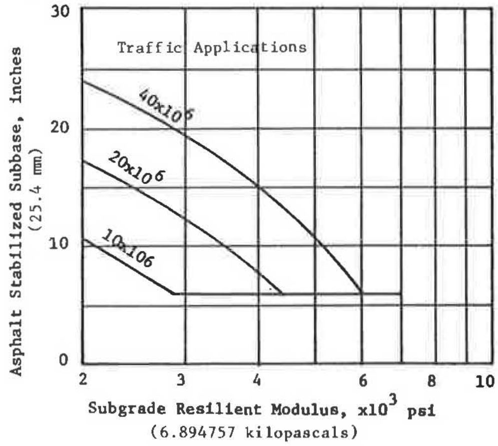
If the engineer elects to protect the subgrade fully from frost penetration, relationships similar to that shown in Figure 8 should be used to estimate the additional thickness of non-frost-susceptible materials required as a part of the pavement structure. A decrease in the stiffness of subgrade soils due to spring thaw will result in a reduction of the stiffness of the granular materials, which may not be recovered with time.

If the engineer desires to analyze the partial-protection alternative, relationships similar to the ones shown in Figure 9 (1) should be used to estimate the increased damage that occurs as a result of reduced strength during the spring thaw. After evaluation of both the partial-protection and full-protection alternatives, the engineer can select the most cost-effective design.

SUMMARY AND CONCLUSIONS

The materials included in this paper identify and examine the factors and requirements for establishing zero-maintenance pavements. We have examined the primary distress manifestations and correspond-

Figure 6. Stabilized subbase thickness of asphalt required to meet surface deflection and subgrade compressive strain criteria.



ing distress mechanisms that govern the behavior of composite pavements. Materials and material properties were reviewed in relation to providing the maximum performance required by the definition of premium pavement.

From this information and experience, candidate premium pavement cross sections were established that have strong potential to function for 20 years or more with minimum maintenance. A unique catalog of designs was chosen to present the resulting cross sections. Examples of these results are shown in Figures 10 and 11. Specific models were selected that, in the opinion of the research team, have the highest potential reliability for predicting actual performance. By using these models and past performance information, design criteria for each distress manifestation were established for design of composite structures. Subsequently, a design procedure was developed and organized so that both environmental and traffic-induced damage would be considered.

Figure 7. Stabilized subbase thickness of cement required to meet surface deflection and subgrade compressive strain criteria.

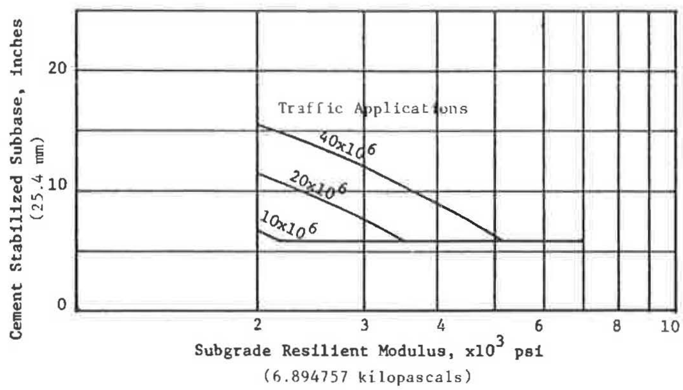


Figure 8. Determination of frost penetration into different materials below pavement surface for environmental region 2.

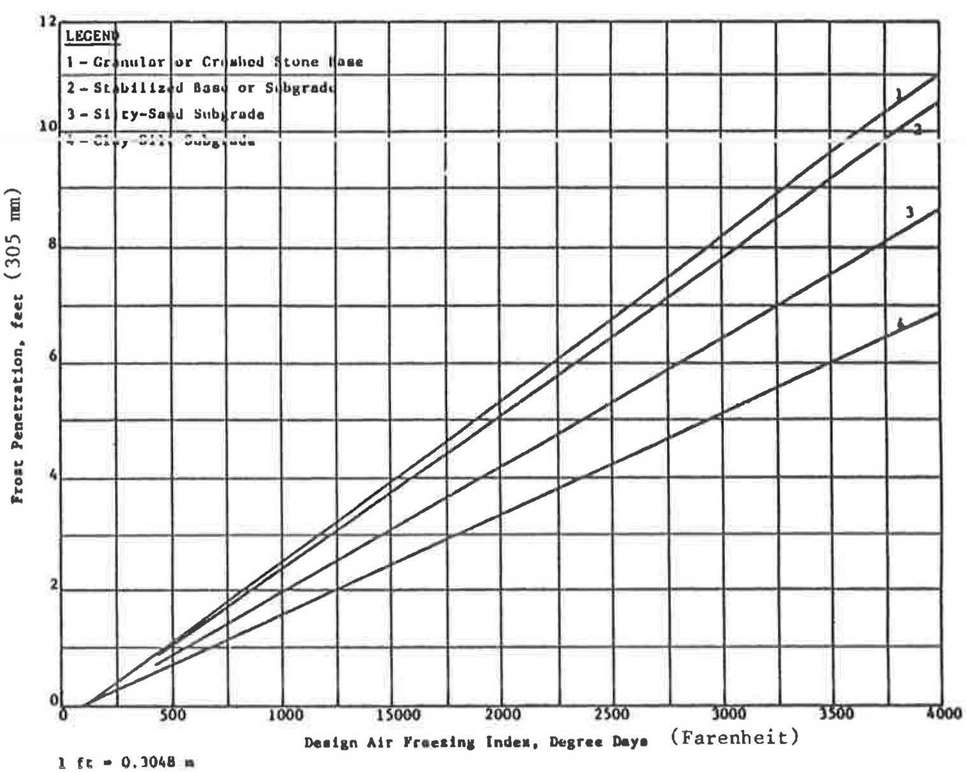
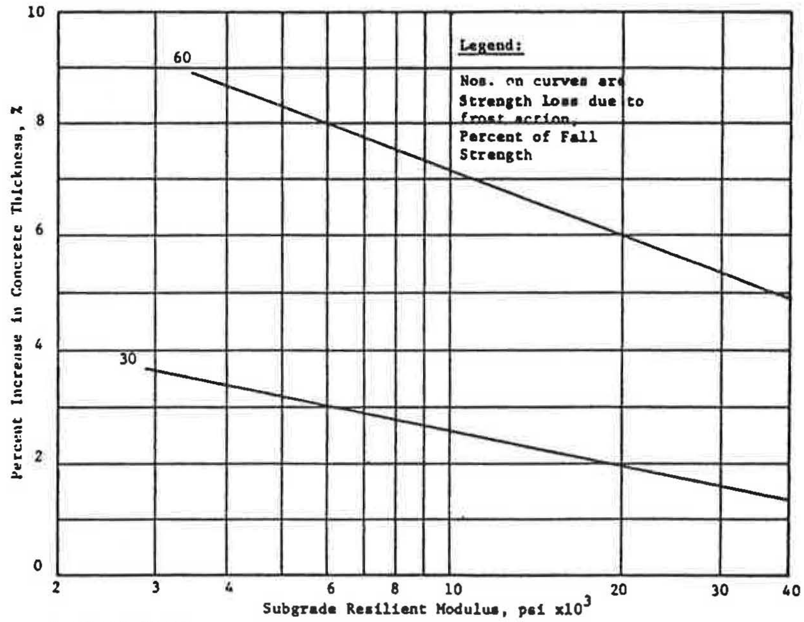
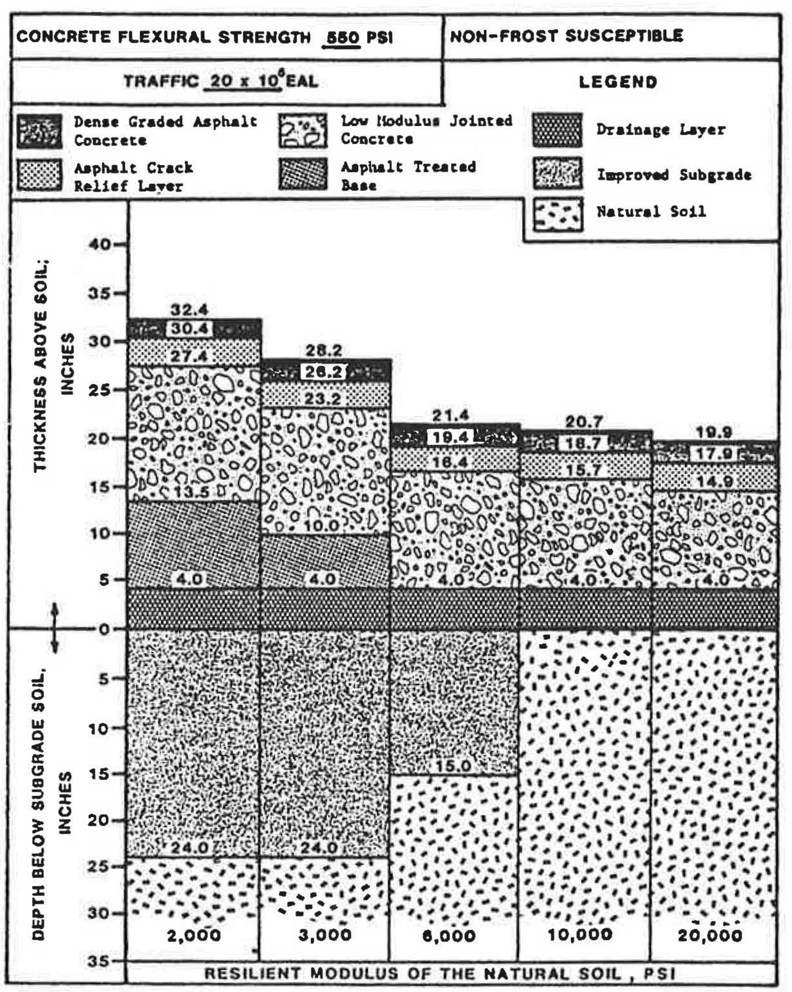


Figure 9. Increase in structural thickness of composite pavements for different levels of frost damage.



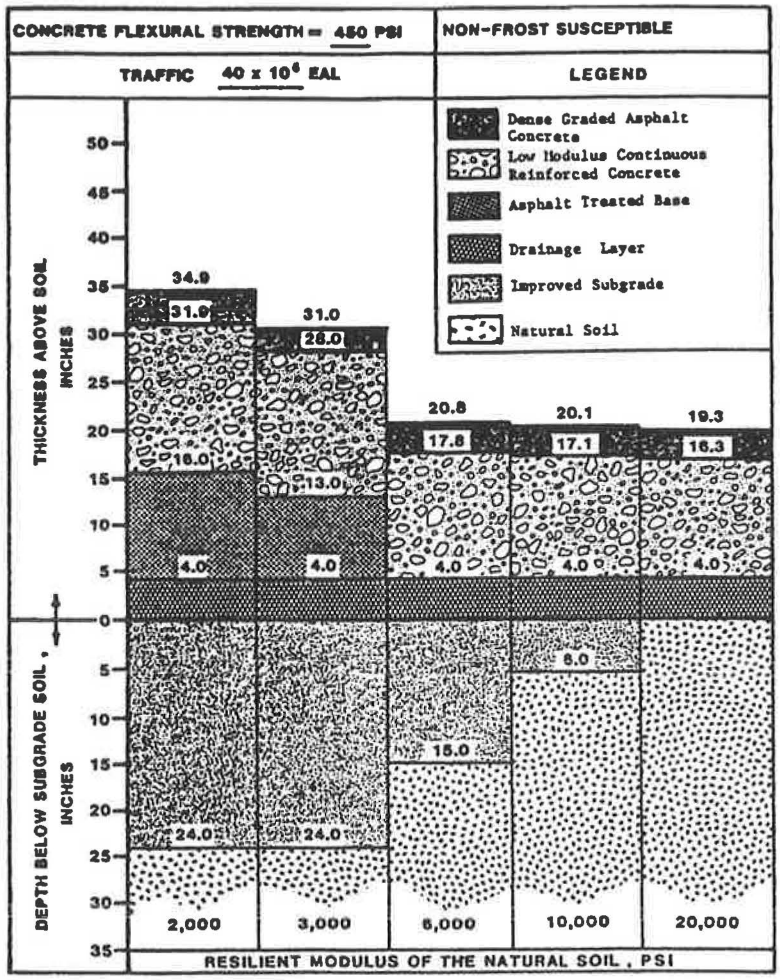
1 psi = 6.89 kPa (6.894757 kilopascals)

Figure 10. Composite pavement cross sections: low-modulus jointed concrete base.



* Filter layer located between drainage layer and underlying layers, if required.

Figure 11. Composite pavement cross sections: low-modulus CRC base.



* Filter layer located between drainage and underlying layers, if required.

In accomplishing this, some extrapolation beyond the normal range of experience was required. Because of this extrapolation, there are certain aspects of the design procedure that may not be as reliable as others. Other factors must remain under the direct decision of the engineer, and no matter how well proved the concepts are, the engineer must provide the correct input and quality control or the pavement's performance will be less than desired.

Any pavement not properly constructed will fail to provide the high level of performance required for the minimum 20-year design. Proper inspection and control to correct material or construction deficiencies must be accomplished in the field. Other factors not well established in terms of performance and of critical concern to the design engineer include low-modulus PCC durability, environmental considerations, and pavement subsurface drainage. In this study, every attempt has been made to investigate available performance data and to synthesize a reasonable and coherent design procedure that considers the effects of changing environmental and material conditions.

In conclusion, the concepts and criteria presented here are recommended for use and study in future practical field implementation by experienced design engineers to increase the reliability of this procedure and to provide additional performance data for needed revisions.

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Model Study of Anchored Pavement

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A laboratory model study of an anchored pavement is described. The objective of the study was to investigate construction problems and development of specifications for a full-scale test. Also, the model tests could be and have been used to verify the analytical model. The model pavement involved 1/20-scale anchored and conventional slabs of similar dimensions and made of aluminum, a subgrade of known properties, a container tank for the whole setup, and loading and measuring equipment. In addition, one set of tests was performed by using the anchored slab in such a way that it is not in contact with the subgrade. The open space (void) between the slab and the subgrade simulates the worst conditions of no support caused by high moisture in the subgrade due to thaw or other actions. The model test results were compared with results from finite-element analysis. The investigations confirm that an anchored slab offers distinct advantages over a conventional slab; for example, the deflections are lower and uniform compared with those from a conventional slab, and stresses in the soil are reduced and distributed more widely by rigid anchors. The ANSYS computer program can analyze such a soil-structure system and incorporate the environmental and mechanical effects.

Serious concern about the maintenance costs and agonizing delays in repairs of highways in highly urban areas raised the question of the feasibility of designing and constructing minimum-maintenance pavements. As a result of research sponsored by the Federal Highway Administration, several structural concepts have been proposed (1) for minimum-maintenance performance. These include pile support, edge stiffening, thick cellular systems, waffle-type systems, modified conventional systems, and a flex-