

CRCP DESIGN BASED ON THEORETICAL AND FIELD PERFORMANCE

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At the time the AASHO National Road Test was undertaken near Ottawa, Illinois, Continuously Reinforced Concrete Pavement (CRCP) had already been developed and was in service in several eastern, midwestern, southern, and western states. Although it was not included in the AASHO Road Test, it soon became a popular design, and within the past two decades, almost 14,000 equivalent two-lane miles of CRCP 24 feet wide have been constructed in the United States. Texas has constructed more than 3800 miles, Illinois 2700 miles, and Mississippi is the third leading user of CRCP with 1000 miles. Twenty-eight states have standard design and construction specifications for CRCP as published in the Associated Reinforcing Bar Producers-CRSI "Summary of Design and Construction Practices of Various States." In the past for highways, it has been customary to design concrete pavement based on stress of the maximum axle load, with a permissible reduction in thickness for CRCP of up to two inches. For airports, the thickness reduction has not been customarily used.

In recent years, various modified procedures have been developed and suggested for the design of CRCP for highways. These are the AASHO Interim Guide, ACI Design Procedure, Texas Design Procedure, and Illinois Design Procedure. The Federal Highway Administration does not specify the method to be used; however, reviews for federal funding compare design proposals by states with the AASHO Interim Guide. In 1972, NCHRP 1-15 "CRCP Design for Highways" was a theoretical design procedure based on field performance observations. Since then additional data has been used to update this procedure, and the University of Texas researchers have published their findings at the 1980 Transportation Research Board. In 1980 a "Highway Design Procedure for CRCP" was developed from this data by ARE, Inc. under contract to the Associated Reinforcing Bar Producers-CRSI. The basis for this design will be presented at the Second International Conference on Concrete Pavement Design. In the course of field service work and observations of CRC highway pavements throughout the United States, the Associated Reinforcing Bar Producers Accumulate statistics, use photographic coverage, and use highway research and performance reports to develop recommendations for improving CRCP

performance. This paper will include a summary of recent developments in pavement design and construction practices which can favorably influence the performance of CRCP. Emphasis will be placed on such pavement elements as the importance of specifying stabilized subbase, proper placement and arrangement of steel, vibration and consolidation of concrete, drainage practices and construction jointing details. Examples of selected state practices will be emphasized to show both favorable and unfavorable results, based on the adherence or disregard of established criteria. Background development will be given on several key design charts that give a new approach for the design of CRCP. The thickness determination chart used by AASHO has been modified to cover a range of loading conditions not previously considered, e.g., edge loading, portland cement shoulders, etc. Also, charts for determining the k-value in terms of material erodability, thickness, and stiffness will be presented.

Introduction

Background

In recent years, the rapid deterioration of highways has prompted a reevaluation of design, construction, and maintenance practices. Highway researchers and maintenance engineers are impatiently looking at ways of transferring the knowledge they have gathered on pavement performance as feedback to improve design and construction of new pavements and overlays. We have particularly learned in the past 20 years on the U.S. Interstate System that when the standards of maintenance are relaxed, vehicle operating costs will rise. Furthermore, where congestion due to inadequate capacity or frequent pavement maintenance is required, energy is wasted and user delay costs skyrocket. Thus, the need of Pavement Management Systems to enable us to consider all of the cost/benefit factors that contribute to keeping in service pavements at an acceptable performance level.

Highway and airport design and construction criteria, as they are evolving in the U.S., are coming much closer to providing reinforced concrete pavements that provide longer life and higher service-

ability at low annual cost--using energy-efficient materials and construction methods. Only by careful evaluation of pavements in service under design loading can pavement engineers refine thickness design procedures that are predictable and useful.

The pavement engineer has four basic options for designing concrete pavements: 1) jointed plain pavements, 2) jointed reinforced concrete, 3) continuously reinforced concrete pavements, and 4) post tensioned concrete. Each type has advantages and is suited to different uses and traffic conditions. Many factors affect pavement design, construction, and performance. A city engineer may choose plain pavement for streets or light traffic roads where future utility cuts and incremental paving with ready-mixed concrete using simple equipment influence choice. Similarly for medium traffic roads in urban or rural areas, the benefits of jointed reinforced concrete with fewer joints may dictate choice. Where high-speed traffic and heavy trucks predominate, CRCP will provide the best ride and serviceability at the lowest annual cost.

Objective

The objective of this paper is concerned with the refinement of design procedures for Continuously Reinforced Concrete based on theoretical studies and field performance observations. The paper will give emphasis to the thickness and reinforcement design procedures, but guidance will be provided in all areas.

Scope

The next section of this paper presents a summary of the experience acquired through the performance observations of in-service CRCP's. This experience is then applied to develop guidelines for cross-section design of a CRCP. Then the design inputs required for a rational design procedure are presented, followed by a design procedure section presenting design charts and nomographs.

Summary of Field Experience

The intent of this section is to provide an overview of the experience acquired from in-service projects in the U.S. First, a short treatise is provided on the evolution in development of CRCP concepts. Next, the experience gained in Texas and Illinois is summarized since they have constructed so many miles of CRCP, and they represent the extremes in environmental conditions in the southern and northern states.

Development of CRCP Concepts

The first use of continuously reinforced concrete pavement (CRCP) dates back to 1921 when the U.S. Bureau of Public Roads built an experimental section of CRCP on the Columbia Pike near Washington, D.C. The first significant length of CRCP came to be known as the Stilesville project constructed in 1938 by the Indiana Highway Department, west of Indianapolis on U.S. Route 40. These early projects established the basic principles of CRCP design which are still valid:

First - Continuous longitudinal reinforcement, in sufficient amount, can be depended upon to control

the width of transverse cracks.

Secondly - Randomly spaced transverse cracks held tightly closed by continuous reinforcing will not impair the structural integrity of the pavement and provide a joint-free riding surface of long-term service life.

As such, CRCP became a viable concept, and by 1980 more than 14,000 two-lane miles of pavement have been constructed, with these features:

- . virtual elimination of transverse joints except at the end of a day's pour and at structures, thereby reducing maintenance joint sealing.

- . adequate load transfer across the random cracks to eliminate faulting and provide surface continuity.

- . compatibility with modern slipform construction and tube feeding of longitudinal bars, and

- . a method to achieve and maintain a smoother pavement for higher serviceability which can be fine-textured for safety.

Texas CRCP Experience

In 1951, the Fort Worth Freeway Authority in Texas selected a CRCP design with 0.7 percent steel, based upon the behavior of the various earlier research projects in Indiana, Illinois, New Jersey, and California. This project included 4-3/4 miles of 4-lane, 8-in. thick pavement. No. 6 rail steel bars were spaced at 8-in., with No. 4 transverse bars at 24 in.

Soon after, the Fort Worth District of the Texas Highway Department built CRCP sections in 1955, 1957, and 1959. These projects were typically 8-in. thick with 0.5 percent Grade 60 longitudinal steel bars supported on preset #4 bars spaced at 30 in.

By 1979, Texas had built more than 3762 equivalent 2-lane miles of CRCP throughout the state; major urban CRCP mileage predominates near Fort Worth, Dallas, Houston, Austin, San Antonio, Amarillo, and El Paso. Over the years, modifications have been made in the design thicknesses and standards for CRCP construction. A recent (1980) change permits increased thicknesses up to 10-in., and on a special project near San Antonio 13-in. of CRCP is to be built. Texas has used its own concrete pavement design nomograph which has been developed through consultation with the University of Texas researchers, under the direction of Drs. S. R. Hudson and F. McCullough. Selected CRCP projects have been under long-term study to determine performance under a variety of soil, traffic, climatic, and drainage conditions. One of the major areas which was investigated during the course of Project 177 "Rigid Pavement Design and Rehabilitation Techniques" was the development of a comprehensive CRCP design procedure. The following sections document some of the significant developments for reinforcement and thickness.

Reinforcement Design. Report No. 177-2 summarizes the earliest CRCP study completed under the project. This was a sensitivity analysis of CRCP-1 for the major variables affecting CRCP behavior. From this study, the relative importance of these variables with regard to reinforcement and thickness was established. Specifically, Report No. 177-2, "A Sensitivity Analysis of Continuously Reinforced Concrete Pavement Model CRCP-1 for Highways," by Chypin Chiang, B. Frank McCullough, and W. Ronald Hudson, describes the overall importance of this

model and the relative importance of the input variables of the model and makes recommendations for efficient use of the computer program. It was published in August 1975. The next relevant investigation completed is summarized in Report No. 177-4. This describes the results of an experiment to investigate the effects of subbase or subgrade support loss on slab deflection distress manifestations and load transfer. Although the results of this study are closely related to slab thickness design, variations in the subgrade and subbase support have an indirect effect on the amount of reinforcing steel required. As such, the findings from this investigation became important for further developmental work which took place towards the end of the project.

Historically, the next significant development was recorded in Report No. 177-6, which reports case studies showing that higher percentages of reinforcement gave better performance with regard to failure. Specifically, CTR Report No. 177-6, "Sixteenth Year Progress Report on Experimental Continuously Reinforced Concrete Pavement in Walker County," by Thomas P. Chesney and B. Frank McCullough, presents a summary of data collection and analysis over a 16-year period. During that period, numerous findings resulted in changes in specifications and design standards. These data were subsequently used for shaping guidelines and for future construction. The report was published in April 1976.

A better understanding of the important variables in reinforcement design was obtained following the work described in Report No. 177-7; however, the next significant advance was not documented until the publication of Report No. 177-9. This report summarizes the procedure for treatment of detailed CRCP reinforcement design as incorporated into the computer program CRCP-2. This program has been functional on the Texas SDHPT computer since May 1979. Report No. 177-9, "CRCP-2, An Improved Computer Program for the Analysis of Continuously Reinforced Concrete Pavements," by James Ma and B. Frank McCullough, describes the modification of a computerized system capable of analysis of a continuously reinforced concrete pavement based on drying shrinkage and temperature drop. This report was published in August 1979. During the final two years of the project, minor improvements were made to the CRCP-2 program where required.

Finally, the latest developments in CRCP reinforcement design have been documented in Report Nos. 177-16 and 177-17. Report No. 177-16, "Nomographs for the Design of CRCP Steel Reinforcement," by C. S. Noble, B. F. McCullough, and J. C. M. Ma, presents the results of an analytical study undertaken to develop regression equations and nomographs. These are to be used as supplementary (to CRCP-2) tools in the design of steel reinforcement in continuously reinforced concrete pavement by the Texas State Department of Highways and Public Transportation at the feasibility study level. CRCP-2 should be used for detailed design. Report No. 177-16 was published in August 1979. An allied study was also finished in August 1979. Report No. 177-17, "Limiting Criteria for the Design of CRCP," by J. C. M. Ma, B. F. McCullough, and C. S. Noble, presents a set of criteria which limits values of a set of variables to be used in the design of CRCP. These criteria are to be used in conjunction with Report No. 177-16.

Finally, the major recommendation to be made with regard to CRCP reinforcement design is that both the charts discussed in Report No. 177-16 and the limiting criteria presented in Report 177-17 should be inserted in the Texas SDHPT Highway Design Division Operations and Procedures Manual, Part IV, Appendix F.

Thickness Design. Following the preliminary work done on the development of CRCP-1 and during the associated sensitivity study, the next significant advances with regard to thickness design were made as part of the study described in Report No. 177-4, which was published in August 1977. This report, "Laboratory Study of the Effect of Non-uniform Foundation Support of CRC Pavements," by Enrique Jimenez, B. Frank McCullough, and W. Ronald Hudson, describes the laboratory tests of CRC slab models with voids beneath them. Deflection, crack width, load transfer, spalling, and cracking were considered. Also described is the SLAB 49 computer program that models the CRC laboratory slab as a theoretical approach. Physical laboratory test results and corresponding theoretical solutions are compared and analyzed, and estimates of prediction accuracy are determined. The major findings of the above study were essentially that voids beneath rigid pavements have an important influence on performance and that a thicker pavement is needed in areas where voids probably exist. These would typically be over subgrades where swelling clays are present or differential settlement has been seen to occur. During the course of this investigation, it was also shown that CRCP slab performance can be adequately modelled using the SLAB 49 program.

Illinois CRCP Experience

Beginning in the late 1930's and continuing through the early 1950's, several states including Indiana, Illinois, New Jersey, California, and Texas constructed experimental CRCP, which provided the initial basic design and performance data. The incentive for the development of CRCP was the elimination of joints, since most of the distress occurs at the joints in jointed concrete pavement. The early Vandalia Road Test was constructed in the fall of 1947 on U.S. 40 principally to establish the optimum reinforcement needed to build CRCP without a prepared base course. The CRCP project consisted of about 5-1/2 miles of 22-ft. wide, 2-lane pavement that was divided into eight sections. CRCP thicknesses were 7-in. and 8-in. with 0.3, 0.5, 0.7, and 1.0 percentages of longitudinal steel. The performance on this test road was compared with the standard pavement at that time which was 10-in. reinforced pavement using a 100-ft. joint spacing placed on a 6-in. granular subbase. Follow-up reports on this project were reported by J. D. Lindsey in Highway Research Board reports the years of 1947, 1950, 1952, and 1959.

Then in 1961-62, CRCP was used on the Chicago Dan Ryan Expressway, a 14-lane roadway with high volumes of heavy trucks. In Illinois, of the total 2700 equivalent 2-lane miles of CRCP, about 2000 miles are on the Interstate. Although CRCP was not included in the Ottawa, Illinois AASHO Road Test (1956), its advantages prompted Illinois to adopt it as a standard for Interstate highway work, and the state has continued its use since the early 1960's. Numerous studies and reports have been prepared, and selected individual sections in various districts have been regularly monitored by the State DOT researchers.

Of particular interest are the recommendations which culminated from a four-year study which began in 1975 by the State of Illinois. This study and another investigation by University of Illinois researchers entitled the "performance of CRCP in Illinois" evaluated 1,230 miles of CRCP of 7-in., 8-in., 9-in., and 10-in. thickness constructed over granular and stabilized subbases in 132 projects on seven

different Interstate routes. These studies evaluated the rate of loading and measured the cumulative distress and performance of the various thicknesses. The study also compared the load-carrying capacity of CRCP with different thicknesses of conventionally reinforced pavements in the State of Illinois. The findings indicated the thicker 9-in. and 10-in. CRCP performed considerably superior to the conventional jointed concrete under conditions of extremely heavy Chicago metropolitan area truck traffic (which is reputed to be the most severe in the U.S. and the world). 10-in. CRCP could be expected to carry four times the traffic of 10-in. jointed. The accumulated 18-kip equivalent single axle loads in the truck lane ranged from 1 to 22 million. Plain or plain-doweled pavements are not used in Illinois.

The performance of the thinner 7-in. and 8-in. CRCP pavements was more varied with a higher maintenance requirement. Proposed 1979 recommendations of Illinois Task Force include extending the nomographs to include 11-in. and 12-in. CRCP thicknesses where high volumes and heavy traffic dictate, increase the amount of longitudinal steel from 0.6 to 0.7 percent of cross sectional area, and limit the Grade 60 bar size to #6 only. Other recommendations relate to construction placement techniques and longitudinal center joint controls.

In summarizing, the Illinois Task Group concluded in comparing CRCP with jointed mesh-dowel pavement:

- CRCP was the best concrete design for volumes of heavy trucks,
- CRCP was better suited for slipform construction, and
- CRCP was the best investment inch for inch for equivalent loads handled, whereas reinforced jointed pavement was better suited to urban road use where patching and utility cuts dictate, and where traffic volumes and heavy truck load frequencies were not as great. The findings that show thinner 8-in. CRCP and comparable conventional jointed concrete pavements in Illinois were grossly under-designed for higher traffic loadings tend to support the trend toward thicker designs.

Experience Applied to Cross Section Design

By examining each component in the cross section of a CRCP pavement and how it performs in service under different climatic conditions, the need for refinements in design and construction become apparent. Let us consider each pavement cross section component separately, i.e., subgrade, subbase, slab thickness, and reinforcement.

Subgrade. The Portland Cement Association has published information on the need for compacting a uniform subgrade to support concrete pavement. The same principles that apply to subgrade preparation and compaction of soils under other types of concrete are equally applicable to CRCP. Chemical stabilization with lime or cements are useful with expansive soils, and in certain climates frost control provisions may also be warranted. Experience in flat topographic areas with high moisture have shown bathtub cross sections that trap water contribute to pavement distress and should be avoided. On high-volume roads with heavy trucks, provision for longitudinal edge drains should be strongly considered to prolong pavement life where precipitation is high. Although CRCP has been successfully constructed on moderate to highly expansive clays in Texas, Idaho, Mississippi, and the Dakotas, the

serviceability may be lowered sooner on these expansive soils.

Subbase. Recent CRCP studies in Texas and Illinois reveal that not all stabilized subbases are non-erodable subbases. Depending on aggregate gradation, and percent cement or asphalt content, the resistance of subbase to erosion can vary considerably. Some states such as South Carolina, Florida, and California have specified Econocrete subbases to assure sounder, moisture-proof non-eroding support beneath the concrete. In many cases, edge underdrains may be warranted to assure lasting support and reduce hydraulic erosion of subbases.

Concrete pavement thickness determination is dependent on the assumptions of support (k-value) and particularly the durability of selected subbase. When heavy wheel loads and water conditions combine to create a pumping environment, it is vital that sufficient support extends beyond the edge of the pavement. The benefits of a concrete shoulder are also obvious and affect the assumptions for edge loading in design.

Often, design assumptions for subbase support are not realized, or support is deficient along the pavement edge due to poor compaction. There are conditions where the subbase may be adequate but drainage is poor and degradation of shoulder material contributes to pavement distress in the outer lane.

A survey of U.S. state standards for CRCP reveals that granular subbases are prohibited under CRCP in seven of 28 states that have built CRCP. FHWA published criteria on the use of subbases under CRCP seem to imply that unless a state's experience shows why "untreated" subbases have performed, stabilized subbases are indicated for good CRCP performance. CRCP should be built on a stabilized material that will not erode under severe climatic and moisture conditions. (The FAA requires that stabilized subbase be used under concrete pavements designed for heavy jet loadings.)

An obvious consideration in subbase design for heavy trafficked highways is recognition that when pavements approach their terminal serviceability or design lives, inadequate subbase is inaccessible for improvement. Certain states are now including renovation of shoulders and adding edge drainage to compensate or improve "less than desirable" subbase and support conditions, particularly at the pavement edges before the PSI is lowered. (PSI is Present Serviceability Index, a rating developed for AASHTO Road Test, Ottawa, Ill.) In future designs the stabilized subbase should be carried out beyond the pavement edge to assure that full support is provided according to design assumptions. Designs that permit the subbase and shoulders to trap surface water runoff should be avoided.

Thickness

Recent surveys of concrete pavement performance in various states indicate increased thicknesses are justified for the degree and rate of truck loadings experienced on Interstate highways. Actually, pavements in some states such as Illinois, Pennsylvania, Indiana, Ohio, and Texas have handled the traffic expected in 20 years in little more than half that time. Furthermore, the percentage of trucks and truck weights have greatly exceeded estimates and permissible loads. U.S. Congressional committees are evaluating this trend.

In addition, earlier design concepts using

interior loadings were based on load placement studies in the early 1950's that indicated wheel loads were away from the edge. Unfortunately, these studies were conducted on pavements without paved shoulders, thus the extensive use of paved shoulders with the Interstate Program created a new condition. Truckers could permit their tires to be near the edge without fear of losing control due to an edge dropoff. Thus, edge loadings were created for pavements designed with interior loading conditions.

The proposed thickness design procedure for CRCP now recognizes that these continued increases in loading and severity require thicker pavements of one inch or more than previously used on roadways. These adjustments are based on traffic loadings and assumption that these loads travel closer to free pavement edges.

CRCP Design Inputs

Material Properties

The properties of portland cement concrete and reinforcing steel are important input variables to the design procedure.

Portland Cement Concrete. The important material properties of portland cement concrete which are required as inputs to this design procedure are 1) strength, 2) modulus of elasticity, 3) shrinkage, and 4) thermal coefficient of expansion. These properties are not independent of each other, and care must be taken by the designer to select a consistent set of properties representative of the mixture to be used. Approximate relationships between material properties are presented as a guide to the selection of a consistent set of properties.

Two measures of concrete tensile strength are used in separate portions of this design procedure. The modulus of rupture derived from a beam flexural test with third point loading is used for determination of the required slab thickness. This test is covered under ASTM C 78 and AASHTO T-97 test specifications. The steel reinforcement design is based on the tensile strength derived from the indirect tensile test. The indirect tensile test which is performed on cylindrical specimen is covered under ASTM C 496-71 and AASHTO T 198-74 test specifications. The 28th-day value should be used for the above strengths.

An approximate relationship between these two strengths has been developed based on aggregate type. This relationship is:

$$f_t = R_T f_r$$

where

f_t = indirect tensile strength, psi

f_r = modulus of rupture, psi, and

R_T = aggregate factor

Table 1 summarizes values of R_T for concrete made from different coarse aggregate types.

The modulus of rupture is used to define a working stress which is used in the thickness design. The working stress is simply 0.75 times the modulus of rupture.

The modulus of elasticity is used in the thickness determination. A guide to selecting a modulus of elasticity which corresponds to the modulus of

Table 1. Aggregate factors for relationship between flexural and indirect tensile strength.

Aggregate	R_T
Gravel	5/8
Limestone	2/3
Light Weight	3/4

rupture, also used in the thickness determination, is given in Table 2. The test for this value is covered in ASTM C-469.

Table 2. Concrete modulus of elasticity corresponding to the modulus of rupture and working stress.

Modulus of Rupture, psi	Working Stress, psi	Modulus of Elasticity, psi
400	300	2.9×10^6
500	375	3.3×10^6
600	450	3.7×10^6
700	525	4.2×10^6
800	600	4.8×10^6
900	675	5.6×10^6

Drying shrinkage due to loss of water is a significant factor in the reinforcement design. The rate of increase in shrinkage decreases with age. The value of shrinkage at 28 days is used for the design shrinkage value. Table 3 may be used as a guide in selecting a value of shrinkage corresponding to the indirect tensile strength used in the reinforcement design. The thermal coefficient of expansion for PCC varies with such factors as water-cement ratio, concrete age, richness of the mix, relative humidity and type of aggregate. Recommended values of thermal coefficient are listed in Table 4 as function of aggregate type.

Table 3. Approximate relationship between shrinkage and indirect tensile strength of portland cement concrete

Indirect Tensile Strength, psi	Shrinkage, in/in
≤ 300	0.0008
400	0.0006
500	0.00045
600	0.0003
$700 \geq$	0.0002

Reinforcement Steel. For reinforcement steel design, yield strength (usually 60,000 psi) is used for longitudinal reinforcement, and nomographs permit selecting appropriate bar sizes of #4, #5, #6, or #7. For transverse reinforcement, working stress is set at 0.75 yield and usually #4 bars are specified. As will be discussed, a higher permissible stress appears warranted for longitudinal bars.

Table 4. Recommended value of the thermal coefficient of PCC as a function of aggregate types.

Type of Coarse Aggregate	Concrete Thermal Coefficient ($10^{-6}/^{\circ}\text{F}$)
Quartz	6.6
Sandstone	6.5
Gravel	6.0
Granite	5.3
Basalt	4.8
Limestone	3.8

The thermal coefficient of steel may be assumed to be $5 \times 10^{-6} \text{ in/in}/^{\circ}\text{F}$ unless specific knowledge is available.

Subbase Material. For subbase material, the resilient modulus is required for determination of the composite k-value on top of the subbase layer. This design procedure uniquely uses an empirically and theoretically derived loss of support factor which ranges from 0 representing "no loss" to 3 for a "high loss" material. No tests are yet available, so these are assigned by judgment from a table of different subbase types. The designer should recognize these losses may be the result of erosion on soil movement. Both bases produce voids beneath the pavement producing a loss of slab support.

Environmental Characterization

Environmental effects such as range of temperature drop and precipitation are used in computing steel stress. The calculated temperature drop is the difference between average concrete temperature at month of construction to average low temperature for coldest month. The nomographs permit a range between 35°F and 100°F with some latitude for extrapolation.

Traffic

Traffic loading for design is expressed in terms of 18 kip equivalent single axle load (ESAL) applications. The accumulated 18 kip ESAL over the design period are simply the annual counts multiplied by design period years. Many agencies have detailed procedures for predicting the traffic loadings; thus, we will not elaborate on this.

The suggested ranges for various design conditions if information is not available are:

Average Annual 18 kip ESAL's	Trucks	Highway Classification
2×10^6	Heavy truck traffic	Major urban expressway, major truck route, major highway (6 lanes, both directions)
1×10^6	Normal truck traffic	Typical Interstate highway, major rural highways, (4-6 lanes, both directions)
50,000	Light truck traffic	Low truck traffic, frontage roads, low volume rural highways

The charts are based on the traffic loadings in the design lane, so corrections will be required if in another form.

Concrete Tensile Stress--Design Load

A nomograph, Figure 1, is provided to evaluate the tensile stress in pavements of various thicknesses for different k-values and moduli.

CRCP Design Procedure

The input information developed in the previous section may be used with the design charts presented in this section to develop a cross-section design. Specific charts are provided for subbase, concrete thickness, and reinforcement. In addition, guidelines are given for construction control joints and terminal joints.

This new CRCP design procedure has evolved from performance data of CRC pavements observed in various regions of the U.S., particularly the southern, southeastern, and northern states. Essentially, it is a thickness design procedure, and the nomographs presented will permit selection of subbase type, concrete material, percentage of steel, bar size and thickness determined for temperature extremes, traffic and environmental climate, and moisture conditions. It permits the trial of various combinations of subbase materials and pavement properties to achieve the most economical section for the design service life.

Subbase Design

The modulus of support or reaction k-value must be evaluated for the existing material. This value can be determined with plate load tests or through correlation with other soil tests. Based on knowledge of materials and costs in a particular locality, the designer should select for trial one or more preliminary subbase types and thicknesses. The information may be used to establish preliminary values or ranges of stiffness (modulus of elasticity) and the support loss factor. The choices of subbase types will depend on the availability of local materials as well as the cost of stabilizing agents and materials processing, such as selective grading for natural subbases or mixing for stabilized materials.

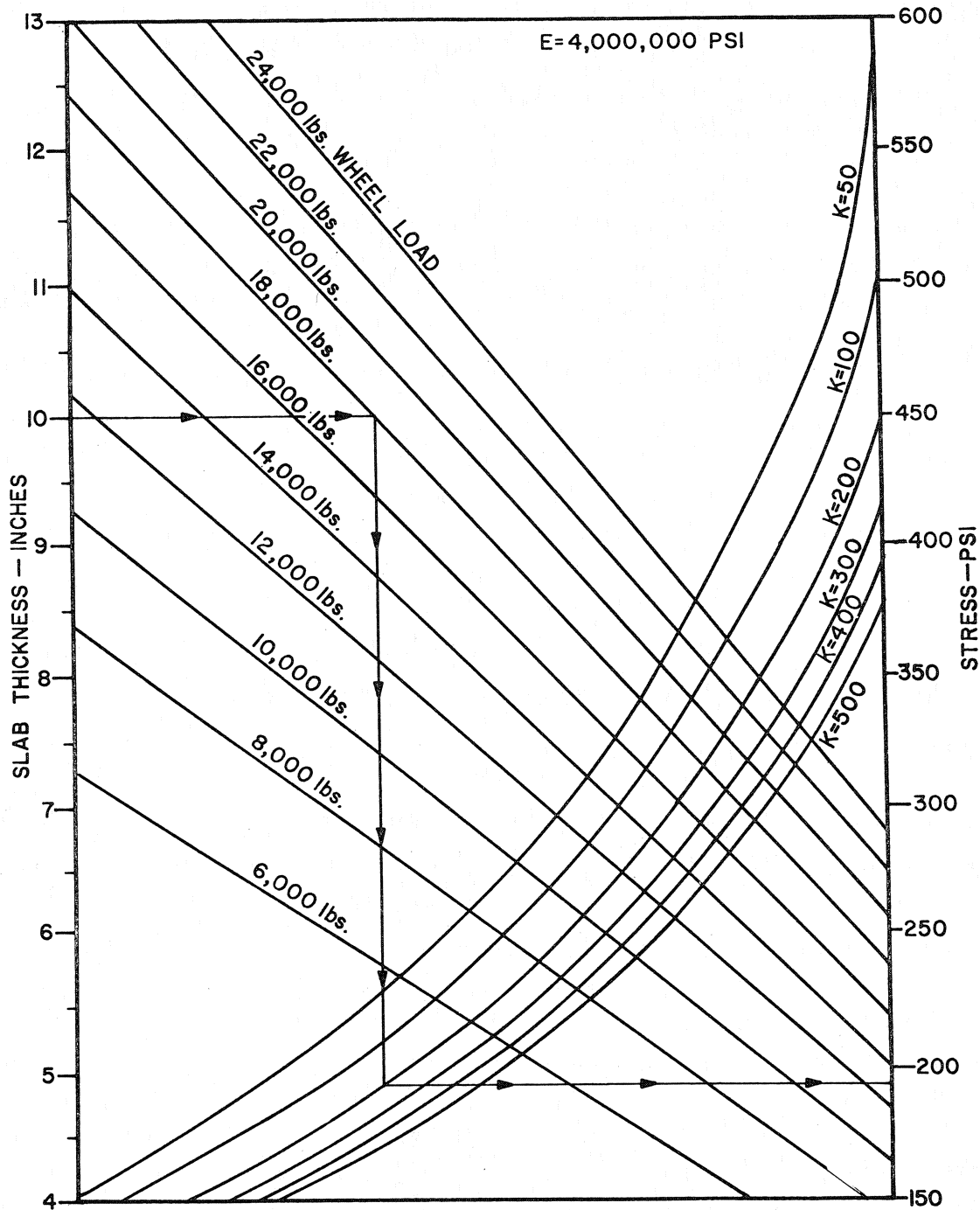
The sequence of design is predict a composite k-value immediately below the slab considering the natural soil support and the thickness and load support character of the subbase material. The composite value is then corrected for possible loss of support.

The influence of material erodability on the long-range characteristics of subbase support may be evaluated by using Figure 3. The composite k-value from Figure 3 is projected from horizontal axis to the appropriate erodability factor of the subbase material. The design k-value will always be equal to or less than the layered k-value, with the reduction depending on the material quality.

The design chart for evaluating the effect of the layers in a pavement structure is shown in Figure 2. The material parameters required in this analysis are the stiffness of the subbase material and the modulus of subgrade reaction. The designer begins with the subbase thickness and projects the corrected k-value at the top of the subbase.

If more than one material is being used for the

Figure 1. Wheel load tensile stress nomograph.



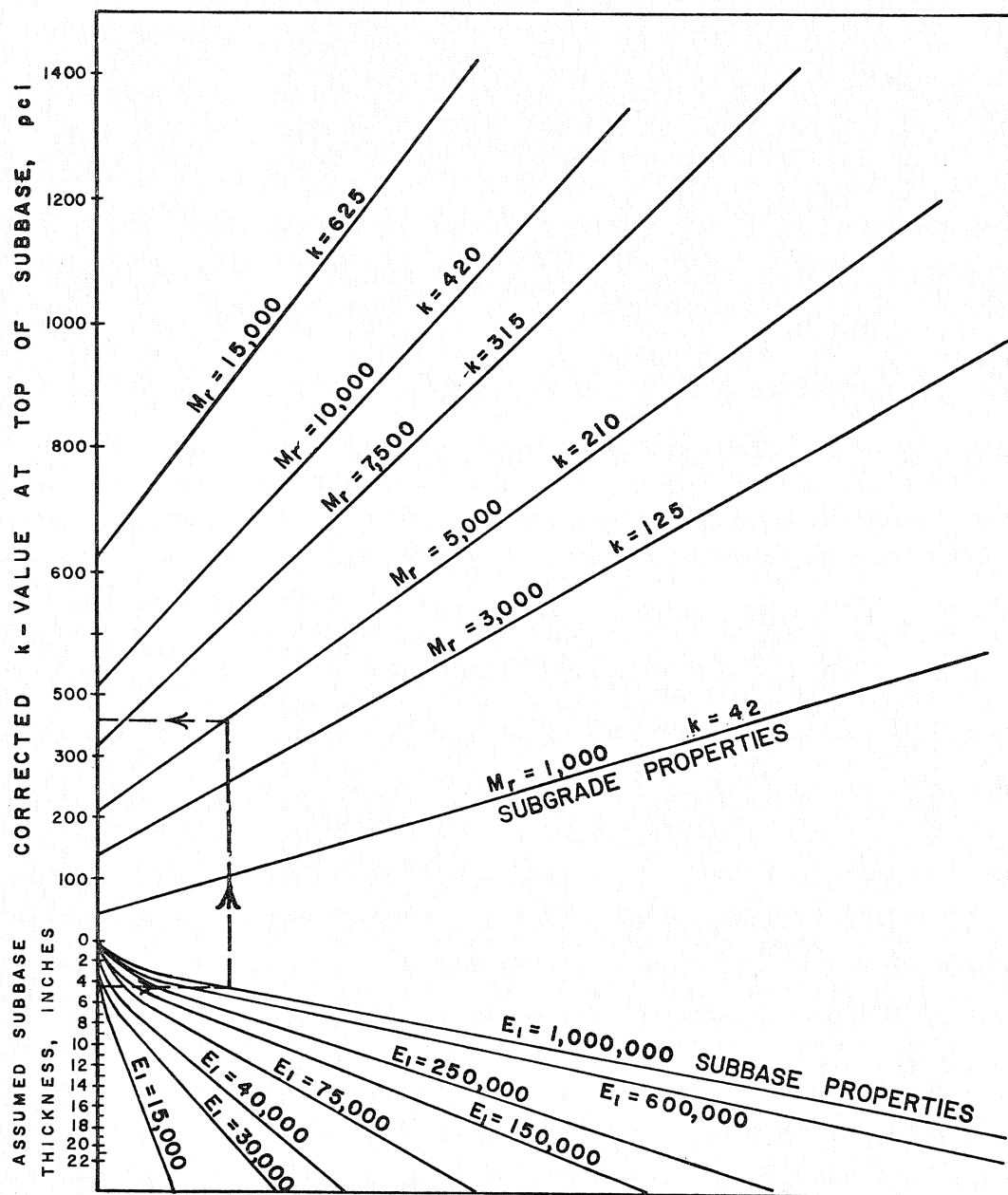
subbase layer, the designer may take this into account by applying this procedure for each layer. The first time through gives the corrected support value at the top of the first layer. With this value and the thickness and stiffness of the next layer, a new k -value at the top of the next layer is determined. This process is repeated until the k -value is immediately below the slab.

CRCP Thickness Determination. Material properties for concrete, steel, subbase, traffic, and other input data are used to enter the design nomographs to determine trial thickness. Using various

trial thicknesses of subbase and CRCP will enable the designer to balance cost between each subbase and CRCP pavement thickness for the environmental conditions and traffic loadings.

On the pavement thickness nomograph (Figure 4), values for traffic, ESAL, and concrete working stress (for interior or pavement edge stress design conditions) are projected to turning line No. 1. Next, k -values for selected trial subbases and the concrete modulus of elasticity are extended through turning line No. 2. Pavement thickness is solved for by connecting points between turning lines 1 and 2. Economic considerations and material costs are used to adjust inputs on which design thickness

Figure 2. Chart for adjusting k-value for effect of subbase layers.



is dependent. On the working stress scale the interior load condition may be used for interior lanes where edge loads may never be expected. Generally, it is recommended that the edge loading scale be used.

CRCP Longitudinal Design

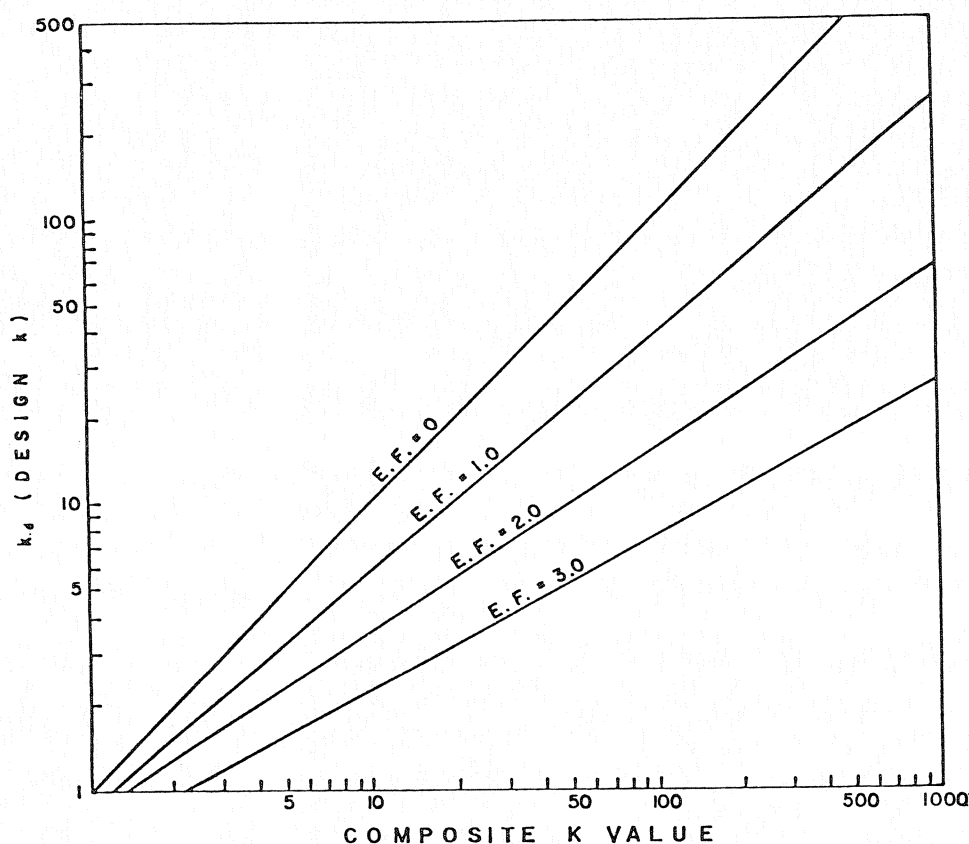
The longitudinal reinforcement is used to control cracks which form in the pavement due to volume change in the concrete. It is the restraint of the concrete due to the steel reinforcement and subbase friction which causes the shrinking concrete to crack. A balance between the tensile properties of the concrete and reinforcement must be achieved to cause the pavement to respond in a satisfactory manner. It is the evaluation of this interaction

which forms the basis of reinforcement design.

To determine levels of steel reinforcement for a CRC pavement, limits on acceptable levels of crack spacing, crack width, and steel stress are established which minimize distress manifestations in this pavement type. These levels are based on theoretical considerations and field performance studies. Limiting levels are then used to estimate the required percentage of reinforcement which will cause the pavement to satisfactorily perform under anticipated environmental and vehicular loading conditions.

Crack Spacing. Limits placed on crack spacing are derived from consideration of spalling and punchouts. A maximum desirable crack spacing is derived from a correlation between crack spacing and

Figure 3. Correction of k-value for subbase erodability.



incidence of spalling. A maximum crack spacing limit for use in design of 8.0 ft. is recommended. A minimum desirable crack spacing is derived from consideration of the effect of slab length on the formation of punchouts. A limiting value on the minimum crack spacing of 3.5 ft. is recommended for use in this design procedure. These criteria may be adjusted for effects of slab thickness and other considerations and used in Figure 5 to determine a percent steel working left to right.

Crack Width. The magnitude of the crack width influences spalling and water infiltration into the pavement. The limiting criteria on crack width is derived from consideration of spalling. The primary spalling mechanisms have been attributed to the combination of stresses resulting from environmental and vehicle loading. Crack width, which is a function of temperature-dependent horizontal stresses has been correlated with spalling. A value of 0.040 in. is recommended for the pavement at its lowest temperature. This value is an extrapolation of measured values at summer temperatures on pavements giving satisfactory performance.

Steel Stress. In addition to the limits on crack spacing and width, the conventional limit on steel stress is 0.75 the yield point. Because many miles of CRC pavements have performed satisfactorily even though the steel stress was predicted to be above the yield point consideration, this criteria and allowance for a small amount of permanent deformation seems warranted and is suggested as a function of rebar size and concrete strength. The required

steel percentage to satisfy the steel stress criteria may be derived from Figure 7.

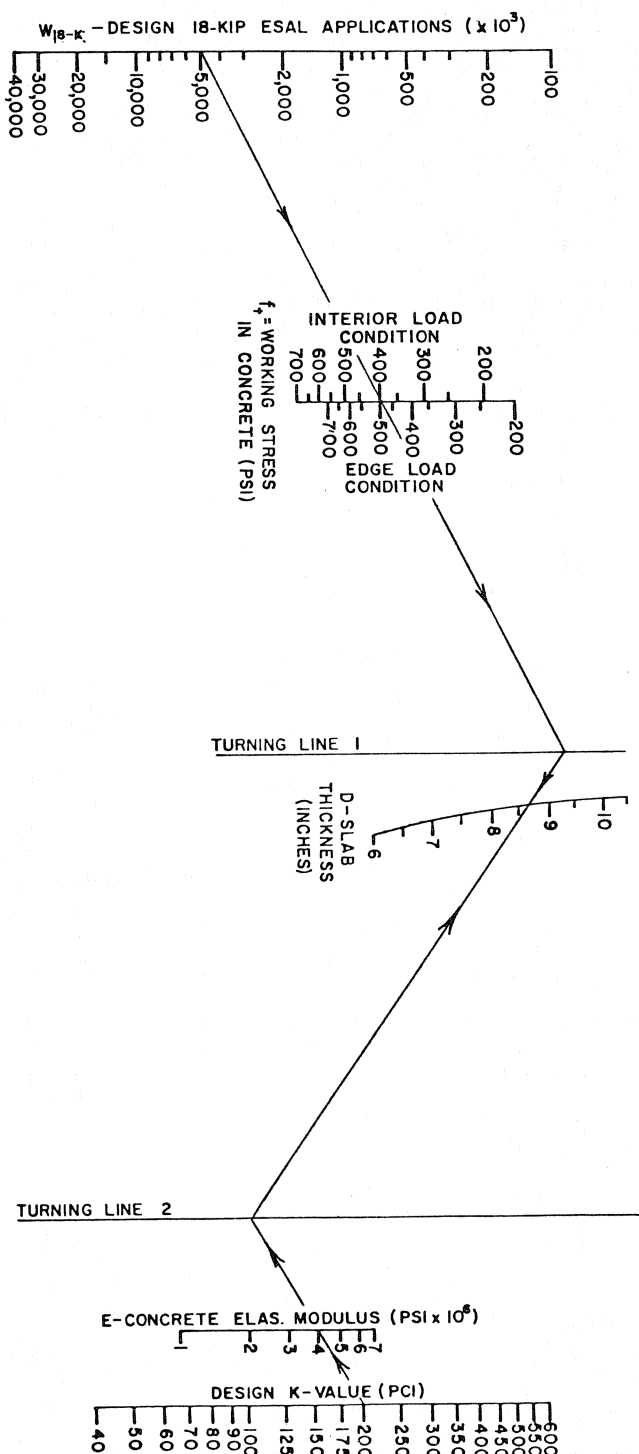
Optimization. The final selection of steel reinforcement should satisfy the criteria for all three factors. Assuming these limits are met, then one or the other may be given more weight. For example, in a northern state where de-icing salts are used, the crack width criteria may assume more importance. Whereas, in a dry area subject to large temperature changes, the steel stress criteria may be of prime importance.

CRCP Transverse Steel Design. The design of the transverse steel in CRCP is based on the subgrade (subbase) drag theory. It is dependent on the pavement thickness, width of lanes tied together, subbase friction factor, and an estimated 0.75 percent working stress of steel. The design steel percentage will keep "chance" longitudinal cracks closed. Transverse steel is usually recommended where frost susceptible or expansive soils exist.

Construction Control Joints

Longitudinal Center Joints. As in conventional concrete, tiebars are used to keep the longitudinal slabs together or unite multiple lanes. Usually, Grade 40, #4 bars are specified at a 30-inch spacing, depending on transverse steel used. State standards vary on tiebar spacings.

Figure 4. Thickness design nomograph for CRC Pavement.



Transverse Construction Joints. Normally, supplemental bars, about 6 ft. in length and of the same size are added between existing longitudinal bars. They are balanced across the header to strengthen the joint constructed at the end of a day's placement. Longitudinal steel is continued through the header at mid-depth to permit lap splicing for continuity on the next day's work.

Details. Refer to U.S. State Standards for the CRCP provisions of other pavement details and special quality concreting procedures which must be adhered to if design provisions are to be achieved and attain best CRCP performance.

CRCP Terminal Joints.

Attention is invited to TRB Special Report #173, "Design of Terminals for Rigid Pavements to Control End Movements: State of the Art." This publication reviews the existing literature and design criteria for rigid pavement terminals and gives the results of a survey of the United States regarding their current practices including the types of end treatment that are being used, their construction and maintenance costs and general performance. Because CRCP end movement is confined to several hundred feet at ends, restraint or accommodation of end movement of about 2 in. is needed. There are two design options available to restrain or provide for the end movements at bridge approaches, or when CRCP abuts other pavements. Either anchor lugs or the wide flange beams ("Burdell" joint) are used to accommodate movement.

Anchor lugs are used at the end of pavements to restrain CRCP end movement by developing the passive resistance of the soil. Highway experience has shown that these are not fully effective and are limited to restraining only 50 percent of the end movement. The balance of movement must be accommodated by the adjacent pavement or structure through the use of additional expansion joints. It is essential that the reinforcing steel between the anchor and the pavement slab above the anchorage area is adequate to permit shear transfer into the lug assemblies. Under normal conditions, the restraint of the end movement is not increased by using more than three transverse lugs, constructed in trenches below the slab.

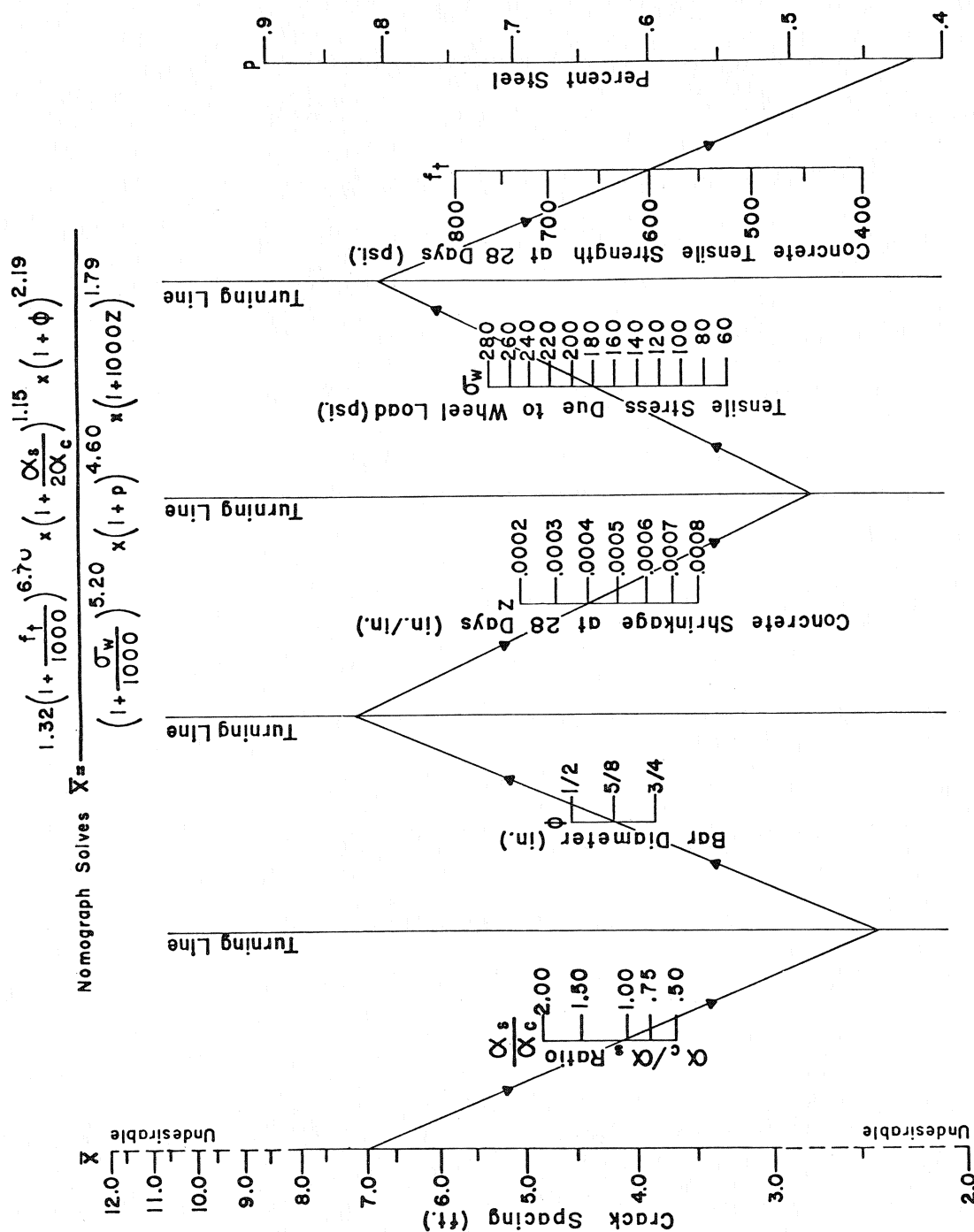
A wide flange beam joint is cast in a reinforced concrete sleeper slab that supports the ends of the abutting pavements. End movement is accommodated by a compressible material placed on the side of the web adjacent to the CRC pavement. This type of joint provides excellent load transfer, a smooth riding transition, and requires very little maintenance. The weight of the WF section should be selected to resist fatigue under heavy truck loadings.

Of states that have built more than 100 two-lane miles of CRCP, eleven have used anchor lugs and the other eleven, the wide flange beam. In Texas, the Fort Worth District successfully constructs CRCP without provision for restraint between the pavement and bridges. The TRB Special Report #173 has revealed no superior method of terminal treatment in terms of performance or total cost.

Summary and Conclusion

Based on the observations of in-service CRC pavements representing a range of environmental conditions, a national design procedure has been developed and presented in this paper. In addition, basic concepts to be applied in cross section design are discussed. The authors conclude that the application of these principles should result in pavements for high traffic volume roads that provide excellent riding quality and minimum maintenance.

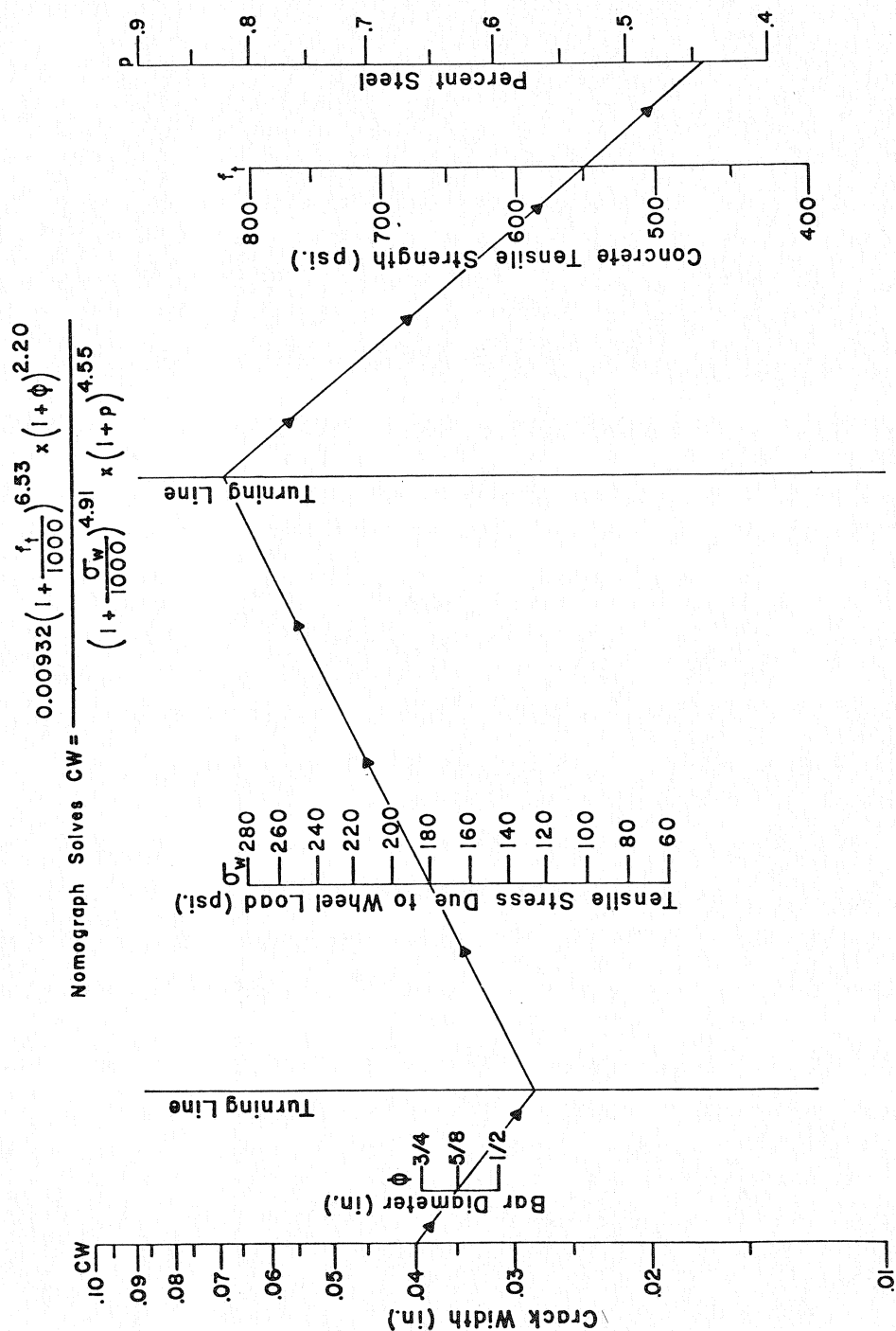
Figure 5. Percent longitudinal reinforcement to satisfy crack spacing criteria.



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Figure 6. Minimum percent longitudinal reinforcement to satisfy crack width criteria.



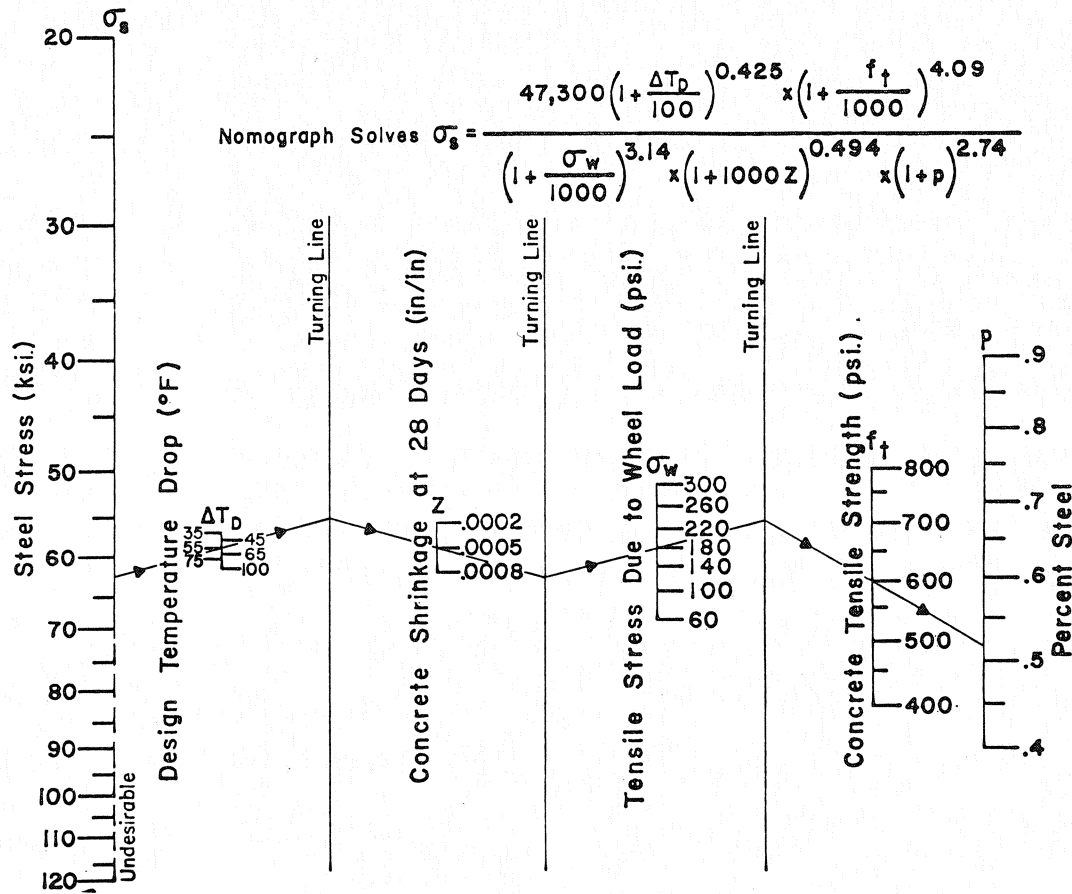
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Figure 7. Minimum percent longitudinal reinforcement to satisfy steel stress criteria.



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