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16. Abstract

The effect of coarse-aggregate type on CRCP performance is analyzed in this report by using laboratory data and condition survey information in conjunction with design equations and a distress-prediction model for CRCP. Three different approaches were followed to estimate thickness equivalencies for continuously reinforced concrete pavements constructed with the two coarse aggregates most commonly available in Texas: crushed limestone and siliceous river gravel. The first approach is based on the AASHTO equation for design of rigid pavements, which can also be used for jointed concrete pavements. The second and third methods rely on models developed through statistical analyses of CRCP condition survey data collected in the State of Texas. Condition survey information shows that, for similar conditions, limestone CRC pavements exhibit less distress than CRCP pavements constructed with siliceous river gravel. A similar observation was made for thickness equivalencies obtained; i.e., less slab thickness than siliceous river gravel.

Findings developed herein could be used to determine approximate equivalent thicknesses for the two aggregate types considered in this study if there is no need for a detailed analysis. Additionally, by using the recommended thickness equivalencies, the contractor could have enough information to estimate costs of construction of a CRCP section when he is allowed to employ either limestone or siliceous river gravel coarse aggregate. Examples for the application of equivalent thicknesses are provided in order to facilitate the implementation of the results of the various analyses carried out in this report.

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THE EFFECT OF COARSE-AGGREGATE TYPE ON CRCP THICKNESS

by

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Gerald B. Peck

Research Report Number 249-7

Implementation of Rigid Pavement Overlay and Design System
Research Project 3-8-79-249

conducted for

Texas State Department of Highways
and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

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PREFACE

Research Report 249-7 presents the development of thickness equivalencies between limestone and siliceous river gravel CRC pavements. A procedure to determine equivalent thicknesses when these two coarse-aggregate types are used is provided and their effect on the performance of CRC pavements is discussed. This study was carried out as a special topic in Research Project 3-8-79-249, "Implementation of a Rigid Pavement Overlay and Design System," which is sponsored by the Texas State Department of Highways and Public Transportation (SDHPT).

We express our appreciation to the staff of the Center for Transportation Research of the University of Texas at Austin, in particular to Lyn Gabbert who was in charge of typing the different versions of this report. Likewise, we acknowledge the cooperation of the personnel of the Texas SDHPT.

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LIST OF REPORTS

Report No. 249-1, "Improvements to the Materials Characterization and Fatigue Life Prediction Methods of the Texas Rigid Pavement Overlay Design Procedure," by Arthur Taute, B. Frank McCullough, and W. Ronald Hudson, presents certain improvements to the Texas Rigid Pavement Overlay Design Procedure (RPOD2) with regard to materials characterization and fatigue life predictions. March 1981.

Report No. 249-2, "A Design System for Rigid Pavement Rehabilitation," by Stephen Seeds, B. Frank McCullough, and W. Ronald Hudson, describes the development, use and applicability of a Rigid Pavement Rehabilitation Design System, RPRDS, developed for use by the Texas State Department of Highways and Public Transportation. June 1981.

Report No. 249-3, "Void Detection and Grouting Process," by Francisco Torres and B. Frank McCullough, presents the results of an experiment and a theoretical analysis to determine an optimum procedure for detecting voids beneath CRC pavements. February 1982.

Report No. 249-4, "Effect of Environmental Factors and Loading Position on Dynaflect Deflections in Rigid Pavements," by Victor Torres-Verdin and B. Frank McCullough, discusses several of the factors that affect Dynaflect deflections in rigid pavements and provides a recommended procedure for Dynaflect deflections measurements which can be implemented in the rigid pavement overlay design procedures. February 1982.

Report No. 249-5, "Rigid Pavement Network Rehabilitation Scheduling Using Distress Quantities," by Manuel Gutierrez de Velasco and B. F. McCullough, presents the development and application of a computer program, PRP01, to prioritize and schedule a set of rigid pavements for rehabilitation within a specified time frame and budget constraints. August 1982.

Report No. 249-6, "Design Charts for the Design of ACHM Overlays on PCC Pavements Against Reflection Cracking," by Alberto Mendoza Diaz and B. F. McCullough, presents the development of a series of nomographs and charts for use by the Texas State Department of Highways and Public Transportation as a supplementary tool in the design of Asphalt Concrete Hot Mix (ACHM) overlays on Portland Cement Concrete (PCC) pavements against reflection cracking. August 1983.

Report No. 249-7, "The Effect of Coarse-Aggregate Type on CRCP Thickness," by Victor Torres-Verdin, B. Frank McCullough, and Gerald B. Peck, describes the effect of coarse aggregate type on the performance of CRC pavements and presents the development of thickness equivalencies between a limestone and a siliceous river gravel CRCP. November 1983.

ABSTRACT

The effect of coarse-aggregate type on CRCP performance is analyzed in this report by using laboratory data and condition survey information in conjunction with design equations and a distress-prediction model for CRCP. Three different approaches were followed to estimate thickness equivalencies for continuously reinforced concrete pavements constructed with the two coarse aggregates most commonly available in Texas: crushed limestone and siliceous river gravel.

The first approach is based on the AASHTO equation for design of rigid pavements, which can also be used for jointed concrete pavements. The second and third methods rely on models developed through statistical analyses of CRCP condition survey data collected in the State of Texas.

Condition survey information shows that, for similar conditions, limestone CRC pavements exhibit less distress than CRC pavements constructed with siliceous river gravel. A similar observation was made for thickness equivalencies obtained; i.e., less slab thickness than siliceous river gravel.

Findings developed herein could be used to determine approximate equivalent thicknesses for the two aggregate types considered in the study if there is no need for a detailed analysis. Additionally, by using the recommended thickness equivalencies, the contractor could have enough information to estimate costs of construction of a CRCP section when he is allowed to employ either limestone or siliceous river gravel coarse aggregate.

Examples for the application of equivalent thicknesses are provided in order to facilitate the implementation of the results of the various analyses carried out in this report.

KEYWORDS: Continuously reinforced concrete pavements (CRCP), coarse-aggregate type, thickness equivalencies, condition surveys.

SUMMARY

The considerable effect of the coarse-aggregate type on the crack pattern developed in a CRCP has not been fully accounted for in the design-construction process. Among the principal properties of concrete that vary with coarse-aggregate type are the modulus of elasticity, the coefficient of contraction and expansion, and the tensile strength. These properties, in turn, influence CRCP performance. However, the selection of coarse aggregate type is often left to the contractor without evaluating the consequences of using an aggregate whose properties were not considered in the design stage.

In order to illustrate the variation of CRCP performance with the two coarse-aggregate types most often used in Texas, i.e., crushed limestone and siliceous river gravel, typical values of the physical properties of concrete produced with these two aggregates were selected from laboratory results.

Three different approaches were used to estimate thickness equivalencies between a limestone and a siliceous river gravel CRCP. In the first approach, the AASHTO equation for design of rigid pavements permitted the development of equivalent thicknesses for both CRCP and JRCP. The second and third approaches rely on a design equation and a distress-prediction model, respectively, derived from CRCP condition survey data collected in the State of Texas.

The theoretical analyses described in this report and laboratory results both agree with the observed performance of CRCP built with these two coarse aggregate types, that is, for similar conditions, generally less distress has been observed in limestone CRCP.

Thickness equivalencies between a limestone and a siliceous river gravel CRCP are provided in Chapter 5, along with examples of their application. A detailed description of the development of the obtained equivalent thicknesses is presented in Appendix A.

IMPLEMENTATION STATEMENT

Establishment of thickness equivalencies between a limestone and a siliceous river gravel CRCP was attempted by means of three different approaches. The recommended equivalent thicknesses were derived from the two methods that are based on condition survey data gathered throughout the State of Texas.

It is recommended that the difference in CRCP performance attributable to the coarse-aggregate type be taken into account if the contractor is allowed to select the coarse aggregate. This variation in performance can be approximately estimated by applying the thickness equivalencies developed in this report.

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CHAPTER 1. INTRODUCTION

BACKGROUND

Texas State Department of Highways and Public Transportation has 7,000 lane miles of CRCP currently in service, and, at the present time, the design plans call for the construction of many road miles of CRCP overlay, and of new pavements. Essentially, the design and construction of CRCP are based on the premise that the concrete volume changes are accounted for by a random occurrence of transverse cracks that are allowed to develop, as a result of shrinkage and temperature changes, in lieu of the more conventional transverse joints dowel system. The movement at the cracks is minimized by longitudinal steel that is placed in the slab to insure a narrow crack width. Thus, the crack pattern, involving the crack spacing and the crack width, is one of the most important physical aspects of the design of CRCP.

Unfortunately, the substantial effect of the coarse aggregate on the crack pattern developed in a CRCP has not been fully recognized in the design-construction sequence. The principal physical properties of concrete that vary with coarse-aggregate type are the modulus of elasticity, the coefficient of contraction and expansion, and the tensile strength, and all of these, in turn, influence CRCP performance.

In the past, it was common practice to design and construct continuously reinforced pavements without taking into account the variation in concrete properties that may be attributed to use of different coarse aggregate types.

In 1981 as a result of the findings recommended in Report 177-22F, "Summary and Recommendations for the Implementation of Rigid Pavement Design, Construction and Rehabilitation Techniques," a new design procedure was issued by the SDHPT Highway Design Division that permits a more rational analysis of all the factors influencing CRCP performance (Ref 15). Although the design process now recognizes the performance difference of the coarse-aggregate types, the selection of coarse-aggregate types used during construction is left to the contractor by the present specifications (Ref 16). Hence, as long as the aggregate meets the gradation and physical requirements, the basic assumption is that all aggregates are equivalent in performance and thus, are acceptable. However, field performance has demonstrated that the pavements constructed with different coarse-aggregate types exhibit a substantial difference in performance life, even though it is assumed that they will have the same life.

At the present time in Texas, most of the concrete pavements are constructed with aggregates in the basic categories of crushed limestone and siliceous river gravel. During the competitive bidding process, a contractor generally selects the aggregate type, based on competitive prices received from the various aggregate suppliers. The contractor will then construct the slab thickness required in the project plan with the coarse aggregate of his own choice even though field performance indicates this is not a realistic approach.

OBJECTIVE

The objective of this report is to document the substantial variation of CRC pavement performance in Texas, as a function of coarse-aggregate types, using laboratory and field performance data. The intent is that the specifications and preparation procedure take into account the difference in performance predicted by the current Texas SDHPT pavement design procedure.

STUDY PLAN

First, typical values of the physical properties of concrete produced with two different coarse-aggregate types, limestone and siliceous river gravel, were selected from laboratory results.

Secondly, the AASHTO equation for design of rigid pavements was used to compute thickness-equivalency factors for both types of CRCP. An alternate approach based on Report 177-7, " Continuously Reinforced Concrete Pavement: Structural Performance and Design/Construction Variables," served to verify the thickness equivalencies obtained from the first method. A third method that considers a distress-prediction equation was used as an additional approach. This distress-prediction equation was derived from regression analyses made on data gathered in condition surveys throughout the State of Texas.

Findings from the theoretical analysis in conjunction with observed performance illustrate the significance of the concept of thickness equivalencies for continuously reinforced concrete pavement built with the above-mentioned coarse aggregates for various support conditions.

SCOPE OF THE REPORT

The scope of this report encompasses the development of thickness equivalencies between a limestone and a siliceous river gravel CRCP. These two coarse aggregates are the types most commonly used in Texas.

Various design parameters representative of the conditions encountered in the state are used in this study.

Chapter 2 is devoted to a discussion of the effect of the coarse-aggregate type on the observed performance of CRCP sections at several locations. Laboratory information is used to supplement the field data.

Chapter 3 presents a brief description of the approaches followed to obtain thickness-equivalency factors. Chapter 4 compares the thickness equivalencies determined from the three different analysis approaches outlined in Chapter 3.

In Chapter 5, the implementation of the thickness-equivalency factors is discussed and application examples are provided.

Chapter 6 summarizes the report and gives some recommendations regarding the effect of the coarse-aggregate type on CRCP thickness.

Appendix A describes in a more detailed way the material presented in Chapter 3. It was decided to keep the discussion contained in the main body of this report as simple as possible in order to convey a quick and clear understanding of the effect of coarse-aggregate type on CRCP thickness. However, tables listing the values of the various design parameters used in the three different approaches are provided in Appendix A and the distinct equations considered in the analysis are also presented along with the results generated from them.

It is hoped that the thickness equivalencies generated in this study will provide a means to compute equivalent CRCP thicknesses when dealing with limestone and siliceous river gravel coarse aggregates. However, if the need arises, for a very detailed design, one for which the basic assumptions made in this analysis would lead to considerably inaccurate results, it is recommended that program CRCP-2 be used as a further verification of the equivalent thickness obtained from the procedure in Chapter 5. This is done by comparing the crack spacing obtained for a given set of conditions with that assumed in the development of the thickness equivalencies, and then performing the analysis presented in the appendix.

In selecting a specific coarse-aggregate type for the construction of a pavement, other factors, such as skid resistance and riding quality, should also be evaluated.

CHAPTER 2. OBSERVED PERFORMANCE OF CRCP WITH DIFFERENT COARSE-AGGREGATE TYPES

This chapter presents a review of the available literature on the performance of continuously reinforced concrete pavements built with different coarse-aggregate types. Both field and laboratory data are used in the following discussion.

FIELD EXPERIENCE

One of the most important responses of a CRCP to the action of traffic and environment is its crack pattern. The design methods for CRCP are based on the principle of keeping the crack spacing within certain limits in order to avoid the development of distress conditions, e.g., for practical purposes mean crack spacings of less than 2 feet can be considered as a distress manifestation.

Data from the 1978 CRCP statewide condition survey conducted in Texas by the Center for Transportation Research (Ref 2) show that in regions with similar environmental conditions the mean crack spacing of CRCP constructed with limestone as the coarse aggregate is generally greater than that of CRCP in which a siliceous river gravel coarse aggregate was employed. Furthermore, limestone CRCP exhibits less spalling than siliceous river gravel CRCP.

Figure 2.1 illustrates the variation in crack spacing with different types of coarse aggregate, using data from the States of Iowa and South Dakota. The coarse-aggregate type was the only parameter varied. The top

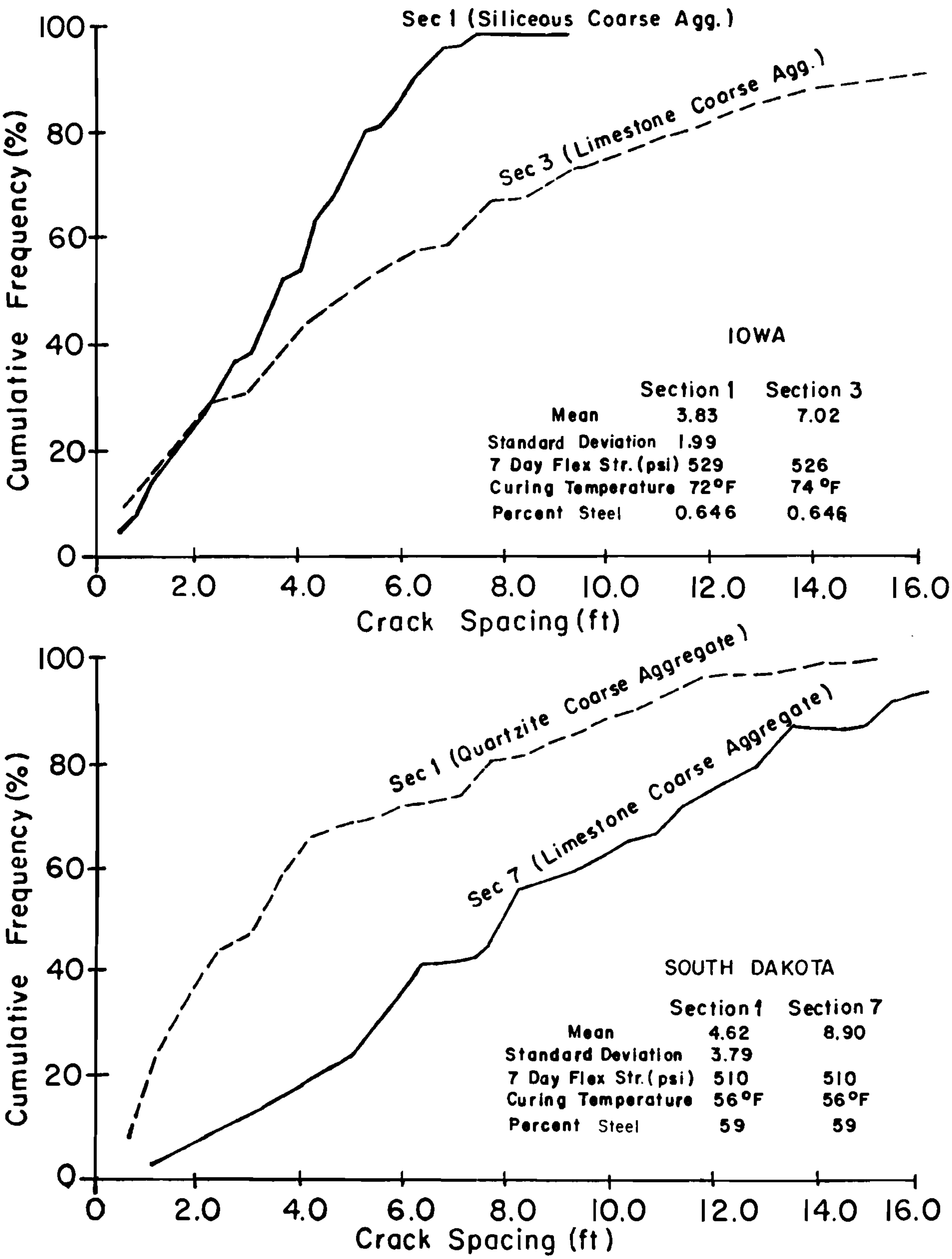

Fig 2.1. Effect of coarse aggregate type on distribution of crack spacing for two different conditions (Ref 3).

graph shows that a limestone coarse aggregate gives a greater mean crack spacing and a slower build up in the crack frequency distribution than a siliceous coarse aggregate under similar conditions. The lower part of Fig 2.1 shows the same trend in South Dakota, for a comparison between a limestone and a quartzite coarse aggregate.

Table 2.1 is a comparison of mean crack widths for each of the pavement sections shown in Fig 2.1. It must be pointed out that the mean crack widths for both the siliceous and quartzite coarse aggregates are greater than that for the limestone coarse aggregate despite the fact that, in general, mean crack spacing is less for the former two aggregates (Fig 2.1). This can be attributed to their different thermal coefficients of expansion and contraction.

LABORATORY RESULTS

A considerable number of laboratory tests have been performed on continuously reinforced concrete pavements to evaluate the response of such pavements to the variation of selected design parameters, but, unfortunately, the effect of the coarse-aggregate type has been analyzed in very few cases.

Laboratory studies (Ref 3) reveal that the type of coarse aggregate has a pronounced effect on spalling and cracking. The crushed-limestone aggregate has consistently shown less damage during laboratory testing. The crushed-limestone slabs have had both less spalling and less cracking when compared to the siliceous river gravel slabs.

This better performance in the area of damage to the slab is due to several factors. First, concrete with crushed limestone as the coarse aggregate generally has a lower modulus of elasticity than concrete containing siliceous river gravel. Second, clean crushed limestone has

TABLE 2.1. COMPARISON OF MEAN CRACK WIDTHS FOR DIFFERENT COARSE AGGREGATE TYPES (REF 3)

State	Section Number	Coarse Aggregate Type	Mean Crack Width (inches)	Standard Deviation of Crack Width (inches)
Iowa	1	Siliceous river gravel	0.025	0.006
	3	Limestone	0.016	0.004
South Dakota	1	Quartzite	0.019	0.003
	7	Limestone	0.014	0.002

better bonding characteristics than siliceous river gravel. Third, at an early age most cracking in concrete occurs in the paste, and concrete containing siliceous river gravel tends to crack around the coarse aggregate rather than through the aggregate, which occurs in crushed stone.

Reference 3 presents an example of the cracking and spalling developed in two slabs, in which the only difference between the makeup and treatment of the two slabs was the coarse-aggregate type used. One slab contained crushed limestone and had 91 inches of surface cracking and 1.2 square inches of surface area spalling; the other slab, containing a siliceous river gravel coarse aggregate, had considerably more damage, with 207 inches of surface cracking and 11 square inches of surface area spalling.

It can be concluded that field data and laboratory results concur in the fact that crushed limestone has proven to be a better coarse aggregate, commonly resulting in less spalling and greater crack spacing as compared to siliceous river gravel.

CHAPTER 3. DEVELOPMENT OF RIGID PAVEMENT THICKNESS EQUIVALENCIES

The purpose of this chapter is to describe in a brief manner the approaches followed to obtain thickness equivalencies between a limestone CRCP and a siliceous river gravel CRCP. In the first approach the AASHTO equation for design of rigid pavements was used. The second approach is based on the utilization of a model for design of new continuously reinforced concrete pavements for severe punch-outs. Additionally, a third method was considered in which a distress-prediction equation developed from condition survey data was used.

The aim of this chapter is to outline concisely the three different approaches followed to obtain thickness-equivalency factors. A detailed description of the various analyses carried out to arrive at these thickness equivalencies can be found in Appendix A.

ANALYSIS USING THE AASHTO EQUATION FOR DESIGN OR RIGID PAVEMENTS

The AASHTO equation for the design of rigid pavement structures (Ref 4) is based on data developed at the AASHO Road Test, supplemented and modified by theoretical analysis, and permits analysis of both continuously reinforced concrete pavements and jointed reinforced concrete pavements. The equation (see Appendix A) computes the number of applications of an 18-kip single axle load required for the pavement to reach a specified terminal serviceability level, and is a function of slab thickness, modulus of rupture and modulus of elasticity of concrete, modulus of subgrade reaction, and load-transfer coefficient.

Average values of the required parameters were considered for both the limestone and the siliceous river gravel concretes. The number of applications of an 18-kip single axle load to reach the terminal serviceability level ($W_{t_{18}}$) was computed for limestone CRCP thicknesses of 6, 8, 10 and 12 inches. Then, the siliceous river gravel CRCP thickness was varied until the obtained $W_{t_{18}}$ was equal to the value corresponding to any of the four limestone CRCP thicknesses which were initially determined. In this way four equivalent thicknesses of siliceous river gravel CRCP were obtained. This same process was repeated for jointed concrete pavements, since the AASHTO equation allows for analysis of both types of pavements by using the appropriate load-transfer coefficient.

Figure 3.1 shows the resulting thickness equivalencies between a limestone CRCP and a siliceous river gravel CRCP for three different support conditions.

ANALYSIS USING REPORT 177-7 DESIGN EQUATION

This approach to obtaining thickness-equivalency factors for CRCP constructed with two different coarse-aggregate types, i.e., limestone and siliceous river gravel, is based on the model developed by Strauss et al (Ref 6). That design equation was derived by assuming that the extent of structural failure can be physically measured in the field and can be expressed in units of area. The recommended model for design of new pavements is the equation for severe punch-outs. The basis for this recommendation is the need to design against structural failure where minor punch-outs, although eligible to be defined as structural failure, have not always progressed to a severe punch-out. As input for both types of CRC pavements and the four different thicknesses considered, this equation

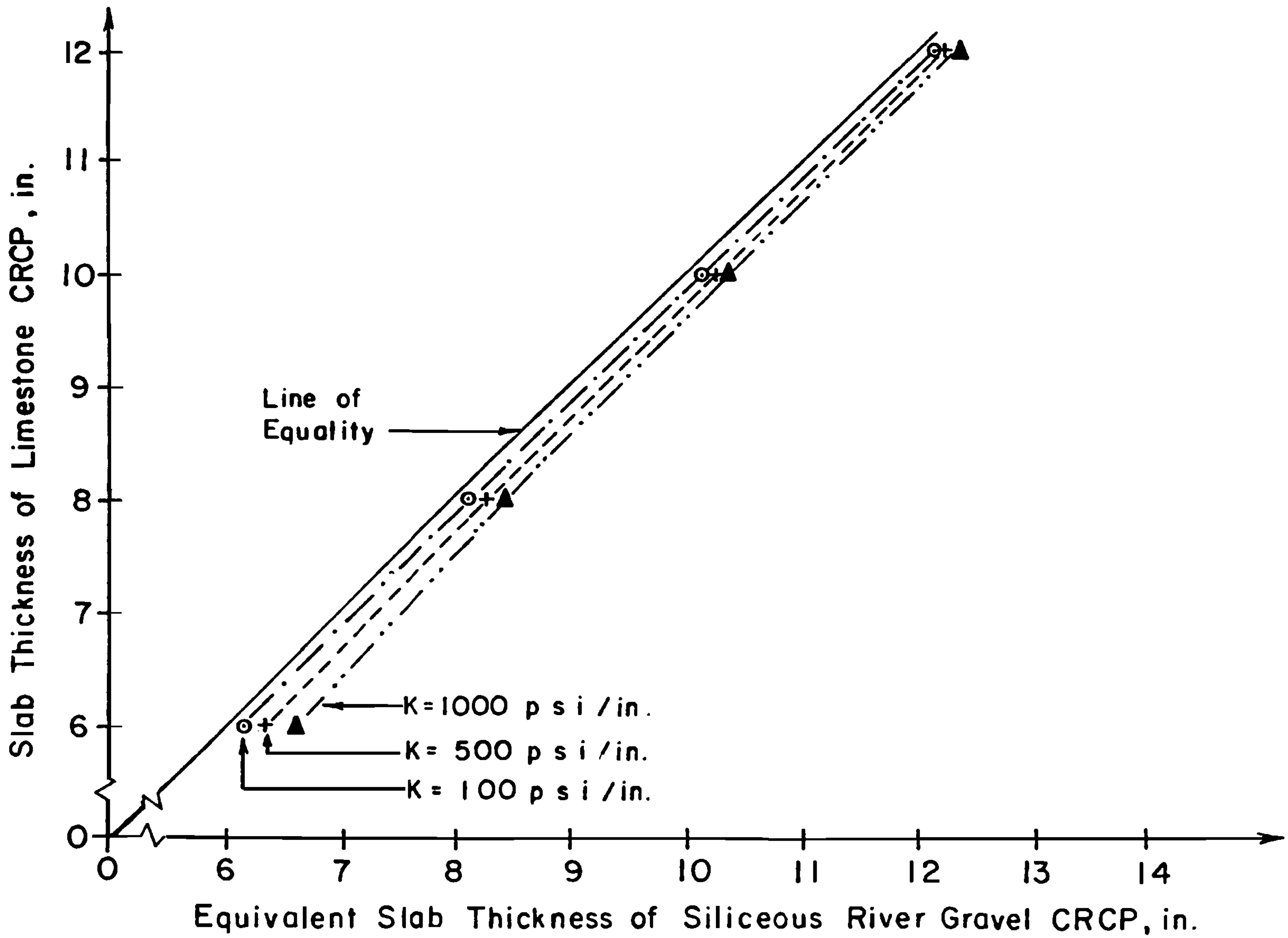

Fig 3.1. Thickness equivalencies between a limestone and a siliceous river gravel CRCP for various K-values, as determined from first approach.

requires parameters such as crack width, mean crack spacing, Dynaflect deflection and curvature values, and number of load applications to date, among others.

Program CRCP-2 (Ref 7) was used to generate the required values of crack width and mean crack spacing, while the Dynaflect loading was simulated by means of program ELSYM5 (Ref 8), which printed out deflection values at the designated locations (five different sensor positions).

Once all the input values necessary for using this design equation were available, the number of load applications was varied from 2 to 20 million for a limestone CRCP with thicknesses of 6, 8, 10 and 12 inches, and Z , which is a relative measure of the pavement area damaged, was computed. Equivalent thicknesses of siliceous river gravel CRCP were then determined by finding that thickness which resulted in the same value of Z as previously obtained for the limestone CRCP for a given number of load applications.

Figure 3.2 presents graphically the thickness equivalencies obtained from the second approach.

ANALYSIS USING DISTRESS-PREDICTION EQUATION

The third method considered in this study was based on a distress-prediction equation developed from regression analyses of condition survey information in Ref 12. Likewise, a fatigue equation for CRCP developed by Taute et al (Ref 13) was also used, under the assumption that distress condition of a pavement is directly related to the accumulated number of load applications.

The distress-prediction equation is a function of several parameters, among which the most important are type of coarse aggregate employed,

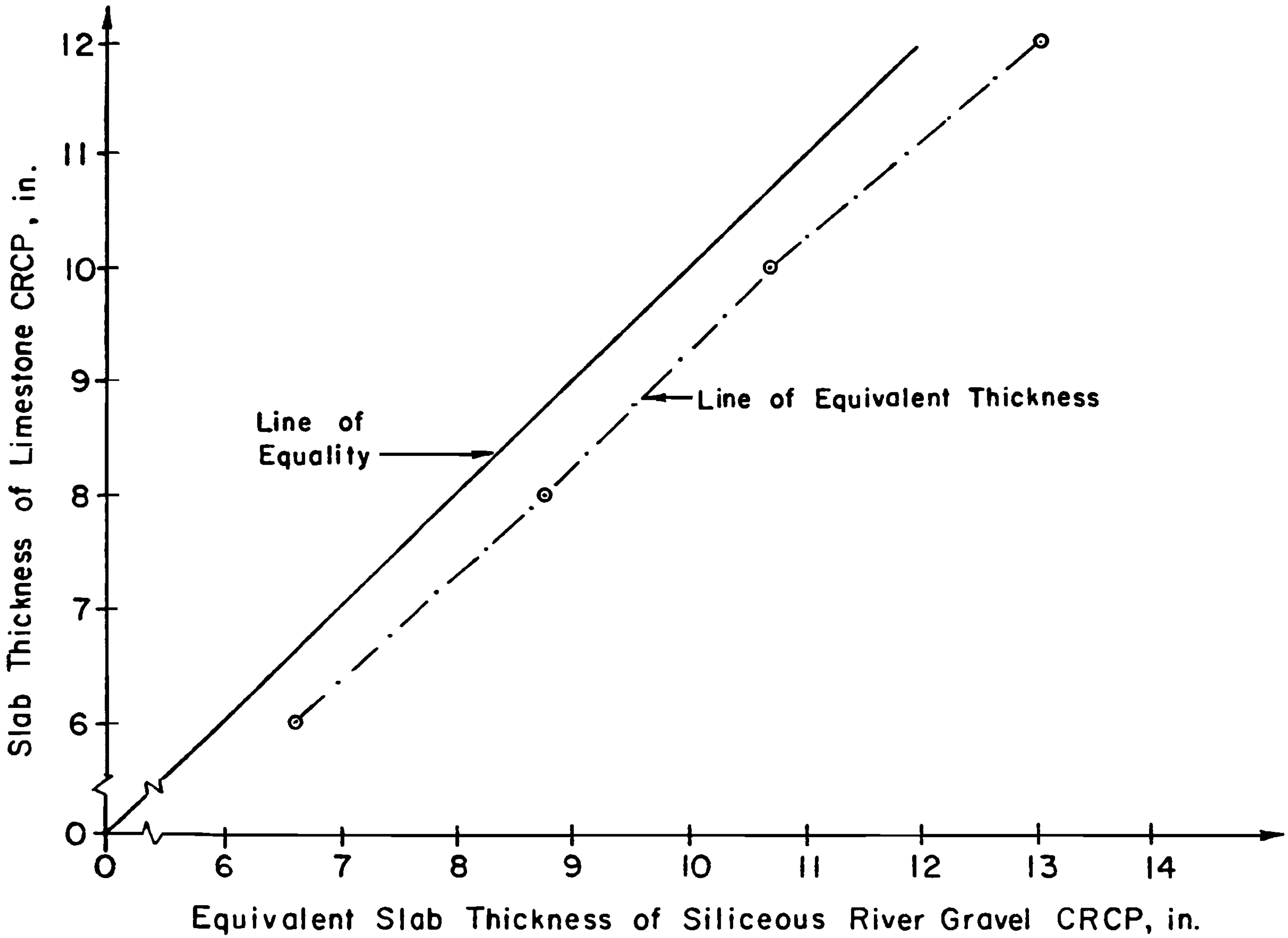

Fig 3.2. Thickness equivalencies between a limestone and a siliceous river gravel CRCP as determined from second approach.

pavement age, type of subbase, shoulder type and type of base stabilization. However, this equation considers a constant surface-layer thickness, which is an adequate assumption for deriving a general distress-prediction model representative of conditions found throughout the State of Texas. Hence, in order to determine thickness equivalencies between a limestone CRCP and a siliceous river gravel CRCP, a fatigue equation was used after establishing the difference in the predicted number of distress manifestations for both limestone and siliceous river gravel CRC pavements. This was accomplished by defining a terminal-condition level of the pavement and estimating the elapsed time to reach it for both pavement types. The Center for Transportation Research has adopted 14 failures per mile as the terminal-condition level, based on the information gathered in the CRCP statewide condition surveys (Ref 2) carried out periodically in recent years. (This number is obtained by converting the condition index that combines patches, severe punchouts, and minor spalling into failures.)

After the time required for both types of pavements to reach the terminal-condition level was computed, the above-mentioned fatigue equation was modified to reflect the findings from the distress-prediction equation. This fatigue equation computes the number of load applications to a terminal distress condition based on the flexural strength of the concrete and the tensile stress level values selected. Tensile stress can be expressed as a function of the pavement slab thickness and, if flexural strength is assumed to be the same for both types of CRC pavements, thickness equivalencies can be determined. A constant thickness relationship between limestone and siliceous river gravel CRCP which agrees very well with that from the second approach is shown in Fig 3.3.

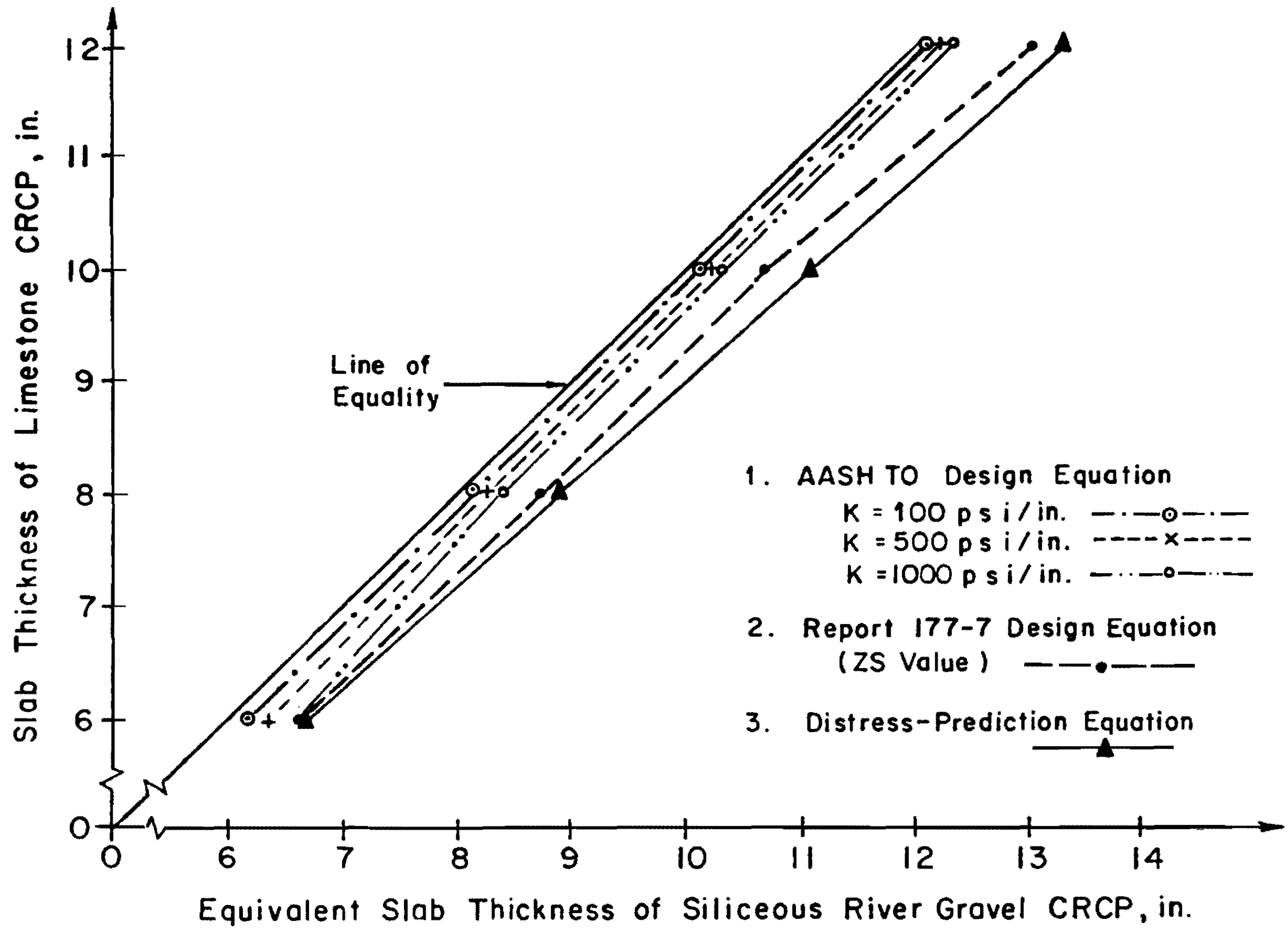

Fig 3.3. Comparison of the thickness equivalencies between a limestone and a siliceous river gravel CRCP obtained from the three different approaches.

Figure 3.3 is also a graphical comparison of the results from the three different methods used to obtain thickness equivalencies for both types of pavements.

CHAPTER 4. DISCUSSION OF RESULTS

Thickness-equivalency factors were obtained by means of three different approaches.

The AASHTO equation for design of rigid pavement structures is based on empirical relationships derived from the AASHO Road Test, supplemented and modified by theoretical analysis, and allows for consideration of both CRCP and JRCP.

In the second approach, the Report 177-7 design equation was used as an alternate method to compute thickness-equivalency factors. This equation is based on a probabilistic model that relates distressed area of a CRCP to theoretical models of fatigue and thus stress in the pavement system. The third method for arriving at thickness-equivalency factors is based on the utilization of a distress-prediction equation that is related to fatigue-life concepts in rigid pavements. Both the second and the third approaches rely on data from CRCP condition surveys.

In order to obtain thickness-equivalency factors through the application of the AASHTO design equation, three different k-values were considered so that a practical range of support conditions could be reflected in the analysis. Likewise, two different values for the load-transfer coefficient (J) were assumed: 2.2 for continuously reinforced concrete pavements and 3.2 for JRC pavements.

The effect of the load-transfer coefficient on the number of applications of an 18-kip single axle load to a terminal serviceability level

($W_{t_{18}}$) was significant, since, for the same set of conditions,a CRCP was found to be able to carry a considerably higher number of load applications until its terminal condition than a JRCP (Tables A.4 and A.5). However, the thickness-equivalency factors for both types of concrete pavements were exactly the same for a given thickness. The thicknesses considered are within the range shown in the design nomographs in the AASHTO Interim Guide for Design of Pavement Structures.

The Report 177-7 design equation is the result of a detailed analysis of design, construction and environmental variables that influence the structural performance of a CRCP. This equation predicts distress on a new pavement due to the accumulation of a given number of load applications and was derived from data gathered in condition surveys conducted in the rural districts of Texas. Several of the input values required for working with this equation had to be obtained from simulation of actual conditions in the field, which was accomplished by using elastic layered theory and a computer program (CRCP-2) commonly employed in Texas to design steel in continuously reinforced concrete pavements. A thickness-equivalency factor for a limestone and a siliceous river gravel CRCP approximately equal to 1.1 was obtained, which does not show any variation with accumulated number of load applications and remains sensibly constant for the various thickness considered (Table A.13).

The distress-prediction equation used in the third method for estimating thickness equivalencies was developed from regression analyses performed on CRCP condition survey information. The terminal-condition level of a CRCP expressed in number of distress manifestations per mile, was considered as a criterion to define a pavement with no remaining fatigue life. Then, fatigue equations for both limestone and siliceous river gravel CRC pavements were expressed in terms of thickness, which allowed the estimation of a thickness-equivalency factor approximately equal to 1.1.

The thickness equivalencies obtained from the AASHTO equation vary with support condition and slab thickness and they are, in general, lower than those thickness equivalencies derived from the other two approaches. The second and third methods are based on conditions considered as representative of the State of Texas, whereas the first approach is more appropriate for an environment similar to that at the AASHO Road Test, where only one type of coarse aggregate was used. Thus, it seems better to recommend 1.1 as an average thickness-equivalency factor between a limestone and a siliceous-river gravel CRCP for projects located within Texas.

CHAPTER 5. IMPLEMENTATION OF FINDINGS

Thickness equivalencies developed herein can be applied to continuously reinforced concrete pavements constructed with limestone or siliceous river gravel, the two types of coarse aggregates most commonly used in Texas to produce portland cement concrete.

Limestone is a coarse aggregate obtained by mechanical fragmentation of rock. This aggregate has an angular shape, i.e., it shows well-defined edges formed at the intersection of roughly planar faces (Ref 14) and a surface texture that can be classified as rough (rough fracture of fine- or medium-grained rock containing no easily visible crystalline constituents).

Siliceous river gravel is classified according to its shape as rounded (fully water-worn or completely shaped by wear) and as a coarse-aggregate with smooth surface texture, i.e., water-worn, or smooth due to fracture of laminated or fine-grained rock.

RECOMMENDED PROCEDURE FOR OBTAINING THICKNESS EQUIVALENCIES

Based on the results from this study, the following simplified procedure is recommended for obtaining thickness equivalencies between a limestone CRCP and a siliceous river gravel CRCP.

(1) Given the thickness corresponding to the limestone CRCP (D_{LI}) that needs to be analyzed, use the following equation to obtain the equivalent thickness of siliceous river gravel CRCP (D_{GR}).

$$D_{GR} = 1.1 \cdot D_{LI} \qquad (5.1)$$

(2) Round D_{GR} up to the nearest tenth of an inch.

(3) This procedure can also be applied to determine the equivalent D if D_{GR} is given:

$$D_{LI} = 0.91 \cdot D_{GR} \qquad (5.2)$$

EXAMPLE OF APPLICATION OF THICKNESS EQUIVALENCIES

An engineer has designed a continuously reinforced concrete pavement to be constructed with limestone coarse aggregate, but at the end of the analysis he realizes that such an aggregate is not locally available. However, he has been informed that an unlimited amount of siliceous river gravel can be used. He had previously figured out that for a limestone CRCP, a slab thickness of 10 inches would be required. Assuming that the rest of the design parameters do not change, it is necessary to determine what the equivalent thickness of siliceous river gravel CRCP would be.

Solution

For a D_{LI} of 10 inches using Eq 5.1, the equivalent thickness of siliceous river gravel CRCP (D_{GR}) is 11.0 inches.

CHAPTER 6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

The determination of thickness-equivalency factors for continuously reinforced concrete pavements has been accomplished using three different approaches: the AASHTO equation for design of rigid pavements, the Report 177-7 design equation and a distress-prediction equation. These thickness equivalencies have been obtained for the two coarse aggregates most commonly used in the construction of PCC pavements in the State of Texas.

Laboratory results and theoretical analyses definitely support the fact that the observed performance of limestone CRCP has been significantly better than that of similar siliceous river gravel CRCP.

The AASHTO design equation permits analysis of both CRCP and JRCP, whereas both the Report 177-7 design equation and the distress-prediction model were developed exclusively from CRCP data. Furthermore, the simplicity of the input data required by the first design approach considerably facilitates the development of thickness-equivalency factors. However, the other two methods encompass conditions found throughout Texas and the thickness equivalencies derived from both are basically the same.

CONCLUSIONS

Among the conclusions resulting from this study are the following:

(1) It is feasible to determine thickness equivalencies between a limestone CRCP and a siliceous river gravel CRCP by using any of the three approaches described in this study.

(2) The thickness equivalencies derived from the last two approaches compare satisfactorily.

(3) Limestone has proven to be a better coarse aggregate than siliceous river gravel when the performance of continuously reinforced concrete pavements built with these two coarse-aggregate types has been compared. Data corresponding to field experience and laboratory testing have been corroborated by theoretical analyses.

(4) For similar conditions in which the only parameter varied was the coarse-aggregate type, wider crack spacings were predicted by program CRCP-2 for a limestone CRCP. Field data and laboratory results confirm this theoretical finding.

(5) When determining thickness-equivalency factors by means of the AASHTO equation for design of rigid pavements the effect of the coarse-aggregate type was taken into account in the selection of the adequate modulus of elasticity of concrete. Thickness-equivalency factors tend to increase with increasing k-value, whereas the opposite is observed for an increase in slab thickness. These trends are similar for both CRCP and JRCP.

(6) Several of the parameters necessary for use of the Report 177-7 design equation reflect the effect of the coarse-aggregate type, and in this study they were generated from computer programs that simulate actual conditions. Among the most important variables affecting thickness equivalencies that are related to the coarse-aggregate type employed in the construction of CRCP are the following: modulus of elasticity of concrete, coefficient of expansion and contraction of concrete, crack width, crack spacing, deflection, and curvature.

(7) The third approach, which is based on a distress-prediction model, resulted in thickness equivalencies similar to those obtained in the second method. This was expected because the models in both approaches were derived from condition survey data gathered in the State of Texas.

(8) It was concluded that the thickness-equivalency factors obtained from analysis approaches 2 and 3 closely reflected average conditions found in Texas.

RECOMMENDATIONS

(1) It is very important to perform all the pertinent laboratory tests to evaluate fully the physical properties of concrete when different coarse-aggregate types are used. Laboratory data significantly affect the final design of a CRCP.

(2) If the choice of the coarse-aggregate type to be employed is left to the contractor, it is recommended that the coarse aggregate with

the worst properties be considered in the estimation of slab thickness. This, although not advisable from an economic standpoint, would result in a conservative design. Alternatively, thickness equivalencies developed herein could be used to estimate the construction costs when both limestone and siliceous river gravel are available for use as coarse aggregates.

(3) It is recommended that a minimum slab thickness of 8 inches be established for design purposes. Otherwise, narrow crack spacings are likely to be developed.

(4) A recommended procedure for obtaining thickness equivalencies between a limestone and a siliceous river gravel CRCP is presented in Chapter 5. Its application can lead to the determination of approximate thickness equivalencies.

(5) When a very detailed steel design of a CRCP is required, in which various coarse-aggregate types need to be evaluated, it is suggested that program CRCP-2 be used to compute a set of feasible designs. The selection of a particular design would depend on constraints such as availability of the various coarse-aggregate types, environmental information, economy, etc.

(6) Monitoring of CRC pavements constructed with different coarse-aggregate types should be continued in districts with different climatic conditions in order to verify the theoretical models for design of continuously reinforced concrete pavements.

(7) Other properties, such as skid resistance, should also be taken into account in the selection of the type of coarse aggregate to be used.

(8) The concept of thickness equivalency could be extended to overlay-thickness determination and analysis of equivalencies between slab and subbase thicknesses when evaluating a given set of feasible designs.

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APPENDIX A

DETAILED DESCRIPTION OF THE THREE DIFFERENT APPROACHES TO DEVELOP RIGID-PAVEMENT THICKNESS EQUIVALENCIES

APPENDIX A. DETAILED DESCRIPTION OF THE THREE DIFFERENT APPROACHES TO DEVELOP RIGID-PAVEMENT THICKNESS EQUIVALENCIES

The aim of this appendix is to describe in detail the various approaches to obtaining rigid-pavement thickness equivalencies, which were outlined in Chapter 3. The values of the parameters considered in this analysis are also provided, along with the supporting equation used, and assumptions are pointed out.

ANALYSIS USING THE AASHTO EQUATION FOR DESIGN OF RIGID PAVEMENTS

This equation was derived from data generated at the AASHO Road Test, supplemented and modified by theoretical analysis (Ref 4).

$$\log W_{t_{18}} = 7.35 \log (D + 1) - 0.06 + \frac{G_t}{1 + \frac{1.624 \times 10^7}{(D + 1)^{8.46}}} + (4.22 - 0.32\, p_t) \left[\log \left(\frac{Sc}{215.63\, J} \right) \left(\frac{D^{0.75} - 1.132}{D^{0.75} - \frac{18.42}{D^{0.25}}} \right) \right] \tag{A.1}$$

$$G_t = \log \frac{4.5 - p_t}{4.5 - 1.5} \tag{A.2}$$

$$Z = \frac{E_c}{K} \tag{A.3}$$

where

P_t = terminal serviceability level;

$W_{t_{18}}$ = number of applications of an 18-kip single axle load to serviceability level;

D = slab thickness, inches;

G_t = a function (the logarithm) of the ratio of loss in serviceability at time t to the potential loss taken to a point where p_t = 1.5;

S_c = modulus of rupture of concrete, psi;

E_c = modulus of elasticity of concrete, psi;

K = modulus of subgrade reaction, psi/in.; and

J = load-transfer coefficient.

The values of the input parameters used in this analysis are shown in Table A.1.

The physical properties of concrete, such as modulus of rupture and modulus of elasticity, were obtained from a laboratory study (Ref 5) in which the two coarse-aggregate types considered in this report were used.

Table A.2 presents a summary of the concrete-mix data and the coefficient of expansion and contraction corresponding to the eight different batches considered in this study. The common characteristic of these eight batches is that no admix was used to modify the physical properties of concrete, whereas in Reference 5, a total of 21 different batches were analyzed, and in 13 of them a certain type of admix was employed.

Table A.3 shows certain physical properties of concrete for the batches described in Table A.2. In both tables average values were computed for use in subsequent analyses.

The implications of assuming an average value for the modulus of elasticity of both concrete types are discussed in this section.

TABLE A.1. VALUES OF THE INPUT PARAMETERS CONSIDERED IN THE DEVELOPMENT OF PAVEMENT-THICKNESS EQUIVALENCIES USING THE AASHTO EQUATION FOR DESIGN OF RIGID PAVEMENTS

(a) Variables	Value for Levels			
	1	2	3	4
D, in.	6	8	10	12
f_t, psi	605 (LIC)*		604 (GRC)**	
E_c, psi	4.63×10^6 (LIC)		6.67×10^6 (GRC)	
K, psi/in.	100	500	1000	
J	2.2 (CRCP)		3.2 (JRCP)	

(b) Parameters Held Constant	Value
p_t	2.5
G_t	$\log\left(\frac{2}{3}\right)$

* LIC - limestone concrete
** GRC - siliceous river gravel concrete

Note:

f_t is the flexural working stress of concrete as defined in Equation A.4

TABLE A.2. CONCRETE-MIX DATA AND COEFFICIENT OF EXPANSION AND CONTRACTION FOR EIGHT DIFFERENT BATCHES

		Quantities Per Cubic Yard of Concrete				
Batch Designation	Aggregate Type	Cement Sacks	Coarse Aggregate, lb	Mixing Water, lb	Initial Unit Weight lb/ft^3	Coefficient of Expansion * and Contraction, $\times 10^{-6}$ in/in/°F
LI-1	Limestone	4.95	1,823	294	141.3	2.6
LI-2		3.69	1,901	234	143.1	3.5
LI-3		5.10	1,870	254	143.4	3.3
LI-4		6.62	1,852	236	143.5	3.4
GR-1	Siliceous River Gravel	5.02	2,112	310	149.1	4.0
GR-2		3.52	2,114	275	147.7	5.0
GR-3		5.09	2,130	289	149.3	4.0
GR-4		6.63	2,139	296	150.3	4.6
Average	Limestone	5.09	1,862	255	142.8	3.2
	Siliceous River Gravel	5.07	2,124	290	149.1	4.4

* Obtained on the 28th day

Notes: No admix was used in any of these batches
Continuous moist-room curing of specimens

TABLE A.3. VARIOUS PHYSICAL PROPERTIES OF CONCRETE FOR THE BATCHES CONSIDERED IN THIS STUDY

Aggregate Type	Batch Designation	Age, Days	Compressive Strength, p s i	Modulus of Rupture, * p s i	Tensile Strength, p s i	Dynamic Modulus of Elasticity in Flexure, x 10^6 p s i
Limestone	LI-1	1	1,385	290	170	2.86
		2	2,140	400	250	3.54
		7	3,220	590	330	4.02
		28	3,435	730	360	4.23
	LI-2	1	451	105	93	1.39
		2	1,161	289	151	3.00
		7	2,290	635	305	4.14
		28	2,885	670	355	4.35
	LI-3	1	986	269	154	2.73
		2	2,257	394	276	3.86
		7	4,020	760	400	4.56
		28	4,190	825	415	4.97
	LI-4	1	1,659	355	232	3.16
		2	2,734	561	306	4.12
		7	4,280	745	355	4.87
		28	4,885	880	485	4.95
Siliceous River Gravel	GR-1	1	1,460	300	225	4.24
		2	2,365	550	250	5.04
		7	3,385	710	315	6.18
		28	3,710	780	440	6.50
	GR-2	1	459	146	62	2.95
		2	1,176	313	81	4.27
		7	2,340	615	300	5.85
		28	2,625	745	330	6.10
	GR-3	1	1,161	285	107	3.62
		2	1,696	405	195	4.96
		7	3,300	695	320	6.65
		28	4,335	780	405	6.88
	GR-4	1	2,240	533	229	4.89
		2	3,117	739	291	5.81
		7	5,060	755	490	6.44
		28	4,980	1,085	460	7.18
Limestone	Average Value	1	1,120	255	162	2.54
		2	2,073	411	246	3.63
		7	3,453	603	348	4.40
		28	3,849	776	404	4.63
Siliceous River Gravel	Average Value	1	1,330	316	156	3.88
		2	2,089	502	204	5.62
		7	3,521	694	356	6.28
		28	3,913	848	409	6.37

*Center-point loading

The AASHTO design method recommends that a flexural working stress in the concrete be used to account for variability. The working stress can be computed by the following equation:

$$f_t = \overline{S}_c - c\,\sigma_c \tag{A.4}$$

where

f_t = flexural working stress of concrete, psi;

$\overline{S}_c$ = mean flexural strength from a series of tests, psi;

σ_c = unbiased estimate of the universe standard deviation of flexural strength from data corresponding to a series of tests, psi; and

c = factor to establish the confidence level in design.

If the data given in Table A.3 are considered, a σ_c of 82 psi is obtained for the limestone concrete, while the σ_c for the siliceous river gravel concrete is 138 psi. Additionally, the factor c corresponding to a 90 percent confidence level is 1.282.

The flexural working stress for both concrete types was determined by applying Eq A.4, and an f_t of 672 psi was computed for the limestone concrete, whereas the flexural working stress for the siliceous river gravel concrete was 671 psi. Hence, a similar flexural working stress was obtained for both concrete types due to the high standard deviation of the siliceous river gravel concrete as determined from data in Table A.3.

The 28-day flexural working stresses computed above needed to be transformed to equivalent third-point loading values. This was accomplished by considering a 10 percent reduction in both flexural working stresses. Final values of this parameter are given in Table A.1.

The first step towards the determination of thickness equivalencies was to compute $W_{t_{18}}$ for the four different thicknesses of limestone CRCP considered and for three support conditions. Then, for a given k-value, the thickness of the siliceous river gravel CRCP was varied until the corresponding $W_{t_{18}}$ had approximately the same value as that of any of the four $W_{t_{18}}$ values previously determined for the limestone CRCP. Thickness equivalencies can be defined as follows, if thickness is the only parameter varied.

If

$$W_{t_{18}} = (D_{LI}) \cong W_{t_{18}} (D_{GR})$$

Then D_{LI} and D_{GR} are said to be equivalent thicknesses where

D_{LI} = slab thickness of the limestone CRCP, and

D_{GR} = slab thickness of the siliceous river gravel CRCP.

The thickness-equivalency factor can be defined if and only if Eq A.5 is satisfied.

$$T_{LI-GR} = \frac{D_{GR}}{D_{LI}}$$

where

T_{LI-GR} = thickness-equivalency factor between a limestone and a siliceous river gravel CRCP.

Values of T_{LI-GR} for three different support conditions are given in Table A.4 for continuously reinforced concrete pavements.

TABLE A.4. THICKNESS-EQUIVALENCY FACTORS, T_{LI-GR}, BETWEEN A LIMESTONE AND A SILICEOUS RIVER GRAVEL CRCP

K, psi/in.	Limestone CRCP		Siliceous River Gravel CRCP		
	D_{LI}, (in.)	$W_{t_{18}} \times 10^6$	D_{GR}, (in.)	$W_{t_{18}} \times 10^6$	T_{LI-GR}
100	6.00	3.166	6.16	3.160	1.03
	8.00	16.280	8.14	16.223	1.02
	10.00	66.863	10.14	66.961	1.01
	12.00	223.191	13.14	223.495	1.01
500	6.00	8.139	6.37	8.115	1.06
	8.00	31.783	8.28	31.738	1.04
	10.00	113.078	10.25	113.059	1.03
	12.00	345.324	12.24	345.505	1.02
1000	6.00	16.156	6.64	16.184	1.11
	8.00	49.868	8.41	49.842	1.05
	10.00	158.999	10.34	158.728	1.03
	12.00	455.450	12.32	456.155	1.03

The above described reasoning can also be applied to obtain a thickness-equivalency factor for JRC pavements if the proper load-transfer coefficient, J, is input into Eq A.1. Results corresponding to this type of rigid pavement appear in Table A.5.

The concept of equivalent thicknesses can be further extended to arrive at thickness-equivalency factors between a CRCP and JRCP, as demonstrated in Tables A.6 and A.7.

It can be observed from Tables A.4 and A.5 that thickness-equivalency factors are the same for both CRCP and JRCP for a given thickness of CRCP and modulus of subgrade reaction. Furthermore, in general, the thickness-equivalency factor increases with modulus of subgrade reaction but decreases with increasing slab thickness.

Figure 3.1 shows the results listed in Table A.4, while Figure A.1 combines the values given in Tables A.5 to A.7 to compare a limestone CRCP with both a siliceous river gravel CRCP and two types of JRCP.

It is pertinent to mention that the k-value considered in this approach is that measured at the top of the layer on which the portland cement concrete slab is to be constructed. This design parameter is commonly referred to as the composite modulus, or k-value on top of the subbase.

ANALYSIS USING REPORT 177-7 DESIGN EQUATION

The design equation on which this second approach is based was developed at the Center for Transportation Research by Strauss et al (Ref 6). In this equation it is assumed that the ratio of area failed to area surveyed can be related to number of load applications through a stochastic model:

TABLE A.5. THICKNESS-EQUIVALENCY FACTORS, T_{LI-GR}, BETWEEN A LIMESTONE AND A SILICEOUS RIVER GRAVEL JRCP

K, psi/in.	Limestone JRCP		Siliceous River Gravel JRCP		T_{LI-GR}
	D_{LI}, (in.)	$W_{t_{18}} \times 10^6$	D_{GR}, (in.)	$W_{t_{18}} \times 10^6$	
100	6.00	0.879	6.16	0.877	1.03
	8.00	4.520	8.14	4.506	1.02
	10.00	18.563	10.14	18.591	1.01
	12.00	61.965	12.14	62.050	1.01
500	6.00	2.260	6.37	2.253	1.06
	8.00	8.824	8.28	8.811	1.04
	10.00	31.394	10.25	31.389	1.03
	12.00	95.874	12.24	95.924	1.02
1000	6.00	4.485	6.64	4.493	1.11
	8.00	13.845	8.41	13.838	1.05
	10.00	44.144	10.34	44.068	1.03
	12.00	126.449	12.32	126.644	1.03

TABLE A.6. THICKNESS-EQUIVALENCY FACTORS, T_{LI-LI}, BETWEEN A LIMESTONE CRCP AND A LIMESTONE JRCP

	Limestone CRCP		Limestone JRCP		
K, psi/in.	D_{LI}, (in.)	$W_{t_{18}} \times 10^6$	D_{LI}, (in.)	$W_{t_{18}} \times 10^6$	T_{LI-LI}
100	6.00	3.166	7.54	3.167	1.26
	8.00	16.280	9.80	16.278	1.23
	10.00	66.863	12.14	66.970	1.21
	12.00	223.191	14.51	223.512	1.21
500	6.00	8.139	7.88	8.144	1.31
	8.00	31.783	10.02	31.771	1.25
	10.00	113.078	12.32	113.087	1.23
	12.00	345.324	14.67	344.919	1.22
1000	6.00	16.156	8.26	16.152	1.38
	8.00	49.868	10.22	49.856	1.28
	10.00	158.999	12.47	159.139	1.25
	12.00	455.450	14.80	455.716	1.23

TABLE A.7. THICKNESS EQUIVALENCY FACTORS, T_{LI-GR}, BETWEEN A LIMESTONE CRCP AND A SILICEOUS RIVER GRAVEL JRCP

	Limestone CRCP		Siliceous River Gravel JRCP		
K, p s i /in.	D_{LI}, (in.)	$W_{t_{18}} \times 10^6$	D_{GR}, (in.)	$W_{t_{18}} \times 10^6$	T_{LI-GR}
100	6.00	3.166	7.69	3.173	1.28
	8.00	16.280	9.94	16.300	1.24
	10.00	66.863	12.27	66.688	1.23
	12.00	223.191	14.65	223.554	1.22
500	6.00	8.139	8.16	8.113	1.36
	8.00	31.783	10.27	31.769	1.28
	10.00	113.078	12.56	113.205	1.26
	12.00	345.324	14.91	345.896	1.24
1000	6.00	16.156	8.66	16.181	1.44
	8.00	49.868	10.58	49.885	1.32
	10.00	158.999	12.79	159.670	1.28
	12.00	455.450	15.10	455.501	1.26

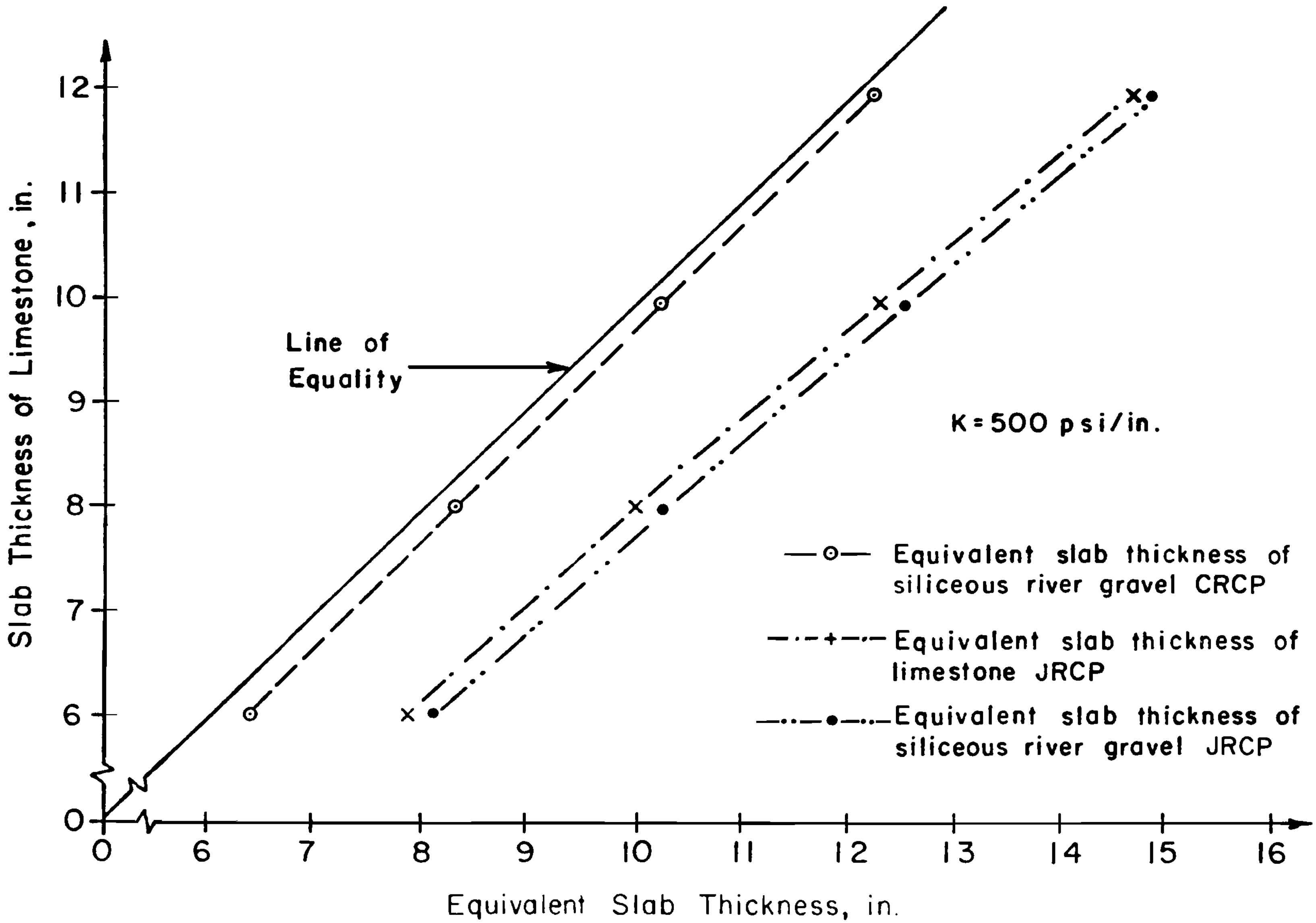


Fig A.1. Thickness equivalencies between a limestone CRCP and three different types of rigid pavements for a K-value of 500 p s i /inch, as determined from first approach.

$$Z = \frac{\text{Log } n - \text{Log } N}{S} \tag{A.7}$$

where

N = the theoretical maximum number of load applications possible as determined from a fatigue analysis,

n = the actual number of load applications recorded so far,

S = the standard deviation of Log N and Log n combined, and

Z = the standard normal variable.

The recommended model for design of new pavements is the equation for severe punch-outs. The basis for this recommendation is the need to design against structural failure where minor punch-outs, although eligible to be defined as structural failures, have not always progressed to severe punch-outs.

The equation for the design of new CRCP is

$$\begin{aligned} ZS = & -1.044 - 0.26 \log \frac{\Delta x}{R} - 1.27 \log \bar{x} \; \alpha \, \Delta T \\ & - 3.62 \log \left(\frac{P}{L \, h^2 \, fc} \; \frac{\bar{x}^{0.033} \, y^{0.51}}{\Delta y^{0.52}} \right) - \frac{256}{\bar{x}^2} \\ & + 6.42 \times 10^{-6} \text{ (variance fc)} - \frac{1.33}{\text{variance fc}} - \frac{256}{\bar{x}^2} \\ & + \frac{0.76}{\text{variance } \bar{x}} - 9.52 \times 10^{5} \text{ (variance y)} - 0.034 \text{ (surface vibration)} \\ & + 0.030 \text{ (asphalt base)} \end{aligned} \tag{A.8}$$

where

ZS = standard deviation times a measure of distress area;

Δx = crack width, inches;

R = radius of maximum coarse-aggregate size, inches;

$\bar{x}$ = mean crack spacing, inches;

α = coefficient of expansion and contraction of concrete, inches/inches/°F;

ΔT = daily change in temperature, °F;

P = axle load, lb;

L = length of crack considered for load transfer, inches;

h = slab thickness, inches;

fc = 7-day flexural strength, psi;

y = deflection, inches;

Δy = curvature, inches; and

n = number of applications to date.

The value of S, the combined standard deviation of Log N and Log n, can be computed from the variance, S^2, which is expressed as

$$S^2 = \left(5.25 \frac{S_p}{P}\right)^2 + \left(6.82 \frac{S_h}{h}\right)^2 + \left(3.41 \frac{S_{fc}}{fc}\right)^2 + \left(0.11 \frac{S_{\Delta x}}{\Delta x}\right)^2 + \left(0.60 \frac{S_{\bar{x}}}{\bar{x}}\right)^2 + \left(0.80 \frac{S_y}{y}\right)^2 + \left(0.82 \frac{S_{\Delta y}}{\Delta y}\right)^2 + \left(S_{\log n}\right)^2 \quad (A.9)$$

where

S_p = standard deviation of p, lb;

S_h = standard deviation of h, inches;

S_{fc} = standard deviation of fc, psi;

$S_{\Delta x}$ = standard deviation of Δx, inches;

S_y = standard deviation of y, inches;

$S_{\Delta y}$ = standard deviation of Δ_y, inches; and

$S_{\log n}$ = standard deviation of log n.

The CRCP-2 program (Ref 7) was used to obtain the values corresponding to mean crack spacing and crack width, for different thicknesses of both limestone and siliceous river gravel CRCP. The Westergaard equation for interior loading may be used within the program to predict the maximum tensile stress at the bottom fiber of the slab; however, it was decided to employ an elastic layered-system computer program to determine this stress in order to have compatibility with subsequent calculations in which program ELSYM5 (Ref 8) was used.

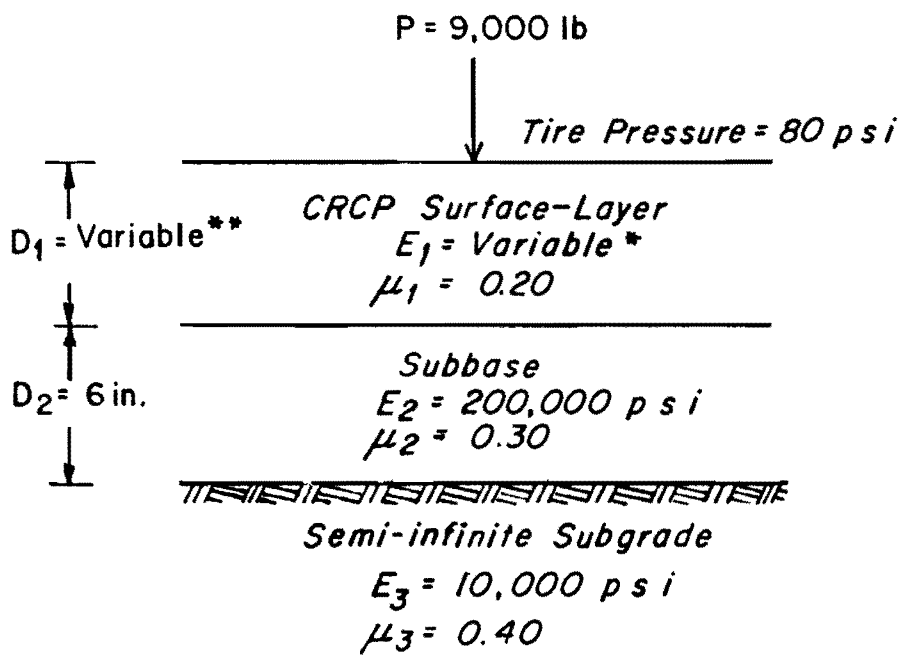
Figure A.2 shows the several combinations of input data for which the program ELSYM5 computed the corresponding stresses.

The maximum tensile stresses at the bottom fiber of the slab are given in Table A.8.

The effect on surface-layer maximum tensile stress when considering an average modulus of elasticity of concrete is illustrated in Fig A.3. The ranges for the modulus of elasticity of concrete depending on the coarse-aggregate type were determined from the set of values provided in Ref 5. These intervals include various concrete batches in which a certain type of admix was used; however, if only the moduli of elasticity presented in Table A.3 are considered, the ranges are significantly smaller, i.e., from 4.23 to 4.97×10^6 psi for limestone concrete and from 6.10 to 7.18×10^6 psi for siliceous river gravel concrete.

The assumption of an average modulus of elasticity for both concrete types is highly satisfactory despite the range considered, since the variation in maximum tensile stress within a given range can be regarded as insignificant, as shown by Fig A.3.

Elastic layered theory was used to compute the aforementioned tensile stresses because an interior loading condition was assumed.



* - E_1 for limestone concrete = 4,630,000 psi

E_1 for siliceous river gravel concrete = 6,670,000 psi

** - D = 6, 8, 10 and 12 in.

Fig A.2. Cross section of pavement structure and materials properties.

TABLE A.8. MAXIMUM TENSILE STRESSES IN THE CRCP SLAB DUE TO A SINGLE LOAD OF 9,000 lb

Slab Thickness, (in.)	Maximum Tensile Stress, p s i	
	Limestone CRCP	Siliceous River Gravel CRCP
6	211	240
8	146	162
10	105	116
12	80	88

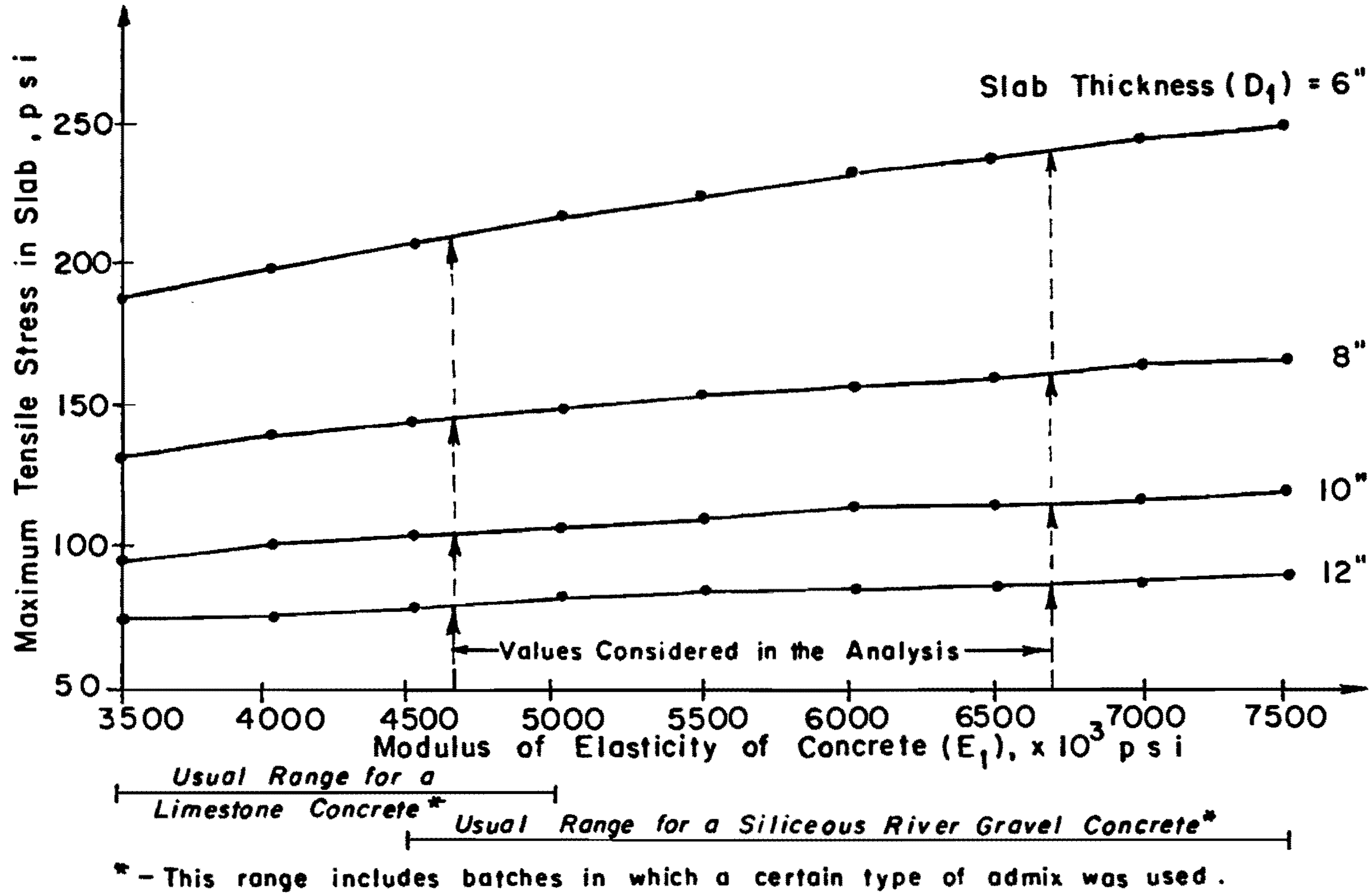


Fig A.3. Maximum tensile stress in the CRCP slab as a function of modulus of elasticity of concrete (E_1) and slab thickness (D_1) for the pavement structure shown in Fig A.2.

Table A.9 presents the values and levels of the input parameters used to run program CRCP-2. The average values of tensile strength of concrete at 1, 2, 7, 14, and 28 days were employed to provide the age-tensile strength relationship for both concrete types (Table A.3).

The values corresponding to the frictional force per area were obtained from the CRCP-2 computer program user's manual (Ref 9) for a horizontal displacement of 0.1 inches and for the various slab thicknesses.

Mean crack spacings and crack widths as computed from program CRCP-2 are given in Table A.10. It can be noted that for a 6-inch CRCP very narrow crack spacings were obtained and they could be classified as distress manifestations if they were recorded in the field during the course of a condition survey. Nevertheless, these crack spacings need to be input into the Report 177-7 design equation if a comparison between different coarse-aggregate types is to be made. It can also be observed from the same table that for any of the analyzed thicknesses the mean crack spacing of the limestone CRCP is greater than that corresponding to the siliceous river gravel CRCP.

Deflection (y) and curvature (Δy) are the last two variables that need to be estimated so that the Report 177-7 design equation can be solved. The Dynaflect is currently used in Texas to evaluate the structural capacity of a pavement, and deflection and curvature are among the parameters obtained from it. Maximum deflection is normally recorded at the sensor 1 location (W_1) and curvature can be computed by subtracting the sensor 2 deflection from W_1.

It has been recommended that when deflections are measured to estimate the moduli of elasticity of the various pavement layers the Dynaflect be placed in the middle portion of the slab so that the effect of

TABLE A.9. VALUES OF THE INPUT PARAMETERS USED TO RUN PROGRAM CRCP-2

(a) Variables	Value for Levels				
	1	2	3	4	8
Slab thickness (D), in.	6	8	10	12	
Coefficient of expansion and contraction of concrete (α_c), x 10^{-6} in./in./°F	3.2(LIC)*	4.4(CRC)**			
Unit weight of concrete (Wc), pcf	142.8(LIC)	149.1(GRC)			
Age-tensile strength relationship of concrete	2 levels as given in Table A.3 for 1, 2, 7, 14 and 28 days				
Fractional force per area (FEXP), psi	0.18 (D=6")	0.49 (D=8")	0.58 (D=10")	0.64 (D=12")	
Wheel-load stress (WHLSTR), psi	8 levels as given in Table A.8				

(b) Parameters Held Constant	Value
Percent steel reinforcement (p)	0.5
Reinforcing bar diameter (ϕ), in	0.625
Yield stress of steel (fy), psi	60,000
Modulus of Elasticity of steel (Es), x 10^6 psi	30
Coefficient of expansion and constraction of steel (α_s), x 10^{-6} in./in./°F	6
Drying shrinkage strain of concrete (ZTOT), x 10^{-4} in./in.	3.9
Number of points in the age-tensile strength relationship (NSTRN)	5
Number of points in the slab-base friction relationship (IFY)	2
Slab movement (YEXP), in.	- 0.1
Curing temperature (CURTEMP), °F	75
Number of days before concrete gains full strength (NTEMP)	28
Minimum temperature expected after concrete gains full strength (DELTATM), °F	30
Number of days after concrete is set before DELTATM occurs (COLDTM)	60
Minimum daily temperature (DT), °F	50
Number of days after concrete is set before wheel load is applied (TMLOD)	14

* LIC - limestone concrete
** GRC - siliceous river gravel concrete

TABLE A.10. SELECTED OUTPUT FROM PROGRAM CRCP-2 FOR THE COMBINATIONS SHOWN IN TABLE A.9

Slab Thickness, (in.)	Limestone CRCP		Siliceous River Gravel CRCP	
	Crack Width, x 10^{-3} in.	Mean Crack Spacing, ft	Crack Width, x 10^{-3} in.	Mean Crack Spacing, ft
6	11.75	1.992	8.42	1.252
8	21.78	3.884	20.28	3.179
10	28.74	5.281	27.10	4.353
12	32.65	6.093	32.75	5.358

discontinuities is minimized (Ref 10). For this study the Dynaflect loads and resulting deflections had to be simulated, and since interior loading conditions could be assumed program ELSYM5 was again used. The displacement in the z direction at the sensor 1 location (W_1) was considered to be equal to the required deflection value (y).

Reasonable values for W_1 were obtained for the different thicknesses; however, the curvature values computed according to the above-mentioned method did not seem to be coherent because in some instances Δ_y was greater in the thicker pavements than in the thinner ones, and an alternate method for deriving curvature was tried. It basically consisted of dividing by four the difference between W_1 and W_5; in this way consistent results, presented in Table A.11, were determined.

For a given thickness the deflection in the limestone CRCP was greater than that in the siliceous river gravel CRCP. This can be attributed to the lower modulus of elasticity of the limestone CRCP.

Figure A.4 shows that the assumption of an average modulus of elasticity for both concrete types is reasonable since sensor 1 deflection does not vary considerably within any of the two ranges for modulus of elasticity of concrete. As previously discussed, if only the moduli of elasticity presented in Table A.3 are considered, the ranges are significantly smaller, i.e., from 4.23 to 4.97 x 10^6 psi for limestone concrete and from 6.10 to 7.18 x 10^6 psi for siliceous river gravel. This means that the variation of W_1 with modulus of elasticity of concrete within any of the two intervals is slight. It has been supported again that it is valid to assume an average modulus of elasticity for both concrete types.

TABLE A.11. SIMULATED DYNAFLECT MEASUREMENTS FROM PROGRAM ELSYM5 FOR THE COMBINATIONS SHOWN IN FIG A.2

Slab Thickness, (in.)	Limestone CRCP		Siliceous River Gravel CRCP	
	Deflection, $\times 10^{-3}$ in.	Curvature, $\times 10^{-4}$ in.	Deflection, $\times 10^{-3}$ in.	Curvature, $\times 10^{-4}$ in.
6	1.026	1.085	0.946	0.913
8	0.822	0.676	0.750	0.548
10	0.686	0.452	0.626	0.370
12	0.596	0.338	0.547	0.290

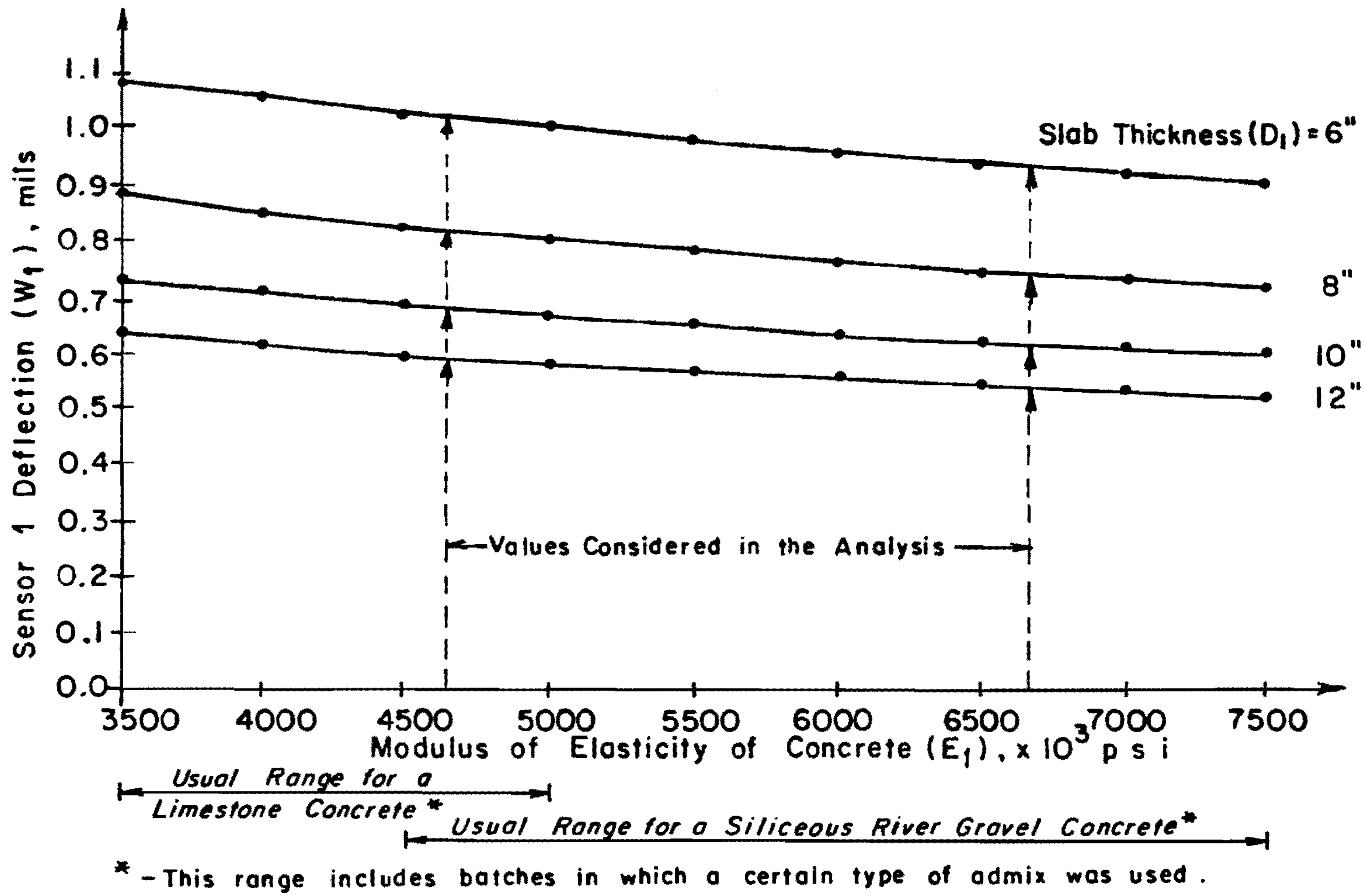


Fig A.4. Simulated sensor 1 deflection (W_1) as a function of modulus of elasticity of concrete (E_1) and slab thickness (D_1) for the pavement structure shown in Fig A.2.

Table A.12 gives the values and levels of the input parameters that were considered to determine the thickness-equivalency factors by means of the Report 177-7 design equation.

The Report 177-7 design equation was used to compute ZS values for limestone CRCP thicknesses of 6, 8, 10 and 12 inches and the number of load applications to date was varied from 2 to 20 million in order to ascertain if this parameter had any discernible effect on thickness-equivalency factors. Then, the thickness of the siliceous river gravel was gradually increased from a starting value of 6 inches until the computed ZS value was about the same as that corresponding to a given combination of D_{LI} and n obtained in the preceding step. Therefore, equivalent thicknesses can be defined following the concept used in the first approach if thickness and number of applications to date are the only parameters varied.

If

$$ZS\ (D_{LI},\ n) \cong ZS\ (D_{GR},\ n) \qquad \text{(A.9)}$$

then D_{LI} and D_{GR} are said to be equivalent thicknesses for a given n-value.

The thickness-equivalency factor (Eq A.10) can be obtained if and only if Eq A.9 is satisfied.

$$T_{LI-GR} = \frac{D_{GR}}{D_{LI}} \qquad \text{(A.10)}$$

where all the parameters are as defined before.

Results corresponding to T_{LI-GR} are presented in Table A.13. Values of S and Z were also computed for all the combinations considered, and attempts were made to determine thickness-equivalency factors from the Z values in a

TABLE A.12. VALUES OF THE INPUT PARAMETERS CONSIDERED IN THE DEVELOPMENT OF PAVEMENT THICKNESS EQUIVALENCIES USING REPORT 177-7 DESIGN EQUATION

(a) Variables	Value for Levels						
	1	2	3	4	5	....	10
Δx, in.	8 levels as given in Table A.10						
$\bar{x}$, in.	8 levels as given in Table A.10						
α, x 10^{-6} in./in./°F	3.2 (LIC)*	4.4 (GRC)**					
h, in.	6	8	10	12			
f_c, psi	683 (LIC)*	694 (GRC)**					
y, in.	8 levels as given in Table A.11						
Δ_y, in.	8 levels as given in Table A.11						
n, x 10^{-6}	2	4	6	8	10	....	20
$S_{\bar{x}}$, in.	8 levels; $S_{\bar{x}} = \bar{x}/2$						

(b) Parameters Held Constant	Value	
R, in.	0.5	
ΔT, °F	25	
p, lb	18,000	
L, in.	144	
S_{fc}, psi	50	(Ref 6)
S_p, lb	920	(Ref 6)
S_h, in.	0.16	(Ref 6)
$S_{\Delta x}$, x 10^{-3} in.	6	(Ref 6)
S_y, x 10^{-4} in.	1.92	(Ref 6)
$S_{\Delta y}$, x 10^{-5} in.	2.20	(Ref 6)
$S_{\log n}$	0.04	(Ref 6)

* LIC - limestone concrete
** GRC - siliceous river gravel concrete

Note: Parameters are as defined previously in Eqs A.8 and A.9

TABLE A.13. THICKNESS EQUIVALENCY FACTORS BETWEEN A LIMESTONE AND A SILICEOUS RIVER GRAVEL CRCP AS COMPUTED FROM REPORT 177-7 DESIGN EQUATION

n	Limestone CRCP		Siliceous River Gravel CRCP		
$\times 10^6$	ZS	D_{LI}, (in.)	ZS	D_{GR}, (in.)	T_{LI-GR}
	2.298	6.00	2.296	6.62	1.10
2	2.847	8.00	2.847	8.76	1.10
	3.201	10.00	3.201	10.72	1.07
	3.554	12.00	3.565	13.06	1.08
	1.997	6.00	1.995	6.62	1.10
4	2.546	8.00	2.546	8.76	1.10
	2.900	10.00	2.900	10.72	1.07
	3.264	12.00	3.264	13.06	1.08
	1.821	6.00	1.819	6.62	1.10
6	2.370	8.00	2.370	8.76	1.10
	2.578	10.00	2.724	10.72	1.07
	3.088	12.00	3.088	13.06	1.08
	1.696	6.00	1.694	6.62	1.10
8	2.245	8.00	2.245	8.76	1.10
	2.599	10.00	2.599	10.72	1.07
	2.963	12.00	2.963	13.06	1.08
	1.599	6.00	1.597	6.62	1.10
10	2.148	8.00	2.148	8.76	1.10
	2.502	10.00	2.502	10.72	1.07
	2.866	12.00	2.866	13.06	1.08
	1.520	6.00	1.518	6.62	1.10
12	2.069	8.00	2.069	8.76	1.o0
	2.423	10.00	2.423	10.72	1.07
	2.786	12.00	2.787	13.06	1.08
	1.453	6.00	1.451	6.62	1.10
14	2.002	8.00	2.002	8.76	1.10
	2.356	10.00	2.356	10.72	1.07
	2.720	12.00	2.720	13.06	1.08
	1.395	6.00	1.393	6.62	1.10
16	1.944	8.00	1.944	8.76	1.10
	2.298	10.00	2.298	10.72	1.07
	2.662	12.00	2.662	13.06	1.08
	1.344	6.00	1.342	6.62	1.10
18	1.893	8.00	1.893	8.76	1.10
	2.247	10.00	2.247	10.72	1.07
	2.610	12.00	2.611	13.06	1.08
	1.298	6.00	1.296	6.62	1.10
20	1.847	8.00	1.847	8.76	1.10
	2.201	10.00	2.201	10.72	1.07
	2.565	12.00	2.565	13.06	1.08

manner analogous to that for the ZS-values; however, Z varies erratically with thickness for a given n-value, as opposed to Z S, which always increases with slab thickness. It must be pointed out that the higher the ZS value the less the pavement area damaged. Therefore, it was considered adequate to use the ZS parameter to establish thickness-equivalency factors.

Figure 3.2 illustrates the results given in Table A.13 for the set of input values presented in Table A.12. Since T_{LI-GR} does not vary with number of load applications to date, Z S in Eq A.9 could be expressed as a function of thickness alone.

ANALYSIS USING DISTRESS-PREDICTION EQUATION

Condition survey information was used in Ref 12 to develop a distress prediction equation for CRCP that takes into account the type of coarse aggregate employed. Distress manifestation was defined as the condition in which an area of CRCP has suffered breakup to the point that the pavement no longer performs its normal structural function. Restoration of the distressed pavement requires removal of the damaged concrete and replacement with new concrete, which is bonded to the original pavement to return load transfer capacity to the entire structure. A distress-prediction equation was developed that computes the accumulated distressed area in a CRCP for the pavement age selected. This equation is

$$
\begin{aligned}
\text{Failures (Sq ft /Mile)} = {} & 0.62 + \big[\, 1.74 \text{ (clay severity)} - 0.77 \text{ (Region 7)} \\
& + 0.003 \text{ (temperature constant)} \\
& + X_1 \text{ (pavement coarse aggregate)} \\
& - 0.31 \text{ (central mix for concrete)} \\
& - 0.25 \text{ (internal vibration for concrete)} \\
& - 0.62 \text{ (asphalt concrete subbase course)} \\
& + 0.46 \text{ (subbase centrally mixed)} \\
& + X_2 \text{ (subbase material)} \\
& + X_3 \text{ (subbase stabilization)} \\
& + X_4 \text{ (shoulder base type)} \\
& + X_5 \text{ (shoulder base stabilization)} \\
& + 0.61 \text{ (subgrade layer thickness in inches)} \big] \\
& \quad \cdot \text{ pavement age in months} \\
& + \big[0.02 \text{ (current distress condition of pavement} \\
& \quad \text{in sq ft /mi)} \cdot \text{ time increment in months} \big]
\end{aligned}
$$

where

X_1 = 0.55, if, siliceous river gravel (GR) used,
-2.13, if limestone river gravel (LI) used,
0.17, if GR + LI used,
0, if other aggregate used;

X_2 = 2.00, if pit run gravel used,
1.08, if limestone material used,
0.89, if oyster shell used, and
0, if other subbase material used;

X_3 = -0.46, if asphalt used,
-0.15, if lime used, and
0, if cement used or not stabilized;

X_4 = -0.90, if flexible shoulder base used,
1.68, if foundation course used, and
0, if other shoulder base type used; and

X_5 = -0.67, if cement used,
1.95, if lime used, and
0, if asphalt or no shoulder base stabilizer used.

In Eq A.11 there are six dichotomous variables (i.e., variables that take a value of 1 if the condition enclosed in parentheses exists and 0 otherwise). Region 7 is a variable that takes a value of 1 when the pavement section is located in the south-central region of Texas. "Temperature constant" refers to the parameter used by the Texas SDHPT to consider regional temperature variations throughout the state.

Table A.14 presents the values of the various input parameters used to predict the number of distress manifestations in a CRCP.

Equation A.11 can be modified to compute the accumulated number of distress manifestations rather than the accumulated distressed area by considering an average of 60 sq ft per distress manifestation.

$$\text{Failures (per mile)} = \frac{\text{Failures (sq ft /mile)}}{60} \qquad \text{(A.12)}$$

The accumulated number of distress manifestations was computed for the distinct combinations given in Table A.14, and it was found out that the SDHPT temperature constant had an insignificant effect on the results obtained. Number of distress manifestations per mile as a function of pavement age and coarse-aggregate type is given in Table A.15 for various combinations selected. These results are plotted in Fig A.5.

It has been observed in the field that, in general, a level of 14 distress manifestations per mile is characteristic of a CRCP requiring an overlay. Thus, the time necessary for a CRCP to reach the terminal-condition level can be estimated as shown in Fig A.5. Since both relationships for number of distress manifestations per mile versus pavement age are sensibly linear, any level could have been chosen as terminal condition for the analysis that is described below.

If it is assumed that terminal-condition level is equivalent to a zero remaining fatigue life, a fatigue equation can be used to arrive at thickness equivalencies between a limestone and a siliceous river gravel CRCP, since the distress-prediction equation does not allow slab thickness to be varied directly.

For concrete pavements, the fatigue equation is generally of the form

$$N = A \cdot (f/\sigma)^B \qquad (A.13)$$

where

N = number of load applications to a terminal-condition level,

f = flexural strength of concrete, and

σ = tensile stress in the concrete under load.

A and B take the values of 46,000 and 3, respectively, if the fatigue equation for CRCP recommended by Taute et al (Ref 13) is used. Additionally, since accumulated number of load applications is proportional to pavement age, the ratio of limestone N to siliceous river gravel N can be estimated from Table A.15 or Fig A.4.

$$\frac{N_{LI}}{N_{GR}} \cong \frac{256}{138} \qquad (A.14)$$

where

N_{LI} = number of load applications to a terminal-condition level in a limestone CRCP and

N_{GR} = number of load applications to a terminal-condition level in a siliceous river gravel CRCP.

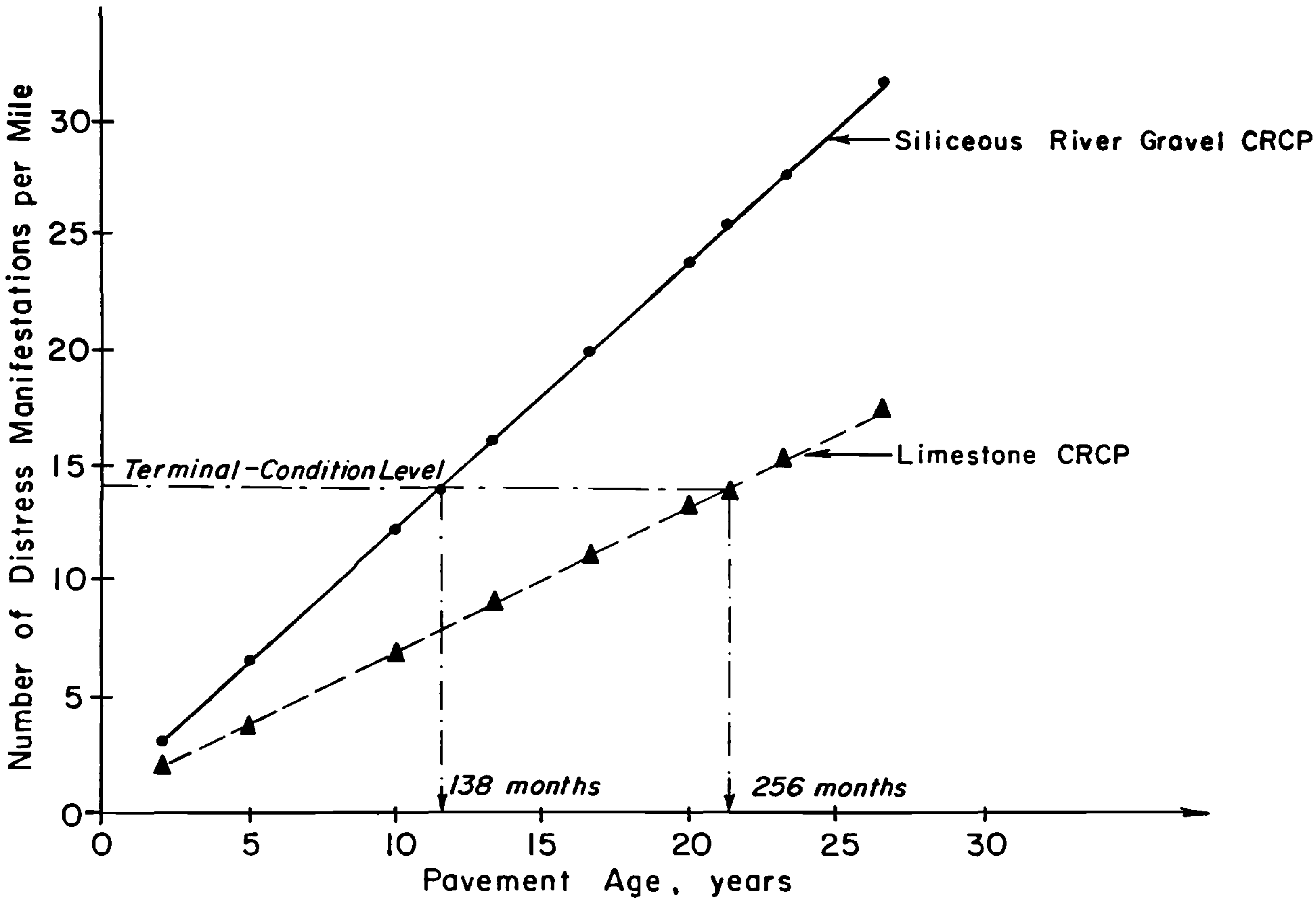


Fig A.5. Graphical determination of the pavement age to reach terminal-condition level for the data given in Table A.15.

TABLE A.14. VALUES OF THE INPUT PARAMETERS USED TO PREDICT THE NUMBER OF DISTRESS MANIFESTATIONS IN A CRCP

(a) Variables	Values for Levels					
	1	2	3	4	....	160
Texas SDHPT temperature constant	10	20	30			
X_1 (pavement coarse aggregate	0.55 (GR)*	-2.13 (LI)**				
Pavement age, months	2	4	6	8	....	320

(b) Parameters Held Constant	Value
Clay severity	0 (low)
Region 7	1
Central mix for concrete	1
Internal vibration of concrete	1
Asphalt concrete subbase course	0
Subbase centrally mixed	0
X_2 (subbase material)	1.08 (limestone)
X_3 (subbase stabilization)	-0.15 (lime stabilizer)
X_4 (shoulder base type)	0
X_5 (shoulder base stabilization)	1.95 (lime stabilizer)
Subgrade layer thickness, in.	6
Current distress condtion of pavement, sq. ft./mile	0

*GR - siliceous river gravel CRCP
**LI - limestone CRCP

TABLE A.15. NUMBER OF DISTRESS MANIFESTATIONS PER MILE AS PREDICTED BY EQUATION A.12 (SDHPT TEMPERATURE CONSTANT = 20)

Pavement Age, Months	Coarse-Aggregate Type	
	Siliceous River Gravel	Limestone
24	2.9	1.9
60	6.4	3.8
120	12.3	6.9
138	14.0	7.8
160	16.1	9.0
200	20.0	11.1
240	23.9	13.2
256	25.5	14.0
280	27.8	15.3
320	31.7	17.4

Another assumption implicit in Eq A.14 is that the accumulated number of load applications can be expressed by means of a linear function.

According to current specifications, concrete should reach a minimum level of flexural strength, which will be considered to be the same for both types of concrete analyzed. Equation A.13 can now be modified to reflect the fact that CRC pavements made with limestone last longer than those constructed with siliceous river gravel:

$$N_{LI} = \frac{256}{138} \cdot A \cdot (f/\sigma_{LI})^3 \qquad (A.15)$$

$$N_{GR} = A \cdot (f/\sigma_{GR})^3 \qquad (A.16)$$

where

σ_{LI} = tensile stress in the limestone CRCP and

σ_{GR} = tensile stress in the siliceous river gravel CRCP.

Dividing Eq A.15 by Eq A.16

$$\frac{N_{LI}}{N_{GR}} = \frac{256}{138} \left(\frac{\sigma_{GR}}{\sigma_{LI}}\right)^3 \qquad (A.17)$$

It has been commonly recognized that tensile stress is inversely proportional to the square of thickness:

$$\sigma \propto \left(\frac{1}{D^2}\right) \qquad (A.18)$$

Applying this concept to Eq A.17

$$\frac{N_{(D_{LI})}}{N_{(D_{GR})}} = \frac{256}{138} \left(\frac{D_{LI}}{D_{GR}} \right)^6 \quad (A.19)$$

where

D_{LI} = slab thickness of the limestone CRCP and

D_{GR} = slab thickness of the siliceous river gravel CRCP.

If

$$N\ (D_{LI}) \cong N\ (D_{GR}) \quad (A.20)$$

Then D_{LI} and D_{GR} are said to be equivalent thicknesses. Then, it follows that

$$1 = \frac{256}{138} \left(\frac{D_{LI}}{D_{GR}} \right)^6$$

$$DGR = 1.11\ D_{LI} \quad (A.21)$$

The thickness-equivalency factor can be defined if and only if Eq A.20 is satisfied.

$$T_{LI\text{-}GR} = 1.11 \quad (A.22)$$

Figure 3.3 compares the equivalent thicknesses obtained from this method with those from the other two approaches.