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STUDY OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

by

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FINAL REPORT
SwRI Project No. 07-1864

to

U. S. Steel Corporation
Five Gateway Center
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APPROVED:

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FOREWORD

The information presented herein was obtained from many sources, including published and unpublished literature, state highway departments, trade associations, design and construction engineers, steel products manufacturers, and others. Collection of information and data was accomplished through literature review and studies, personal visitations, observation of construction, questionnaires, and other appropriate means.

Sincere thanks and appreciation are extended to all who assisted and gave their time throughout the study. Acknowledgement and thanks are also given to the many authors of papers, articles, and other publications which provided a great deal of the information that is presented.

SUMMARY

The technology of continuously reinforced concrete pavements (CRCP) has been advanced a great deal since the first projects were completed nearly 30 years ago. While many engineers feel that a rational method of design for this type of pavement has not yet been fully developed, others feel that a reasonable solution to the overall design problem is within grasp.

Aside from the fundamental design concept, there are two basic design details for CRCP; these are concerned with the use of deformed steel bar reinforcement on the one hand, and wire mesh on the other. To date, the former material has been used in most projects, though most states permit the use of either, according to contractors' option. The wider use of wire mesh appears to be dependent on the gaining of further experience with it and the economics associated with its utilization in areas of different wage scales.

Construction of early CRCP posed numerous problems due to inexperience in the building of such pavements. Much of the practice employed was logically derived from that used in constructing conventional jointed concrete pavements. Experience with CRCP has led to rather well established procedures which, when followed, have resulted in durable pavements having excellent performance records. The use of efficient construction methods and modern equipment has permitted high paving rates and minimized difficulties on many projects.

When compared to other types of pavements, CRCP offer several distinct advantages. As to simplicity of construction and initial cost, they compare very favorably with conventional concrete pavements. Definite advantages are afforded in their low maintenance costs, long service life, and superior riding qualities. It is widely felt that these pavements meet the requirements for future highway construction, even in their present state of development. For new construction as well as pavement replacement, a number of standard designs are available. Such designs must be adapted to local conditions and environments. There is considerable appeal to the use of CRCP as overlays for existing pavements that have reached the ends of their service lives.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF TABLES

I. INTRODUCTION

Among rigid concrete pavement types, those normally constructed with expansion and contraction joints spaced according to regular patterns are by far the most common and best known. These joints have the purpose of relieving internal stresses and controlling the location and configuration of cracks that occur from volume changes in the concrete due primarily to moisture content change and temperature variation. While being functional and useful from this standpoint, the joints are also a major source of the maintenance problems encountered during the service life of pavement sections. Among the phenomena contributing to costly maintenance of jointed pavements are subgrade pumping, slab faulting, spalling, and diagonal cracking at joint corners. Periodic cleaning, repair, and resealing operations are not only costly but also present a safety hazard on roads carrying high-speed and/or heavy-volume traffic. A further undesirable feature is the often annoying and monotonous riding quality associated with conventional jointed pavements. When viewed collectively, it is not surprising that these persistent problems have led to increased interest in continuously reinforced concrete pavements.

The concept of CRCP concerns the use of continuous reinforcing steel to maintain reasonable continuity in long paving slabs by distributing the effects of concrete contraction due to shrinkage and temperature decrease. From a design standpoint, the steel is considered to add little to the load-carrying capacity of the pavement.

Studies of experimental continuously reinforced concrete highway pavements have indicated that the continuous slab does not change significantly in length due to shrinkage and temperature drop, except at the end portions where it is free to move. Consequently, it is considered valid to analyze the interior portions of the slab as being fixed at both ends. When appreciable contraction occurs in a section of concrete pavement restrained at its ends, cracking takes place because the concrete lacks sufficient ductility to maintain its original length. If only a few cracks develop, each is of such width as to produce a serious gap in the continuity of the pavement. This condition is little better than that which exists in conventional jointed concrete pavements and permits rapid deterioration at crack sites. Continuity is more nearly achieved if the cracks which develop are rather closely spaced and therefore relatively narrow. The idea then is to place continuous reinforcing steel longitudinally in the pavement in such arrangement and amount that the cracks which develop will be optimally spaced and so narrow that the granular interlock at the cracked faces will be preserved to a maximum degree.

For a number of reasons, the use of CRCP has received increased attention and has become more justifiable in recent years as a result of developments in areas of design, construction methods and equipment, and economics. Among these reasons are the following:

- Because they can be placed on subbases appropriate to a variety of underlying subgrades or, in some cases, even be built without base courses, pavements of this type are indicated to have much potential in areas where high quality base-course materials are scarce.
- While from a design standpoint the reinforcing steel is not considered to add to the structural capacity of concrete pavements, it has been indicated(1) that the increase in effective slab thickness afforded by continuous reinforcement can be as much as 30 to 40 percent.
- The use of improved construction methods, practices and equipment has led to greater proficiency of steel placement and higher paving rates, with accompanying cost reductions that make CRCP competitive with other types of pavements.
- Since, by intent, the cracks in CRCP remain small, the infiltration of water, soil, and other matter is minimized and little or no maintenance is required.
- Although minor surface spalling or raveling may occur at some crack sites, the overall result is a smooth, strong, durable pavement.
- Experience to date indicates that on the basis of first cost, maintenance cost, service life, and salvage value, continuously reinforced concrete pavements are economically sound.

The work carried out in this study has been concerned with determination of the current status and trends of CRCP technology with primary regard to areas of materials, design, construction, pavement characteristics, and behavior. Results of the study are incorporated in this report, which has the purpose of presenting an overall picture of CRCP, past and present, with comments on the future of this type of pavement as indicated by past and current developments. Because major percentages of the constructed mileage of CRCP have been in Texas, Mississippi, Illinois, and North Dakota, this study has given particular attention to the work done in these states.

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(1) Mellinger, F. M., Sale, J. P., and Wathen, R. R., Proceedings, Highway Research Board, 1957.

II. HISTORY OF DEVELOPMENT

Interest in improved types of rigid pavements is not new in the field of highway construction, as indicated by the building of the first continuously reinforced concrete pavement in 1921. This consisted of several relatively short sections of the Columbia Pike, near Washington, D.C., constructed by the U.S. Bureau of Public Roads. The next significant construction of this type of pavement occurred in 1938 when several sections were built by the State of Indiana near Stilesville; these reportedly are still performing satisfactorily. In the following 21 years, nearly 54 miles of equivalent two-lane continuously reinforced concrete pavement were built in eight states.

Since 1960, the mileage has increased at a rapid rate. At mid-1966, the total built or under contract in 388 projects in twenty-one states was approximately 3151 equivalent two-lane miles; this included 12.56 miles of airport runway, taxiway, and holding area pavement in one project. Figure 1 graphically shows the total mileage and indicates the rate of construction increase. It is noteworthy that, of the total mileage shown for mid-1966, 3051 miles were built or contracted for in the seven years since 1959. Four states -- Texas, Mississippi, Illinois, and North Dakota -- accounted for 87 percent of this amount. Table I shows status of CRCP construction by states as of mid-1966. Although experimental sections incorporating new or improved design features are still being constructed, indications are that past experience plus confidence in areas of design, construction, and economics will carry continuously reinforced concrete pavements forward as a major form of paving in many states.

The development of continuously reinforced concrete pavements has received increased attention during the last few years, resulting in better understanding of design parameters, refinement of design procedures, new approaches to recognized problems, and improvement of construction methods and equipment. Much time has been required for the evaluation of performance of pavements built according to particular designs and practices. However, experience gained in earlier work has been helpful in the task of reducing theory to practice and has provided invaluable background for guidance in current programs. Although there is frequent questioning among engineers on the interpretation of data and the use of various design features and modifications, a rather methodical development of continuously reinforced concrete pavement technology is occurring. Among individuals and groups concerned with this technology, there is

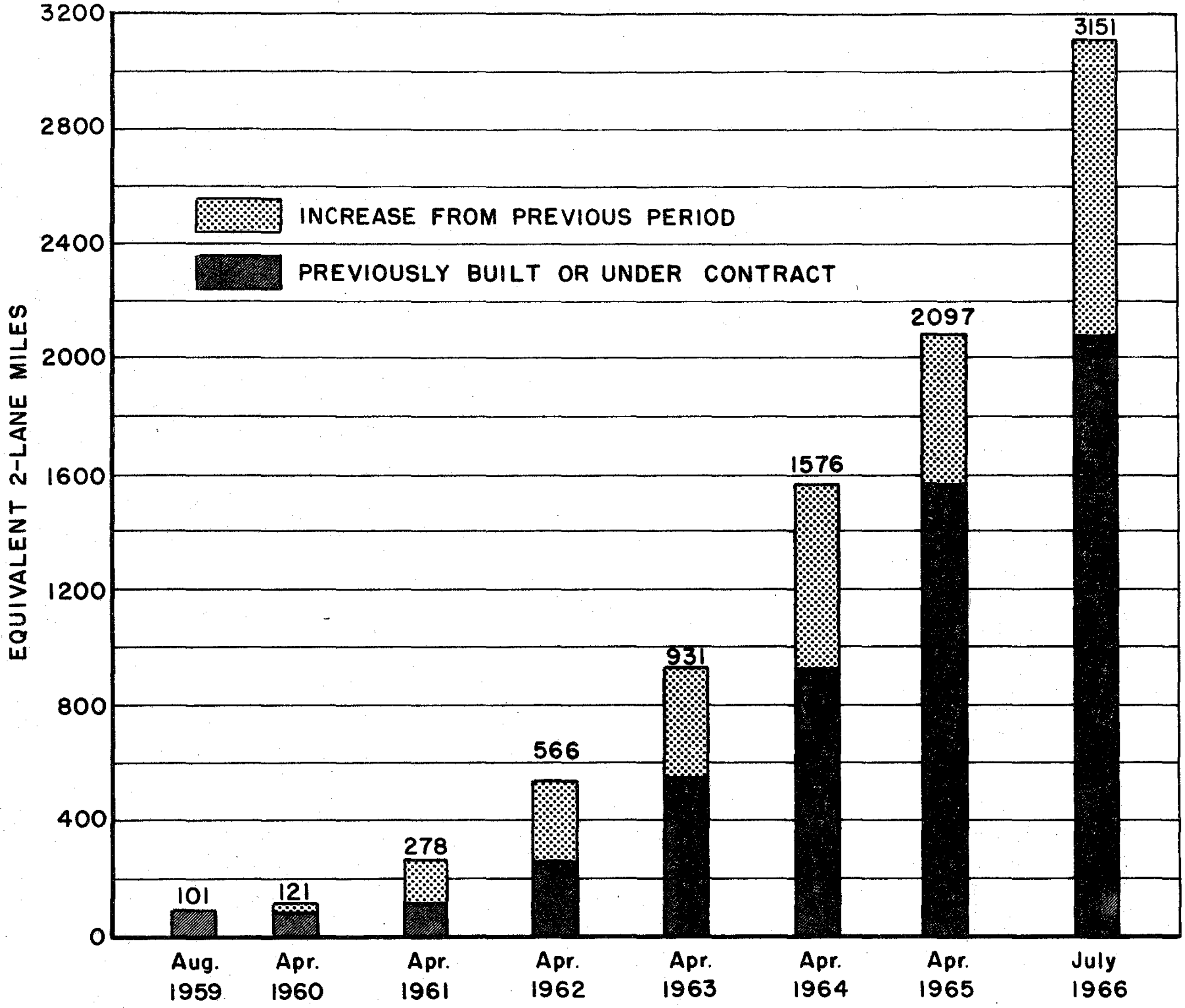


FIGURE 1. TOTAL MILEAGE OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENT IN THE UNITED STATES (BUILT OR UNDER CONTRACT AS OF DATE SHOWN)

TABLE I

STATUS OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENT HIGHWAY AND AIRPORT

(Built or under Contract on July 1, 1966)

State	Projects	Equivalent Two-Lane Miles
Arkansas	2	10.63
California	1	1.00
Connecticut	1	3.12
Illinois	73	391.82
Indiana	2	7.86
Iowa	9	92.41
Maine	1	0.57
Maryland	3	21.45
Michigan	11	48.24
Minnesota	2	29.34
Mississippi	40	510.62
New Jersey	1	1.96
North Dakota	9	160.78
Ohio	3	18.74
Oregon	8	53.64
Pennsylvania	2	8.42
Rhode Island	1	1.02
South Dakota	1	1.50
Texas	201	1,680.46
Virginia	8	28.03
Wisconsin	8	67.34
Total Highways	387	3,138.95
Total Airport (O'Hare Field)	1	12.56
Grand Total	388	3,151.51

Source: Concrete Reinforcing Steel Institute, Committee on Continuously Reinforced Concrete Pavement, Chicago, Illinois, July 1966.

frequent exchange of information based on experience, plus a cooperative effort to solve common problems. Before undertaking actual construction programs incorporating their own designs, some have preferred to study past projects and monitor the progress of current ones; others have elected to look at CRCP from theoretical analytical viewpoints or through laboratory experiments. Regardless of the approach, there is much evidence of progress in the search for some rational method of design to replace the "rule-of-thumb" method that has been used.

In the transformation of designs into finished pavements, progress in CRCP development has not been made without problems. Occasionally, failures have occurred, leading to a decrease of interest in CRCP in a few states. However, interest has usually been revived by continued satisfactory performance records of properly constructed projects and realization that many of the problems experienced likely would have occurred with conventional types of concrete pavement. Significant advancements in the proficiency of building CRCP have been made in the past few years, due to the use of new and/or improved methods, procedures, and equipment.

Of the CRCP sections built in several hundred projects to mid-1966, a high proportion have shown good to excellent performance and behavior, a few over periods of nearly 20 years. In most cases where failures occurred in pavements, causes could be identified with improper construction practices, poor materials quality, or other factors not associated with the basic design features. A primary consideration with respect to failures in early projects is that the work was experimental, and few of the contractors and highway department engineers were experienced in CRCP construction. Today, the picture is much different. The need for materials of adequate quality, control of concrete properties, and good construction practices are recognized and provided for in specifications. Many engineers have gained experience with CRCP, and numerous contractors have built many miles of this type of pavement. Evidence that it has moved beyond the experimental state is found in Texas, where projects totaling more than 400 miles have been built or contracted during the 12-month period to August 1966, and in North Dakota where it has been announced that all remaining Interstate paving will consist of CRCP.

Under optimum conditions, pavements 24 feet wide and 8 inches thick can currently be laid at rates ranging from about 3000 to over 6000 feet per day, depending on methods and equipment. These rates are substantially higher than were possible a few years ago and in many cases are reflected in reduced construction costs. Numerous current projects involve pavements that are tens of miles long, whereas, not long ago, sections not more than a few miles or even several thousand feet in length were being built.

III. DESIGN

The design of CRCP has presented many challenging problems; some of these have been reasonably well resolved, while others are still being studied. Gaps in the fundamental understanding of the behavior of this type of pavement have led to the use of various designs in attempts to identify controlling variables and define design criteria. The effects of some variables have been evaluated under actual service conditions in many states through the use of experimental sections of CRCP. Currently, the efforts of numerous engineers in state highway departments, federal agencies, universities, research institutes, and other organizations are directed toward the development of simplified, workable solutions for various design problems encountered in CRCP.

The overall design of a continuously reinforced concrete pavement must take many factors into consideration. Among the variables to be dealt with are: tensile, bond, and flexural strength of the concrete; tensile and shear strength of the reinforcing steel; steel bond area; expected temperature differential; shrinkage coefficient of the concrete; combined modulus of elasticity of the concrete and steel; modulus of subgrade reaction (k) developed; resistance to fatigue of the combined concrete and steel; and intensity, duration, frequency of application, and lateral placement of loads. In the present stage of CRCP development, means of evaluating and correlating many of these factors and values with respect to each other have been found or are gradually evolving. However, the total number and complexity of variables to be considered makes theoretical approaches to design extremely difficult to conceive.

Many facets of overall CRCP design are well enough developed and tried to give confidence in structures incorporating them and provide an understanding of certain behavior patterns. Where such a condition exists, it may be said that standard or valid designs exist. However, opinions on design validity vary among engineers according to the manner of studying problems and obtaining answers, as through theoretical analysis, laboratory experimentation, or studies of the behavior of prototype pavements built according to particular designs. It is obvious that much weight is placed on work wherein pavement behavior and performance, as determined by the latter method, are rated good to excellent and in reasonable agreement with expectations. This is particularly true when study periods have extended over five or more years.

A. General Design Considerations

Many of the design variables which apply to conventional jointed concrete pavements are also applicable to CRCP; however, it is apparent that special consideration must be given to particular features of the continuously reinforced pavement such as crack spacing and width, continuity of slab, absence of joints and corners, etc. The three types of common variables are as follows:

- Structural variables which describe the strength characteristics of pavement layers and roadbed material, the thicknesses of pavement layers, other design features, and the overall or composite strength of the pavement. Roadbed material includes all soils and/or other materials that are below the pavement structure and affect the supporting capability of the pavement structure.

- Load variables in terms of accumulated axle loads, the number of years over which the accumulation has taken place, and the general rate of axle load accumulation. Load applications are ordinarily expressed as equivalent 18,000-pound axle loads.

- Climatic and regional variables that describe external influences -- other than load -- which can lead to performance differences among pavement sections that have the same load and initial structural conditions. Measures of regional factors and relative composite strength are utilized as indirect indicators of regional and climatic variables, the first in terms of geographical regions only, and the second in terms of strength changes that may be induced by these variables between or within geographical regions.

The general design variables that are applicable to CRCP on a nationwide basis are outlined as follows:

- Structural
  - Pavement Structure
    - Pavement
    - Base Course or Subbase
    - Treated Subgrade
    - Roadbed Soils
  - Roadbed Material

  $\left\{\begin{array}{l}\text{Strength Characteristics}\\ \text{Thickness of Pavement}\\ \text{Other Design Features}\\ \text{Composite Strength}\end{array}\right.$

° Load	Accumulated Axle Loads Years of Service Rate of Accumulation
° Climatic and Regional	Conditions of Precipitation, Moisture, Temperature, and Frost Topography Relative Strength in Different Climates Regional Factors

The variables shown in the above outline indicate a number of dominant factors for which data must be compiled and correlated in the design of a concrete pavement structure, continuously reinforced and/or conventional. Based on findings of the American Association of State Highway Officials (AASHO) Road Test and results of studies by the Illinois Division of Highways, these are as follows:

- Volume and axle-load distribution of the traffic that the pavement shall carry.
- Type and strength of the roadbed soil(s) over which the structure is to be built.
- Period of time over which the pavement is expected to satisfactorily serve traffic of a given volume and character.
- Environmental and climatic conditions of the area in which the pavement is to be built, see service, and be maintained.
- Relative ability of the pavement slabs to support loads.

It is apparent that the noted factors can be applied more effectively to design work if supplemented by performance data for pavements that have been constructed and seen service under conditions similar to those anticipated for a given project.

B. Roadbeds and Subgrades

The importance of roadbed soils qualities lies in the fact that the performance of concrete pavements, CRCP included, is directly related to the physical properties and supporting power of the soils. Evaluation of the strength and other properties of soils for determination of values used in designing CRCP structures is accomplished through well-known testing procedures, many of which have been standardized. In order to be useful, test results must be correlated with results of field performance studies, with experience gained in materials testing, previous design work, and actual highway construction playing an important role in the final analysis.

The AASHO Road Test Project findings have provided much information on relationships between subgrades, subbases and rigid concrete pavement performance and behavior. That portion of the work concerned with roadbed soils under conventional jointed reinforced concrete pavements is of value in design work related to CRCP, even though sections of the latter were not used and only one soil type was taken into consideration in the project. Results of the AASHO Road Test are used by many design engineers as guides to recognition of problems that may arise due to the various properties of roadbed soils, such as permanant deformation, excessive deflection and rebound, excessive volume changes, and frost susceptibility. However, it should be noted that the findings of the AASHO work must be translated into local conditions in order to be useful in pavement structure design.

Current CRCP design practice makes use of established correlations of pavement performance with subgrade roadbed soil types, plus, when needed, supplemental information provided from appropriate tests. Testing procedures employed for determining soil properties vary from one state to another. However, all have the common objective of providing required information relative to the strength and stability of materials, moisture-density-strength relationships, shrinkage and swelling characteristics, compaction requirements, need for stabilization, and other factors which affect overall design of CRCP.

For design considerations, the roadbed material is described as being of such thickness as influences the load-bearing capacity of the pavement structure. This is normally 2 to 4 feet, and the nature of the material(s) should be known for the full depth. In many cases, any variations will occur merely as a range for the recorded variable, while, in others, definite layers of materials having different classifications may be found. Recommended practice in the latter case is to provide two sets of data with applicable depths being shown. In forming subbases, common practice is to modify the top 6 inches, or other definite thickness, of roadbed by rolling or admixture prior to adding any construction.

Strength characteristics of roadbed materials are determined through the use of appropriate testing procedures, including triaxial, California Bearing Ratio (CBR), plate load, Stabilometer tests, and so on, plus field information. The CBR test is widely used, and it is noteworthy that, in good design practice, the values selected will represent the minimum values for the soils being examined. Other measurements are made to provide soil classification data with respect to gradations, liquid limit, plasticity index, maximum density, and optimum moisture content. Knowledge of the swelling characteristics of materials is important. Pavement structure design, construction practices, and modifications of materials are based on overall evaluation of the indicated test results. Modification of materials can apply to one or more layers of the structure, as by addition of lime or cement, or rolling to increase natural density. It is of interest to note that practice relative to such treatments varies from one state to another, some employing soil stabilization and others making use of rolling and watering, or even both methods. Still others do almost nothing to the natural ground.

An indication of the number and variety of tests that may be employed to provide data on roadbed and subgrade materials can be obtained from Table II which lists test methods used in Texas. The actual tests performed vary from one project to another; however, design work in that state places considerable importance on the results of triaxial compression tests. In Illinois, the CBR value of soils is the only soil support value normally determined; other soil strength test procedures can be used, provided that test results can be correlated with those obtained by the CBR test procedure used by the Illinois Division of Highways.

C. Base and Subbase Courses

The base courses used under CRCP have functions which include prevention of pumping, protection against frost action, provision for drainage, facilitation of construction, control of volume changes in the subgrade, and so on. These functions are the basis of a large portion of the criteria for base course design and construction. Availability of materials and economics usually have a major influence on the choice of type of base course. The effects of particle-size distribution, particle shape, relative density, internal friction, and cohesion on the stability of soil-aggregate mixtures composing base courses have been studied extensively; it is apparent that a basic knowledge of soil mechanics is important in many design considerations. Designs for subpavement structures normally take these factors into account, with current CRCP practice giving attention to providing adequate base and underlying courses. Subbases should be provided according to the types of subgrade soils encountered. Currently, a 3-inch minimum subbase thickness is recommended for prevention of pumping. Thicker courses are needed to protect against high volume

TABLE II

TESTS USED IN TEXAS FOR DETERMINATION OF PROPERTIES OF SOILS AND RELATED MATERIALS

Test Method No.	Title
Tex-100-E	Surveying and Sampling Soils for Highways
Tex-101-E	Preparation of Soil and Flexible Base Materials for Testing
Tex-102-E	Determination of Slaking Time for Preparing Base Material
Tex-103-E	Determination of Moisture Content in Soil Materials
Tex-104-E	Determination of Liquid Limit of Soils
Tex-105-E	Determination of Plastic Limit of Soils
Tex-106-E	Method of Calculating Plasticity Index of Soils
Tex-107-E	Determination of Shrinkage Factors of Soils
Tex-108-E	Determination of Specific Gravity of Soils
Tex-109-E	Pressure Pycnometer Methods for Determination of Specific Gravity, Moisture Content and for Slaking or Wetting Material
Tex-110-E	Determination of Hydrometer and Mechanical Analysis of Soils
Tex-111-E	Determination of the Amount of Minus No. 200 Sieve Material in Soils
Tex-112-E	Method of Admixing Lime to Reduce Plasticity Index of Soils
Tex-113-E	Determination of Moisture-Density Relations of Soils and Base Materials
Tex-114-E	Compaction Ratio Method for Selection of Density of Soils and Base Materials in Place
Tex-115-E	Field Method for Determination of In-Place Density of Soils and Base Materials
Tex-116-E	Ball Mill Method for Determination of the Disintegration of Flexible Base Material
Tex-117-E	Triaxial Compression Test for Disturbed Soils and Base Materials
Tex-118-E	Triaxial Compression Tests for Undisturbed Soils
Tex-119-E	Soil-Asphalt Strength Test Methods
Tex-120-E	Soil-Cement Compressive Strength Test Methods
Tex-121-E	Soil-Lime Compressive Strength Test Methods
Tex-122-E	Cohesiometer Test Method for Stabilized Mixtures of Soil-Asphalt, Soil-Lime or Soil-Cement

TABLE II (CONT'D)

TESTS USED IN TEXAS FOR DETERMINATION OF PROPERTIES OF SOILS AND RELATED MATERIALS

Test Method No.	Title
Tex-123-E	Method for Determination of the Drainage Factor of Soil Materials
Tex-124-E	Methods for Determining the Potential Vertical Rise, PVR
Tex-125-E	Method for Determination of Subgrade Modulus of Reaction (K Value)

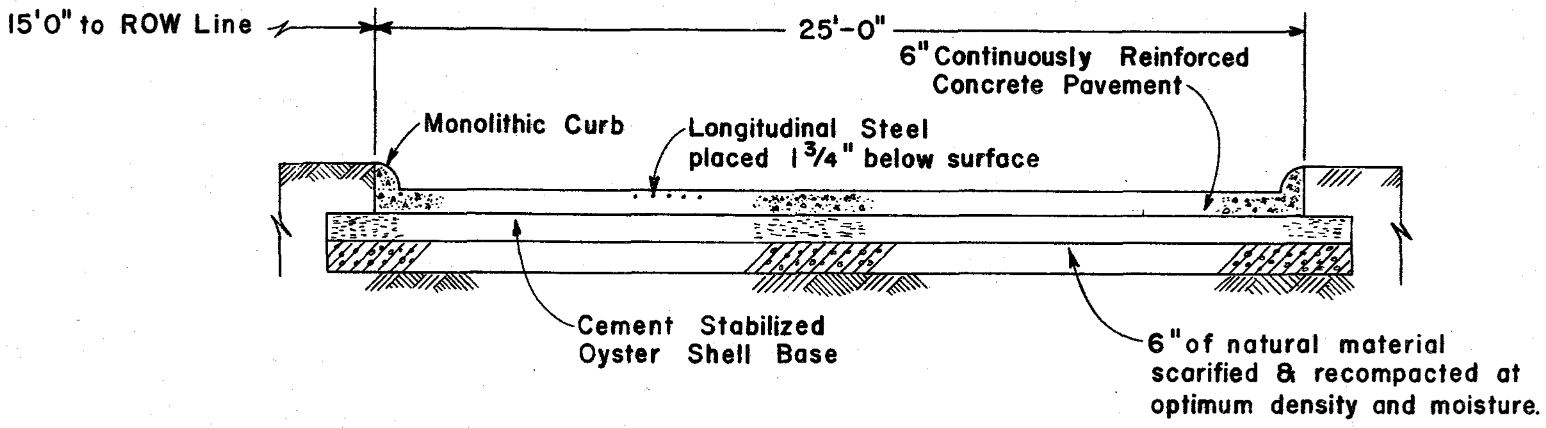
change and frost-susceptible soils. Experience with CRCP has indicated that actual thickness, type of subbase material, and construction practice should conform to approved state design standards and construction specifications applying to subbase for conventional jointed reinforced concrete pavements.

Types of base courses vary considerably from one area to another in the United States, with those in the northern states being open-graded as protection against frost action. Among the southern states and throughout the Midwest, dense-graded base courses are used; this is presumed to reflect the relative unimportance of frost action and the types of materials available. As protection against pumping, base courses 4 to 6 inches thick are common in the South and Midwest.

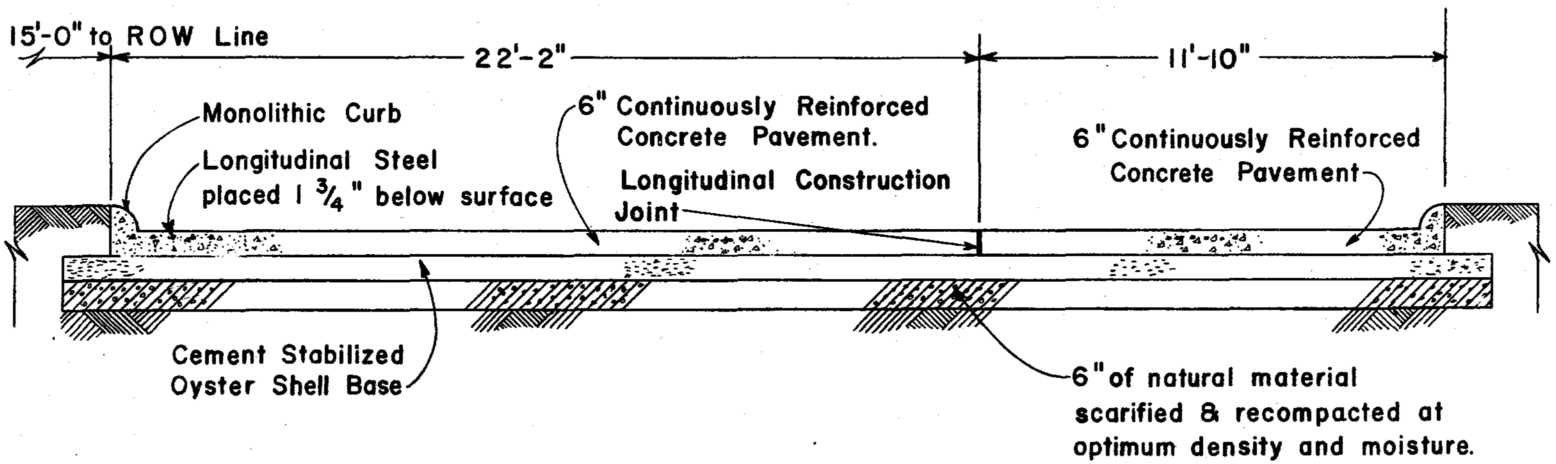
In Texas, considerable mileage of CRCP has been placed on a hot-laid asphaltic concrete base course or level-up layer, 3.5 to 4 inches thick, overlying lime- or cement-stabilized layers which reach to the subgrade. This type of base course has provided an excellent flat surface or platform for the placement of the continuous reinforcing steel and has reduced construction delays due to wet weather conditions. Additional mileage, particularly in the coastal region, has been laid on a cement-stabilized oystershell base underlain by natural material that was scarified and recompacted at optimum density and moisture. Throughout the state, subbases have been designed according to the characteristics of local subgrade materials, with crushed stone from 4 to 20 inches thick being used in some cases and 4 to 6 inches of lime- or cement-stabilized materials in others. Figures 2 and 3 show typical sections for CRCP construction in Texas.

The use of CRCP in Texas as a base for a flexible wearing course and as an overlay for the salvage of existing concrete pavement is of interest. In the former case, the existing concrete pavement was structurally adequate but required resurfacing to correct surface degradation. In the latter case, an existing concrete pavement was badly cracked and inadequate in combination with the subbase to serve traffic as required. Here the existing pavement served as a rigid base over which was laid a 7-inch continuously reinforced pavement. Where similar opportunities for salvage of concrete pavements exist, a thinner continuously reinforced concrete overlay might be used, provided that the existing structure had adequate load-bearing capacity.

Base courses stabilized with 4-1/2 to 5 volume-percent of cement have been used in CRCP designs in Mississippi. Figure 4 shows a typical section of the structure used in one project there.



TWO LANE PAVEMENT



THREE LANE PAVEMENT

FIGURE 2. TYPICAL SECTIONS FOR CRCP STRUCTURE USED IN HARRIS COUNTY, TEXAS PROJECT

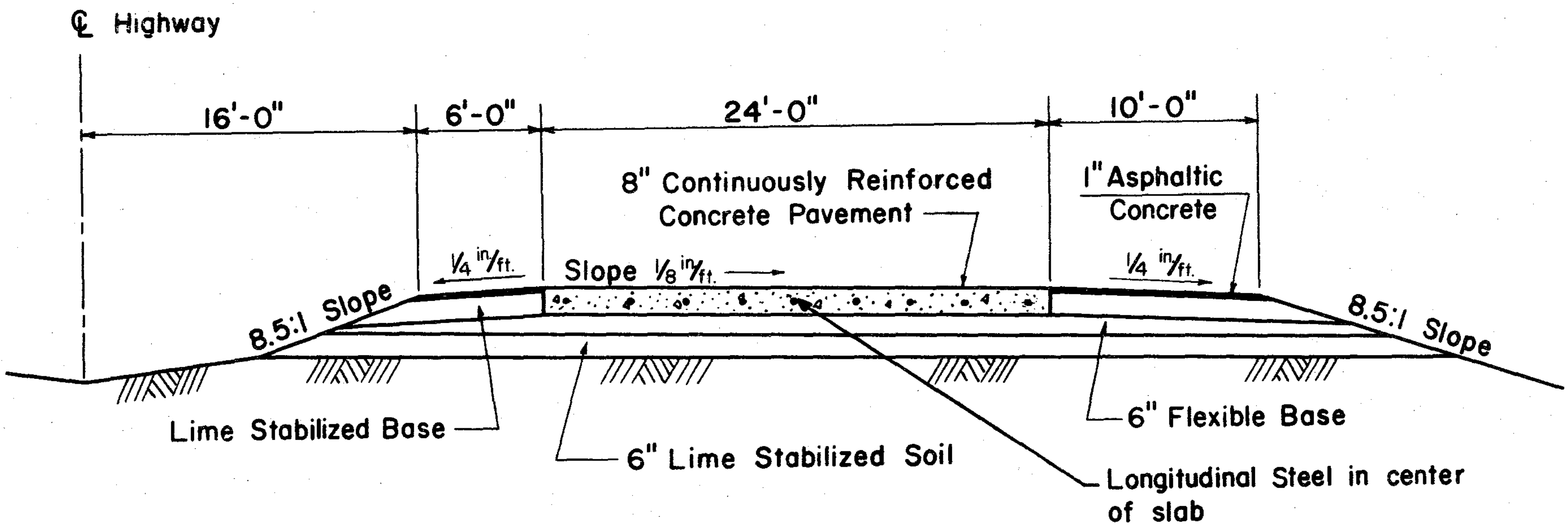
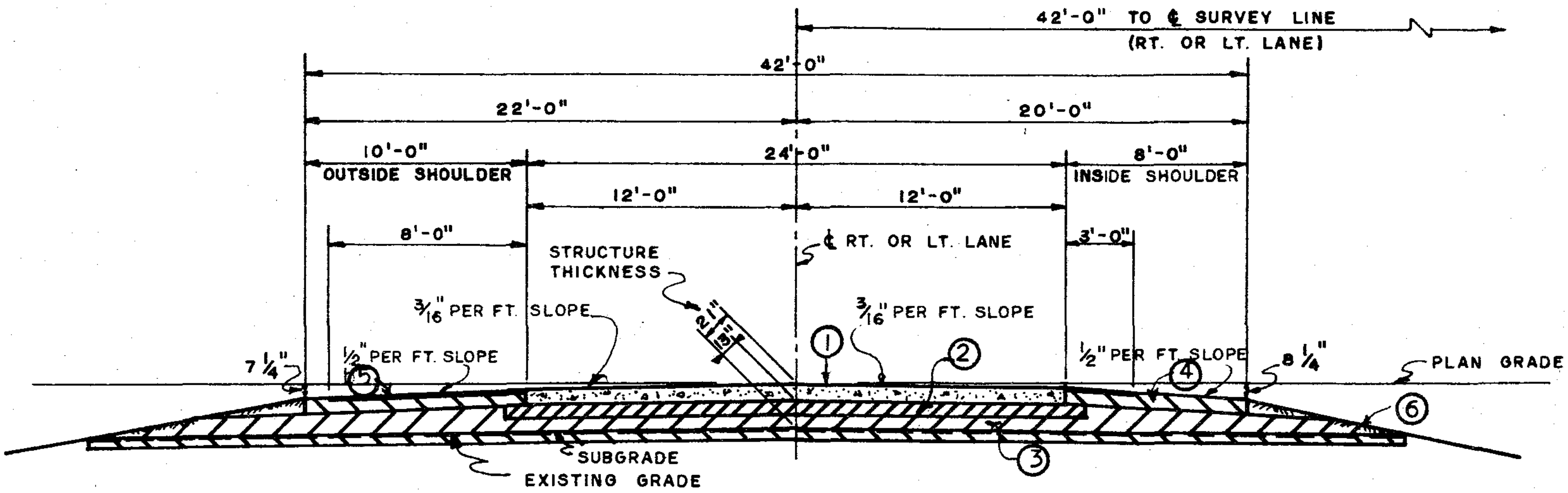


FIGURE 3. TYPICAL HALF SECTION FOR CRCP STRUCTURE USED IN WALKER COUNTY, TEXAS



1. Continuously Reinforced Concrete Pavement
2. Cement Treated Base 6" deep, 26' wide, Cement 4.5% by Volume (Semi-gravel or Clay-Gravel)
3. Sub-base, Semi-Gravel or Clay-Gravel
4. 8" Roadbed Topping, Clay-Gravel (Shoulders) Top 6" cement treated.
5. Double Bituminous Surface Treatment 8' wide outside shoulder, 3' wide inside shoulder
6. Seeding and mulching.

FIGURE 4. TYPICAL SECTION EACH LANE, MISSISSIPPI EXPERIMENTAL PROJECT
1-55-4(20)283 DeSoto County

In Illinois, it is specified that the subbase of concrete pavements, continuously reinforced or conventionally jointed, shall consist of a compacted layer of stabilized material placed between the subgrade and the slab for the prime purpose of minimizing pumping of roadbed soils. This design feature is based on AASHO Road Test findings which showed that variations of between 3 and 9 inches in subbase thickness had no significant effect on the performance of concrete test pavements. However, the performance of sections of pavement having a subbase was superior to that of sections of the same thickness but without a subbase. Subbase thickness is not considered as a design variable in Illinois highway work. The current design procedure was developed on a basis which assumes that a subbase will be used under all concrete pvaements. To provide subbases having minimum pumping susceptibility, it is specified that only stabilized granular materials be used. Table III shows the minimum requirements for subbase type and thickness in Illinois.

D. Pavement Design

The design of the actual pavement portion of CRCP structures requires consideration of many variables related to structure, load, and climatic and regional factors. These have been previously noted, as has the difficulty faced by design engineers in understanding the interrelationship between the variables which act on the pavement while it is in service. Much effort has been put into studies directed toward development of a rational method of designing CRCP. Formulae for determining pavement thickness and percentage of reinforcing steel have resulted from mathematical analyses of stresses, transverse crack spacing, and crack width in existing pavements. Also, formulae for use in estimating crack width and spacing for planned projects have been developed. However, because of the need to make many assumptions in this work, some engineers feel that the formulae are more useful as research tools than they are in actual pavement design. Others feel that some of the formulae are of definite use in pavement design work, particularly when used in conjunction with the experience and judgment gained in previous projects. Whatever the individual thoughts of design engineers may be in this matter, most feel that a rational means of designing CRCP has not yet been clearly established. On the other hand, there is a wealth of information and data on the performance of pavements under a wide range of service conditions. Many design variations have been used in these pavements with the result that in some states standard designs relative to some features of CRCP have been adopted. The validity of these designs has been based on the frequency and success of their use in projects in a number of states. It should be noted that the basic approach to design of CRCP may be applicable from one geographic area to another only if proper attention is given to differences in the values for variables that must be considered.

TABLE III

MINIMUM STRUCTURAL DESIGN REQUIREMENTS FOR CONCRETE PAVEMENTS IN ILLINOIS

	Portland Cement Concrete Pavement*		Subbase†	
Road and Street Classification	Type	Thickness, In.	Type	Thickness, In.
Class I	Continuously reinforced	7	Stabilized Granular Material	4
Class II	Standard reinforced	8	Stabilized Granular Material	4
Class III	Standard reinforced	8	Stabilized Granular Material	4

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*For Class II and Class III municipal streets having curbs and gutters and storm sewer systems, and for which the responsibility for maintenance is to be borne entirely by the municipality, the minimum required pavement thickness shall be 6 inches. The design thickness shall in no case be less than that required by Figure 11. Where the design thickness is 6 inches or 7 inches, standard reinforcement may be omitted at the option of the designer provided sawed transverse contraction joints are spaced no greater than 20 feet apart.

†For municipal streets with a traffic factor of less than 2.6, a granular material 4 inches thick, meeting the requirements for Subbase Granular Material-Type A of the Standard Specifications, may be used. Subbase will not be required for municipal streets having curbs and gutters and storm sewer systems that are to serve only residential traffic.

It is not the purpose here to go into the many theories, formulae, and approaches, or discuss in detail the various practices that have been used in the structural design of CRCP. However, it is considered worthwhile to discuss briefly some of the design practices, variables and controls, and actual designs used in states where significant highway mileage of this type of pavement has been constructed, and to present some of the findings of pavement studies.

Among the important design determinations and decisions that must be made are those pertaining to (1) subbase requirements, (2) pavement thickness, (3) joints, and (4) longitudinal steel reinforcement requirements as related to control and restraint of volume changes in the concrete, as well as control of transverse crack spacing and width. Considerations applicable to subbase requirements have been discussed previously; design of other elements of CRCP is discussed in the following sections.

1. Pavement Thickness

Much of the experience gained in designing conventional concrete pavements has been applied to the design of CRCP. The pavement thickness in early projects was determined through the use of formulae and mathematical computations required to obtain values for flexural stresses produced by various wheel loads. More recently, design charts and nomographs have been developed which permit the designer to select pavement thickness more quickly and without having to make lengthy and tedious calculations. In using these aids, values for wheel load, load factor, subgrade modulus, and allowable flexural stress, previously found by experience to be satisfactory, are applied. The resulting flexural stress for any given pavement thickness is read directly from some charts. Examples of these charts and nomographs are shown in Figures 5 through 9.

From one project to another, the thickness of CRCP has ranged from 6 to 10 inches, depending on the expected traffic characteristics and volume. The thinner pavements, usually 6 inches, were designed to handle the lighter traffic accommodated by frontage roads paralleling urban expressways; that of 10-inch thickness was designed to carry heavy truck traffic in large volumes in an industrial area. Based on results of pavement performance studies, an 8-inch thickness is indicated to be adequate for most conditions experienced on Interstate and heavy duty primary routes. This thickness has been used in a high proportion of the total mileage of CRCP built in recent years and currently appears to be a standard design feature.

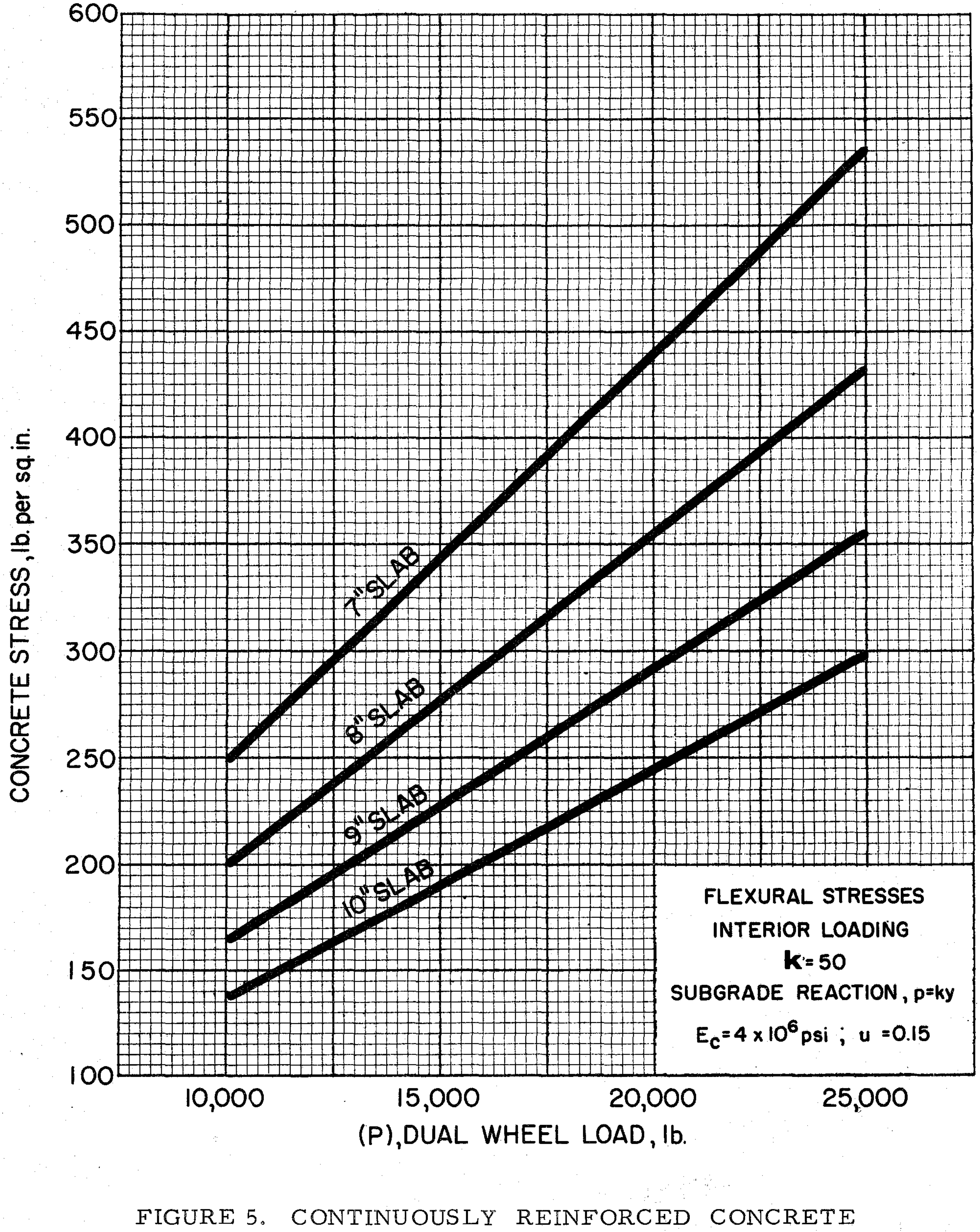


FIGURE 5. CONTINUOUSLY REINFORCED CONCRETE PAVEMENT SLAB THICKNESS DESIGN CHART

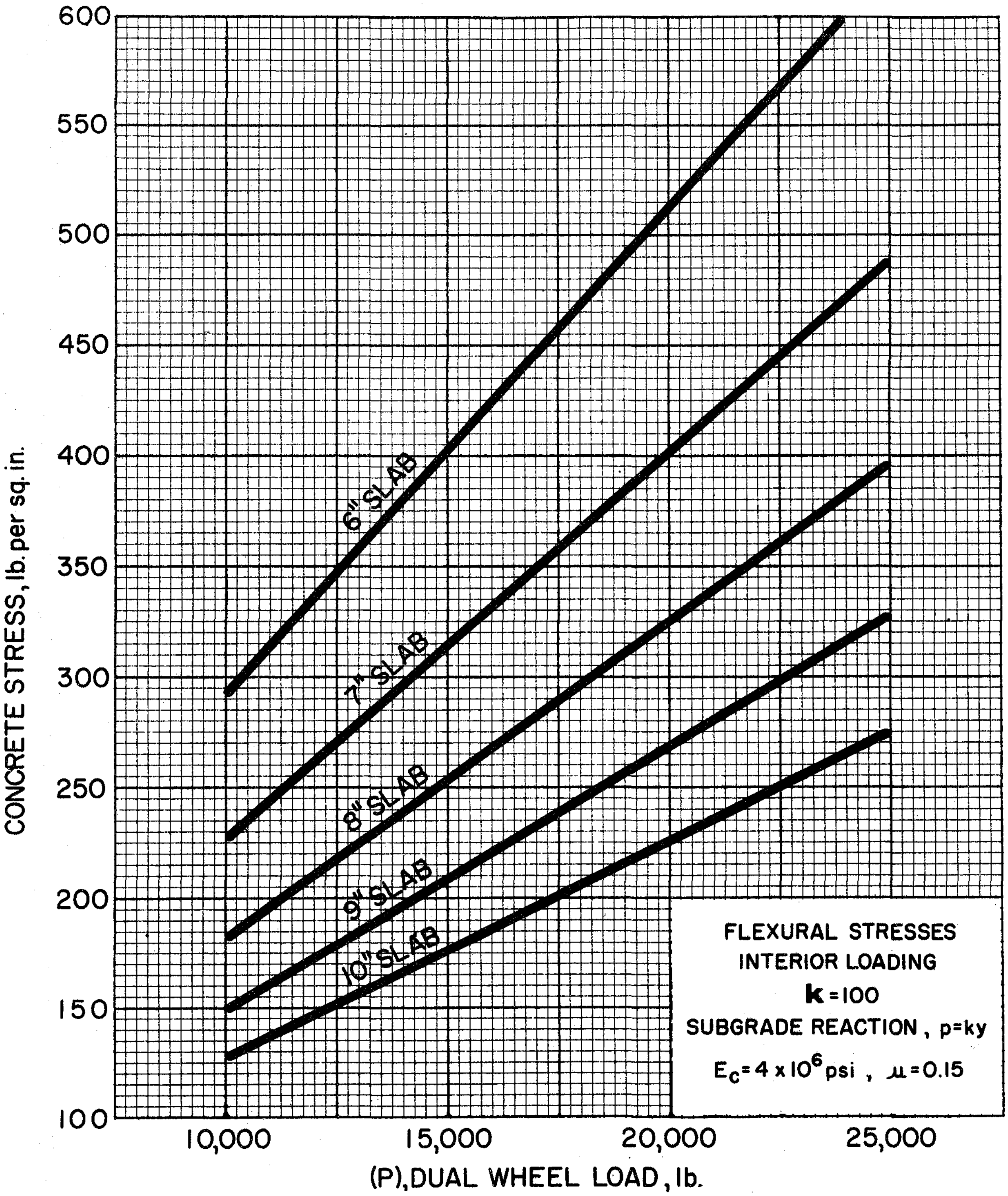


FIGURE 6. CONTINUOUSLY REINFORCED CONCRETE PAVEMENT SLAB THICKNESS DESIGN CHART

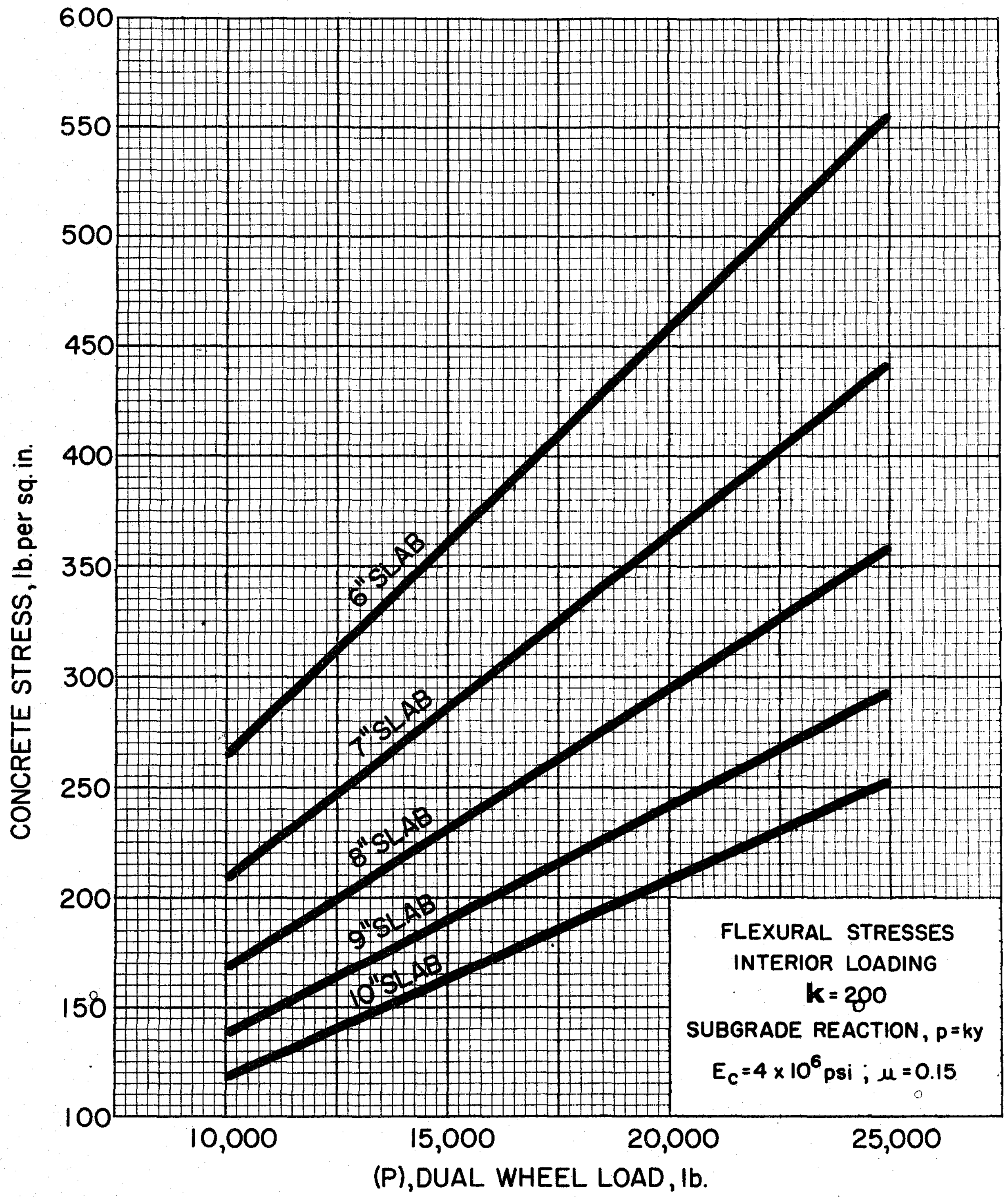


FIGURE 7. CONTINUOUSLY REINFORCED CONCRETE PAVEMENT SLAB THICKNESS DESIGN CHART

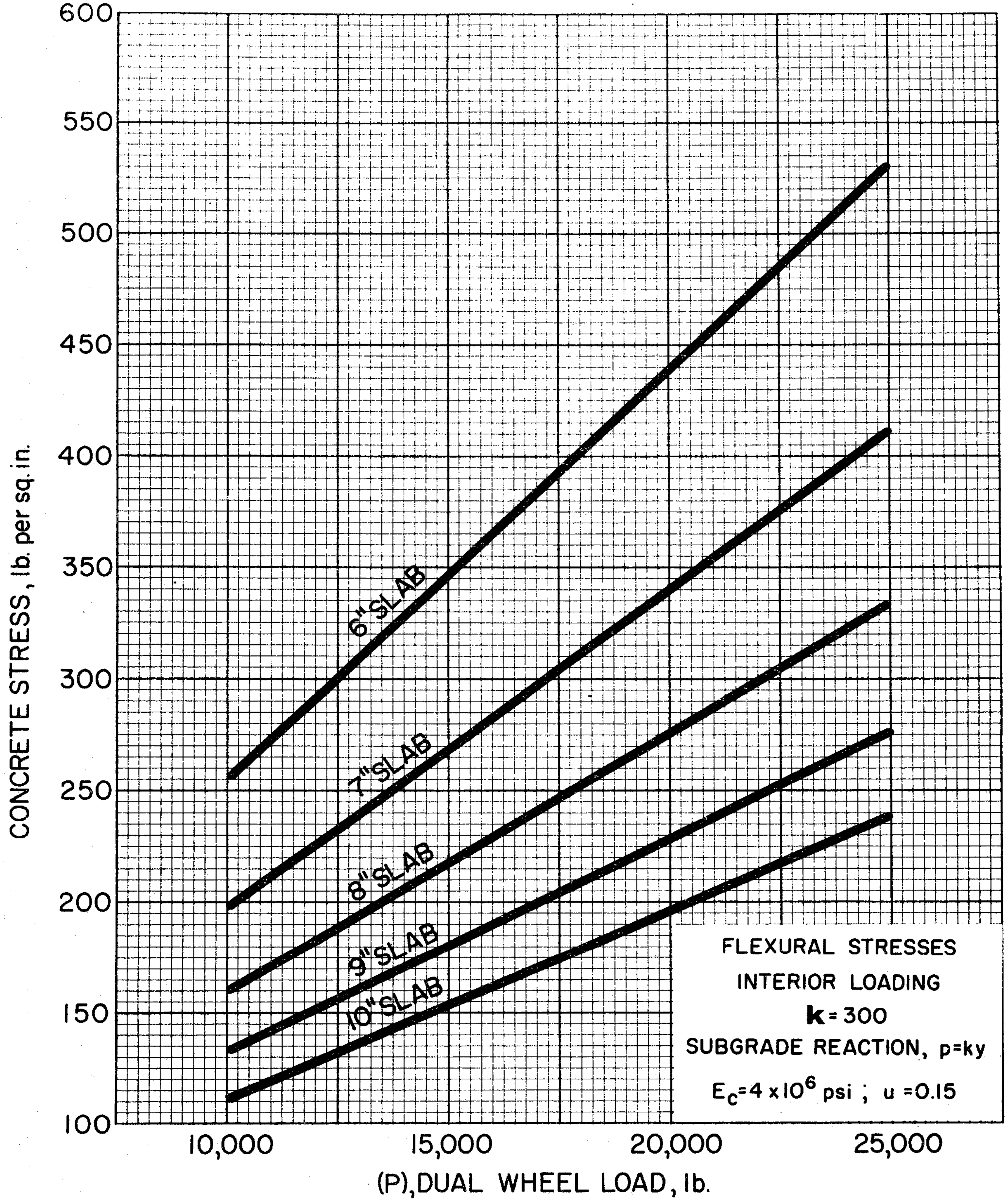


FIGURE 8. CONTINUOUSLY REINFORCED CONCRETE PAVEMENT SLAB THICKNESS DESIGN CHART

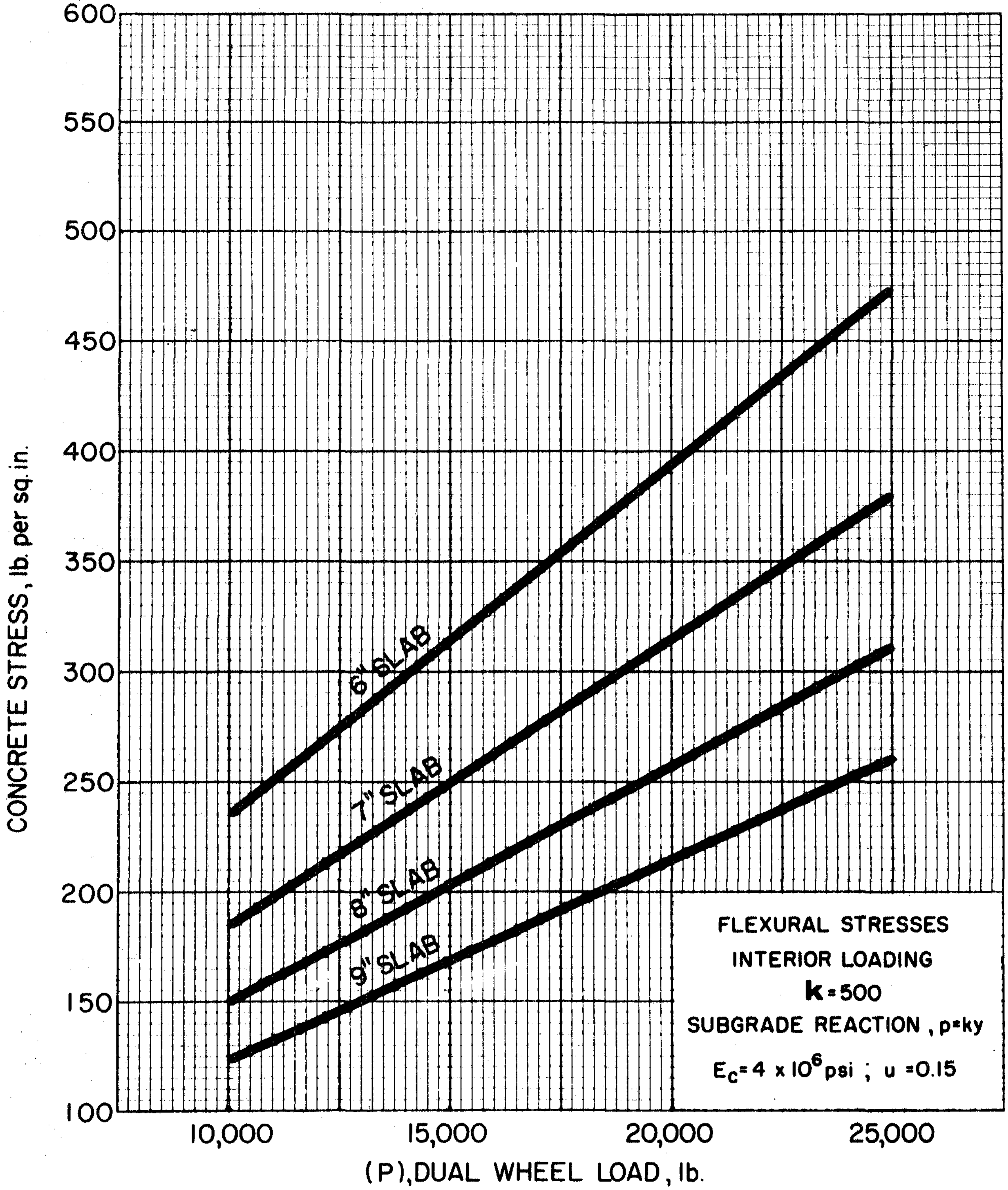


FIGURE 9. CONTINUOUSLY REINFORCED CONCRETE PAVEMENT SLAB THICKNESS DESIGN CHART

In some states, design practice has been to relate thickness of CRCP to standard designs for conventional jointed reinforced concrete pavements. For example, in Illinois, experience has shown that a factor of 0.7 may be applied; this indicates that, for a given set of service conditions, a thickness of 7 inches for CRCP is equivalent to a standard jointed pavement thickness of 10 inches. The type and thickness of concrete pavement required to handle the structural design traffic for a given design period are obtained directly from design charts. However, it is stipulated that the minimum requirements for type and thickness of pavement as previously noted in Table III must not be violated. Charts for use in designing reinforced concrete pavements in Illinois are shown in Figures 10 and 11. As a provision against impractical and inadequate designs, the following basic rules have been established as a guide for the designer while using the charts:

- When the analysis indicates a design that is less than the minimum requirements shown in Table III, the structural design shall be based on the minimum requirements.

- When the analysis indicates a pavement thickness greater than 9 inches for standard reinforced concrete, the selected design shall be based on the use of continuously reinforced concrete.

In Texas, design practice for determination of pavement thickness is based on an interior loading condition. This approach is used because close observations of CRCP under heavy traffic loads have indicated that a very high order of load transfer efficiency exists at the narrow transverse cracks. The pavement thickness determined by this method is used uniformly across the width of the slab. While most designers are familiar with the variables that are applicable in the determination, the methods used to evaluate modulus of rupture, modulus of elasticity, and wheel load are worthy of note:

- Modulus of Rupture. The specifications generally require that the concrete be designed with the objective of producing a modulus of rupture (flexural strength) of 600 psi at the age of seven days. For design purposes, the seven-day modulus of rupture is divided by two for provision of a safety factor to prevent excessive fatigue. In choosing a suitable modulus of rupture, consideration should be given to local conditions and properties of available materials.

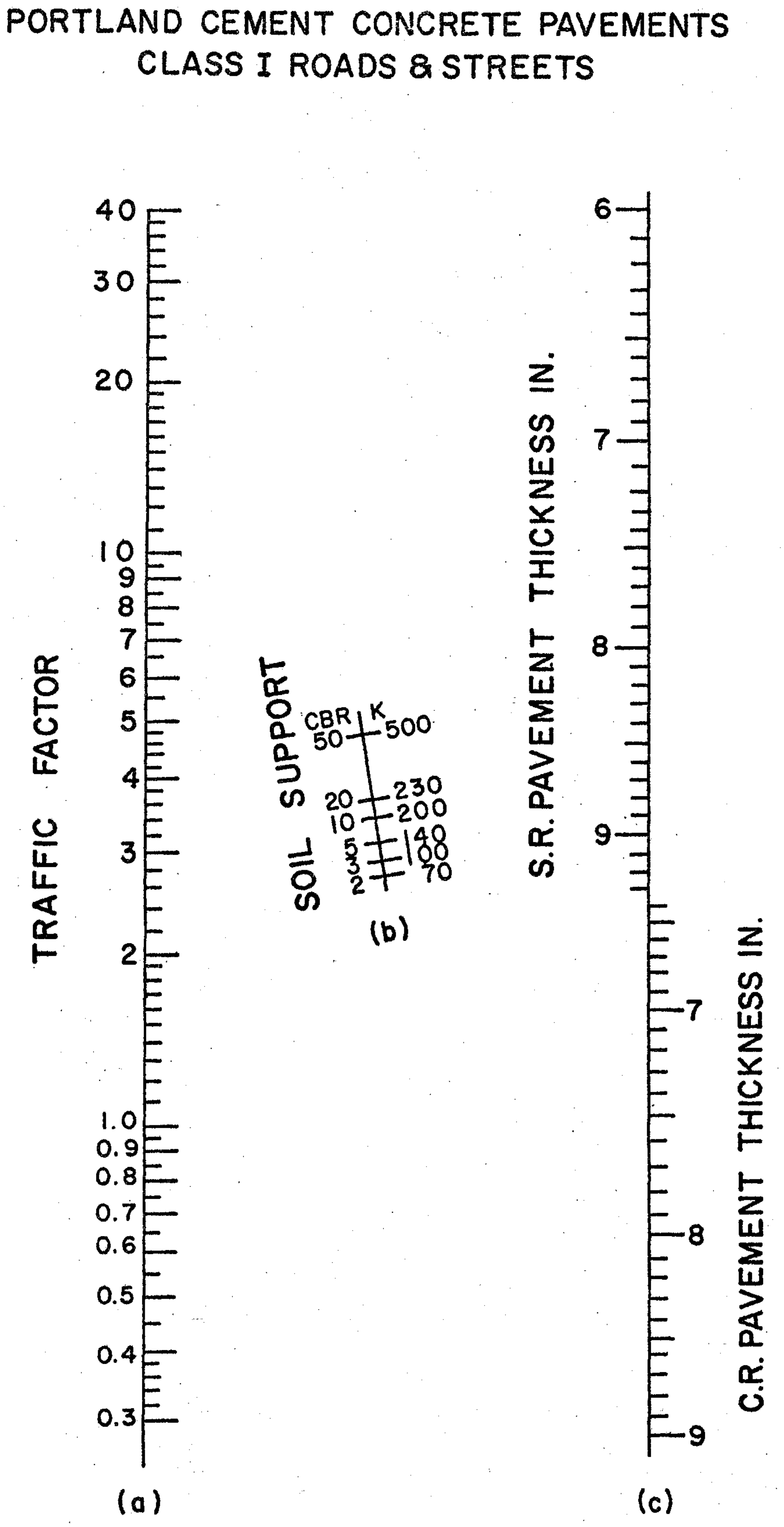


FIGURE 10. PAVEMENT DESIGN CHART -- ILLINOIS

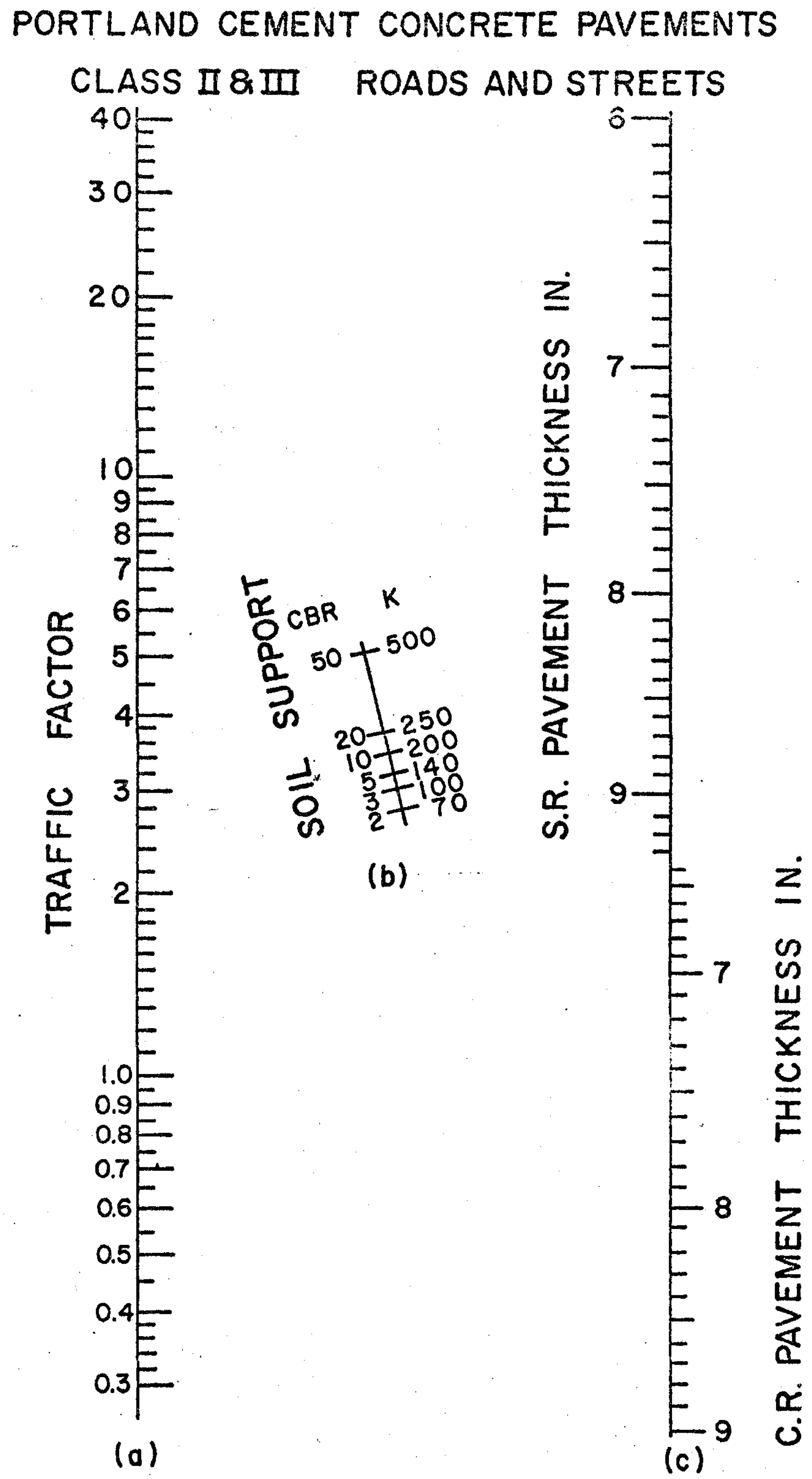


FIGURE 11. PAVEMENT DESIGN CHART -- ILLINOIS

- Modulus of Elasticity. For the flexural strength noted previously, a modulus of elasticity of 4,000,000 psi is used. In cases where different flexural strengths are required, the tangent modulus of elasticity is determined for a test batch of concrete prepared with the actual materials that will be used in the final concrete.

- Wheel Load. The Texas Highway Department uses the average of the ten heaviest daily wheel loads expected on the portion of the highway system under consideration as the basis of design for rigid-type pavements. Where consideration was given to the use of CRCP, a study of loadometer data indicated a wheel load of 16,000 pounds would be adequate. This value encompasses the predicted wheel load increase and effect of tandem axles expected during the life of the pavement. Current practice is to increase this design wheel load by 25 percent to allow for impact forces developed, giving a design load of 20,000 pounds for the most critical highways.

Using the noted considerations for modulus of rupture, modulus of elasticity, wheel load, and a modulus of subgrade reaction (k) of 100 in calculations for an interior loading condition, a pavement thickness of 7-1/2 inches was determined. This figure was rounded off to 8 inches for use in construction. Considerable mileage of CRCP of this thickness has been built in Texas; the pavements were in excellent condition after two to eight years of service.

2. Design of Reinforcing Steel

The amount of reinforcing steel used in CRCP is expressed in terms of percentage of cross-sectional area of the concrete and is generally four to five times that used in conventional reinforced concrete pavements. The design of all CRCP has been based on the criteria that the function of the longitudinal steel is to control transverse cracking of the concrete. This control provided by the steel is not for the prevention of cracking, although this would be an ultimate condition, but rather for keeping the cracks at an optimum width. The optimum width, generally felt to be about 0.02 inch, should be small enough to (1) prevent the entrance of water, and (2) provide adequate load transfer through aggregate interlock. If these conditions are satisfied, then the cracks would have no detrimental effect on the ultimate life of the pavement.

In view of the importance of crack spacing and crack width to pavement performance and behavior, considerable attention has been given to the controls and influences that reinforcing steel size, type, and amount have on these features. In past pavement design work, it was logically assumed that transverse crack spacing was inversely proportional to the percent of longitudinal steel. The plot of crack spacing versus steel percentage for CRCP in five states, shown in Figure 12, indicates this assumption to be valid. The graph indicates that an increase in the steel beyond 1 percent does not materially affect the crack spacing, but a small reduction below 0.4 percent has a very pronounced effect. In view of this indication, there appears to be some question as to the advisability of reducing steel below 0.4 percent for, under certain conditions, crack spacings greater than 16 feet could result in detrimental crack widths. An average crack spacing of 6 to 7 feet is considered to be optimum by many engineers.

Until the last few years, most designers of CRCP considered the steel-concrete bond area from the principal standpoint of providing sufficient bond to develop the design stresses. Design work by the Texas Highway Department pointed out that the total bond area also affects crack spacing. Correlation of data on crack spacing versus bond area per volume of concrete for projects in different states showed an inversely proportional linear relation between these two factors as indicated in Figure 13. The graphs show that, under a given set of conditions, pavements with varying percentages of steel but equal bond area per volume of concrete would have equal crack spacings. For use in designing CRCP, the recommendation drawn from these data is that the ratio of bond area to concrete volume should not be less than 0.03 for summer construction and 0.04 for late fall and early spring construction. Using these criteria, indicated optimum crack spacing would be about 7 feet for warm weather construction and about 12 feet for winter construction. In either case, a maximum average crack width of about 0.03 inch is indicated in cold weather.

Determination of the amount of longitudinal reinforcing steel required in CRCP is not as tedious a task today as in earlier years, thanks to the results of many studies concerned with this matter and experience gained with pavements containing various amounts of reinforcement. The percentage of steel may be determined by correlating a number of variables such as tensile strength of the concrete, yield strength of the steel, frictional resistance of the subbase, etc., and by using engineering judgment based on experience. The task is eased through the use of design charts and nomographs, plus design data related to expected service conditions for the pavement structure. Figure 14 shows a nomograph which graphically solves the indicated formula used for calculation of the theoretical minimum percentage of longitudinal steel. The formula is based on the assumptions that:

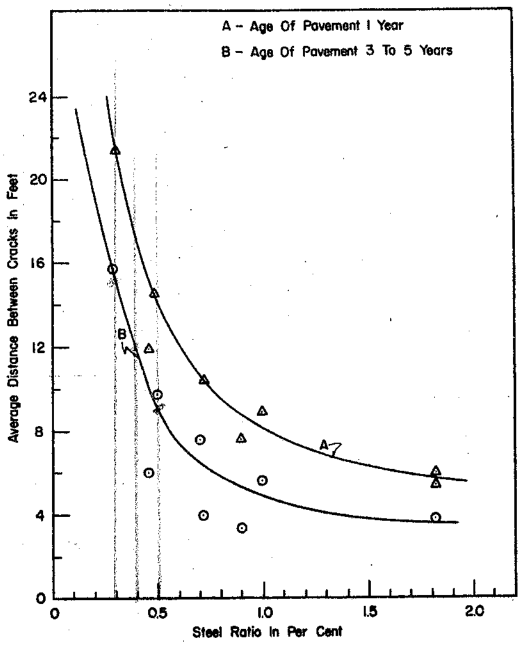


FIGURE 12. RELATIONSHIP BETWEEN STEEL RATIO AND CRACK SPACING

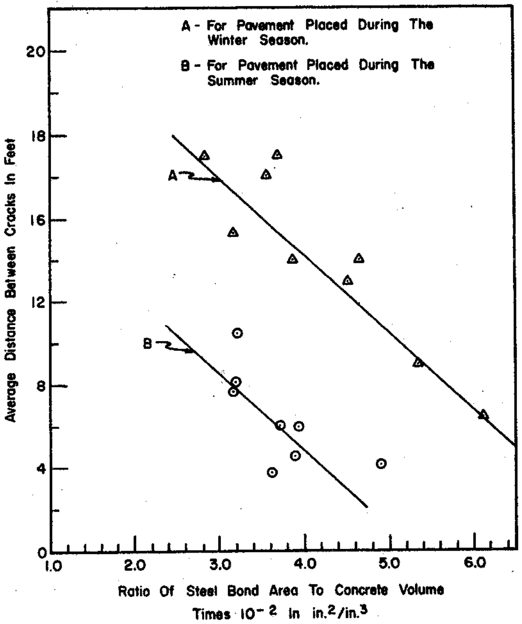


FIGURE 13. RELATIONSHIP BETWEEN BOND AREA PER CONCRETE VOLUME AND CRACK SPACING

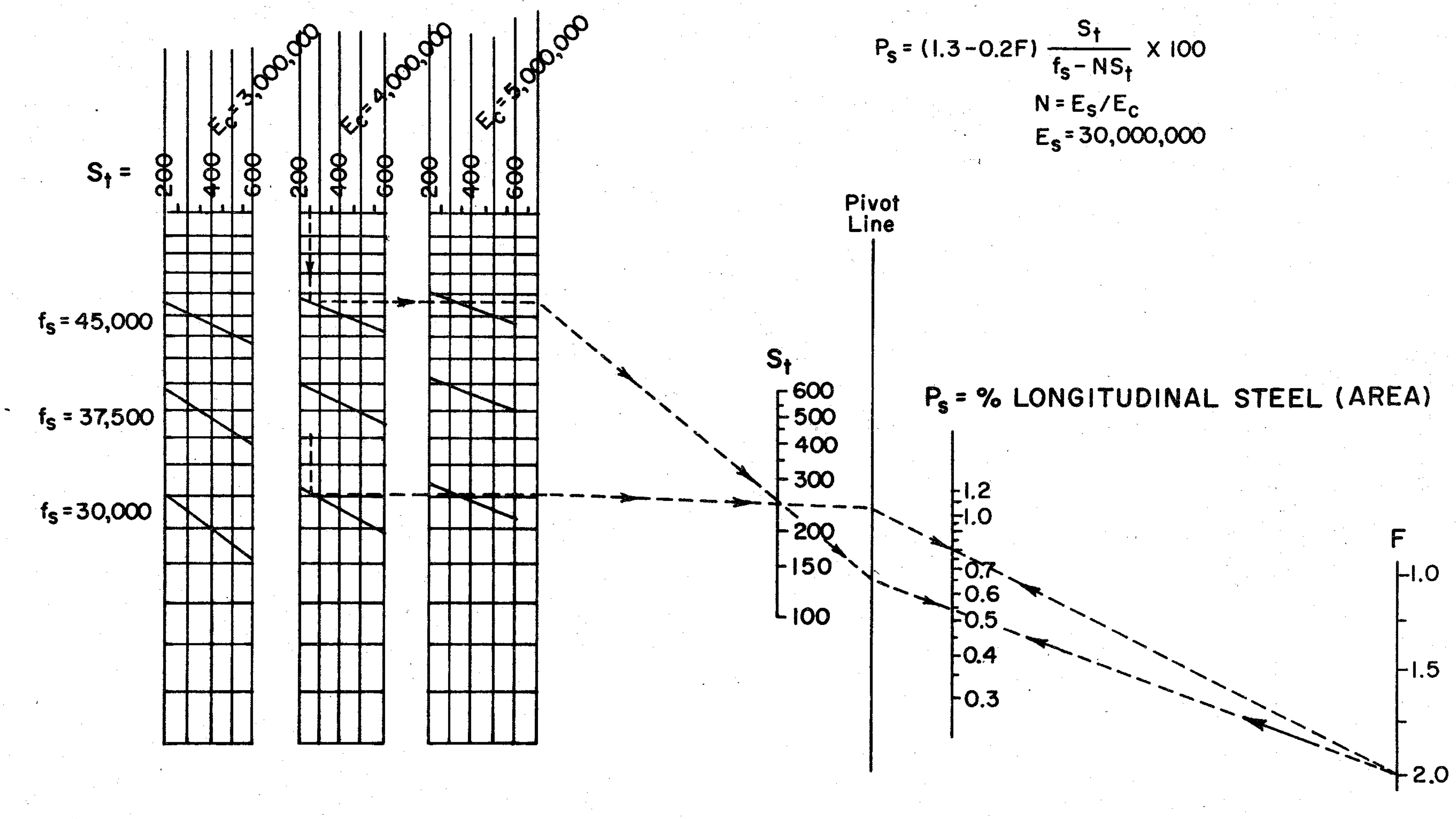


FIGURE 14. NOMOGRAPH FOR DETERMINING LONGITUDINAL STEEL REQUIREMENTS CONTINUOUSLY REINFORCED PAVEMENTS

Source: AASHO Interim Guide for the Design of Rigid Pavement Structures, April 1962

- Sufficient bond area is provided to develop the full working stress of the steel, and

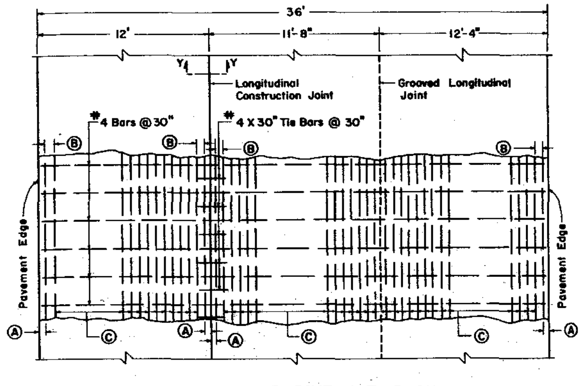
- Adequate load transfer is provided at transverse construction joints.

This design method has been adopted by the AASHO Committee on Design and appears in the "AASHO Interim Guide for the Design of Rigid Pavement Structures."

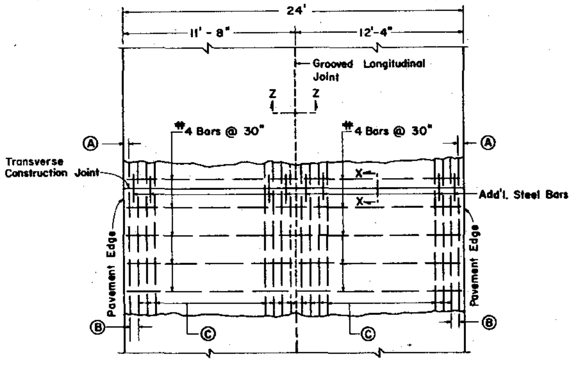
Review of designs for CRCP in various states indicates that longitudinal steel requirements lie in the range of 0.5 to 0.6 percent of the concrete area. In Texas, a design calling for 0.5-percent longitudinal and 0.1-percent transverse steel has been used in the majority of pavements 6, 7 and 8 inches thick over the past six to seven years. Reinforcement has been with deformed steel bars in all but one project. Currently, design details as to steel grade, size, spacing, splicing, placement depth, etc., are as shown in Figures 15 and 16 which apply to steel bars and deformed wire mat, respectively. Also shown in these figures are details of transverse and longitudinal construction joints to be used with the different types of reinforcement.

Spacing of longitudinal steel is dependent on the area of reinforcement to be used, as determined by design. Some latitude is afforded by the variety of steel types and grades that are available. For a given pavement design, the size of the reinforcement to be used is a function of steel properties, bond area, concrete strength, and other considerations. Spacing is on a distributed steel basis in most designs for CRCP, though additional steel is often provided to compensate for edge loading. Current practice in spacing for steel bars and wire mesh in Texas is as shown in Figures 15 and 16. It will be noted in the figures that the spacing ratio for longitudinal to transverse steel is 4:1 for steel bars and about 3:1 for wire mesh.

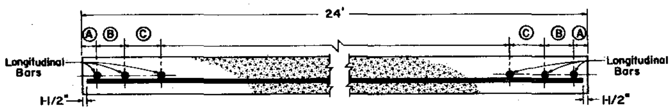
The transverse steel functions as reinforcement across the concrete pavement and as a means of spacing the longitudinal steel. The width of CRCP is very small as compared to length; this factor coupled with the relative freedom of the concrete to contract in the transverse direction results in the need for considerably less reinforcement across the slab. The transverse steel is adequate as support stringers on which to space the longitudinal steel. The design practice for this steel in CRCP is generally the same as that for conventional reinforced concrete pavements. There have not been any indications of difficulty or problems associated with projects in which the normal amounts of transverse steel



THREE LANE PAVEMENT PLAN
(12ft. and 24ft. Placement) *



TWO LANE PAVEMENT PLAN
(24ft. Placement) *



TYPICAL SECTION
(24ft. Placement) *

*LANE WIDTHS ARE FOR ILLUSTRATIVE PURPOSES ONLY AND SHOULD NOT BE USED IF IN CONFLICT WITH TYPICAL CROSS SECTIONS SHOWN ELSEWHERE IN THE PLANS.

GENERAL NOTES

1. NO EXPANSION JOINTS WILL BE USED EXCEPT AT STRUCTURAL ENDS OR FIXED OBJECTS AS SHOWN ELSEWHERE IN THE PLANS.

2. FOR FURTHER INFORMATION REGARDING THE PLACEMENT OF CONCRETE AND REINFORCEMENT, REFER TO THE GOVERNING SPECIFICATIONS FOR "CONCRETE PAVEMENT".

3. DETAILS AS TO PAVEMENT WIDTH, PAVEMENT THICKNESS AND THE CROWN CROSS-SLOPE SHALL BE AS SHOWN ELSEWHERE IN THE PLANS.

4. WITHIN ANY AREA BOUNDED BY TWO FEET OF PAVEMENT LENGTH MEASURED PARALLEL TO THE CENTERLINE AND TWELVE FEET OF PAVEMENT WIDTH MEASURED PERPENDICULAR TO THE PAVEMENT CENTERLINE, NOT OVER 33% OF THE REGULAR LONGITUDINAL STEEL SHALL BE SPLICED.

5. LONGITUDINAL AND TRANSVERSE BARS SHALL BE OF HIGH YIELD STEEL CONFORMING TO ASTM A-432 OR ASTM A-61 (SPECIAL GRADE) AS NOTED IN THE SPECIFICATIONS.

6. SPLICES SHALL BE A MINIMUM OF 24 TIMES THE NOMINAL DIAMETER OF THE BAR.

7. BARS OF HIGH YIELD STEEL SHALL NOT BE BENT. IF THE CONTRACTOR ELECTS TO BEND THE TIEBARS, THEY SHALL BE OF STRUCTURAL OR INTERMEDIATE GRADE STEEL AND SPACED AT 24" C-C.

8. AT TRANSVERSE CONSTRUCTION JOINTS, THE REGULAR LONGITUDINAL BARS SHALL EXTEND BEYOND THE JOINT SO THAT THE BAR SPLICES FOR THE REGULAR LONGITUDINAL BARS SHALL BE A MINIMUM OF FOUR FEET FROM THE CONSTRUCTION JOINT. AT LONGITUDINAL CONSTRUCTION JOINTS IF THE CONTRACTOR ELECTS TO CONTINUE THE REGULAR TRANSVERSE STEEL THROUGH THE JOINT, THE #4 ϕ TIEBARS SHOWN HEREON MAY BE DELETED. VIBRATION WITH HAND MANIPULATED MECHANICAL VIBRATORS WILL BE REQUIRED ADJACENT TO ALL TRANSVERSE CONSTRUCTION JOINTS.

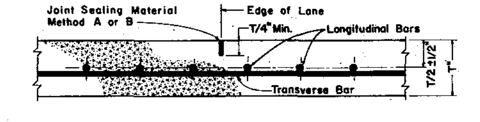
9. WITH THE APPROVAL OF THE ENGINEER, MULTIPLE PIECE TIEBARS (THREADED COUPLING OR OTHER ADEQUATE DEVICE) MAY BE USED TO FACILITATE CONSTRUCTION PROVIDED THE SYSTEM DEVELOPS A FORCE EQUAL TO 1-1/2 TIMES THE MINIMUM YIELD FORCE OF THE TIEBAR SHOWN. THE SPACINGS FOR THE SYSTEM SHALL BE LESS THAN OR EQUAL TO THE SPACING ALLOWED FOR BARS OF SIMILAR YIELD STRENGTH.

10. THE CHAIRS USED TO SUPPORT THE BAR MAT SHALL BE OF SUFFICIENT STRUCTURAL QUALITY AND NUMBER TO HOLD THE MAT WITHIN THE PLACEMENT HEIGHT TOLERANCES, AND SHALL BE OF A TYPE APPROVED BY THE ENGINEER.

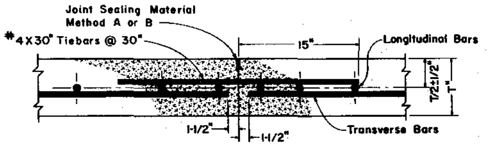
11. IN THE NORMAL 30" PLACEMENT FOR THE TRANSVERSE BARS, CHAIRS SHALL BE PLACED UNDER EVERY TRANSVERSE BAR. THE TRANSVERSE SPACING SHALL BE A 48" MAXIMUM. PLACEMENT MAY BE STAGGERED SO THAT CHAIRS IN ALTERNATE ROWS ARE CENTERED BETWEEN THE CHAIRS IN ADJACENT ROWS.

12. JOINT GROOVE AND SEAL DETAILS SHALL BE AS SHOWN ELSEWHERE IN THE PLANS.

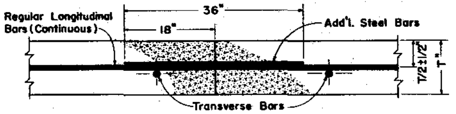
13. IN THE PLANE OF THE STEEL PARALLEL TO THE NEAREST SURFACE OF CONCRETE, BARS SHALL NOT VARY FROM PLAN PLACEMENT BY MORE THAN ONE-TWELFTH OF THE SPACING BETWEEN BARS.



GROOVED LONGITUDINAL JOINT
Section Z–Z



LONGITUDINAL CONSTRUCTION JOINT
Section Y–Y



TRANSVERSE CONSTRUCTION JOINT
Section X–X

Pavement Thickness "T" in.	Bar Size	24 ft. Placement Width					12 ft. Placement Width					Add'l Steel @ Trans.Const.Jt.			
		Spacing C-C			No. of Bars	Steel #/sy ①	Spacing C-C			No. of Bars	Steel #/sy ①	Size	Avg. Spa. in.	② No. per Lane	Weight #/ft.
		Ⓐ in	Ⓑ in	Ⓒ in			Ⓐ in	Ⓑ in	Ⓒ in						
8	No.5	3	6	7.5	39	17.66	3	5.25	7.5	20	18.05	5/8" ϕ x36"	14	10	2.61
7	No.5	3	5	8.5	35	16.09	4	8.5	8.5	17	15.70	5/8" ϕ x36"	14	10	2.61
6	No.4	3	4.5	7	42	12.93	3	6	7	21	12.93	1/2" ϕ x36"	8	18	3.01

NOTE: THE SPACINGS Ⓑ SHOWN IN THE ABOVE PLACEMENT TABLE ARE THE MAXIMUM ALLOWABLE SPACINGS. WHERE THE PROPOSED PLACEMENT WIDTHS VARY FROM THE BASIC DESIGN WIDTH SHOWN, THE SPACING Ⓑ AND THE ADJACENT SPACING Ⓒ SHALL BE ADJUSTED TO ACCOMMODATE A REINFORCEMENT ARRANGEMENT EQUAL TO OR SLIGHTLY HEAVIER THAN THAT SHOWN AS DIRECTED BY THE ENGINEER.

① INCLUDES BOTH REGULAR LONGITUDINAL AND TRANSVERSE BARS BASED UPON 1 FOOT PAVEMENT LENGTHS FOR THE WIDTH INDICATED. ALL TRANSVERSE STEEL IS #4 BARS AT 30" CENTERS.

② THIS SHALL BE THE MINIMUM NUMBER OF ADDITIONAL STEEL BARS TO BE PLACED PER LANE. THE SPACING OF THE ADDITIONAL STEEL BARS SHALL BE VARIED AS DIRECTED IN ORDER TO PROVIDE A MINIMUM CLEARANCE OF 2 1/2" FROM EACH REGULAR LONGITUDINAL REINFORCING BAR.

SPECIAL NOTE
THE CONTRACTOR SHALL HOLD AND SAVE THE STATE, ITS OFFICERS, ITS AGENTS, AND ITS EMPLOYEES HARMLESS TO LIABILITY OF ANY NATURE OR KIND, INCLUDING COST AND EXPENSES FOR OR ON ACCOUNT OF ANY PATENT OR UNPATENTED INVENTION, ARTICLE OR APPLIANCE MANUFACTURED OR USED IN ACCORDANCE WITH THE DETAILS OF THESE PLANS.

TEXAS HIGHWAY DEPARTMENT

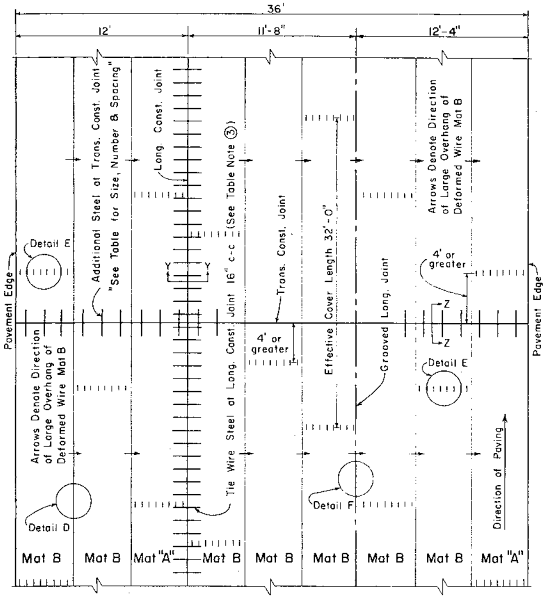
CONCRETE PAVEMENT DETAILS
CONTINUOUSLY REINFORCED

STEEL BARS

CPCR (B)-65

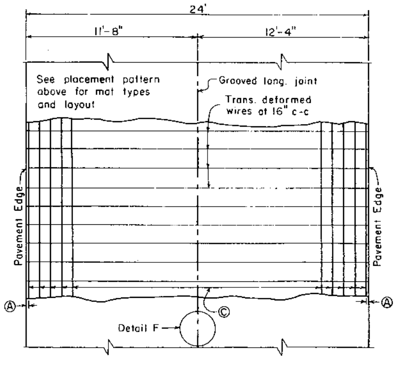
DN.	DRAWING	DATE	FED. RD. DIV. NO.	STATE	FEDERAL PROJECT NO.				SHEET NO.
CK.DN.	ORIGINAL	SEPT. 1964	6	TEXAS					
DW.	Revised	JAN. 1965	STATE DIST. NO.	COUNTY		CONT.	SECT.	JOB	HIGHWAY NO.
CK.DW.	Revised	JULY 1965							
TR.									
CK.TR.									

FIGURE 15. TEXAS HIGHWAY DEPARTMENT CONCRETE PAVEMENT DETAILS, CONTINUOUSLY REINFORCED (STEEL BARS)



THREE LANE PAVEMENT PLAN

(12 foot and 24 foot Placement)*

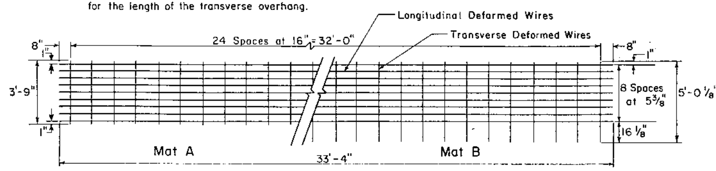


TWO LANE PAVEMENT PLAN

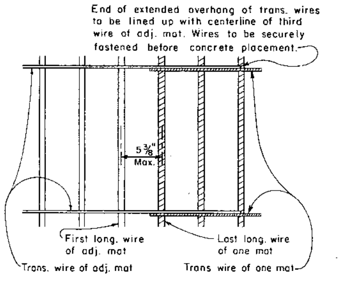
(24 ft. Placement) *

*LANE WIDTHS ARE FOR ILLUSTRATIVE PURPOSES ONLY AND SHOULD NOT BE USED IF IN CONFLICT WITH TYPICAL CROSS SECTIONS SHOWN ELSEWHERE IN THE PLANS.

NOTE: Mat A & Mat B are the same except for the length of the transverse overhang.

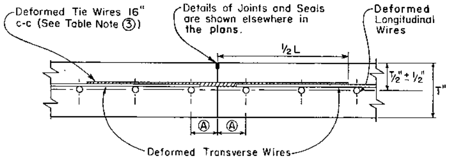


PREFABRICATED DEFORMED WIRE MATS



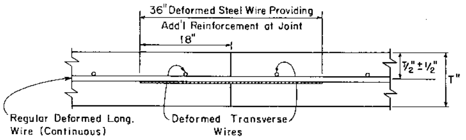
DETAIL D

TYPICAL LAP OF TRANSVERSE WIRES



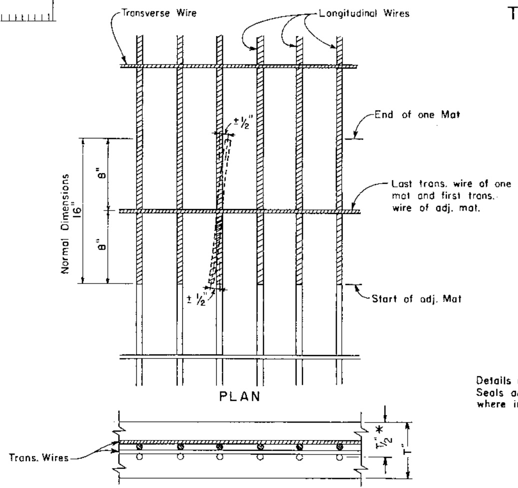
LONGITUDINAL CONSTRUCTION JOINT

SECTION Y-Y



TRANSVERSE CONSTRUCTION JOINT

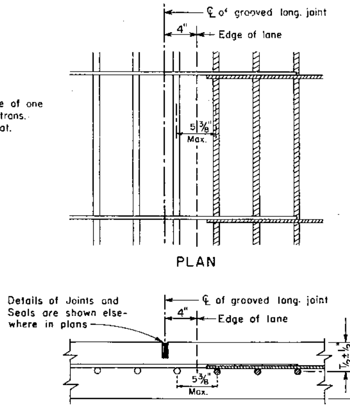
SECTION Z-Z



*Note: At long. laps of mats the centerline of the bottom layer of long. steel shall be located within 1/2" of the slab center. The centerline of the upper layer of long. steel shall be within 1-1/2" of the slab center.

SECTION - DETAIL E

TYPICAL LAP OF LONGITUDINAL WIRES



SECTION

DETAIL F

TRANSVERSE LAP AT GROOVED LONGITUDINAL JOINT

GENERAL NOTES

1. NO EXPANSION JOINTS WILL BE USED EXCEPT AT STRUCTURE ENDS OR FIXED OBJECTS AS SHOWN ELSEWHERE IN THE PLANS.
2. JOINT GROOVE AND SEAL DETAILS SHALL BE AS SHOWN ELSEWHERE IN THE PLANS.
3. CONSTRUCTION JOINTS MAY BE FORMED BY THE USE OF METAL OR WOOD FORMS EQUAL IN DEPTH TO THE NOMINAL DEPTH OF THE PAVEMENT, OR BY OTHER MEANS WHICH HAVE BEEN APPROVED BY THE ENGINEER PRIOR TO THEIR USE.
4. DETAILS AS TO PAVEMENT WIDTH, PAVEMENT THICKNESS, AND THE CROWN CROSS-SLOPE SHALL BE AS SHOWN ELSEWHERE IN THE PLANS.
5. IT IS THE INTENT OF THIS DESIGN THAT THE LONGITUDINAL STEEL BE AT THE CENTER OF THE SLAB. IT SHALL BE THE RESPONSIBILITY OF THE CONTRACTOR TO TAKE ALL NECESSARY PRECAUTIONS TO INSURE THAT THE FINAL POSITION OF THE STEEL IS WITHIN 1/2 INCH OF THE SLAB CENTER EXCEPT THAT THE TOLERANCE SHOWN IN THE LONGITUDINAL LAP DETAIL SHALL GOVERN AT THAT POINT. TRANSVERSE WIRES MAY BE PLACED ON TOP OR BOTTOM.
6. THE DEFORMED WIRE MATS SHALL BE PREASSEMBLED AND PLACED AT THE SPECIFIED HEIGHT PRIOR TO THE CONCRETE PLACEMENT OPERATIONS. THE ENTIRE DEPTH OF CONCRETE SHALL BE PLACED IN ONE OPERATION.
7. ADJACENT DEFORMED WIRE MATS SHALL BE SECURELY FASTENED TOGETHER IN A MANNER TO PRECLUDE SEPARATION OF THE STEEL DURING CONCRETE PLACEMENT AND FINISHING OPERATIONS.
8. THE CHAIRS USED TO SUPPORT THE PREFABRICATED MATS SHALL BE PLACED UNDER THE LONGITUDINAL WIRES AND SHALL BE OF A TYPE APPROVED BY THE ENGINEER. A MINIMUM OF TEN CHAIRS PER MAT WILL BE USED TOMEET THE STEEL PLACEMENT REQUIREMENTS.
9. WITHIN ANY AREA BOUNDED BY TWO FEET OF PAVEMENT LENGTH MEASURED PARALLEL TO THE CENTERLINE, AND TWELVE FEET OF PAVEMENT WIDTH MEASURED PERPENDICULAR TO THE PAVEMENT CENTERLINE, NOT OVER 33% OF THE REGULAR LONGITUDINAL STEEL SHALL BE SPLICED.
10. ALL SPLICES SHALL BE A MINIMUM OF 31 TIMES THE NOMINAL DIAMETER OF THE WIRE.
11. AT TRANSVERSE CONSTRUCTION JOINTS THE REGULAR LONGITUDINAL STEEL SHALL EXTEND A MINIMUM OF FOUR FEET ON EITHER SIDE OF THE JOINT.
12. IF WIDTHS GREATER THAN TYPICAL WIDTHS OCCUR, INDIVIDUAL WIRES MAY BE ADDED TO OBTAIN ADDITIONAL WIDTH, PROVIDED THE C TO C SPACING IS NOT EXCEEDED AND LAP REQUIREMENTS ARE MET.
13. THE EDGE SPACING DIMENSION, Ⓐ, SHALL BE THE MINIMUM DIMENSION ALLOWED. THE SPACING, Ⓒ, SHALL BE THE MAXIMUM DIMENSION ALLOWED BETWEEN MATS. SLIGHT VARIATIONS IN MAT DIMENSIONS MAY BE ABSORBED WITHIN THESE SPACINGS.
14. IN THE PLANE OF STEEL PARALLEL TO THE NEAREST SURFACE OF CONCRETE, TIEBARS OR TIEWIRES SHALL NOT VARY FROM PLAN PLACEMENT BY MORE THAN ONE-TWELFTH OF THE SPECIFIED SPACING.

	LONGITUDINAL REINFORCEMENT											TRANS. REINF.		
Pavement Thickness (T) in.	Wire Size	24' Placement Width			12' Placement Width			Add'l Steel Trans. Const. Jt.				Wire Size	Tie Wires ③	
		Spacing c-c		① Steel lb/SY	Spacing c-c		① Steel lb/SY	Wire Size	Length in.	② No. Per Lane	Weight lb/ft.		Size Length(L) & Spacing	Weight lb/ft.
		Ⓐ in.(Min)	Ⓒ in.		Ⓐ in.(Min)	Ⓒ in.								
8	D 19.5	1 9/16	5 3/8	16.51	2 1/8	5 3/8	16.40	D 19.5	36"	16	2.65	D8.8	D8.8x24" @ 16" cc	0.450
7	D 17.0	1 9/16	5 3/8	14.40	2 1/8	5 3/8	14.30	D 17.0	36"	18	2.60	D7.7	D7.7x22" @ 16" cc	0.361
6	D 14.6	1 9/16	5 3/8	12.36	2 1/8	5 3/8	12.28	D 14.6	36"	21	2.61	D6.6	D6.6x20" @ 16" cc	0.282

TABLE NOTE: ① INCLUDES BOTH LONGITUDINAL AND TRANSVERSE WIRES BASED ON THE WIDTH INDICATED AND AN EFFECTIVE COVER LENGTH OF 32 FEET. (ESTIMATING QUANTITIES INCLUDE SPLICES)

② THIS SHALL BE THE MINIMUM NUMBER OF ADDITIONAL STEEL WIRES TO BE PLACED PER LANE. THE ADDITIONAL STEEL WIRES SHALL BE PLACED EQUIDISTANT BETWEEN TWO REGULAR LONGITUDINAL REINFORCING WIRES AT AS NEAR A UNIFORM SPACING ACROSS THE LANE AS POSSIBLE.

③ AT THE OPTION OF THE CONTRACTOR, #4 BARS x 30 IN. AT 30 IN. C-C MAY BE USED IN LIEU OF THE DEFORMED TIE WIRES AT 16 IN. C-C SHOWN, PROVIDED WRITTEN APPROVAL HAS BEEN RECEIVED FROM THE ENGINEER.

TEXAS HIGHWAY DEPARTMENT

CONCRETE PAVEMENT DETAILS
CONTINUOUSLY REINFORCED
DEFORMED WIRE MAT
CPCR (DW) — 65 A

DN. BFM+FCH	DRAWING	DATE	FED. RD. DIV. NO.	STATE	FEDERAL PROJECT NO.				SHEET NO.
CK. DN. MDS	ORIGINAL	MARCH 1964	6	TEXAS					
DW. [illegible]	REVISED	MAY 1965							
CK. DW. BFM+FCH	REVISED	NOV. 1965	STATE DIST. NO.	COUNTY		CONT.	SECT.	JOB	HIGHWAY NO.
TR. [illegible]									
CK. TR. FCH									

File 8.88-29

FIGURE 16. TEXAS HIGHWAY DEPARTMENT CONCRETE PAVEMENT DETAILS, CONTINUOUSLY REINFORCED (DEFORMED WIRE MAT)

were used. For a major portion of the total mileage of CRCP installed, these amounts have generally been in the range of 0.1 to 0.2 percent. In some projects, amounts below and above the indicated were used, reflecting design variations and different types and grades of steel.

The placement of reinforcing steel is at mid-depth of the slab in most current designs, with the centerline of the longitudinal steel serving as the index for this purpose.

3. Joints and End Anchorages

In most CRCP, the joints used fall into three categories: construction, longitudinal, and terminal. These are discussed and described below.

a. Construction Joints

Transverse construction joints are required at the end of each day's paving run or at any time the paving operation is suspended for a prolonged period. The longitudinal reinforcing steel is continued through the construction joint and securely lapped with the steel to be covered when paving is resumed. Where reinforcement consists of deformed steel bars, additional steel bars are used to ensure adequate provision for load transfer across the joint. Details of such a joint are illustrated in Figure 15 which shows the current design used in CRCP in Texas. The design details shown in Figure 16 apply to construction joints in cases where wire fabric reinforcement is used.

b. Longitudinal Joints

A longitudinal joint is required when placement of concrete is for the full pavement width of 24 feet. Currently, this joint is generally of the weakened plane type, formed either in the plastic concrete or sawed after hardening of the concrete. The transverse steel passes through the joint to hold it tightly closed in both cases. Supplementary tie bars or sections of wire fabric are used for supplemental reinforcement, depending on the individual case. When deformed fabric is used in the center joint, eliminating the need for deformed tie bars, design practice in many cases is to locate it at the same level across the joint as in the rest of the slab. Deformed tie bars, generally located at mid-depth of the concrete, may be placed above or below the level of the wire fabric, but not below mid-depth.

Figures 15 and 16 show designs currently used for longitudinal joints in CRCP in Texas. It should be noted that provision is made for a weakened plane joint and a sawed groove joint in cases where total pavement width is 36 feet, and placement is made of 24-foot and 12-foot widths in separate stages.

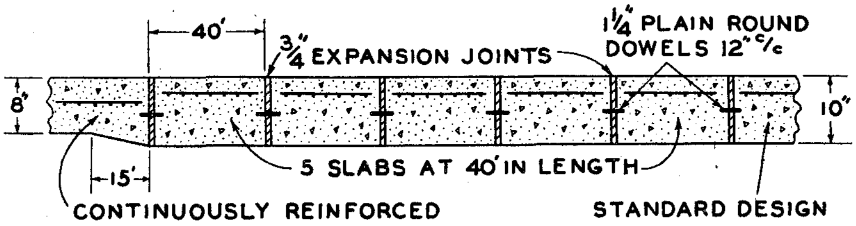
c. Terminal Joints

The longitudinal movements produced in CRCP by shrinkage phenomena and temperature differential are limited to the end 400 to 500-foot sections. The movement may be as much as 2 inches, which is more than conventional types of expansion joints can accommodate.

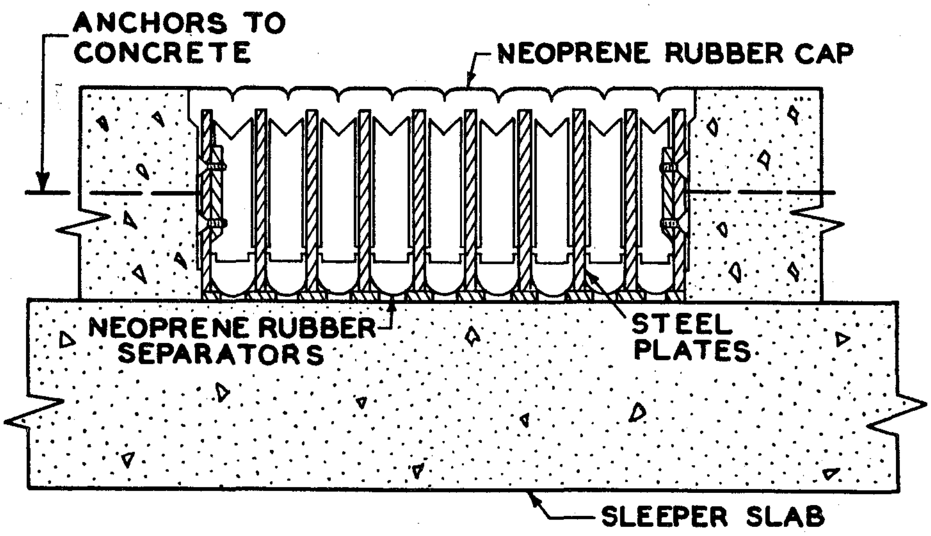
Two systems have been used to cope with changes of length, one for pavements with free ends and the other for those with anchored ends. The simplest terminal joint design for a free end provides for a series of short, conventionally reinforced slabs separated by standard doweled expansion joints, the number varying according to the total movement expected. Another design for a free end pavement employs a single expansion joint of large width. Both of the noted designs are for systems to absorb the thrust of full seasonal expansion forces and prevent damage to abutting pavements or structures. Obviously, the pavement ends must be free to contract, and the joints should remain operative over the service life of the pavement. Figure 17 shows examples of normal-width expansion joints similar in design to those used on a project in Michigan (top) and a fabricated steel and rubber joint used in Maryland (bottom). Another free end joint of a design similar to that used in Pennsylvania and North Dakota is shown in Figure 18.

d. End Anchorages

As previously noted, the free end of CRCP undergoes a seasonal movement which may be as much as 2 inches. Many engineers have felt that elimination of the large end movements associated with free ends would be a more effective concept than to make provision for them. This concept requires that some form of anchorage be provided at the ends or distributed gradually along the active 400 to 500-foot lengths near the ends. Designs were developed for systems of concrete piles or transverse trench lugs to accomplish this. End anchorages are usually designed to resist the full tensile force of the continuous reinforcement at yield point or an equal and opposite expansion force. In some designs, the restraint is concentrated as near the end as possible. In others, it is distributed through the usual active length of the end zone. Due to inherent uncertainties in assessing the soil resistance, anchor stiffness, forces involved,



RELIEF SECTION AT JUNCTION OF CONTINUOUSLY REINFORCED PAVEMENT AND STANDARD PAVEMENT



STEEL AND RUBBER EXPANSION JOINT

FIGURE 17. TERMINAL JOINTS

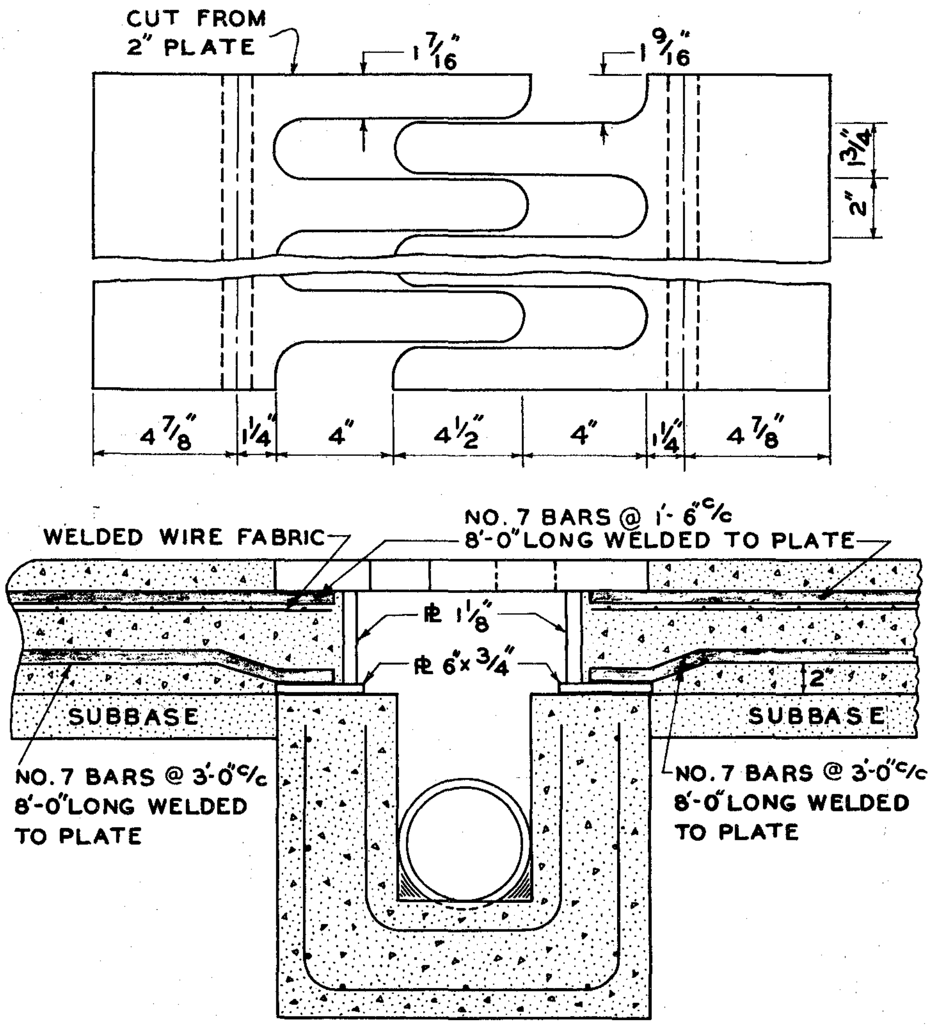
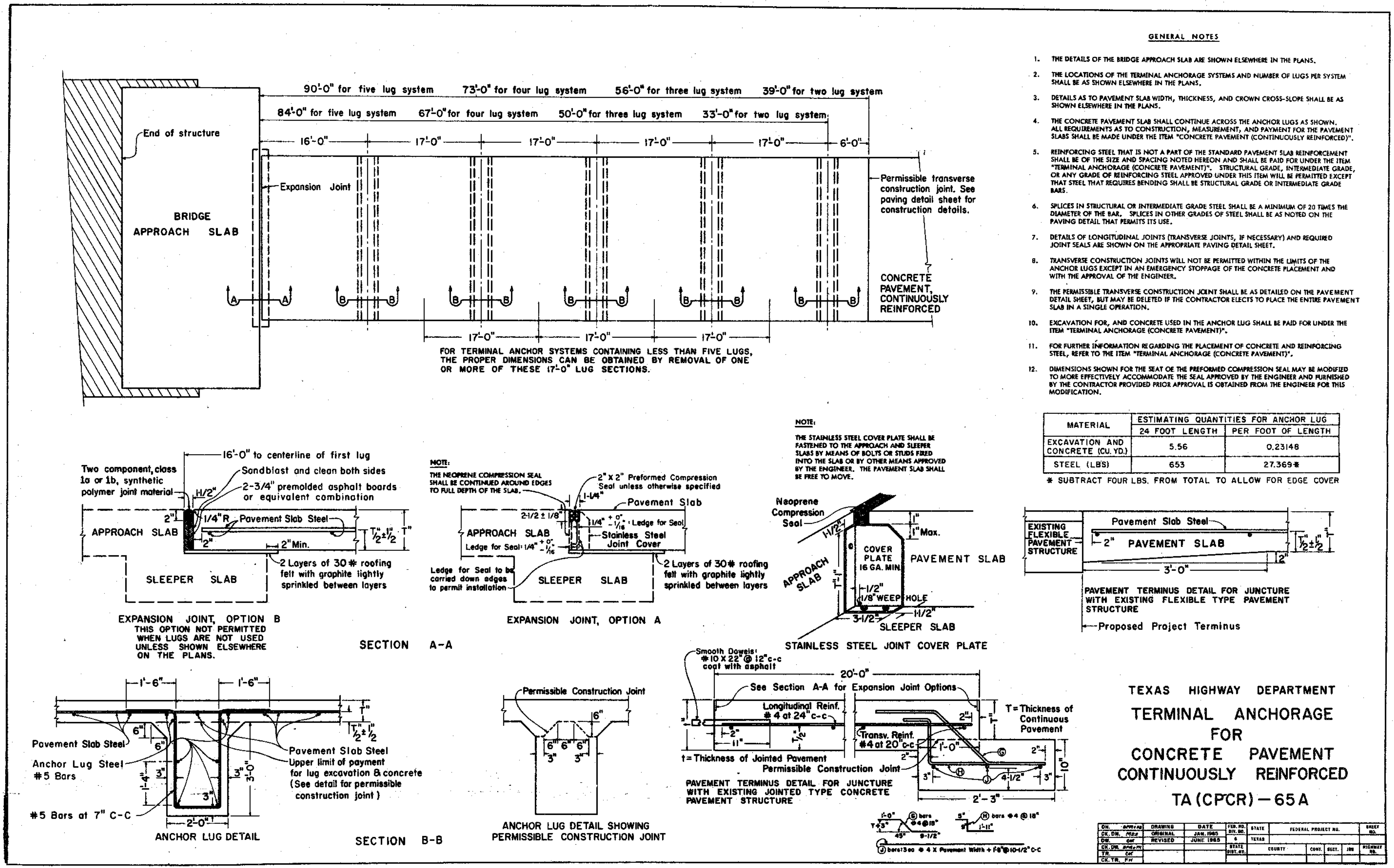


FIGURE 18. FINGER TYPE BRIDGE TERMINAL JOINT

effect of frost, etc., different designs for end anchorage systems have been used. A variety of designs have been used in projects in Texas, Mississippi, Wisconsin, and Maine. Figure 19 shows a Texas lug-type anchorage system design, Figure 20 a Mississippi design employing piles, and Figure 21 a design for a lug system used in Wisconsin. Results obtained with end anchorage systems to date indicate the approach to be sound; the general designs that have been used are considered valid.



GENERAL NOTES

1. THE DETAILS OF THE BRIDGE APPROACH SLAB ARE SHOWN ELSEWHERE IN THE PLANS.
2. THE LOCATIONS OF THE TERMINAL ANCHORAGE SYSTEMS AND NUMBER OF LUGS PER SYSTEM SHALL BE AS SHOWN ELSEWHERE IN THE PLANS.
3. DETAILS AS TO PAVEMENT SLAB WIDTH, THICKNESS, AND CROWN CROSS-SLOPE SHALL BE AS SHOWN ELSEWHERE IN THE PLANS.
4. THE CONCRETE PAVEMENT SLAB SHALL CONTINUE ACROSS THE ANCHOR LUGS AS SHOWN. ALL REQUIREMENTS AS TO CONSTRUCTION, MEASUREMENT, AND PAYMENT FOR THE PAVEMENT SLABS SHALL BE MADE UNDER THE ITEM "CONCRETE PAVEMENT (CONTINUOUSLY REINFORCED)".
5. REINFORCING STEEL THAT IS NOT A PART OF THE STANDARD PAVEMENT SLAB REINFORCEMENT SHALL BE OF THE SIZE AND SPACING NOTED HEREON AND SHALL BE PAID FOR UNDER THE ITEM "TERMINAL ANCHORAGE (CONCRETE PAVEMENT)". STRUCTURAL GRADE, INTERMEDIATE GRADE, OR ANY GRADE OF REINFORCING STEEL APPROVED UNDER THIS ITEM WILL BE PERMITTED EXCEPT THAT STEEL THAT REQUIRES BENDING SHALL BE STRUCTURAL GRADE OR INTERMEDIATE GRADE BARS.
6. SPLICES IN STRUCTURAL OR INTERMEDIATE GRADE STEEL SHALL BE A MINIMUM OF 20 TIMES THE DIAMETER OF THE BAR. SPLICES IN OTHER GRADES OF STEEL SHALL BE AS NOTED ON THE PAVING DETAIL THAT PERMITS ITS USE.
7. DETAILS OF LONGITUDINAL JOINTS (TRANSVERSE JOINTS, IF NECESSARY) AND REQUIRED JOINT SEALS ARE SHOWN ON THE APPROPRIATE PAVING DETAIL SHEET.
8. TRANSVERSE CONSTRUCTION JOINTS WILL NOT BE PERMITTED WITHIN THE LIMITS OF THE ANCHOR LUGS EXCEPT IN AN EMERGENCY STOPPAGE OF THE CONCRETE PLACEMENT AND WITH THE APPROVAL OF THE ENGINEER.
9. THE PERMISSIBLE TRANSVERSE CONSTRUCTION JOINT SHALL BE AS DETAILED ON THE PAVEMENT DETAIL SHEET, BUT MAY BE DELETED IF THE CONTRACTOR ELECTS TO PLACE THE ENTIRE PAVEMENT SLAB IN A SINGLE OPERATION.
10. EXCAVATION FOR, AND CONCRETE USED IN THE ANCHOR LUG SHALL BE PAID FOR UNDER THE ITEM "TERMINAL ANCHORAGE (CONCRETE PAVEMENT)".
11. FOR FURTHER INFORMATION REGARDING THE PLACEMENT OF CONCRETE AND REINFORCING STEEL, REFER TO THE ITEM "TERMINAL ANCHORAGE (CONCRETE PAVEMENT)".
12. DIMENSIONS SHOWN FOR THE SEAT OF THE PREFORMED COMPRESSION SEAL MAY BE MODIFIED TO MORE EFFECTIVELY ACCOMMODATE THE SEAL APPROVED BY THE ENGINEER AND FURNISHED BY THE CONTRACTOR PROVIDED PRIOR APPROVAL IS OBTAINED FROM THE ENGINEER FOR THIS MODIFICATION.

MATERIAL	ESTIMATING QUANTITIES FOR ANCHOR LUG	
	24 FOOT LENGTH	PER FOOT OF LENGTH
EXCAVATION AND CONCRETE (CU. YD.)	5.56	0.23148
STEEL (LBS)	653	27.369*

* SUBTRACT FOUR LBS. FROM TOTAL TO ALLOW FOR EDGE COVER

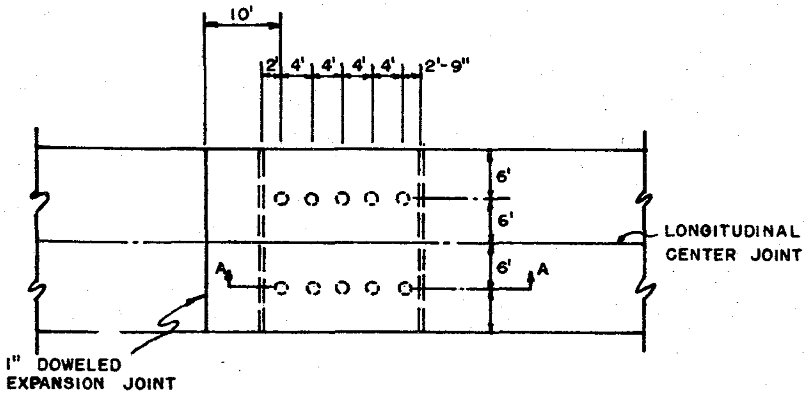
TEXAS HIGHWAY DEPARTMENT

TERMINAL ANCHORAGE
FOR
CONCRETE PAVEMENT
CONTINUOUSLY REINFORCED
TA (CPCR) — 65 A

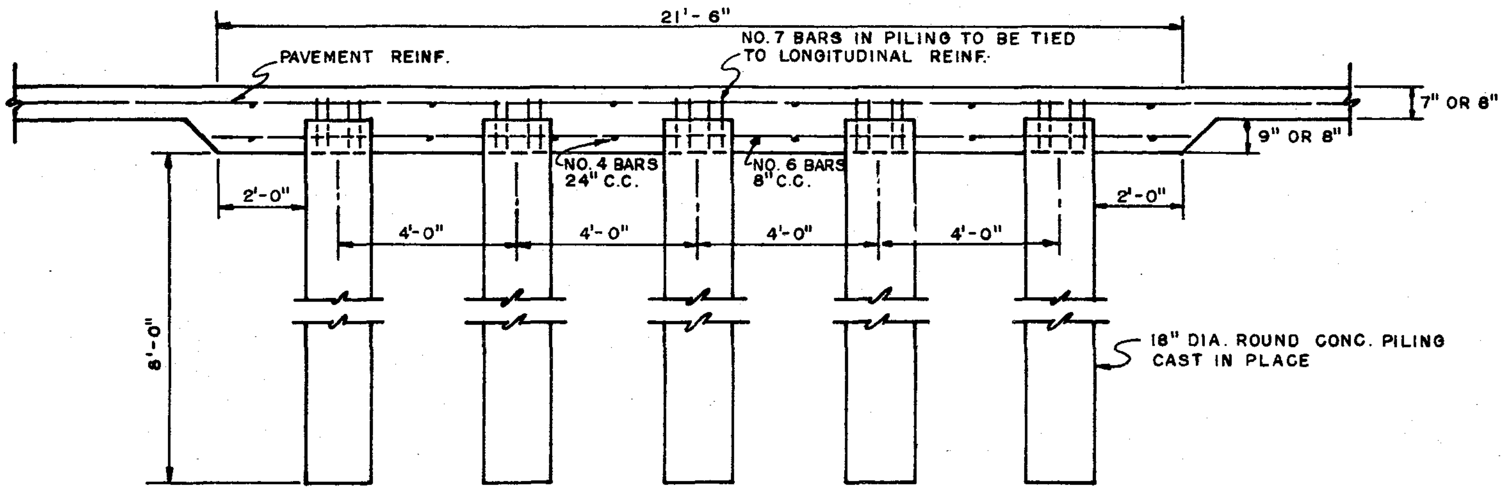
	DRAWING	DATE	FED. RD. DIV. NO.	STATE	FEDERAL PROJECT NO.	SHEET NO.
DN.	ORIGINAL	JAN. 1965	6	TEXAS		
CK. DN.	REVISED	JUNE 1965	STATE DIST. NO.	COUNTY	CONT. SECT. JOB	HIGHWAY NO.
DW.						
CK. DW.						
TR.						
CK. TR.						

File 8.39

FIGURE 19. TERMINAL ANCHORAGE FOR CONCRETE PAVEMENT CONTINUOUSLY REINFORCED, TA(CPCR)-65A



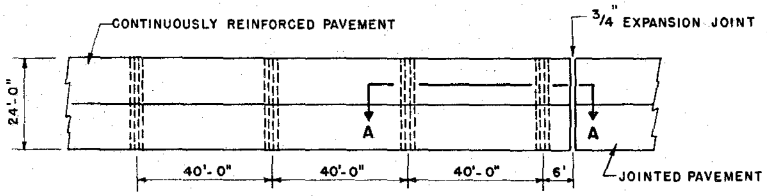
PLAN OF CONCRETE ANCHORAGE - PILING



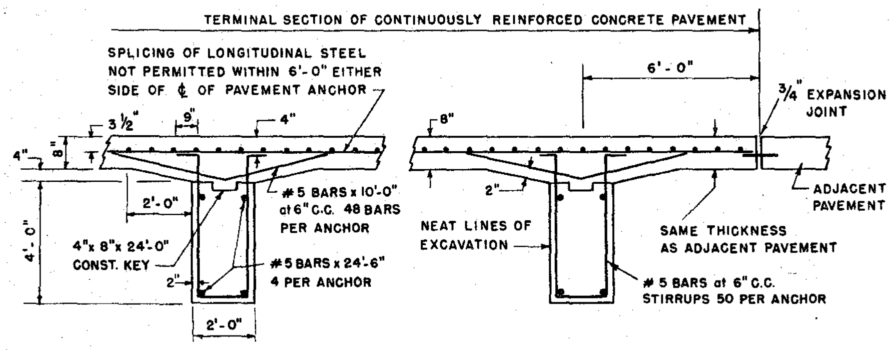
SECTION A-A

FIGURE 20. SPECIAL PAVING DETAILS AT PILING ANCHORAGE

Source: Mississippi Experimental Project 1-55-4(20)283 DeSoto County



PLAN OF TRANSVERSE LUGS



SECTION A-A

FIGURE 21. LUG TYPE TERMINAL ANCHOR

IV. MATERIALS

A. Reinforcing Steel

It is a credit to the steel industry that engineers from all state highway departments working with CRCP have indicated reinforcing steel products to be adequate for design, construction, and structural requirements. The choice of materials is wide, permitting the use of alternates according to the needs indicated by design and/or construction practice.

Steel used for reinforcement of CRCP is available in two forms: bars and fabricated wire mats. In both forms, the members may be plain or deformed, with the former seldom being used in concrete pavement reinforcement. Bars are made from billet, axle, and rail-steels, the first two of which are produced in several different grades identified according to strength properties. Bars made from rail steel are rolled from standard section "T" rails. Fabricated mats are produced from steel wire that has been cold-drawn from rods that have been hot-rolled from billets. Production of concrete reinforcing bars and wire mats is in accordance with well-defined specifications; the steels from which these items are made must meet specified requirements with respect to mechanical and other properties. Specifications pertaining to the steels and reinforcing products will be listed later. Data applicable to use limitations of steels are shown in Table IV. Steel bars and wire fabric are discussed below.

1. Steel Bars

Deformed steel bars have long been a standard form of concrete reinforcement. As previously noted, smooth bars are seldom used as concrete reinforcement. The range in properties of steels used for bar production may be said to offset the somewhat limited size range in which the bars are available. Bar numbers are based on the number of eighths of an inch included in the nominal diameter of the bars. The nominal diameter of a deformed bar is equivalent to the diameter of a plain bar having the same weight per foot as the deformed bar. For the sizes most commonly used, size graduation is based on an even one-eighth inch. An appealing feature of steel reinforcing bars, from the standpoint of design and construction, is their simple form which provides wide latitude in the configurations which can be made from them to fit a wide range of reinforcing needs. Advantages claimed for steel bars are in connection with

TABLE IV

ALLOWABLE UNIT STRESSES - STEEL

The unit stresses in pounds per square inch in the various types of steel should not exceed the following:

Type of Steel	Minimum Yield, psi	Unit Stress*, psi
Billet and Axle Steel		
Structural Grade	33,000	24,750
Intermediate Grade	40,000	30,000
Hard Grade	50,000	37,500
Billet Steel		
60,000-psi Minimum Yield	60,000	45,000
75,000-psi Minimum Yield	75,000	57,250
Rail Steel		
Regular Grade	50,000	37,500
Special Grade	60,000	45,000
Cold-Drawn Wire	60,000	45,000

---

*The unit stress is obtained by dividing the minimum yield by a factor of 1.33.

the relative ease with which they may be transported, stored, and handled. Also, damage to or loss of a single member is easily remedied by its replacement.

Mechanical properties of reinforcing bar steels and fabrication requirements for deformed bars are covered by the following specifications of ASTM Designation:

A 15: "Billet-Steel Bars for Concrete Reinforcement"

A 16: "Rail-Steel Bars for Concrete Reinforcement"

A 61: "Deformed Rail-Steel Bars for Concrete Reinforcement with 60,000-psi Minimum Yield Strength"

A 160: "Axle-Steel Bars for Concrete Reinforcement"

A 305: "Minimum Requirements for the Deformations of Deformed Steel Bars for Concrete Reinforcement"

A 408: "Special Large Size Deformed Billet-Steel Bars for Concrete Reinforcement"

A 431: "High-Strength Deformed Billet-Steel Bars for Concrete Reinforcement with 75,000-psi Minimum Yield Strength"

A 432: "Deformed Billet-Steel Bars for Concrete Reinforcement with 60,000-psi Minimum Yield Strength"

2. Wire Fabric

Welded wire fabric or mesh appears not to have been used as widely as deformed bars in reinforcing CRCP in past construction. One reason for this is that contractors have had more experience in the use of bars; another reason is that bars have been more readily available than the fabric. In most states, the option as to type of reinforcement rests with the contractor. In Texas, engineers have prepared a design detail to take advantage of deformed wire fabric, a product that has been commercially marketed by several steel companies in recent years. In the design, the deformed wire has been designated to distinguish it from the smooth wire which is often thought of when reference is made to cold-drawn wire.

The deformed wire has several advantages over plain wire and conventional reinforcing bars. First, it has very high strength properties with a yield of 70,000 psi which is about 17 percent over that for high-yield reinforcing bars; this allows a reduction in weight of steel per square yard of pavement. Second, the deformations give good bonding properties, thus overcoming a major objection to the smooth cold-drawn wire. Bond tests have shown the bond strength to be similar to that provided by conventional reinforcing bars. In addition, positive anchorage between the wire and the concrete is provided by the welded transverse wires. A third advantage of the deformed wire is afforded by the low carbon content which renders the material more malleable and less brittle than the high-yield reinforcing bars. The low-carbon wire can be bent at 90 degrees and straightened without breaking. Also, the low carbon content permits the material to be welded; this points to the possibility of a future practice wherein laps may be welded to replace the long laps and wire ties that are currently used. A fourth advantage of deformed wire fabric is that any cross-sectional steel area can be specified. For example, if a design requires a wire with a cross-sectional area of 0.185 square inches, the steel order can call for the exact size. If reinforcing bars were used, a 1/2-inch bar with a cross section of 0.20 square inches would have to be utilized which is a waste of steel.

Because of the very high tensile stresses that develop in the steel reinforcement in CRCP, it is the practice to specify that the longitudinal steel have a yield strength of 60,000 to 70,000 psi. The cold-drawn steel wire from which deformed welded wire fabric is fabricated provides such strength, and the material is usually specified for use in fabric reinforcement of CRCP. This is because cold-drawn wire has no definite yield point at or near its true elastic limit. It tends to resist stress practically throughout its entire strength range without any sudden excessive elongation such as develops in hot-rolled bar at about 65 percent of its ultimate strength. The value of this feature is apparent in CRCP. A cold-drawn wire having an ultimate strength of 75,000 psi will prevent excessive crack-opening up to a stress of about 65,000 psi or more. Hot-rolled steel of the same strength would fail to prevent a crack-opening at a stress of 40,000 psi which is the yield point of the wire. Therefore, with the same reinforcing factor of safety, a higher designing stress is possible with cold-drawn wire.

Cold-drawn steel wire to be used as such or in fabricated form is often used for the reinforcement of concrete. Wire fabric for CRCP is usually specified as welded wire fabric and can be of deformed and/or non-deformed types. Cold-drawn steel wire for concrete reinforcement is specified in ASTM Designation A 82. These specifications cover cold-drawn steel wire to be used as such, or in fabricated form, in gages not less than 0.080 inch or greater than 0.625 inch. The steel is made by open-hearth, electric-furnace, acid-bessemer, or basic-oxygen processes and cold-drawn from rods which have been hot-rolled from billets.

For use in fabricated welded fabric, the steel must have a minimum tensile strength of from 70,000 to 75,000 psi, depending on size, and a minimum yield strength of 56,000 psi for less than 11-gage wire or 65,000 psi for coarser than 10-gage wire. Other requirements are detailed in the following ASTM Specifications:

A 82: "Cold-Drawn Steel Wire for Concrete Reinforcement"

A 184: "Fabricated Steel Bar or Rod Mats for Concrete Reinforcement"

A 185: "Welded Steel Wire Fabric for Concrete Reinforcement"

A 496: "Deformed Steel Wire for Concrete Reinforcement"

A 497: "Welded Deformed Steel Wire Fabric for Concrete Reinforcement"

B. Concrete Materials and Concrete

The requirements of concrete for use in CRCP are the same as those for conventional pavements. Much has been written on the subject of concrete for use in pavements, and it seems unnecessary to treat the subject at length here. Suffice to say that cement, aggregates, admixtures, and water should be obtained only from sources of supply which have been approved before shipments are begun. The materials should be used only so long as they meet the requirements of specifications. The basis of approval of such sources should be the ability to produce materials of the quality and in the quantity required. Judging from reports of some problems and failures in CRCP, these ground rules have not always received due attention. There have been some cases where pavement disintegration was attributed to the use of reactive aggregates.

Requirements of concrete for CRCP are the same as for other types of high-quality concrete pavements. Strength is specified to conform with design, and inspection schedules are set up to monitor quality. Air-entrained concrete is used in the pavements, with 4 percent entrained air being nominal.

In most cases, concrete slumps of 1-1/2 to 2 inches have been employed. With proper vibration, this range of consistency has worked well with pavers of various types. Most modern mixing facilities are capable of producing concrete of uniform characteristics; this leads to reduction of problems in paving.

C. Other Materials

Other materials such as curing compounds, sealants for sawed grooves, etc., are specified on the basis of experience and economics. It is noteworthy that the amount of sealants used in CRCP is less than that for conventional jointed pavements; this represents a saving in the case of the continuous pavement.

V. CONSTRUCTION OF CRCP

Experience gained in the construction of conventional jointed concrete pavements has been utilized in building CRCP, particularly with respect to design of base courses, materials, and construction methods and equipment. In the past few years, substantial gains have been made in the rates at which the pavements can be constructed. This has been due in part to the fact that the size of projects has increased in some states where established designs are used, and there has been justification for contractors to employ high-production-rate equipment and methods. Another factor of significant influence has been the experience gained in the building of many experimental CRCP projects which, though only 1 or 2 miles in length, have been proving grounds for construction techniques.

Although a CRCP requires far fewer joints than conventional concrete pavements, such joints as are used have caused problems for some contractors. Former problems with the construction joints required at the end of a day's paving appear to have been reasonably well resolved, and the number of expansion joints at slab terminals may soon be greatly reduced by the use of terminal anchorage systems such as have been used in several states. Other difficulties associated with terminal joints may be greatly reduced if experimental designs now under study are successful. One of these allows for the continuation of CRCP over structures such as bridges, with the bridge deck tied to and/or being a portion of the slab. A structure incorporating this design has been built in Texas and is reported to be performing well.

Experience in constructing CRCP has shown the need for rather complete specifications pertaining to construction practice. There have been projects where problems developed during construction, and failures occurred in pavements as a result of inexperience and lack of attention to certain details. In some cases, the importance of splice lengths and secure tying at splices was not clearly understood, while, in others, the need for proper and prompt vibration of concrete during placement was neglected. Currently, attention is given to the need for adequate and proper construction practices, and, in most states, requirements are covered by specifications.

A. Equipment

Prior to and during much of the past decade, the almost completely experimental status of CRCP plus unfamiliarity with construction requirements resulted in added costs and limited use of this type of pavement.

Most projects were relatively small, and there was lack of opportunity, incentive, or justification for the employment of advanced construction methods and high-capacity equipment that could serve to reduce costs. This situation was often reflected in low paving rates of a few hundred feet per day.

An important operation in the construction of CRCP is the installation of the continuous reinforcing steel. Many contractors have designed and built equipment to improve the efficiency and reduce labor costs of this work, particularly in projects using steel bars as reinforcement. Steel placement rates of over 500 feet per hour for 24-foot pavements have been achieved with such equipment, with resulting alignment and spacing of bar members being very accurate.

Currently, the combined use of a central-mix concrete plant, nonagitating side-dump wet-batch trucks, and slip-form pavers is considered to be the most efficient method of constructing concrete pavements, whether of the conventional jointed or CRCP type. Modern automated central-mix plants provide effective control of concrete properties and quality while supplying practically any amount of concrete required by paving equipment. Wet-batch trucks used in conjunction with such plants are of various capacities and of agitating or nonagitating types; even conventional dump trucks have been utilized successfully to haul central-mixed concrete. In some states, the use of agitating equipment is required as a measure to prevent segregation and/or degradation of concrete properties during transit from central-mix plant to paving site. Contractor experience with both types of trucks has indicated that transport with nonagitating equipment does not have adverse or undesired effects on the properties of concrete having the consistency normally called for in paving work.

In recent years, the use of slip-form pavers has gained favor in many states. This has been due to reduced paving costs and other advantages that can be realized through utilization of this equipment. Since no side forms are required and it is possible to place continuous strips of concrete, the slip-form paver is particularly adaptable to the building of CRCP. Using concrete with slumps of about 2 inches, paving rates of over 7200 feet per day have been reported, and rates of 5000 to 6000 feet per day are not uncommon.

Figures 22 through 39 show equipment used on a recent major project in Texas. Noteworthy is the high degree of mechanization which was characteristic of this operation. Of interest in Figure 26 is the asphalt-stabilized (mixed and laid hot) base, or level up, on which the

FIGURE 22. STOCKPILE SAND (BACKGROUND) AND HARD SILICEOUS. AGGREGATE ADJACENT TO HIGH-CAPACITY CENTRAL MIX CONCRETE PLANT. BULLDOZERS MOVE MATERIALS TO CRANES WHICH FEED CONVEYOR TO BATCHING PLANT.

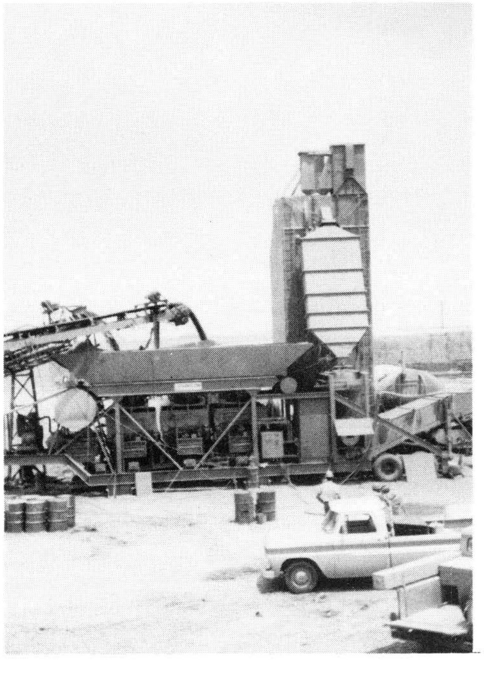


FIGURE 23. FULLY AUTOMATIC BATCHING UNIT AT CENTRAL MIX PLANT. ENTIRE OPERATION IS CONTROLLED FROM CONSOLE BEHIND CAB OF PICKUP TRUCK IN RIGHT FOREGROUND.

FIGURE 24. TWO 9-YARD MIXERS OF 540 CU YD HOURLY CAPACITY AT CENTRAL MIX PLANT. ALL BATCH INGREDIENTS ARE FED TO MIXERS BY CONVEYOR AT LEFT.

FIGURE 25. 9-YARD MIXER DUMPING INTO "AGITOR" WET BATCH TRUCK AT CENTRAL MIX PLANT.

FIGURE 26. APPROACHING PAVING TRAIN LAYING 24-FOOT BY 8-INCH CRCP ON ASPHALTIC CONCRETE LEVEL-UP. CHAIR-SUPPORTED CONTINUOUS REINFORCING STEEL IN FOREGROUND WAS FABRICATED FROM DEFORMED STEEL BARS.

FIGURE 27. WET BATCH TRUCKS DELIVERING CONCRETE TO JOBSITE. SURFACE OF ASPHALTIC CONRETE LEVEL-UP IS BEING WET DOWN IN LEFT REAR, AHEAD OF PAVING TRAIN.

FIGURE 28. WET BATCH "AGITOR" TRUCK DUMPING CONCRETE INTO #1 SPREADER; "PANCAKE" OF CONCRETE SPREAD BY THIS EQUIPMENT IS SHOWN IN CENTER OF PHOTO.

FIGURE 29. CONCRETE BEING DELIVERED TO #2 SPREADER; BACK END OF #1 SPREADER IS AT RIGHT. HOT-MIX ASPHALTIC CONCRETE LEVEL-UP CAN BE SEEN IN FOREGROUND.

FIGURE 30. FRONT VIEW OF SLIP-FORM PAVER SHOWING CONCRETE-DISTRIBUTING AUGER AND ELECTRIC CABLES TO VIBRATING UNITS. CONCRETE IN FOREGROUND WAS PLACED BY TWO SPREADERS. STRING GUIDELINE FOR PAVER IS VISIBLE IN LEFT FOREGROUND.

FIGURE 31. ADVANCING SLIP-FORM PAVER SHOWING LEADING EDGE OF SLIP FORM AT LEFT.

FIGURE 32. CONTINUOUSLY REINFORCED CONCRETE PAVEMENT BEING PLACED BY PAVING TRAIN CONSISTING OF TWO SPREADERS AND SLIP-FORM PAVER. TRAIN IS MOVING FROM LEFT TO RIGHT.

FIGURE 33. PORTION OF CONCRETE SURFACE FINISHING OPERATIONS FOLLOWING SLIP-FORM PAVER.

FIGURE 34. SIDE VIEW OF EQUIPMENT USED FOR APPLICATION OF CURING COMPOUND TO SURFACE OF WET PLACED CONCRETE.

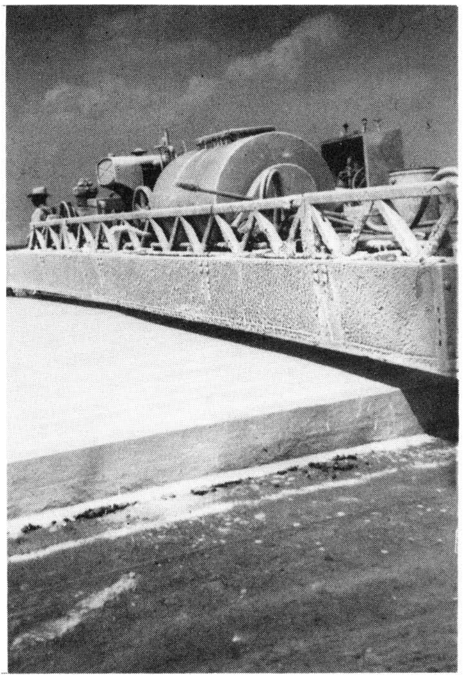


FIGURE 35. EQUIPMENT USED TO APPLY CURING COMPOUND TO FRESHLY LAID CONCRETE PAVEMENT; COMPOUND HAS BEEN APPLIED TO CONCRETE IN LEFT FOREGROUND.

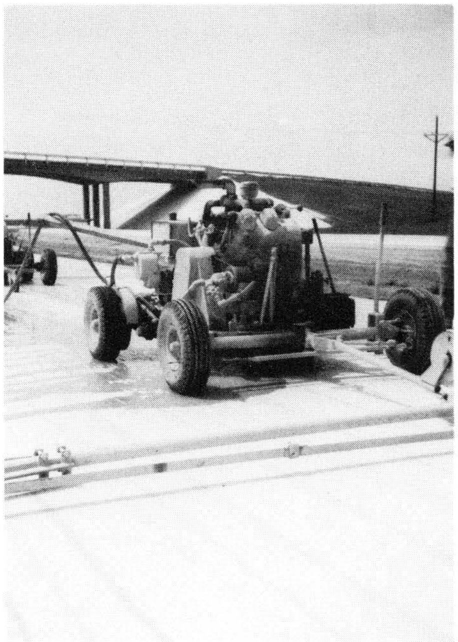


FIGURE 36. SELF-PROPELLED, MOTOR-DRIVEN DIAMOND SAW UNITS CUTTING LONGITUDINAL CENTER GROOVE IN 24-FOOT CONTINUOUSLY REINFORCED CONCRETE PAVEMENT.

FIGURE 37. PAVER USED IN CRCP PROJECT IN TEXAS. MECHANICALLY DRIVEN VIBRATORS CAN BE SEEN AT RIGHT. PREVIOUSLY PAVED 12-FOOT LANE IS IN FOREGROUND.

FIGURE 38. TRAVELING MIXER USED TO SUPPLY CONCRETE AT A CRCP PROJECT IN WHICH STEEL FORMS WERE EMPLOYED. THE 24-FOOT WIDE PAVEMENT WAS PLACED IN TWO SEPARATE PASSES A SINGLE LANE AT A TIME. DESIGN WAS THE SAME AS FOR THE PROJECT ILLUSTRATED IN FIGURES 22 THROUGH 36.

FIGURE 39. CONCRETE BEING PLACED FOR A 12-FOOT LANE BY THE TRAVELING MIXER SHOWN IN FIGURE 38. REINFORCING STEEL IS TIED DEFORMED STEEL BAR; PREVIOUSLY PAVED 12-FOOT LANE IS IN FOREGROUND.

steel bar reinforcement was fabricated and placed. This base not only provided a graded, durable, smooth surface on which the steel was installed rapidly and easily, but also served to expedite subsequent paving operations. The advantages of bases of this type being apparent, it is likely that their use with CRCP will become standard practice.

B. Steel Placement

Several of the structural features of CRCP require the use of construction procedures that are not common in the building of conventional concrete pavements. Among these is the continuity of the steel reinforcement which must extend over long distances. In order to assure this, construction practice must be such that the steel will not part during concrete placement and finishing operations. Experience has shown that secure fastening of reinforcement members in splice areas, as by wire tying, is necessary to reduce the possibility of parting. Several methods of steel installation have been used, with varying degrees of effectiveness. In the interest of minimizing delays and interruptions in paving due to problems in placing reinforcement and maintaining a steady rate of construction, preplacement of steel well ahead of the paving train is favored. This applies to welded wire fabric as well as tied bar reinforcement. This method has been employed in most CRCP constructed in recent years and is being used on the majority of current projects. Figures 40 through 56 show various stages of steel installation for "Deformed Steel Bars" and Figures 57 through 68 for "Welded Wire Fabric" used in recent Texas projects. The figures also show typical concrete placement and finishing operations and equipment.

The use of adequate overlap of steel members is of considerable importance in avoiding possible gaps in reinforcement continuity. Lap or splice length is considered as a design detail and is included in construction specifications. Results of studies related to required splice lengths for deformed bar and welded wire fabric reinforcement for CRCP have indicated that a 32-diameter lap (20 inches in the case of No. 5 bar, average yield strength 64,000 psi) was adequate in all respects. For welded wire fabric (5/0-longitudinal wires, 0.147-square inch area, average yield strength 81,000 psi), 26-inch splices were found to be adequate. Tests were made at early concrete ages of one to 14 days.

Current practice in Texas is to specify splice lengths equal to not less than twenty-four times the bar diameter for steel bars and thirty-one times the nominal wire diameter for deformed wire mat.

DEFORMED STEEL BARS

FIGURE 40. INITIAL STAGE OF PLACING LONGITUDINAL REINFORCEMENT COMPOSED OF DEFORMED STEEL BARS.

FIGURE 41. INITIAL POSITIONING OF LONGITUDINAL STEEL PREPARATORY TO SPLICING AND TYING.

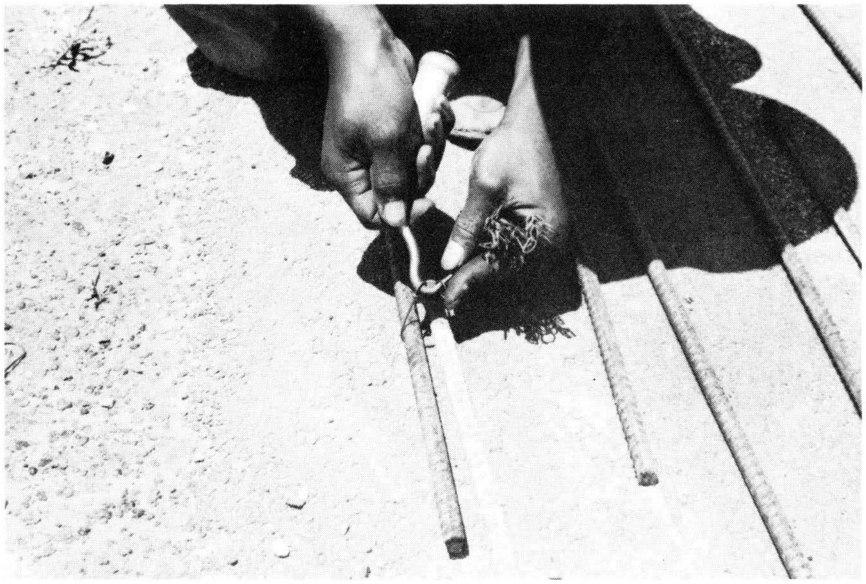


FIGURE 42. INITIAL STAGE OF TYING OPERATION AT SPLICE IN LONGITUDINAL STEEL.

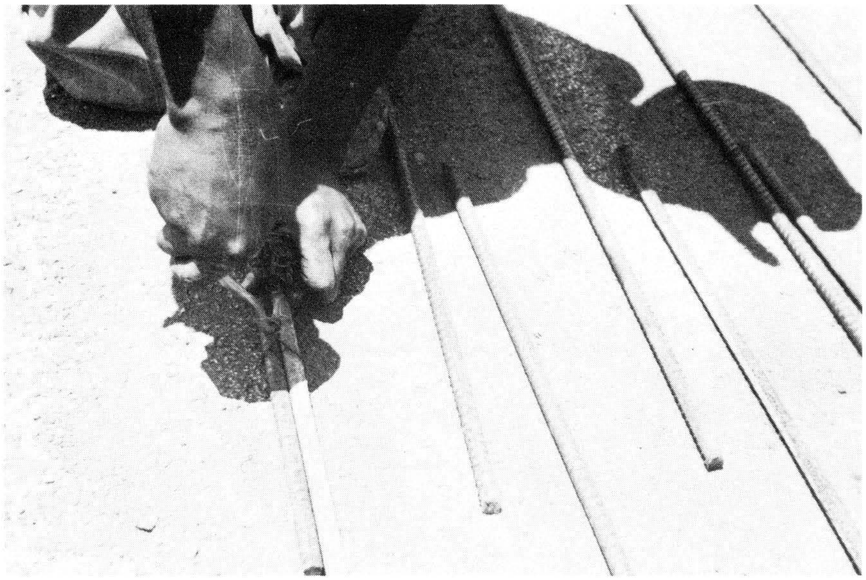


FIGURE 43. FINAL TWIST BEING APPLIED TO TYING WIRE AT SPLICE.

FIGURE 44. LONGITUDINAL STEEL BEING TIED AT SPLICES; NOTE STAGGERED SPLICE PATTERN.

FIGURE 45. CREW TYING AND ALIGNING LONGITUDINAL STEEL.

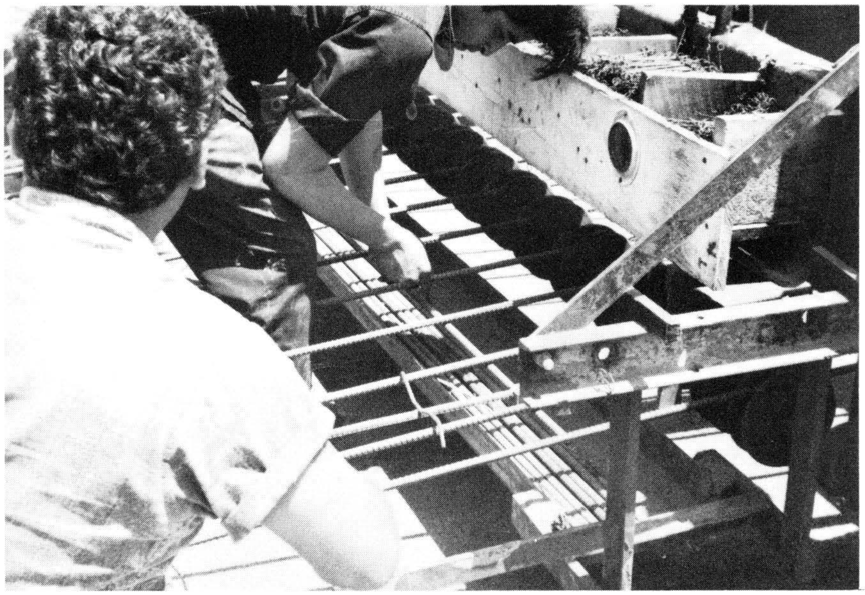


FIGURE 46. TRANSVERSE STEEL BEING TIED TO LONGITUDINAL STEEL.

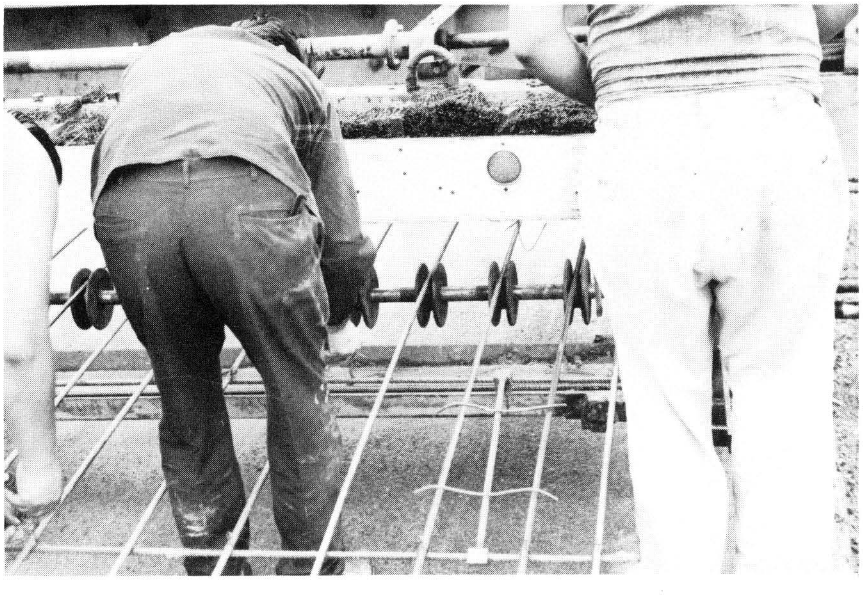


FIGURE 47. GAGE AND PULLEYS USED FOR SPACING TRANSVERSE AND LONGITUDINAL STEEL, RESPECTIVELY.

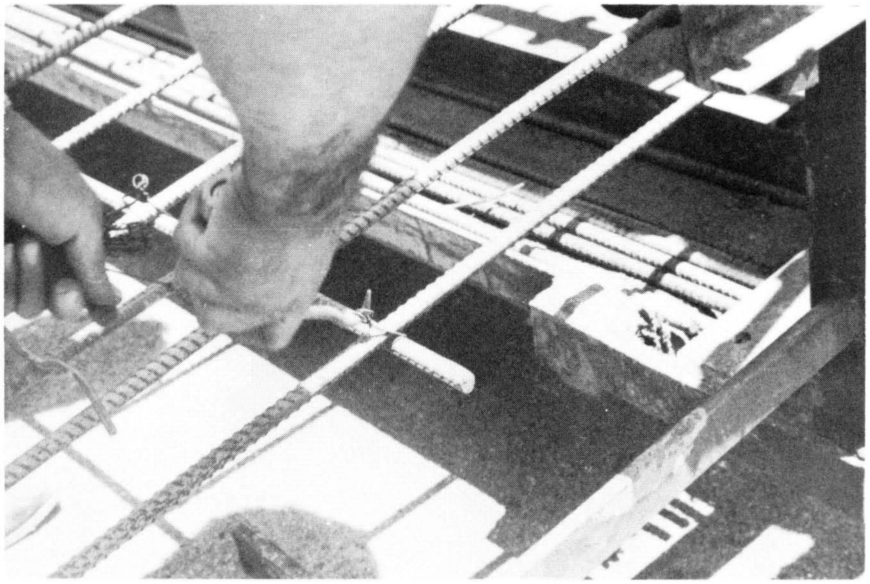


FIGURE 48. PROTRUDING END OF TRANSVERSE STEEL AT PAVEMENT EDGE.

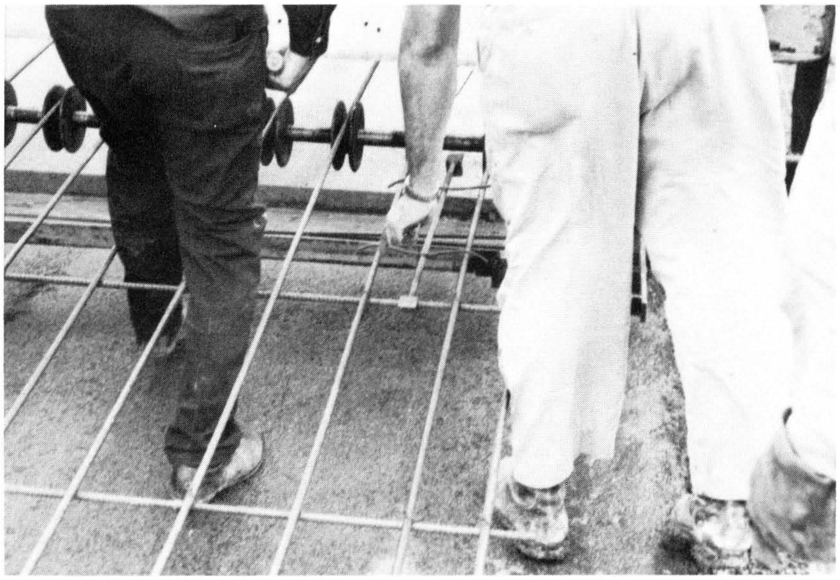


FIGURE 49. TIED DEFORMED BAR MAT EMERGING FROM MECHANIZED EQUIPMENT.

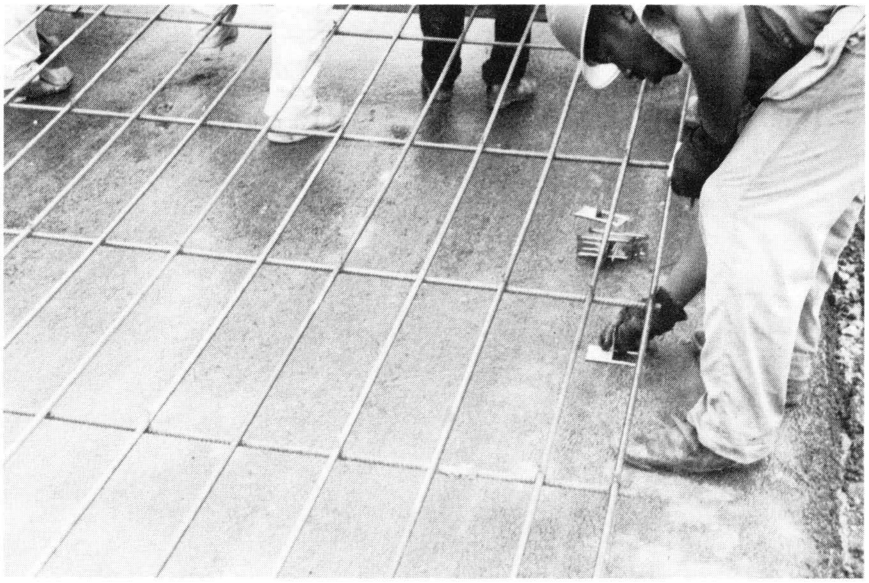


FIGURE 50. PLACING SHEET STEEL CHAIR FOR EDGE SUPPORT OF TIED DEFORMED STEEL BAR MAT.

FIGURE 51. SPACING OF STEEL CHAIRS SUPPORTING TIED DEFORMED STEEL BAR MAT.

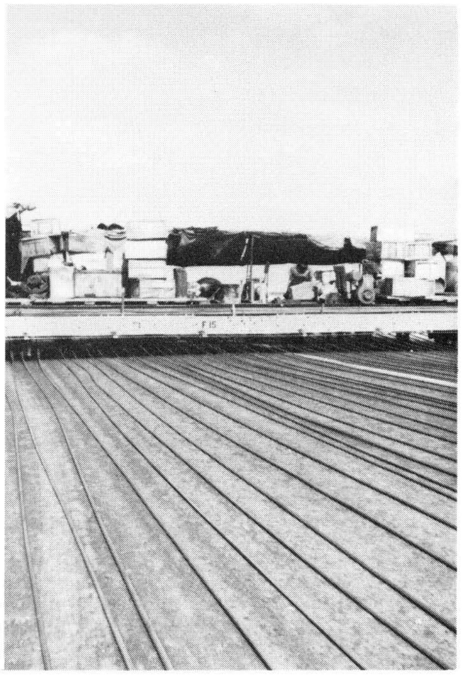


FIGURE 52. FRONT VIEW OF EQUIPMENT USED FOR FABRICATION OF REINFORCING MAT FROM DEFORMED STEEL BARS; LONGITUDINAL STEEL IS IN FOREGROUND. PAVEMENT WIDTH IS 24 FEET.

FIGURE 53. SIDE VIEW OF EQUIPMENT FOR FABRICATING REINFORCING STEEL MAT FROM DEFORMED STEEL BARS; TRANSVERSE STEEL IS BEING TIED TO LONGITUDINAL STEEL BENEATH CANOPY; TRAILER CARRIES PRESSED STEEL CHAIRS USED TO SUPPORT MAT.

FIGURE 54. DEFORMED BAR CONTINUOUS REINFORCING STEEL IN PLACE ON 4-INCH BASE COURSE OF HOT-MIX ASPHALTIC CONCRETE LEVEL-UP. STEEL MAT FABRICATING EQUIPMENT CAN BE SEEN IN THE DISTANCE.

FIGURE 55. LONG STRETCH OF CONTINUOUS REINFORCING STEEL MAT FABRICATED FROM DEFORMED STEEL BARS. PAVEMENT WIDTH IS 24 FEET; BASE COURSE IS HOT-MIX ASPHALTIC CONCRETE.

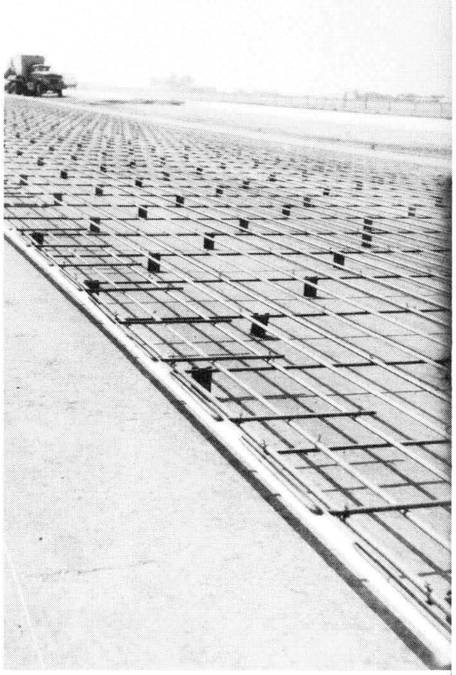


FIGURE 56. DEFORMED BAR CONTINUOUS REINFORCING STEEL IN PLACE AHEAD OF PAVING TRAIN SHOWING DESIGN AND ARRANGEMENT OF STEEL FOR ATTACHMENT OF APPROACH AND ACCELERATION LANE TO MAIN PAVEMENT IN LEFT FOREGROUND.

WELDED WIRE FABRIC

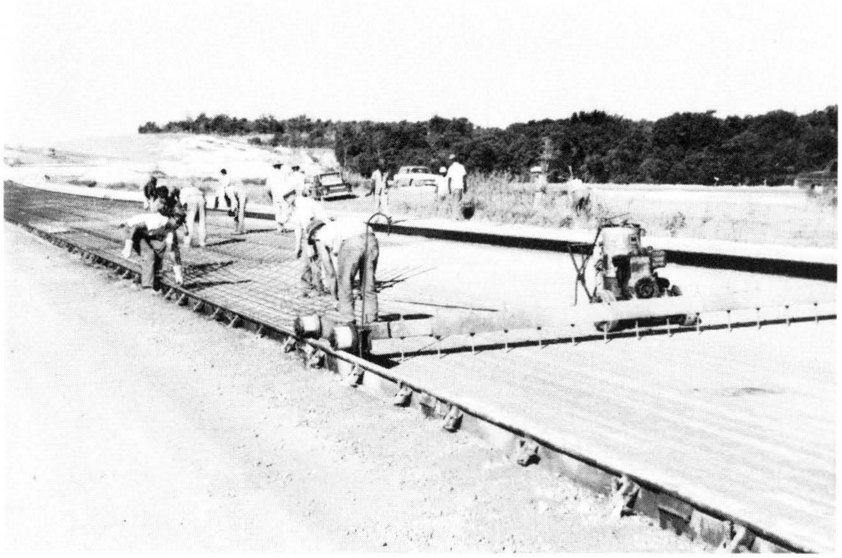


FIGURE 57. INITIAL POSITIONING OF WIRE FABRIC MAT.

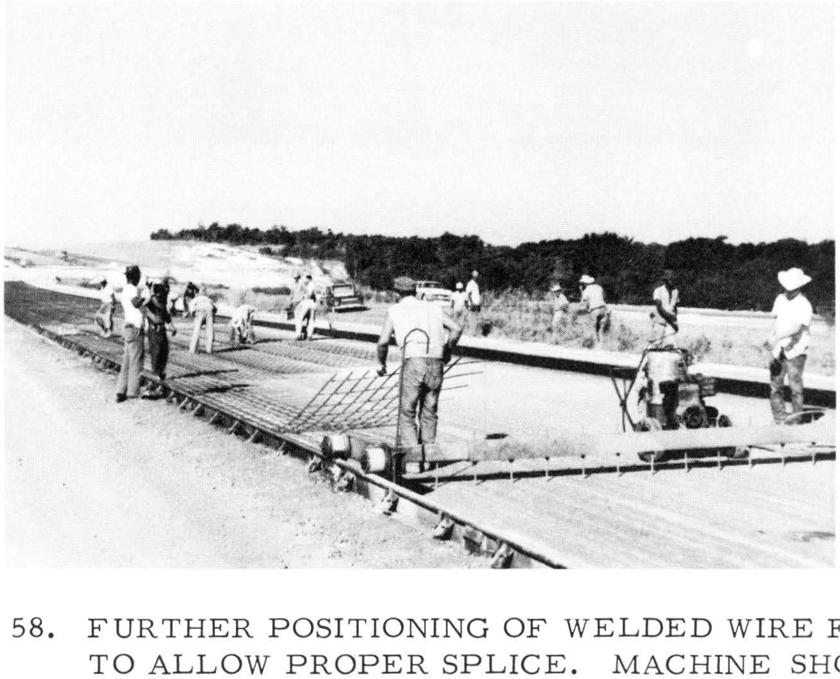


FIGURE 58. FURTHER POSITIONING OF WELDED WIRE FABRIC TO ALLOW PROPER SPLICE. MACHINE SHOWN IS FOR DETECTING HIGH SITES IN GRADE.

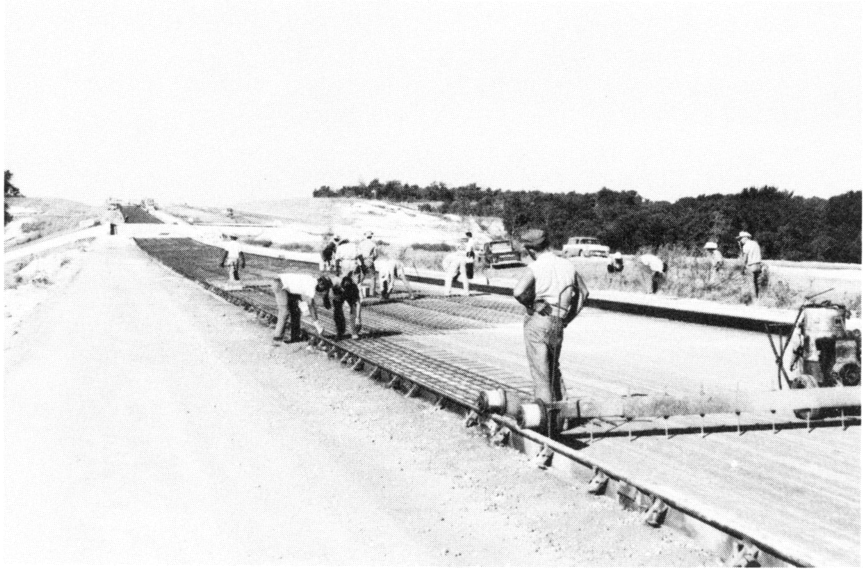


FIGURE 59. INITIAL TYING OF WIRE FABRIC MAT.

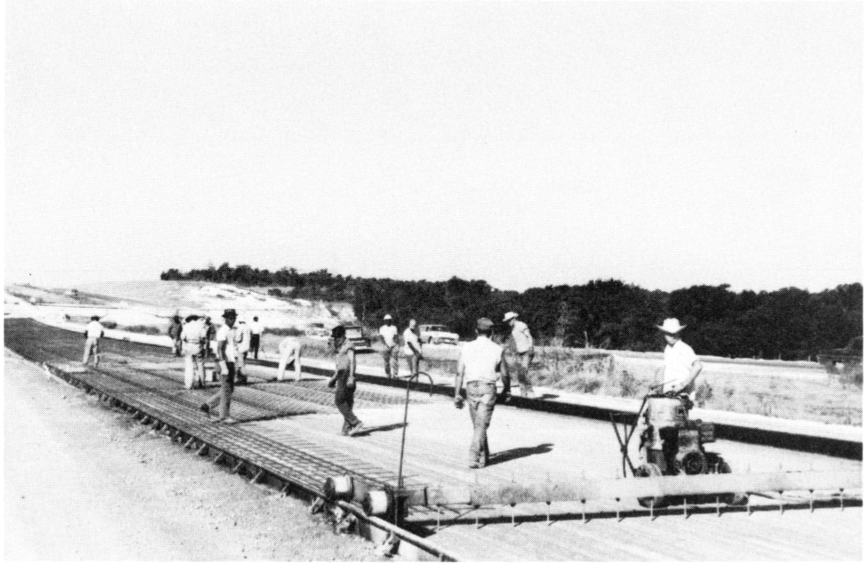


FIGURE 60. FINAL POSITION OF WIRE MAT.

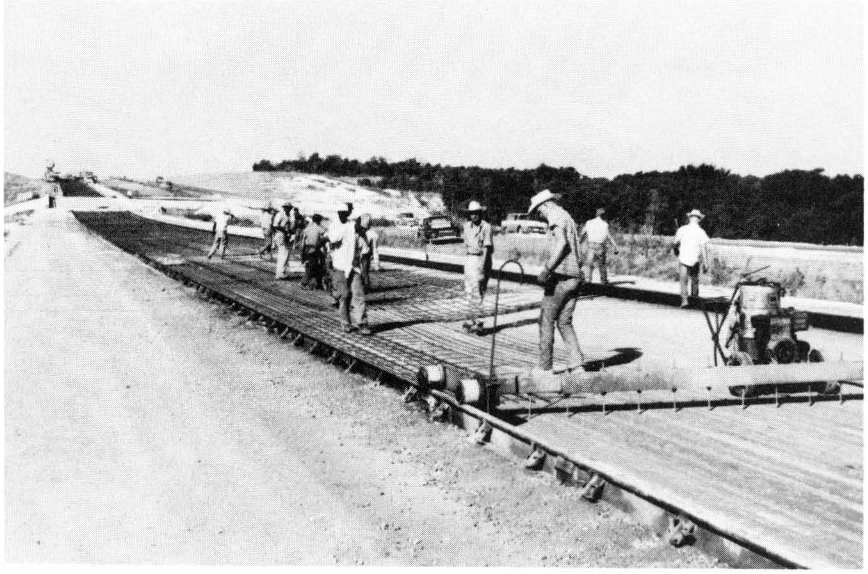


FIGURE 61. DELIVERY OF SECOND MAT FROM PAVEMENT EDGE.

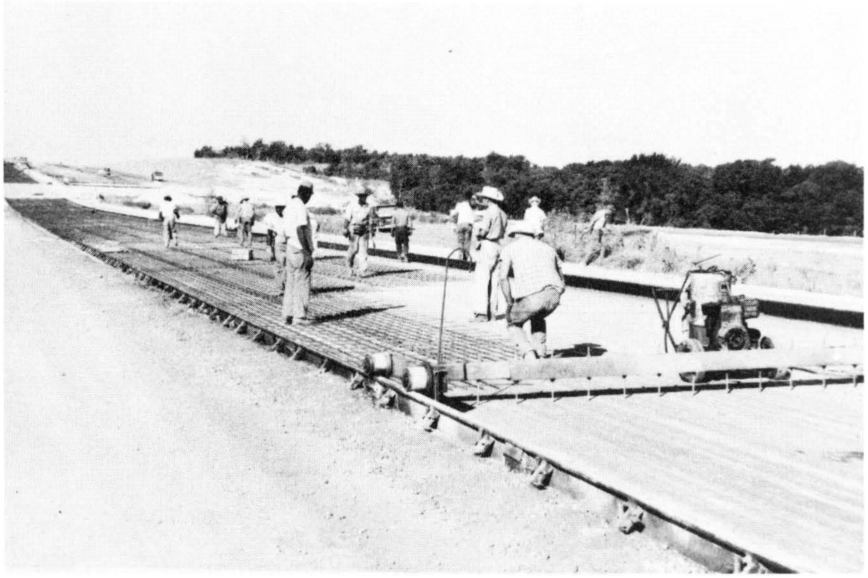


FIGURE 62. ALIGNING MAT TO ENSURE PROPER POSITIONING.

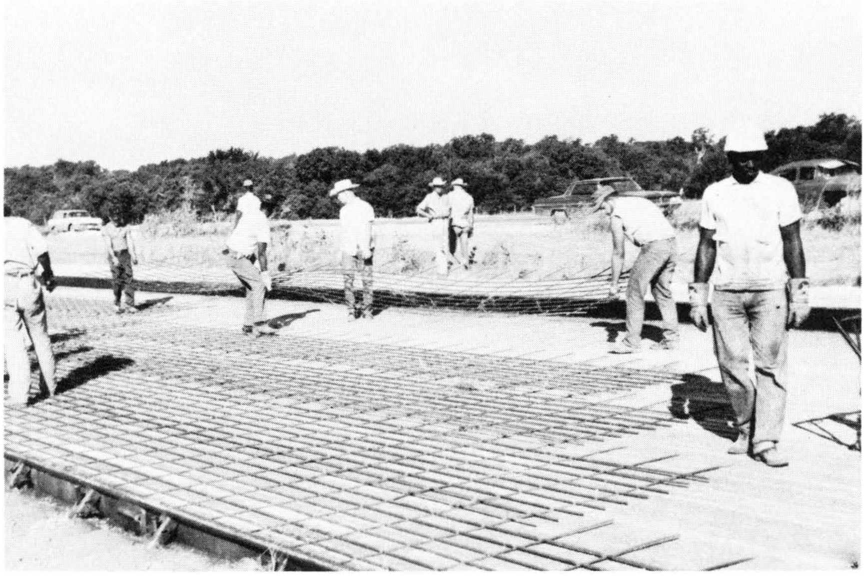


FIGURE 63. STAGGERED SPLICE PATTERN IN WELDED WIRE FABRIC REINFORCEMENT.

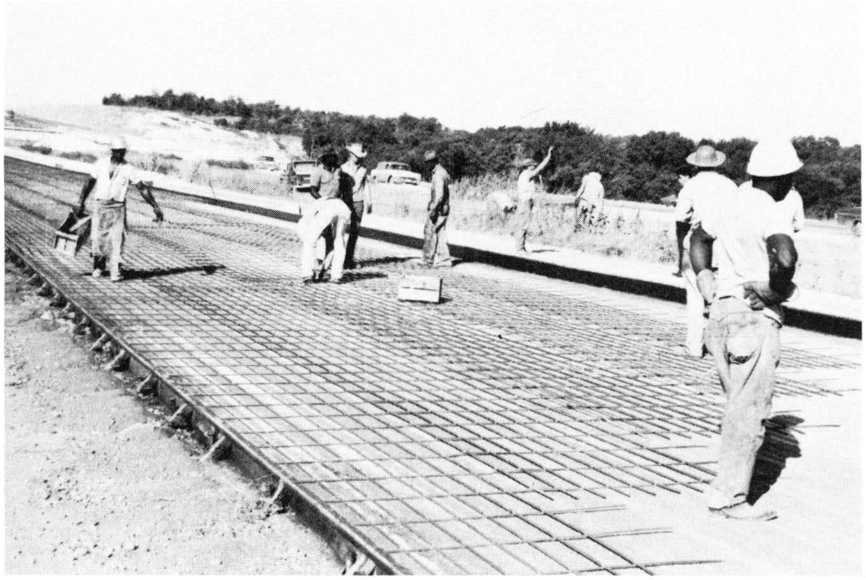


FIGURE 64. TYING WELDED WIRE FABRIC AT SPLICES.

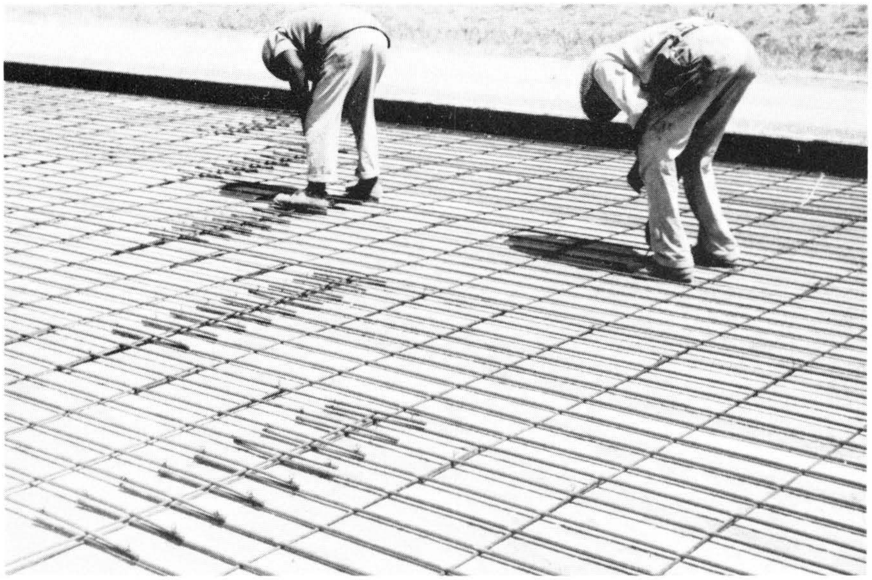


FIGURE 65. TIED STEEL SHOWING STAGGERED SPLICE PATTERN.

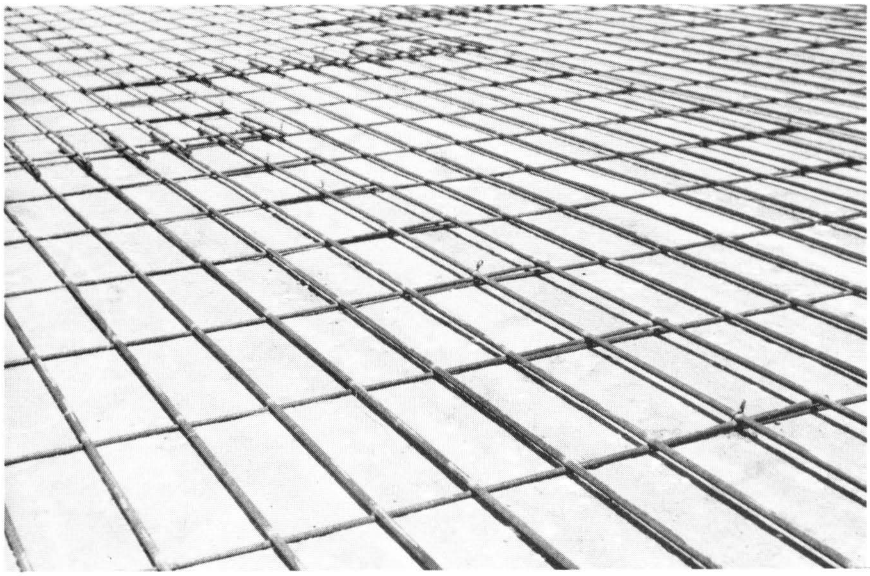


FIGURE 66. TIED WELDED WIRE FABRIC REINFORCEMENT READY FOR FINAL POSITIONING ON CHAIRS.

FIGURE 67. STRETCH OF WELDED WIRE FABRIC SUPPORTED ON CHAIRS AND READY FOR CONCRETE PLACEMENT.

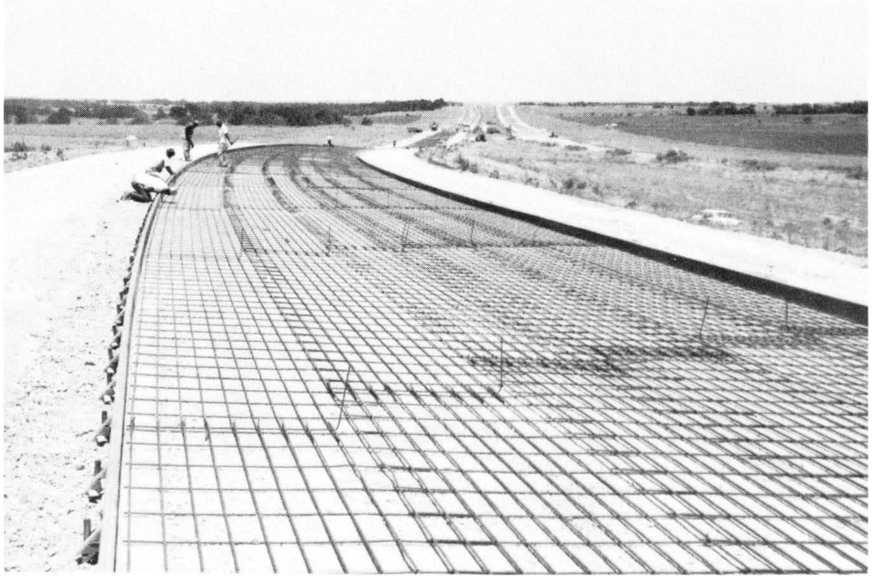


FIGURE 68. WELDED WIRE FABRIC WITH STAGGERED SPLICE PATTERN.

C. Vibration

Vibration of concrete at the time of paving is essential for uniform and adequate slab density. Most of the failures in CRCP due to inadequate vibration have been at or near construction joints, according to experience in Texas, though they have occurred at numerous other points in the slab. When paving takes place in warm weather, initial set of the concrete takes place more rapidly than in cooler weather; in such cases, vibration must be applied as soon as possible after placement. In some states, the frequency of vibration is specified. The general recommended range is 3000 to 5000 impulses per minute, the optimum is felt by some engineers to be near the higher frequency.

The question arises as to how much vibration may be applied without causing segregation and loss of entrained air due to either frequency or amplitude, or both. Vibration requirements will vary with aggregate shape, water, and air content. There appears to be a need for more information on the various aspects of vibration of concrete in building CRCP and the establishment of guidelines for use in construction.

VI. PERFORMANCE

To mid-1966, twenty-one states had either built CRCP or let contracts for construction in 387 highway projects. Observations made on a large number of these pavements over significant service periods have provided an adequate basis for judging their performance under a variety of traffic, structural, and climatic and regional conditions. In general, judgment of performance has been a relative matter, often based on comparisons between CRCP and conventional jointed concrete pavements built at the same time, near each other, and subjected to the same or very similar service conditions. It seems likely that CRCP performance evaluations of the future will be more comprehensive and objective and place considerable emphasis on determining the dependency of pavement performance upon pavement design variables. Performance variables will include individual manifestations of surface deformation and deterioration, as well as a current serviceability index which combines certain of the individual surface behavior elements into a variable that is related to user judgment of the pavement's ability to serve traffic at a given time. Studies of this type for pavement evaluation have been advocated in recent years and are discussed in National Cooperative Highway Research Program Reports 2 and 2A, respectively titled "An Introduction to Guidelines for Satellite Studies of Pavement Performance" and "Guidelines for Satellite Studies of Pavement Performance."

The performance of CRCP in numerous states has been closely observed and monitored over periods ranging from a few to more than 20 years. Overall, the record is impressive, even in view of the experimental nature of most projects and the wide range of design variations used. The present feeling of many engineers as to the advantages afforded by the use of CRCP and the anticipated wider acceptance of this type of pavement undoubtedly are based largely on the overall favorable performance ratings that many existing sections have received after years of service. The following annotations are indicative of favorable pavement performance in various states where significant experience has been gained with CRCP:

- It would be remiss to omit mention of the oldest CRCP in the United States. The first continuously reinforced concrete slabs of significant length were built in Indiana in 1938 on a heavily traveled, heavy-duty highway. This project has surpassed all expectations, both service-wise and maintenance-wise.

- In Texas, where more than 50 percent of the total CRCP mileage for the United States exists, highway officials and engineers are convinced that the merits and performance of CRCP far outweigh any of the so-called demerits.

- Based in part on the superior performance and behavior of CRCP built over swelling-type soils, the North Dakota Highway Department plans to surface remaining Interstate mileage with this type of pavement.

- Practically all rural concrete pavement in Mississippi is of the continuously reinforced type. On the basis of limited but very satisfactory performance of these pavements, several new projects using CRCP are being constructed (1963) and others are being planned.

- CRCP constructed in Illinois in 1948 has given outstandingly good service. The maintenance cost has been low, and the pavement surface, when compared to that of regular pavements of equal age and traffic load, is superior to any that has been measured elsewhere in the state.

The performance-behavior records of CRCP have varied, and it would be misleading to indicate that all pavements of this type have performed well. Performance ratings of experimental CRCP in some cases have not been favorable, leading a few states to be reluctant to expand beyond their original work until more experience could be gained. Review of reports has revealed the nature of failures; it is noteworthy that apparently none has been definitely attributed to the pavement type or the basic design concept. Reported failures in CRCP appear to be in two categories: (1) those due to structural breakup in pavement areas of especially short crack spacing (Indiana, New Jersey, Pennsylvania), and (2) corner and end fracturing at some "wide" cracks, as at construction joints or where extended bond failures have occurred (Illinois, Pennsylvania), or where cracks were far apart on poor subgrades (Illinois). In specific cases, failures have been traced to improper or deficient construction practices, localized weakness in subgrade, poor consolidation of concrete, use of inferior materials, concrete quality and/or consistency, and other causes of problems commonly associated with conventional types of reinforced concrete pavements. Examples of failures and causes in a number of projects are as follows:

- On projects in Pennsylvania and Maryland, pavement failures developed from wide cracks resulting from gaps in the reinforcing steel and/or inadequate overlap of the steel. Bar mats were used on both projects, except for a 2000-foot subsection in Maryland which was reinforced with welded wire fabric mats. Those cases involving gaps in the steel resulted in localized areas without reinforcement and lack of fulfillment of the continuous reinforcement design concept. In the Maryland project, it is noteworthy that concrete was of a low slump, and no vibration was used except for that provided by the usual two internal vibrators along the face of the steel forms. Concrete was laid in two lifts; it was believed that the principal cause of failure was probably a lack of bond between the two lifts of concrete pavement and between the concrete pavement and the reinforcing steel.

- In Illinois, early CRCP (1947-48) was built directly on natural subgrade without a granular subbase. Serious pumping occurred at expansion joints which separate pavement sections, and at some construction joints that were built at the end of each day's run. This led to failures in which the ends of some slabs cracked and broke, necessitating removal and replacement of concrete. Although pumping at these joints created a problem, it should be noted that they are not a necessary element in CRCP. Currently, pavement sections, miles in length, are being built without expansion joints; designs for construction joints have been improved such that they are not sources of trouble.

- In Texas, impending pavement failure was evidenced by closely spaced cracks that were severely spalled and exceptionally wide. Investigation revealed that the concrete above the reinforcing steel was dense, but was honeycombed below the steel. Inadequate vibration of concrete during construction was determined to be the cause of the problem. In another Texas project, deterioration of the concrete surface occurred as a result of aggregate pop-out over a limited pavement area.

- Two failures occurred in CRCP in an Oregon project within a short time after paving. The first case of failure started as a loss of bond at a bar lap in one of the 12-foot lanes, caused by local excessive segregation of aggregates in the concrete mix, possibly superimposed on a substandard mixer load. In the second case, inferior concrete resulting from a temporary malfunctioning of the automatic batch plant led to failure of lap splices, owing to lack of bond strength. Subsequent investigation showed extremely low cement contents and compressive strengths as low as 875 psi.

- Reported problems and actual or impending failures in Mississippi CRCP have been primarily associated with inadequate lap of steel reinforcement.

In addition to the performance of CRCP with respect to failures due to various causes, most projects have also been evaluated with regard to riding qualities. Results have usually been expressed in terms of smoothness as determined by the use of roughometers and profilographs, though, in many cases, only general riding qualities as compared to those of standard pavements have been reported. In many states, some importance has been placed on changes in roughness index during pavement service as a measure of performance. Such changes have been influenced by failures of bridge-type expansion joints as well as roughness features due to various other causes. By far, the majority of the pavements that have been monitored generally have shown little or no change in roughness index.

VII. MAINTENACE AND REPAIR

The maintenance of CRCP, on the whole, has been substantially less than that required for conventional concrete pavements. This has been attributed to the relative absence of joints and simplicity of construction of the continuous pavements which show a natural tendency for self-preservation by actively resisting damage from wheel loads.

Evidence of distress in CRCP has been reported for localized areas in some projects, but often it unfortunately has not been clearly indicated whether this distress came about because of a weak design, poor construction practice, or other conditions that could have been equally destructive to other types of highway pavements. Failures in continuous pavements usually have occurred at transverse cracks which opened to excessive width, leading to loss of aggregate interlock of the concrete.

Repairs to CRCP can be made successfully and without undue difficulty. Consideration must be given to restoring and maintaining continuity of reinforcement in repair work and the effects of patches on existing crack patterns. Some repair work has made use of welding for rejoining reinforcing steel but only where there was assurance that steel strength would not be greatly weakened through this procedure. Concrete made with high early-strength cement has been used in a number of repair jobs. In general, the procedures specified for repairs to concrete pavements of conventional types are applicable to CRCP, but it is apparent that the basic differences of the latter must receive due attention in planning the work and specifying procedures.

VIII. ECONOMICS

A major factor to be considered in making a choice of pavement type in any highway project is economics, both as to initial cost and maintenance costs during the service life of the pavement. Initial costs for early CRCP and many built in recent years were abnormally high due to to the experimental nature of the projects, lack of experience in constructing this type of pavement, the higher amounts of steel required, construction practices employed, and other factors. As a result, there was a widespread impression that the costs were too high to justify the use of the pavement, particularly in view of a general lack of knowledge with respect to how well the structures would perform and what the order of maintenance costs would be.

A. Initial Cost

Considerable background in the economics associated with CRCP has been provided by construction of many projects in the last five to six years. Initial costs have shown a significant downward trend during this period. In Texas, records kept on nearly 200 projects indicate that average costs for CRCP decreased from well over $5.00 in 1958 to a mid-1966 level of $4.50 per square yard; further reduction is predicted. Table V shows average costs for CRCP projects in the state for the fiscal 1965-66 year. Bid figures reported during the same period for various projects under contract in a number of other states have ranged from $3.99 to $4.28 per square yard for 8-inch pavements 24 feet wide. In Pennsylvania, reported bids for 7 and 8-inch continuously reinforced pavements with 0.5-percent longitudinal steel showed, respectively, 15.2 and 9.5-percent savings over the cost of a 10-inch standard reinforced pavement. A number of contractors experienced in constructing CRCP have indicated that costs for this type of pavement are competitive with those for conventional reinforced concrete pavement and, in some cases, may be substantially less. The latter applies particularly to projects of substantial size where improved construction practices and labor-saving equipment are employed.

A breakdown of costs involved in constructing CRCP would involve a rather comprehensive study even for a single project. In attempting to make a preliminary comparison of initial costs for this type of pavement with those for conventional concrete pavements, differences as to labor, materials and construction requirements are among the principal factors

TABLE V

CRCP QUANTITIES LET FOR CONSTRUCTION IN TEXAS

Letting Period	Number of Projects	Plan Miles	Square Yard Quantity	Equivalent Miles of Two-Lane Pavement	Average Cost/sq yd
Total CRCP let prior to September 1965:	169	Not Tabulated	16, 175, 199	1, 148.8	Not Tabulated
September 1965	6	35.809	1, 085, 271	77.1	4.76
October 1965	2	22.636	825, 873	58.7	4.69
November 1965	1	4.424	175, 561	12.5	4.00
December 1965	2	16.587	443, 836	31.5	4.59
January 1966	5	29.997	1, 020, 107	72.5	4.35
February 1966	1	3.676	100, 100	7.1	5.00
March 1966	2	11.706	378, 884	26.9	4.73
April 1966	5	19.612	396, 220	28.1	4.90
May 1966	3	11.531	304, 709	21.6	4.29
June 1966	4	18.505	526, 482	37.4	4.80
July 1966	None	None	None	None	None
August 1966	2	17.753	430, 592	30.6	4.51
Total for Year	33	192.236	5, 687, 635	404.0	4.61

to be examined. Also, it is necessary to assume that a given set of conditions exists for both types of pavement; comparison of costs from one area to another is not realistic. Many elements may be assumed to be similar or very nearly so for both pavement types, as subpavement structures, concrete materials and preparation, method of paving, and so on.

One of the principal differences in labor costs is attributed to the additional manpower needed for placement of reinforcing steel for CRCP. This applies particularly to areas where wage scales for worker classifications engaged in particular construction activities are high as compared to those for other areas. For example, in some areas, the wage scale for laborers tying and placing steel bar reinforcing is $1.40 to $1.50 per hour, while, in others, the scale is $3.00 or more. For crews of thirty men or more, such as are often used, the cost difference is high and may be prohibitive to the use of CRCP. In such areas, the use of wire fabric may prove to be substantially more economical.

For some of the principal materials and labor costs for the two pavement types, a comparison can be made in a hypothetical case wherein it is assumed that (1) the pavement structures up to the concrete slab are similar; (2) a common wage scale applies; (3) the same concrete materials, concrete preparation methods, and paving methods are used; (4) the pavement widths are the same; (5) welded wire fabric is used for the conventional jointed pavement, and tied steel bars for that which is continuously reinforced; (6) the pavements, designed for the same traffic service, are 8 inches thick for the continuously reinforced and 10 inches for the conventional jointed reinforced; and (7) concrete cost is $10.00 per cubic yard, steel bar cost is $0.064 per pound, and wire mesh cost is $0.075 per pound. Costs for various items indicated below are based on discussions with an experienced contractor and do not include considerations as to profit, indirect costs, etc.:

Item	8-In. Continuously Reinforced Pavement	10-In. Conventional Jointed Reinforced Pavement
Steel cost	19#/sq yd - $1.22	8.4#/sq yd - $0.63
Steel placement cost	.14	.05
Concrete cost	2.22	2.78
	$3.58/sq yd	$3.46/sq yd

The remaining costs are distributed among labor and/or materials required according to special structural features associated with each type of pavement. Based on statements of experienced contractors, the absence of joints in CRCP is a strong factor tending to balance out these costs.

Reinforcing steel costs for CRCP have been reported to be as much as $2.00 more per square yard of pavement than for conventional unreinforced jointed pavements. According to estimates of some engineers, each 0.1-percent increase in steel area adds $0.35 per square yard to the cost, using the tied bar type of reinforcement. Average costs of steel reported by contractors are $0.065 per pound for deformed bars and $0.075 for welded wire fabric; fob Houston prices for the two materials have been reported as $0.06 and $0.08 per pound, respectively. Stamped sheet steel chairs for support of both types of reinforcement are said to be available at $0.025 to $0.05 each, depending on type and quantity purchased.

Based on results of time and motion studies, the costs of placing the steel by experienced crews are less for the welded wire mesh; this should offset the higher cost of this material. A possible reduction of more than 22 percent in placing costs for wire fabric over those for tied bar reinforcing was indicated by one study. Most contractors appear to have gained experience with the deformed bar type of reinforcement, and many have devised their own mechanized equipment to improve the efficiency and reduce the cost of its placement. It remains to be seen how quickly more efficient means of placing wire fabric can be developed, as through mechanical placers and/or depressors, and placement costs can be further reduced.

B. Maintenance Costs

Costs of maintenance for CRCP, expressed in terms of dollars and cents, are not readily available. While it is certain that records of some sort have been kept for most projects, it is felt in many cases that periods of service for pavements have not been of sufficient length to provide conclusive cost data. In some states, methods of accounting do not permit ready differentiation between maintenance charges for CRCP and conventional jointed concrete pavements. In others, it is felt that the experimental nature of the projects precludes the development of other than relative data on maintenance costs.

In the absence of actual figures on maintenance, one approach to obtaining cost approximations has been to estimate time and effort spent in repairing and maintaining CRCP as compared to that for upkeep of conventional pavements. Where this method is used, only relative comparisons can be made. In evaluating reports on maintenance from various states, primary weight has been given to information related to maintenance of 78 percent (2480 miles) of the total highway mileage of CRCP (3139 miles) that was under contract or built to mid-1966; this was in Texas, Mississippi, Illinois, North Dakota, Oregon, Indiana, and Minnesota. Highway departments in all of these states reported lower maintenance costs for CRCP than for conventional concrete pavements. States representing a little more than 2 percent of the previously noted total mileage indicated no differences between costs for the two types of pavements; nearly all of the remainder reported that experience has been inadequate to permit cost comparisons. Only one state reported higher costs; the pavement section in this case was less than a mile long.

For all states, the maintenance costs for CRCP are indicated to be about half those for conventional pavements. Where estimates have been given, the range has been from 25 percent upward. Some projects ranging in age from two to eight years reportedly have been entirely free of maintenance.

The economics associated with the use of CRCP appear attractive, not only for new construction on the Interstate system but for secondary and urban road systems as well. Noteworthy is the good performance to date of CRCP used as overlays on existing old pavements; this indicates that such construction may be one economic answer to the overall problem of maintenance and replacement. The promise is that the use of CRCP may provide an effective means of realizing higher salvage values for old pavement structures and, at the same time, permit the building of high-performance roads and highways in the future replacement of pavements in the Interstate system as well as in urban systems. Lower maintenance is a factor that has considerable appeal with respect to reduced costs and improved traffic safety due to the minimized need to halt or interrupt traffic on highways and roads in both systems while repairs are being made.

Experience with CRCP over many years has shown this type of pavement to have longer service life than other types. The combination of longer service life and reduced maintenance assures appreciably lower annual costs.

IX. TRENDS AND THE FUTURE

Since 1960, the construction of CRCP has been increasing at a substantial rate on a national scale. It is noteworthy that, in the period of 1959 to 1966, the number of states that had built or contracted to build this type of pavement rose from nine to twenty-one, indicating a noticeable trend toward its wider acceptance. Primary factors influencing this acceptance are a downward trend in costs of construction plus the superior riding qualities, reduced maintenance requirements, and good performance associated with CRCP.

Although most completed, current, and planned projects have been or are experimental, it is apparent that highway engineers in several states have gained sufficient experience in the design, construction, and performance of CRCP to allow them to proceed confidently with broader construction plans. The expectation is that this situation will become apparent in other states where needed experience is still being accumulated.

In areas of design and construction, trends are also apparent. More stress is being placed on designs which will improve the economics of CRCP and provide better control of performance. This is in contrast to earlier work, which was concerned primarily with determining how various designs would perform.

The conservatism that has been apparent in much of the design work for earlier CRCP is being replaced by a somewhat bolder approach in which the usually omitted structural values of certain features of these pavements are being taken into account by some engineers. Such factors as better protection of the subgrade and an indicated increase in effective slab thickness afforded by the continuous reinforcement are among those being examined. It is reasonable to expect that the future will bring design refinements leading to better economics of CRCP without sacrifice in performance.

The validity of the basic concept of CRCP having been established, design engineers are looking to wider use of this type of pavement in secondary road systems as well as the Interstate system. Another promising application is in the resurfacing and salvage of old pavements in both systems.

In construction, there is a noticeable trend toward the use of equipment and methods that improve efficiency, increase paving rates, and reduce costs. Central-mix concrete plants, more highly mechanized methods of placing reinforcement, and slip-form pavers are being employed on more and more projects.

In projects where the type of reinforcement to be used is at the contractor's option, the labor costs associated with steel installation will be a primary factor affecting decision on whether steel bars or wire mesh will be employed. In areas where high wage scales exist, the use of wire mesh appears to be more economic; the use of steel bars is favored for areas of lower wage scales. This indicates a trend toward the use of mesh in many urban and suburban areas and of steel bars in rural areas where local labor can be used. Obviously, if highly efficient mechanized means of reinforcement placement and/or installation are developed for either mesh or bars, this trend could change.

Several design variations and new developments now being evaluated have the potential of improving the economics and performance of CRCP. Some of these are:

- A design in which transverse steel is not used in the pavement would reduce steel and construction costs.
- A design in which the continuous pavement is extended over bridge structures, thus eliminating the need for joints and/or anchorage systems at these sites.
- An expanding cement which has promise of providing a means of controlling concrete shrinkage and the cracking associated with it.
- Equipment to integrate the placement of reinforcement with paving operations in which slip-form pavers are used.

In a number of states where rigid pavements are used to a significant degree in road and highway systems, CRCP are being built on an expanding scale. The future of this type of pavement in those states appears bright, not only in new construction but also in the replacement and salvage of old pavements. Standardization of design is evident in several states, and the desire for such is strong in many others; continuously reinforced pavements promise an answer to that desire. From an overall viewpoint and according to the opinion of many engineers, the future of CRCP is regarded with optimism.

APPENDIX I

DEFINITION OF TERMS

The following is a list of terms with the generally accepted definition as used in concrete paving practice. The list, by no means complete, contains many of the terms used in this report. For other terms and definitions, it is suggested that publications of ASTM, ACI, AASHO, and other organizations concerned with concrete pavements be consulted. The American Concrete Institute, particularly, has a committee working on the standardizing of concrete terminology.

Pavement Design (design, structure design). The specifications for materials and dimensions of the pavement components.

Pavement Structure (pavement). One or more layers of specially processed materials overlying the embankment soil or subgrade.

Surface (surfacing). The top course of a pavement designed to provide a surface resistant to traffic abrasion or to impart structural value to the pavement.

Base. Crushed stone, gravel, cement-treated or asphalt-treated sand-gravel material (subbase material) immediately under the surfacing material.

Rigid Base. Those which due to high bending resistance distribute loads to the foundation over a comparatively large area.

Flexible Base. Those having sufficiently low bending resistance to maintain intimate contact with the underlying structure, and to distribute loads to the foundation by aggregate interlock, particle friction and/or surface tension, e.g., macadam, crushed stone, gravel, and all bituminous types.

Subbase. The layer of graded sand-gravel material between the surface of the embankment soil and the base course (or surfacing course when there is no base course), further defined for specification purposes in "Specifications for Concrete Pavements and Concrete Bases" (ACI 617).

Subgrade (embankment soil). The material in excavations (cuts), embankments (fills), and embankment foundations immediately below the first layer of subbase, base or pavement and to such depth as may affect the structural design.

Nonreinforced Pavement. Plain portland cement concrete pavement.

Reinforced Pavement. Portland cement concrete pavement with or without doweled transverse contraction joints.

Reinforcement (surfacing reinforcement). A qualitative variable for rigid pavement used to distinguish between plain portland cement concrete and surfacing reinforced with wire mesh or steel bar.

Aggregates. Hard inert material composed of graduated fragments for mixing with a cementing material to form concrete or mortar or used to furnish stability to a pavement by its interlocking action. Coarse aggregate may be considered as the material which will be retained on approximately a 1/4-inch sieve and fine aggregate as the material which will pass approximately a 1/4-inch sieve.

Bitumens. Mixtures of hydrocarbons of natural or pyrogeneous origin or combinations of both frequently accompanied by their nonmetallic derivatives which may be gaseous, liquid, semisolid, or solid, and which are completely soluble in carbon disulfide.

Air-Entraining Cement. A cement to which an air-entraining agent has been added which causes air to be incorporated in the concrete during mixing, usually to increase its workability and frost resistance.

Joints. The constructed junctions between sections of pavement or between pavement and structures.

Expansion Joint. A joint in which provision is made to permit the pavement to expand to a length greater than that at which it was laid. An expansion joint may also function as a contraction joint.

Contraction Joint. A joint of either the full depth or weakened plane type designed to establish the position of any crack caused by contraction while providing no space for expansion of the pavement beyond its original length.

Longitudinal Joint. A joint of either the full depth or weakened plane type constructed parallel to or along the centerline of a pavement to control longitudinal cracking.

Construction Joint. A vertical or notched plane of separation in a pavement, made necessary by any prolonged stoppage of the concreting operation.

Surface Texture. The character of the surface of a pavement which depends on the size, shape, arrangement and distribution of the aggregates and cement or binder.

Cracks. Approximately vertical cleavage, due to natural causes or traffic action, within a concrete pavement at which tensile stress in the concrete has exceeded the tensile strength of the concrete.

Transverse Cracks. Cracks which follow a course approximately at right angles to the centerline.

Longitudinal Cracks. Cracks which follow a course approximately parallel to the centerline.

Corner Cracks. Diagonal cracks forming a triangle with a longitudinal edge or joint and a transverse joint or crack, whose legs are not less than 12 inches or more than one-half the lane width.

Pumping. The ejection of water and subbase material or embankment soil from beneath the pavement surfacing.

Deflection. The difference in elevation of a point on or in the pavement before and after a specified condition of loading.

Serviceability Rating. The judgment of a qualified observer as to the current ability of a pavement to serve the traffic it is meant to serve.

Experiment Design. A set of test sections that form the basic units for controlled variation in pavement design or load factors.

Aggregate Interlock. The projection of aggregate particles from one side of a joint or crack in concrete into recesses in the other side of the joint or crack so as to effect load transfer in compression and shear.

Allowable Stress. Maximum permissible stress used in design of pavement structures based on a factor of safety against rupture or yielding of any type.

Bar Mat. An assembly of steel reinforcement composed of two layers of bars placed at right angles to each other and secured together by welding or ties.

Bond. Adhesion of concrete or mortar to reinforcement or to other surfaces against which it is placed; the adhesion of cement paste to aggregate.

Deformed Bar. A reinforcing bar with manufactured surface deformations which provide a locking anchorage with surrounding concrete and conforming to "Specifications for Minimum Requirements for the Deformations of Deformed Steel Bars for Concrete Reinforcement" (ASTM A304). Bars not conforming to these specifications are classed as plain bars.

Design Strength. The load capacity of a member computed on the basis of the allowable stresses assumed in design.

Dowel. A pin or plain bar placed between two elements of a concrete pavement to transfer load between the two parts.

Slab. For design purposes, a monolithic portion of concrete pavement bounded by joints or edges, within which continuity of tensile stress in the concrete is possible.

High Strength Steel. Steel with a high yield point; in the case of reinforcement for concrete, generally 60,000 psi or higher.

Lap or Splice. A connection of reinforced steel made by lapping the ends of the bars or fabric.

Nonagitating Unit. A truck-mounted container, for transporting central-mixed concrete, not equipped to provide agitation (slow mixing) during delivery.

Slip Form. A form which is pulled as concrete is placed, and moves in a generally horizontal direction to lay concrete evenly on a prepared subbase for laying of pavement of uniform cross section.

Spreader. A device consisting of reciprocating paddles, a revolving screw or other mechanism for distributing concrete to required uniform thickness in a paving slab.

Axle-Steel Reinforcement. The established trade and technical term designating "axle-steel bars," plain or deformed, rolled from carbon-steel axles for cars and locomotive tenders in standard journal sizes.

Billet Steel. Steel produced by the Bessemer or open-hearth process, cast in billets.

California Bearing Ratio. The ratio of (1) the force per unit area required to penetrate a soil mass with a 3-square inch circular piston at the rate of 0.05 inch per minute to (2) the force required for corresponding penetration of a standard crushed rock base material; the ratio is usually determined at 0.1-inch penetration.

Continuously Reinforced Concrete Pavement. A pavement without transverse joints, except tied construction joints placed between each successive day's concreting, with sufficient longitudinal reinforcement, adequately lapped to develop tensile continuity, so that transverse cracks will be held tightly closed, resulting in the central portion of the pavement, exclusive of the end 400 to 500 feet, being in substantially complete restraint.

Mesh Reinforcement (wire fabric). Series of wires welded or clipped together at right angles so as to form a wire fabric, either in sheets or rolls, used in reinforcing concrete slabs.

Rail Steel Reinforcement. The established trade and technical term designating "rail steel bars" hot-rolled from standard T-section rails.

Sawing. Cutting joints in hardened concrete by means of special equipment utilizing diamond or silicon carbide blades or discs; cut goes only part way through the slab.

Tie Bar. A deformed bar embedded in a concrete pavement at a joint and designed to hold abutting edges together, but not designed for direct load transfer as a dowel.

Welded Wire Fabric. A two-way reinforcement system, fabricated from cold-drawn steel wire, having parallel longitudinal wires welded at regular intervals to parallel transverse wires and conforming to "Specifications for Welded Steel Wire Fabric for Concrete Reinforcement" (ASTM A185 and AASHO M55).

APPENDIX II

SPECIFICATIONS

The specifications of the American Society for Testing and Materials referred to in the report are listed below with their serial designation including the year of adoption or revision. All specifications and standards are current to July 1966.

A 15-65	Specifications for Billet-Steel Bars for Concrete Reinforcement.
A 16-65	Specifications for Rail-Steel Bars for Concrete Reinforcement.
A 61-65	Specifications for Deformed Rail-Steel Bars for Concrete Reinforcement with 60,000-psi Minimum Yield Strength.
A 82-62T	Specifications for Cold-Drawn Steel Wire for Concrete Reinforcement.
A 160-65	Specifications for Axle-Steel Bars for Concrete Reinforcement.
A 184-65	Specifications for Fabricated Steel Bar on Rod Mats for Concrete Reinforcement.
A 185-64	Specifications for Welded Steel Wire Fabric for Concrete Reinforcement.
A 305-65	Minimum Requirements for the Deformations of Deformed Steel Bars for Concrete Reinforcement.
A 408-65	Specifications for Special Large Size Deformed Billet-Steel Bars for Concrete Reinforcement.
A 431-65	Specifications for High-Strength Deformed Billet-Steel Bars for Concrete Reinforcement with 75,000-psi Minimum Yield Strength.
A 432-65	Specifications for Deformed Billet-Steel Bars for Concrete Reinforcement with 60,000-psi Minimum Yield Strength.
A 496-64	Deformed Steel Wire for Concrete Reinforcement.
A 497-64	Welded Deformed Steel Wire Fabric for Concrete Reinforcement.

C 10-64	Specifications for Natural Cement.
C 31-65	Method of Making and Curing Concrete Compression and Flexure Test Specimens in the Field.
C 33-64	Specifications for Concrete Aggregates.
C 39-64	Method of Test for Compressive Strength of Molded Concrete Cylinders.
C 42-64	Methods of Securing, Preparing, and Testing Specimens from Hardened Concrete for Compressive and Flexural Strengths.
C 94-65	Specifications for Ready-Mixed Concrete.
C 109-64	Test for Compressive Strength of Hydraulic Cement Mortars.
C 131-64T	Method of Test for Abrasion of Coarse Aggregate by Use of the Los Angeles Machine.
C 138-63	Method of Test for Weight per Cubic Foot, Yield, and Air Content (Gravimetric) of Concrete.
C 143-58	Method of Test for Slump of Portland Cement Concrete.
C 150-65	Specifications for Portland Cement.
C 171-63	Specifications for Waterproof Paper for Curing Concrete.
C 172-54	Method of Sampling Fresh Concrete.
C 173-58	Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method.
C 175-65	Specifications for Air-Entraining Portland Cement.

C 192-65	Method of Making and Curing Concrete Compression and Flexure Test Specimens in the Laboratory.
C 205-64T	Specifications for Portland Blast-Furnace Slag Cement.
C 231-62	Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method.
C 260-65T	Specifications for Air-Entraining Admixtures.
C 309-58	Specifications for Liquid Membrane-Forming Compounds for Curing Concrete.
C 330-60T	Specifications for Lightweight Aggregates for Structural Concrete.
C 340-58T	Specifications for Portland-Pozzolan Cement.
C 350-60T	Specifications for Fly Ash for Use as an Admixture in Portland Cement Concrete.
C 358-62T	Specifications for Slag Cement.
C 402-62T	Specifications for Raw or Calcined Natural Pozzolans for Use as Admixtures in Portland Cement Concrete.
C 494-62T	Specifications for Chemical Admixtures for Concrete.
D 98-59	Specifications for Calcium Chloride.
D 994-53	Specifications for Preformed Expansion Joint Filler for Concrete (Bituminous Type).
D 1751-62T	Specifications for Preformed Expansion Joint Fillers for Concrete Paving and Structural Construction (Nonextruding and Resilient Bituminous Types).
D 1752-60T	Specifications for Preformed Expansion Joint Fillers for Concrete Paving and Structural Construction (Nonextruding and Resilient Non-bituminous Types).

ACI and CRSI Standards

Detailed recommendations for acceptable practices are available in the following Standards and Recommendations of the American Concrete Institute and the Concrete Reinforcing Steel Institute.

ACI 214-65	Recommended Practice for Evaluation of Compression Test Results of Field Concrete.
ACI 315-65	Manual of Standard Practice for Detailing Reinforced Concrete Structures.
ACI 325-58	Recommended Practice for Design of Concrete Pavements.
ACI 347-63	Recommended Practice for Concrete Form Work.
ACI 306-66	Recommended Practice for Cold Weather Concreting.
ACI 604-56	Recommended Practice for Winter Concreting.
ACI 605-59	Recommended Practice for Hot Weather Concreting.
ACI 609-60	Consolidation of Concrete.
ACI 613-54	Recommended Practice for Selecting Proportions for Concrete.
ACI 613A-59	Recommended Practice for Selecting Proportions for Structural Lightweight Concrete.
ACI 614-59	Recommended Practice for Measuring, Mixing and Placing Concrete.
ACI 617-58	Specifications for Concrete Pavements and Concrete Bases.
CRSI 63	Recommended Practice for Placing Reinforcing Bars.
CRSI 65	Recommended Practice for Placing Bar Supports, Specifications and Nomenclature, 1965.

Included in the ACI 1965 Book of Standards, American Concrete Institute

ACI 325-58 presents recommendations for the design of rigid concrete pavements and bases determined by practice and proved successful in the United States. It offers comprehensive directions for the design of rigid airport and highway pavements or bases under conditions of climate, traffic, construction materials and equipment, and construction methods common in the United States.

The proportioning of concrete, including mixes containing entrained air, is set forth in the recommended practice ACI 613-54. ACI 613A-59 is intended as a supplement to ACI 613-54 and describes a procedure for proportioning structural grade concrete containing lightweight aggregates.

ACI 614-59 is an outline of practices which have generally been found desirable for first-class results in measuring, mixing, and placing concrete. The specifications in ACI 617-58 apply to construction of portland cement concrete pavements and bases under normal conditions for both highways and airports.

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