NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **16**

CONTINUOUSLY REINFORCED CONCRETE PAVEMENT

HIGHWAY RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION
OF STATE HIGHWAY OFFICIALS IN COOPERATION
WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
- PAVEMENT DESIGN
- PAVEMENT PERFORMANCE
- CONSTRUCTION
- MAINTENANCE, GENERAL

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING 1973

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectvity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the Federal Highway Administration. Individual fiscal agreements are executed annually by the Academy-Research Council, the Federal Highway Administration, and participating state highway departments, members of the American Association of State Highway Officials.

The study reported herein was undertaken under the aegis of the National Academy of Sciences—National Research Council. The National Cooperative Highway Research Program, under which this study was made, is conducted by the Highway Research Board with the express approval of the Governing Board of the NRC. Such approval indicated that the Board considered that the problems studied in this program are of national significance; that solution of the problems requires scientific or technical competence, and that the resources of NRC are particularly suitable for the oversight of these studies. The institutional responsibilities of the NRC are discharged in the following manner: each specific problem, before it is accepted for study in the program, is approved as appropriate for the NRC by the NCHRP Program Advisory Committee and the Chairman of the Division of Engineering of the National Research Council.

Topics for synthesis are selected and defined by an advisory committee that monitors the work and reviews the final report. Members of the advisory committees are appointed by the Chairman of the Division of Engineering of the National Research Council. They are selected for their individual scholarly competence and judgment, with due consideration for the balance and breadth of disciplines. Responsibility for the definition of this study and for the publication of this report rests with the advisory committee.

Although reports in this category are not submitted for approval to the Academy membership nor to the Council, each report is reviewed and processed according to procedures established and monitored by the Academy's Report Review Committee. Such reviews are intended to determine *inter alia,* whether the major questions and relevant points of view have been addressed, and whether the reported findings, conclusions and recommendations arose from the available data and information. Distribution of the report is permitted only after satisfactory completion of this review process.

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PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, the American Association of State Highway Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Highway Research Board to undertake a continuing project to search out and synthesize the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the various practices without in fact making specific recommendations as would be found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available concerning those measures found to be the most successful in resolving specific problems. The extent to which they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

FOREWORD

By Staff
Highway Research Board

This report should be of special interest to design, materials, foundation, and construction engineers responsible for continuously reinforced concrete pavements. The report offers information on current design practices, current construction practices, and continuing research trends and needs for continuously reinforced concrete pavements.

Administrators, engineers, and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information often is fragmented, scattered, and unevaluated. As a consequence, full information on what has been learned about a problem frequently is not assembled in seeking a solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem. In an effort to resolve this situation, a continuing NCHRP project, carried out by the Highway Research Board as the research agency, has the objective of synthesizing and reporting on common highway problems—a synthesis being identified as a composition or combination of separate parts or elements so as to form a whole greater than the sum of the separate parts. Reports from this endeavor constitute an NCHRP report series that collects and assembles the various forms of information into single concise documents pertaining to specific highway problems or sets of closely related problems. This is the sixteenth report in the series.

Since construction of the first significant length of continuously reinforced concrete pavement (CRCP) by the State of Indiana in 1938, installations of CRCP have increased until more than 10,000 miles of equivalent two-lane pavement were in use or under contract at the end of 1971. Thirty-three states currently have some CRCP, and interest in its use is increasing, as manifested by continuing research into more sophisticated methods of design and construction.

This report of the Highway Research Board attempts to record current design practices, current construction practices, and guidelines for the design and construction of CRCP, and to indicate the scope of present and future research. More specifically, discussion is presented on the significance of steel content, type of reinforcement, nonerodible bases, construction processes, terminal treatment, and the use of CRCP as an overlay. The Board has attempted in this project to set down those design and construction practices for CRCP found to be most effective. The report discusses those guidelines for the design and construction of CRCP that have proven effective from the standpoint of improved pavement performance, more effective construction techniques, and achieving rational design methods.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from many highway departments and agencies responsible for highway planning, design, construction, operations, and maintenance. A topic advisory panel of experts in the subject area was established to guide the researchers in organizing and evaluating the collected data, and to review the final synthesis report.

As a follow-up, the Board will attempt to evaluate the effectiveness of this synthesis after it has been in the hands of its users for a period of time. Meanwhile, the search for better methods is a continuing activity that should not be diminished. An updating of this document is ultimately intended so as to reflect improvements that may be discovered through research and practice.

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W. G. Gunderman, Engineer of Materials and Construction, and L. F. Spaine, Engineer of Design, both of the Highway Research Board, assisted the Special Projects staff and the Advisory Panel.

Information on current practice was provided by many highway agencies. Their cooperation and assistance were most helpful.

CONTINUOUSLY REINFORCED CONCRETE PAVEMENT

SUMMARY

Continuously reinforced concrete pavement—CRCP—is portland cement concrete pavement with continuous longitudinal steel reinforcement and no intermediate transverse expansion or contraction joints. Instead, the pavement is allowed to crack in a random pattern and the cracks are held tightly closed by the steel reinforcement. Cracking starts within a few days after construction, and almost all cracking will occur within the first few years. There are many factors that influence the spacing of cracks. The most important is the percentage of steel (ratio of cross-sectional area of longitudinal steel to cross-sectional area of concrete slab). Other factors include bond area of steel, depth of reinforcement, friction between concrete and base, concrete strength, season of year when constructed, and curing temperature.

Regardless of the total length of the CRCP, any longitudinal movement will occur within only about 500 ft (150 m) of the pavement ends. These end movements are controlled or accommodated by proper end treatment.

The current design methods for CRCP have generally evolved from long-term observation of test pavements under highway traffic. Several analytical methods also are available, but they have not been generally accepted.

The base used for CRCP usually has been the same as for jointed concrete pavement, but nonerodible bases (asphalt, cement, or lime-stabilized) have gained favor in recent years because of better support and reduced deflections. Reduced deflections are important because the thickness of CRCP usually has been less than for jointed pavement.

The reinforcing steel in continuously reinforced concrete pavements is deformed bars, bar mats, or deformed wire fabric. Smooth wire fabric has given unsatisfactory performance and no longer is used. Steel percentages in current use range from 0.5 to 0.7 percent (0.6 percent is most often used) and the reinforcement usually is placed at or slightly above mid-depth of the concrete slab. Transverse reinforcement has been used to space and support longitudinal steel, to serve as tie bars between lanes, and to hold longitudinal cracks closed. However, recent improvements in construction methods have largely eliminated these needs, and several states no longer require transverse reinforcement.

Terminal treatments used at the ends of CRCP are of two types: anchors, and expansion systems. Several states use heavily reinforced concrete lugs to anchor the ends. These anchors prevent only about one-half of the movement that would occur if the ends were free and, therefore, are used in conjunction with a few short reinforced concrete slabs separated by dowelled expansion joints. The most successful expansion system is the wide-flange beam terminal. This consists of a concrete sleeper slab with a wide-flange beam set in it. The side of the beam abutting the CRCP has 1 or 2 in. (25 or 51 mm) of expansion material to absorb the end movements.

CRC appears to have much potential as an overlay, particularly over newer

highways with good geometric alignment. However, there are only a few projects that are more than three years old—too young to make any real conclusions, but they appear to be working well.

Continuously reinforced concrete pavement generally is constructed in the same manner as jointed concrete pavement, and with the same equipment, except for placement of reinforcement. Because CRCP seems to be less forgiving of errors, extra care during construction is important. Reinforcement usually has been supported on chairs in advance of paving. However, several methods of mechanical placement have been developed, and these are becoming common. Splicing of reinforcement is extremely important—failures have occurred where laps were inadequate or nonexistent. Another area of great concern is the construction joint. Proper consolidation of the concrete at construction joints is important, and problems have occurred where proper consolidation was not obtained.

Some of the important guidelines for design and construction of CRCP are:

- CRCP should be constructed on a nonerodible base, properly designed for durability.
- Concrete thickness should be designed for each project on its own merits, and should be adequate to keep deflections to levels that the base can tolerate.
- Only deformed reinforcement should be used.
- Steel percentage probably should be higher where anticipated temperature drop is great; i.e., where winters are extremely cold.
- Steel placement tolerances should not be set so tight as to add to costs without significantly improving performance.
- Care during construction is essential. Attention should be placed on obtaining uniformity of base and concrete. Reinforcement laps and proper consolidation of concrete at construction joints should receive special attention.

Although much research has been done, there are several areas where additional research would be beneficial. These include:

- Optimum steel percentage considering such factors as steel stress, bond area, steel location, crack width, crack spacing, subgrade friction, concrete strength, and temperature.
- Relation of base thickness and strength to deflection of CRCP.
- Rational design method for determining concrete thickness.

CHAPTER ONE

INTRODUCTION

Continuously reinforced concrete pavement—CRCP—is portland cement concrete pavement with continuous longitudinal steel reinforcement and no intermediate transverse expansion or contraction joints. Instead, the pavement is allowed to crack in a random pattern and the cracks are held tightly closed by the continuous steel reinforcement.

The first significant length of CRCP was built by the State of Indiana in 1938. During the following 20 years a number of projects, mostly research-oriented, were built at various locations in the United States. These amounted to about 80 miles (130 km)* of equivalent two-lane pavement by the end of 1958. As the results of research projects accumulated and as experience was gained in the design and construction of CRCP, mileage increased until more than 10,000 miles (16,000 km) of equivalent two-lane pavement were in use or under contract at the end of 1971 (Fig. 1). Thirty-three states currently have some CRCP; 19 have 100 miles (160 km) or more, including two states that have more than 1,000 miles (1,600 km). A complete list of states that have CRC pavements appears in Appendix C.

Instead of providing contraction joints in an attempt to control cracking, the design of CRCP allows the effects of shrinkage and temperature change to produce random transverse cracks. Sufficient steel is provided to hold the cracks closely together, thereby retaining aggregate interlock for near 100 percent load transfer and preventing the intrusion of water and incompressibles.

Cracking starts within the first few days following construction, and almost all cracking will occur within the first three or four years (Fig. 2). The spacing of cracks has been found to be inversely proportional to the percentage of steel † in the pavement—the more steel, the shorter the crack spacing—and crack widths are directly related to crack spacing. (A simplified analysis of cracking in CRCP appears in Appendix B.) A spacing of about 3 to 10 ft (1 to 3 m) is desirable to produce acceptably small crack widths. It should be noted that the width of a crack is greatest at the surface and noticeable because of slight raveling and abrasion of the crack edges by traffic. As the crack goes deeper into the slab it becomes progressively smaller. At and below the reinforcing steel the width usually is very fine or microscopic (Fig. 3).

In addition to steel percentage, several other factors influence the spacing of cracks. Although not enough quantitative information is available, what is available indicates that factors such as bond area of steel, depth of reinforcement, friction between concrete and base, concrete strength, time of year and even time of day when constructed, and temperature while curing definitely influence crack spacing. Pavement placed in warm or summer weather has exhibited closer crack spacing than pavement placed in colder weather. Table 1 includes many other factors that influence crack spacing to some degree. The exact significance and relative importance of each of these factors is not fully known at this time.

Regardless of the total length of the pavement, any longitudinal movement will occur only within about 500 ft

* SI equivalents are conversion of U.S. customary units in accordance with *Metric Practice Guide,* ASTM E 380-70.
† Ratio of cross-sectional area of longitudinal steel to cross-sectional area of concrete slab.

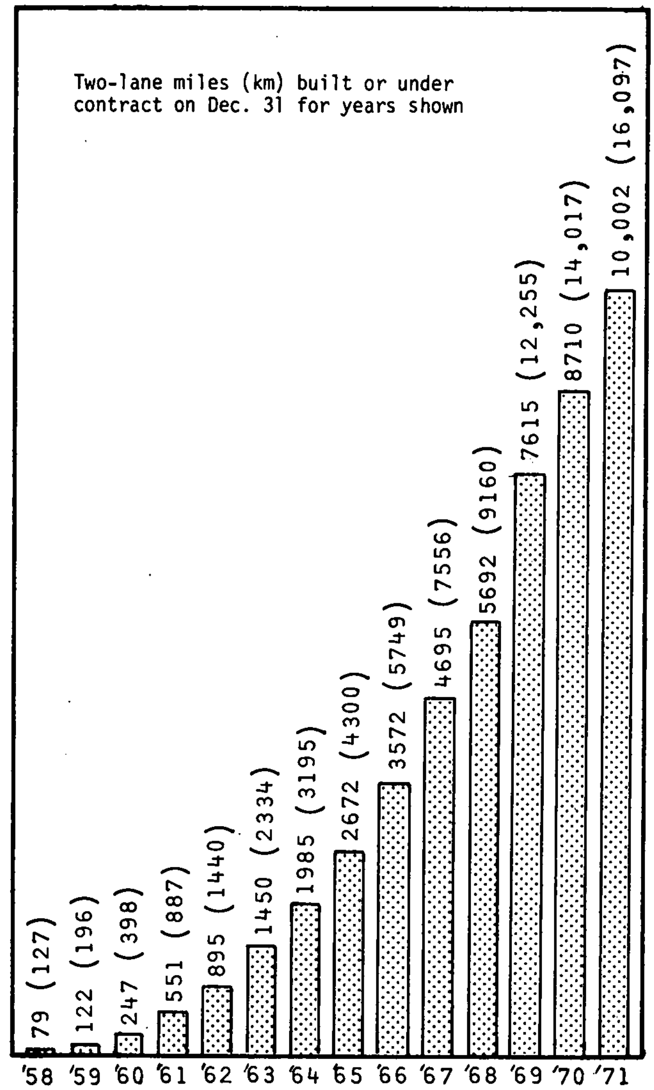

Figure 1. Increase in use of CRCP.

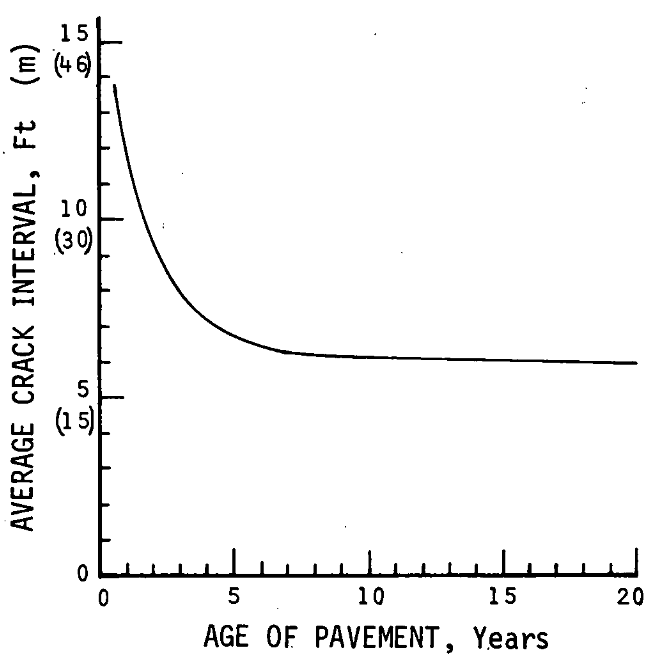

Figure 2. Crack interval vs age of pavement.

TABLE 1

FACTORS THAT INFLUENCE CRACK SPACING

I. *System Stiffness*
   - A. Thickness of concrete
   - B. Concrete modulus of elasticity
   - C. Underlying support
   - D. Bond
   - E. Steel amount and depth

II. *Restraint to Length Changes*
   - A. Internal restraints
     1. Steel: amount, surface area, deformations, connection to transverse steel, strength, coefficient of expansion, creep characteristics.
     2. Concrete: thickness, strength, modulus of elasticity, shrinkage, creep.
   - B. External restraints
     1. Friction on base
     2. Bond to adjacent lane
     3. Distance from end
     4. Encroachment of adjacent pavement

III. *Construction*
   - A. Laps
   - B. Consolidation
   - C. Construction joints
   - D. Environmental conditions
     1. Temperature
     2. Precipitation

IV. *Time*
   - A. Changing concrete properties
   - B. Environmental conditions
     1. Temperature variations
     2. Precipitation
   - C. Changing bond conditions
   - D. Corrosion
     1. Deicing chemicals
   - E. Traffic
   - F. Base erosion

Figure 3. Pavement core through crack.

(150 m) of the ends—the central portion remains fully restrained. These end movements are controlled or accommodated by proper end treatment. The number of cracks decreases in the ends of CRCP, although crack widths do not. This is attributed to movement of the pavement ends, which reduces the restraint stresses.

CHAPTER TWO

CURRENT DESIGN PRACTICES

The design of CRCP has evolved partly from theoretical analyses but mostly from observation of the many research and experimental projects that were constructed between 1938 and the early 1960's. These projects tested many of the parameters that make up the design of CRCP and have led to "standard" designs, developed for use in a particular state.

Rational design methods also are available (*1, 2, 3, 4,* *13*). These methods have been based on analyses of stresses, deflections, crack spacing, etc., but because of the many assumptions necessary in their preparation, they have not been generally accepted. Empirical methods of design have been derived from the experiences of several states (*5, 6*). Use of these requires considerable judgment on the part of the designer.

The major elements of the pavement structure that must be designed are: base, concrete, reinforcing steel, construction joints, and terminals.

BASE *

Early CRCP's were placed directly on the subgrade. It was believed that with the absence of joints, pumping would not be a problem. However, there has been evidence of edge pumping, and the belief that even a small amount of pumping eventually will result in serious problems has led to almost universal use of a base under CRCP (*7*). Usually the base used has been the same as that for jointed pavement; i.e., 3 to 6 in. (80 to 150 mm) of granular material. Thicker bases, usually open-graded, sometimes are used where frost is a problem, but caution must be exercised to prevent them from becoming saturated. The base, regardless of type, must be stable and durable.

Because of problems with degradation, retention of moisture, consolidation, and erosion of granular bases, many states have changed to cement, lime, or bituminous stabilized bases, 4 to 6 in. (100 to 150 mm) in depth. At least one state is using a stabilized subbase below the base, and some states are stabilizing the top few inches of the subgrade before constructing the stabilized base. Stabilization chemically or mechanically binds the granular particles. A properly designed stabilized base provides a better and more uniform support, reduces deflections, and serves as a useful working platform. Moreover, a stabilized base with a rough textured surface can provide a high friction value between the base and concrete and thereby reduce end movements of the pavement (*2, 16*).

CONCRETE THICKNESS

At present, there is no single method of designing CRC pavement thickness that is universally accepted. A common practice has been to determine the thickness required for a jointed pavement and then use a lesser thickness for the CRCP. This lesser thickness is arrived at by applying a predetermined ratio to the jointed pavement thickness or by subtracting a specified amount from it. The 1962 "AASHO Interim Guide" mentions 1 or 2 in. (25 or 50 mm) as the amount to be subtracted (*8*). The 1972 "Interim Guide" simply states that the thickness of CRCP "may be less than that obtained from the charts, with the amount of reduction in thickness being based on local experience or other studies" (*3*). However, an appendix to the 1972 "Interim Guide" contains an alternate design procedure for concrete pavement, including a nomograph for concrete thickness considering: traffic, concrete strength and modulus of elasticity, modulus of support (subgrade reaction), terminal serviceability index, and load transfer. For CRCP, the "Interim Guide" uses a load transfer factor of 2.2, as compared to a factor of 3.2 for jointed pavement.

A deflection study of CRCP in one state indicated that the practice of using lesser thickness for CRCP was reasonable (*9*); however, a recent report does not confirm this (*22*).

Most agency designs are based on "local experience or other studies." Currently, the most common "standard" thickness is 8 in. (200 mm), although 9 in. (230 mm) frequently is used. One state uses 6 in. (150 mm) on a stabilized base for frontage roads and city streets. Another state, which tested both 7- and 8-in. (180 and 200 mm) thicknesses extensively, recommends 8 in. as a minimum because of the continuing increase in the volume of heavy vehicles and because the 7-in. CRCP did not have "the structural characteristics required to overcome the variety of construction imperfections and other deficiencies that sometimes contribute as a group to the failure of pavements carrying heavy traffic" (*7, 10*).

LONGITUDINAL REINFORCEMENT

The primary purpose of the longitudinal reinforcing steel in continuously reinforced concrete pavements is to hold the transverse cracks tightly closed. Deformed reinforcing bars, bar mats, and deformed wire fabric are used for this purpose. Plain wire fabric has given unsatisfactory performance and no longer is used (*11, 12*). At least one agency has reported problems (wide surface cracks and broken steel) where deformed wire fabric was used.

Although specific reference is made herein to steel percentage, bond area, steel strength, etc., the crack widths (and, thus, performance) of a CRCP depend on a complex interrelationship of these items.

Steel Percentage

Several similar methods are currently available for the design of longitudinal reinforcement (*1, 2, 3, 8, 13*). Under most circumstances these will result in a requirement of 0.5 to 0.7 percent steel; and, indeed, this range covers the current practice. By far the most commonly used amount of steel is 0.6 percent. A few states use 0.65 or 0.7 percent, and one state uses 0.5 percent for some of its CRCP where temperature variations are not large. The higher percentages are used in northern areas because of the greater temperature range.

The concentration around 0.6 percent resulted from many experiments with steel amounts ranging from 0.3 to 1.82 percent. It has been shown that less than 0.5 percent usually will result in large crack spacings with large crack widths, and that steel content greater than 0.7 percent probably will not significantly improve pavement performance (*7*).

The use of a steel percentage less than that required for the expected temperature range and traffic volume usually results in crack widths that allow water (and deicing

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* Although the layer of material directly supporting the concrete surface course is frequently referred to as "subbase," the correct term, according to HRB and AASHO definitions (*25, 26*), is "base." Base, therefore, is used throughout this report.

chemicals) to reach the steel. Corrosion of the steel will then occur, thus reducing the effective steel area and allowing even wider cracks. Eventually a failure will result.

Bond Area

Most states do not consider bond area in designing longitudinal reinforcement. However, one theoretical analysis indicates that pavements with equal bond area per volume of concrete will have equal crack spacing regardless of steel percentage, provided the bond area is sufficient to develop the yield strength of the steel (*1*). The analysis also indicates a relationship between bond area and season of the year when construction takes place with a minimum ratio of 0.03 sq in. of bond area per cubic inch of concrete volume (120 cm^2/m^3) for summer placement and 0.04 in^2/in^3 (160 cm^2/m^3) for late fall and early spring. The 1972 "AASHO Interim Guide" suggests that the bond area ratio be greater than 0.03 in^2/in^3 (*3*). [An 8-in. (200-mm) slab with 0.6 percent steel using No. 5 bars at 6½-in. (165-mm) spacing has 0.037 sq in. of bond area per cubic inch of concrete (146 cm^2/m^3)].

Steel Strength

For longitudinal reinforcing bars, 60,000-psi (414-MPa) yield is virtually the only strength currently being used. Deformed wire fabric is used in 70,000-psi (483-MPa) yield because this is the only strength available.

Location and Spacing

Most states are locating the longitudinal reinforcement slightly above mid-depth, although a few specify mid-depth. Frequently, the placement tolerance is such that the lower limit is mid-depth; for example, a specification for 8-in. (200-mm) thick pavement might call for steel depth of 3½ in. ±½ in. (89 mm ±13 mm). The ½-in. tolerance is typical, but ¼ in. (6 mm), ¾ in. (19 mm), and 1 in. (25 mm) also are used. There is a tendency toward the 1-in. tolerance because of difficulty in obtaining lesser tolerances with present equipment. A minimum cover of 2½ in. (64 mm) also is frequently specified.

There has been some disagreement as to the proper depth of the reinforcement. One laboratory study indicated higher steel stresses under wheel loads when the steel was placed above mid-depth rather than below mid-depth (*14*). This study recommended ¾ in. (19 mm) below mid-depth as the optimum location to equalize and minimize crack widths at the top and bottom surfaces of CRCP slabs. Another source, reporting on a field study, showed an average crack spacing of 1.7 ft (0.52 m) with centerline of steel 2½ in. (64 mm) below the surface [8-in. (200-mm) slab], and an average spacing of 2.9 ft (0.88 m) with steel 3¹¹⁄₁₆ in. (94 mm) below the surface (*15*). The pavement with the lower steel had a more uniform pattern of cracking. However, a conclusion of this field study was that the depth of steel was not a critical factor in cracking. Another report of experiments with 2-in. (51-mm), 3-in. (76-mm), and mid-depth steel placement concluded that the 3-in. depth was optimum, considering crack spacing and uniformity of cracking pattern (*10*).

The spacing of steel should be large enough to permit easy placement and consolidation of concrete, yet not so large as to lose bond strength. Current practice in spacing reinforcing bars varies within a range from 4½ to 9 in. (114 to 230 mm). For the typical 8-in. (200-mm) thick pavement with 0.6 percent steel, the use of No. 5 bars at 6½ in. (165 mm) frequently is specified. The wires in deformed fabric are almost always spaced at 4 in. (100 mm), and the wire size is changed for various combinations of slab thickness and steel percentage.

Splices

Splicing of reinforcing steel is extremely important in CRCP. Failures have occurred because of inadequate laps of the steel bars or fabric. Current specifications are in a range of 16- to 20-in. (410- to 510-mm) overlap for reinforcing bars (corresponds to 25 to 32 diameters for No. 5 bars) and 16 to 28 in. (410 to 710 mm) for deformed wire fabric (32 to 56 diameters for D-19 wire). Current design manuals recommend 25 diameters for bars and 32 diameters for wire with minimum dimensions of 16 in. (410 mm) and 18 in. (460 mm), respectively (*2, 6, 13*).

The laps are staggered or skewed in many different ways. One recommendation is that not more than one-third of the bars be lapped in any transverse plane (Fig. 4). Some of the many other methods include: not more than one-fourth of the bars in a 4-ft (1.2-m) length of slab; 60° skew; not more than four bars in any cross-section and 6 ft (1.5 m) between adjacent laps; and skewed across a single-lane width over a length of 20 ft (6.1 m). The common objective of these methods is to prevent all of the bars from being spliced at a single transverse plane. However, results from a research project, which used No. 6 bars lapped 15 in (380 mm; 20 diam.), showed no difference in performance between a 60° skew (from centerline) and a transverse arrangement of the splices (*17*).

TRANSVERSE REINFORCEMENT

Transverse reinforcement has been used for several purposes: (1) to maintain the spacing of the longitudinal steel; (2) to aid in supporting longitudinal steel at the desired depth; (3) to serve as tie bars across longitudinal joints; and (4) to hold chance longitudinal cracks tightly closed for proper load transfer. However, recent improvements in construction methods have decreased or eliminated the need to use transverse reinforcement to maintain spacing and depth of longitudinal steel. Moreover, conventional tie bars can be used for the longitudinal joints. Therefore, the only remaining reason for transverse reinforcement is to hold longitudinal cracks tightly closed.

One design manual states that the probability of chance longitudinal cracking in a "properly designed and constructed pavement, with a longitudinal joint, . . . is remote" (*6*). This is especially true if the centerline joint is made early enough and deep enough. Another report outlines a method to determine whether to use transverse steel based on probability of cracking and cost savings realized by elimination of the transverse steel (*18*). One agency, which does not use transverse steel, experienced longitudinal cracking where ramps were tied to the CRCP main line. The problem was solved by eliminating the ties.

Several states do not require transverse reinforcement in CRCP; for those that do, however, the design is based on the "subgrade drag theory," which is much the same as for longitudinal steel in jointed pavement (*18*). Typical current uses are No. 4 at 36 in. (910 mm) or No. 5 at 48 in. (1,220 mm).

LONGITUDINAL JOINT

An experiment with omission of the longitudinal joint on a 22-ft (6.7-m) pavement resulted in meandering longitudinal cracks, rarely more than about 3 ft (1 m) from the centerline (*7*). These were highly visible from vehicles traveling on the highway and showed the need for a centerline joint. Most states now use a longitudinal weakened plane joint with tie bars provided as in jointed pavement unless the transverse reinforcement also serves as a tie bar. To simplify construction, the tie bars usually are placed above the longitudinal steel but low enough to avoid interference with the groove for the longitudinal joint.

TERMINAL TREATMENTS

Terminal treatments are necessary at the free ends of continuously reinforced concrete pavements. The free ends occur at bridges as well as at the beginning and the end of the pavement. Outward movements (growth) exceeding 2 in. (50 mm) at free ends have been reported (*7, 19*), and annual movements of 1 to 2 in. (25 to 50 mm) are not uncommon. The terminal must be designed either to restrain the movement (an *anchor*), or to accommodate it (an *expansion system*).

Anchors

The only anchor system in extensive use consists of heavily reinforced concrete lugs rigidly connected to the CRCP slab (Fig. 5). Two to six lugs at spacings from 15 to 40 ft (4.6 to 12 m) have been tried, but most installations have three or four lugs on about 20-ft (6-m) centers.

A model analysis of several configurations recommended cast-in-place concrete piles as an end anchorage (*4*). These were tried in one state where groups of six, eight, and ten piles [8-ft (2.4-m) depth] were placed on one project (*19*). No significant differences in performance were found among the various numbers of piles. Another project in the same state showed no performance difference between 4-lug and 5-lug anchors. This state has since adopted the 4-lug anchor as a standard.

Studies have shown that lug anchors will prevent only about one-half the movement that would occur if the ends were free (*19*). Therefore, the lugs frequently are used in conjunction with a few short reinforced concrete slabs connected by dowelled expansion joints. These joints absorb the movement not prevented by the lugs.

Expansion Systems

If the end of a CRCP is not anchored, all of the movement must be accommodated with an expansion and contraction

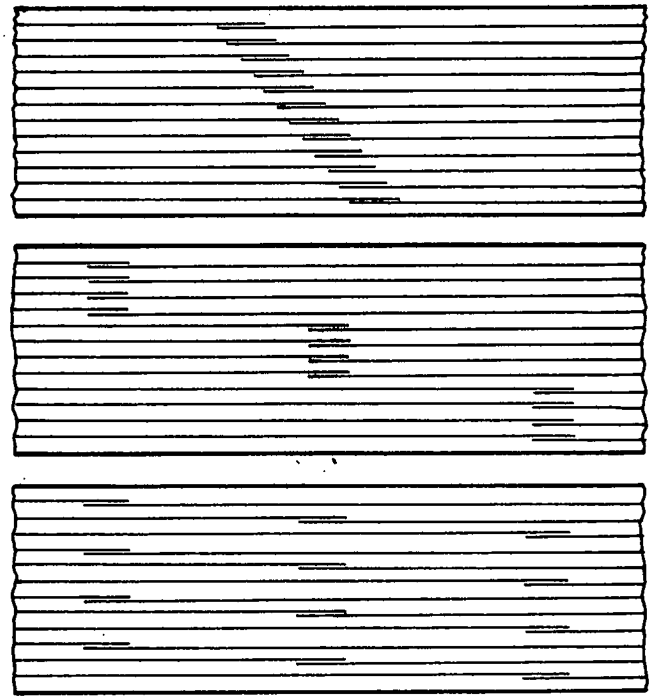

Figure 4. Some of the many methods of lapping reinforcing bars.

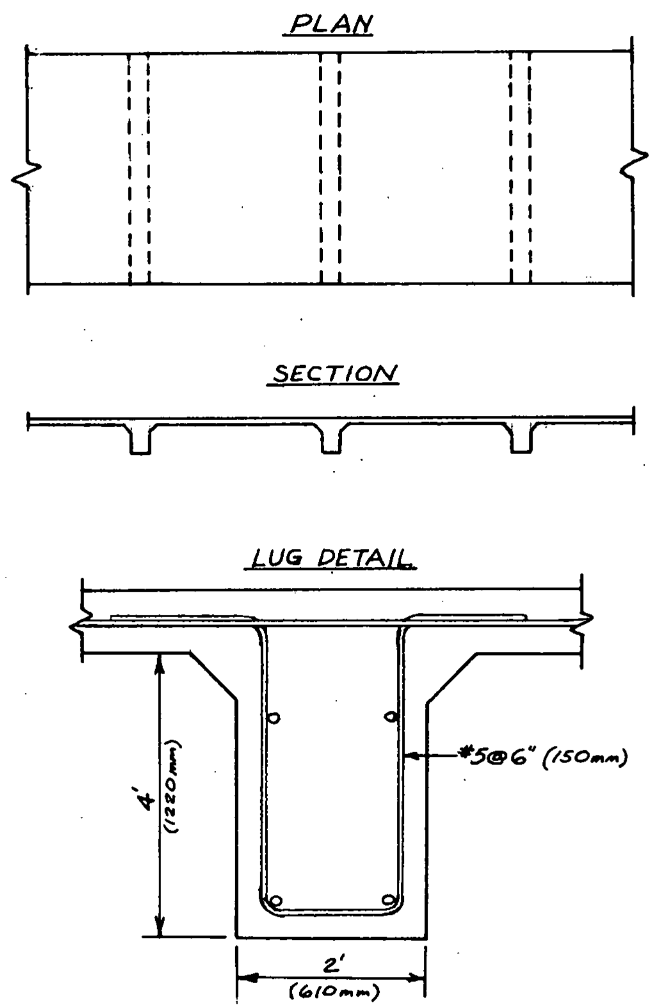

Figure 5. Lug anchor.

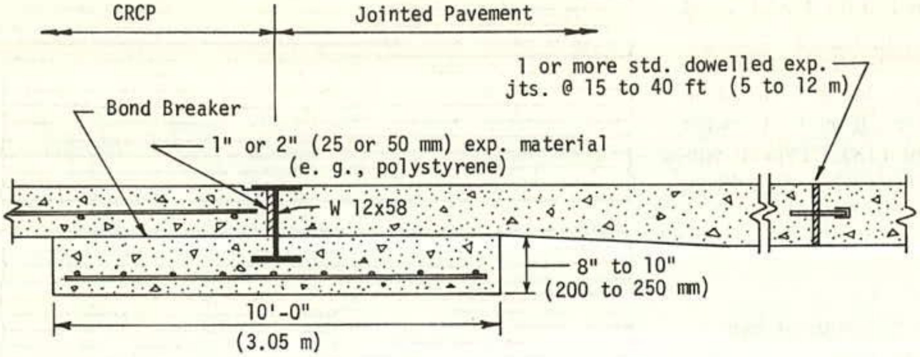

Figure 6. Wide-flange terminal joint.

system. Several different methods have been used with varying degrees of success.

The simplest method consists of several short slabs [20 to 40 ft (6 to 12 m)] of reinforced concrete separated by 1-in. (25-mm) dowelled expansion joints. This has been reported to be unsatisfactory because of severe spalling at the joints (*24*).

Another method of accommodating expansion movements is a bridge-type joint. Steel finger joints and elastomeric joints have been used, but at least one state has experienced some trouble with the elastomeric joint (*12*) and other states have had problems with the steel finger joints.

Because of problems with other methods, the wide-flange-beam terminal joint was developed and is now being used by several agencies. This consists of a concrete sleeper slab with a wide-flange beam set into it (Fig. 6). Originally the design of this joint was for contraction movements only, but recent installations have included expansion space. Various beam sizes have been tried, but the W 12 × 58 is now the size most frequently specified. A few states require that the beam be galvanized. The wide-flange joint has been reported to work well and, in fact, to be a more satisfactory design than other systems (*15, 20*).

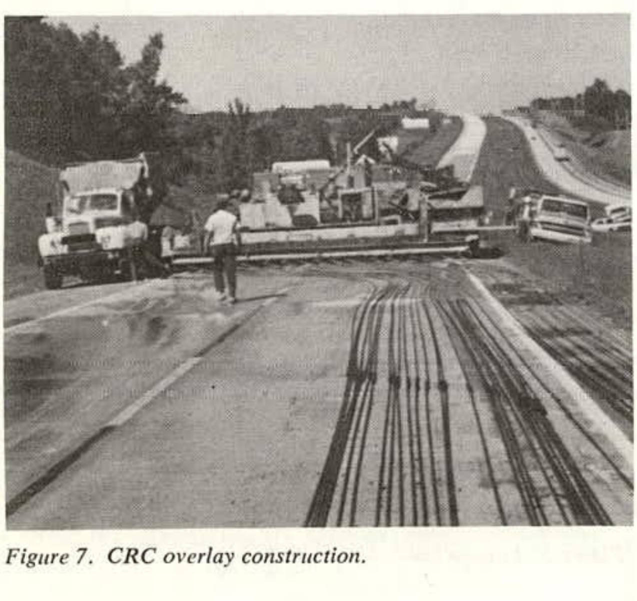

Figure 7. CRC overlay construction.

RAMPS AND PCC SHOULDERS

Most states do not tie their ramps to the CRCP main line. A common practice for those that do use ties is to tie only the middle one-third of each ramp panel to the main line. In at least two states, the portion of ramp adjacent to the main line is CRCP.

In the few instances where PCC shoulders have been used with CRCP, the middle one-third of each shoulder panel usually was tied to the CRCP main line, although one state ties the complete length of each panel. One state has used CRCP shoulders with the same thickness as the main-line CRCP on one project.

OVERLAYS

CRC appears to have much potential for use as an overlay, particularly over the newer highways that have good geometric alignment. Some Interstate highways are carrying heavier traffic than anticipated and will need resurfacing in the near future. Unfortunately, little information on the design of overlays is available. Prior to 1971, only Illinois, Indiana, and Texas had built CRC overlays on existing concrete highway pavements. Arkansas, Georgia, and Mississippi constructed such overlays during 1971, and Maryland did so in 1972. Oregon and Texas have built CRC overlays on existing bituminous pavements.

On Bituminous Pavements

Overlays on existing bituminous pavements are designed as a CRCP to be placed on a good nonerodible base. A bituminous leveling course usually has been used to keep concrete thickness variations within reasonable limits. The few CRC overlays that have been built on existing bituminous pavements have not been in service long enough for any judgment to be made about their performance, but it should be similar to or better than that of CRCP built on a bituminous stabilized base.

On Concrete Pavements

Most of the CRC overlays on existing jointed concrete pavement have used a bituminous leveling or bond-breaker course, or were constructed on pavements that previously had received a bituminous overlay. Thicknesses have ranged from 6 to 8 in. (150 to 200 mm); steel content has ranged from 0.56 to 0.8 percent. The oldest projects are located in Texas—a 7-in. (180-mm) overlay placed in 1959, and two 6-in. (150-mm) overlays placed in 1965—and are reported to be performing excellently.

Indiana recently has constructed two projects without a bituminous layer between the CRC and existing concrete pavement. In the first project, the CRC was placed directly on the existing concrete (partially bonded). This overlay appeared to have some reflection cracking. The other project used a polyethylene bond breaker and appears to be working well. Figure 7 shows construction of a recent overlay in Georgia. The CRC was placed directly on an old concrete pavement to upgrade it to Interstate standards. This pavement has been open to traffic less than a year and no conclusions can be made as to its performance.

CHAPTER THREE

CURRENT CONSTRUCTION PRACTICES

Continuously reinforced concrete pavement generally is constructed in the same manner as jointed concrete pavement, and with similar equipment, except for placement of reinforcement. A few states have a separate section of their standard specifications for CRCP. However, these usually contain only a few items, such as reinforcement and construction joints, and refer to the section covering jointed concrete pavement for most of the details of materials, equipment, placement, finishing, etc.

Because CRCP seems to be less forgiving of errors, extra care during construction is important. This is especially true at areas that are problem-prone—reinforcement splices and construction joints, in particular. It is important that steel be properly positioned at all locations and that adequate consolidation of the concrete be obtained throughout.

BASE

Base construction for CRCP must receive careful attention. Whereas clean, fine-grained granular bases are used widely under jointed pavements with success, one state recently has experienced CRCP failures that appear to be caused by the creation of voids in the base as the pavement deflected and rebounded under traffic (*22*). The pavement was 8 in. (200 mm) thick with 0.6 percent steel (deformed wire fabric), placed on a clean granular base ranging from 3 in. (76 mm) thick at the inside pavement edge to 7½ in. (190 mm) thick at the outside pavement edge. The base was sloped to drain to an underdrain system along the outside edge of the pavement. When the first signs of pavement distress were noticed, investigators also discovered hollow sounds at other places by tapping on the pavement. This experience should serve as a warning that a CRCP, because of the longitudinal steel, may depress and rebound under traffic and actually promote void spots in a base that is not uniformly compacted.

When possible, the surface of the base should have a rough texture, as this will ensure higher friction between the base and the pavement (*5*), thus reducing end movements and promoting a more even cracking pattern.

In one state, cracks that developed in stabilized bases placed considerably before paving were found to reflect into the CRCP. A seal coat or a thin bituminous overlay was used to prevent the reflection cracking.

REINFORCEMENT *

The placement of reinforcing steel for continuous pavements originally followed the methods used for jointed pavement: the steel was either supported on chairs, or placed between lifts. More recently, acceptance has been gained for mechanical placement, and several different methods and machines currently are being used.

The support of reinforcement on high chairs was the original method used for reinforced concrete pavement and has been an accepted standard for many years. In some states, this method is the only one permitted with slipform paving. This method has the advantage of allowing easy checks for location of steel and for laps and splices. The major disadvantage is the cost of the large amount of hand labor required to locate and set the chairs and tie intersections and laps. The steel setting operations are slow and have caused delays to the entire paving operation. Steel must be set far in advance of paving to avoid these delays (Fig. 8), and movement of the steel caused by temperature change has occurred. Recent improvements, such as continuous high chairs with welded clips (Fig. 9) and mechanical assembly aids have helped to reduce costs and delays.

Placement of wire fabric or bar mats between concrete lifts was devised as a means of eliminating chairs. A layer

* Much of the information in this section was extracted from Olateju (*21*).

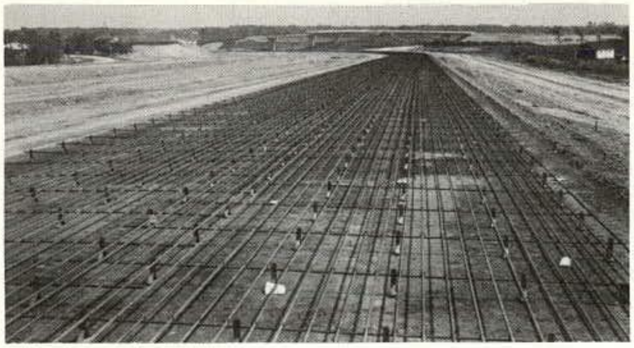

Figure 8. Steel set on chairs in advance of paving.

of concrete is placed and struck off at, or slightly above, the level of the steel. The steel is laid on the surface of the first layer, and the second layer of concrete is then placed. Because the second layer must be placed before the first has begun to set, a continuous supply of concrete is necessary. In addition, two spreaders or slip-form pavers are required. This method generally is not recommended because of the possibility of a plane of weakness being formed between the two layers; in fact, it is prohibited by several states.

Among the mechanical placement methods is the depressor which uses vibration and pressure to push wire fabric or bar mats into the full depth concrete. A device is built into the depressor to stop the steel at the proper depth. Some care must be used with this method as trouble with obtaining proper overlap has been reported (*10*). This occurred when the depressor caught the fabric and dragged it forward, thus reducing or eliminating the lap. This can be avoided by tying all laps. When bars are used, they are assembled on a platform behind the spreader and fed through spacers to the surface of the concrete. The depressor then presses the bars into the concrete in about 15-ft (4.6-m) lengths.

A variation of the depressor method allows loose bars to be assembled in advance of the paving operations. The bars are laid out on the base, lapped and tied, but not spaced. A roller on the front of the spreader raises the bars and threads them through in two groups (Fig. 10). The bars go over the belt and out to a trailing unit where they are roughly spaced. Another spacer on the front of the paver gives accurate spacing and is followed by a saw-toothed rotary tamper that depresses the steel into the concrete to the desired elevation. One advantage of this and the following method is that the contractor may drive his equipment on the base during construction because the bars may be pushed to one side.

Another method uses tubes through which the reinforcing bars are threaded into the concrete. The bars are laid out on the base, lapped, tied, and roughly spaced. They are then picked up on rollers and fed through flared tubes on the spreader (Fig. 11). The tubes are set to the proper spacing and elevation of the steel and hold the bars in the proper location while concrete is placed and consolidated.

No matter which method of steel placement is used, it

Figure 9. Continuous high chair with welded clips.

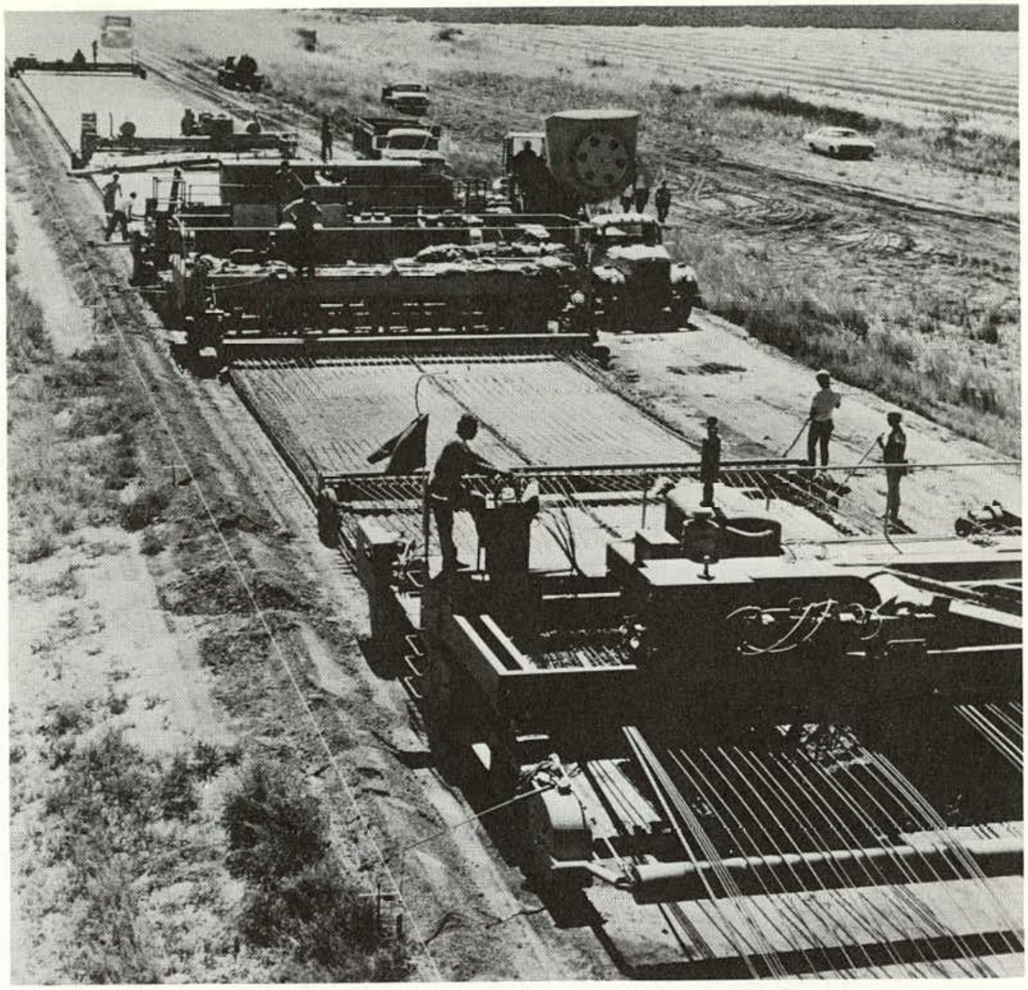

Figure 10. Equipment used to depress continuous bars into concrete. Source: Olateju (21).

is important that the laps be made properly, or the desired continuity will not be obtained. Many states require tying of all laps—even when wire fabric depressors or two-lift construction is used—to ensure that the overlap is maintained and that the members are in contact.

CONCRETE

The materials, and the mixing, handling, and placing of concrete for CRCP are generally no different than for jointed pavement. The aggregate size should be such that the minimum bar spacing is at least twice the maximum aggregate size. This is not a problem as most states have a maximum aggregate size of 1½ in. (38 mm) or less and a minimum bar spacing of 4 in. (100 mm) or more.

Proper vibration of the concrete is important; both surface and internal vibration are used, sometimes in combination. The internal vibrators should be operated so as not to dislocate the steel. One author has suggested that problems are more likely to be caused by undervibration than by overvibration (*2*).

A problem that has occurred in a few states is longitudinal depressions in the concrete surface, directly over the longitudinal reinforcing bars. In one case the depressions were deep enough to require surface grinding before the roadway could be opened to traffic. These depressions are attributed to movement of the steel during concrete placement, with resultant settlement of the concrete above the bars. The problem also appears to be related to the concrete mix design—it is more prevalent when smaller aggregates are used.

CONSTRUCTION JOINTS

Transverse Joints

The transverse construction joint has been one of the largest problem areas in continuous pavements. Because the joint faces are smooth, there is no aggregate interlock, and the joint thus is weaker than an ordinary crack. Strengthening of the joint area and special care in construction are required.

Construction joints are bulk-headed with a slotted or split headerboard that allows the steel to project through; the split headerboard is preferred. The projecting steel is supported on chairs to prevent deflections that might dis-

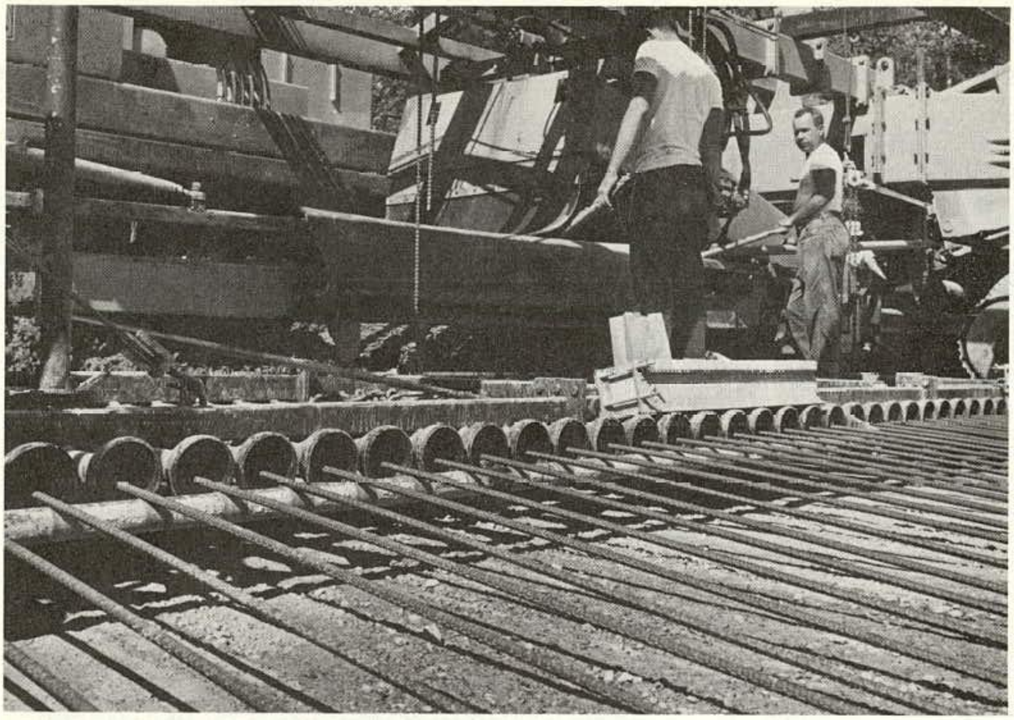

Figure 11. Tube device for placing reinforcing bars.

Figure 12. Construction joint failure caused by lack of consolidation.

turb the fresh concrete. Additional deformed bars to increase the steel area by at least one-third, and frequently one-half, are added at the joint, primarily to provide shear transfer. When bar reinforcement is used, the additional bars usually are the same size as the longitudinal bars. Lengths of added bars range from 2½ to 6 ft (0.8 to 1.8 m). Sometimes smooth dowel bars are used in lieu of deformed bars.

Splices adjacent to a construction joint have been a source of trouble. Some states now require the joint to be at least 3½ or 4 ft (1.1 or 1.2 m) from a splice. Another recommendation is to increase the lap length or to add additional bars at laps occurring between 3 ft (0.9 m) back of and 8 ft (2.4 m) beyond a construction joint.

Proper consolidation of the concrete at construction joints is important, and problems will develop where it is not obtained (*10*) (Fig. 12). Because of the extra steel at these joints, hand vibration is used to assure proper consolidation.

If more than five days elapse before construction continues beyond the joint, or if temperatures are fluctuating widely, special procedures may be required to prevent failure in the new pavement caused by high tensile stresses in the steel (Fig. 13). These procedures include:

- Starting construction early in the morning so the concrete can develop more strength prior to sunset when contraction movements of the previously poured pavement put tension on the projecting reinforcement.
- Putting extra cement in the first few batches.

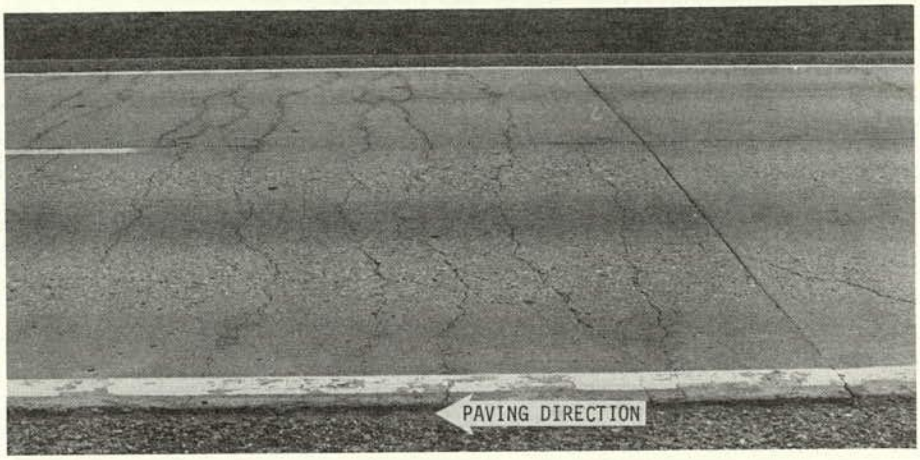

Figure 13. Closely spaced cracks in pavement beyond construction joint.

- Stabilizing the movement by covering the last 100 to 300 ft (30 to 90 m) of the existing slab with water, wet sand, wet straw, etc.
- Avoiding placement if a severe temperature drop is expected.
- Increasing the longitudinal steel by 50 to 100 percent for a distance of 16 to 25 ft (4.9 to 7.6 m) beyond the construction joint (*2, 6*).

Leave-Outs

A gap in the pavement to allow the movement of cross traffic is called a leave out. This is an undesirable feature and should be avoided if possible (*2, 6*). Most states do not permit leave-outs. Placement of concrete at these areas beforehand will eliminate the need for a leave-out. Another method of avoiding leave-outs is the use of temporary or portable bridges to carry cross traffic over the pavement. If a leave-out *must* be used, one of the previously described procedures for delayed paving beyond a transverse construction joint can be used at both sides of the leave-out.

TERMINALS

Anchor lugs are formed by excavating the subgrade to required dimensions, setting reinforcement, and filling the excavation with concrete. No forms are used—concrete is placed directly against the excavated sides of the trench. The concrete may be placed in advance of the paving (Fig. 14) or together with it. Similar methods are used to construct the sleeper slabs for expansion devices, although the sleeper slab must be constructed prior to the paving (Fig. 15).

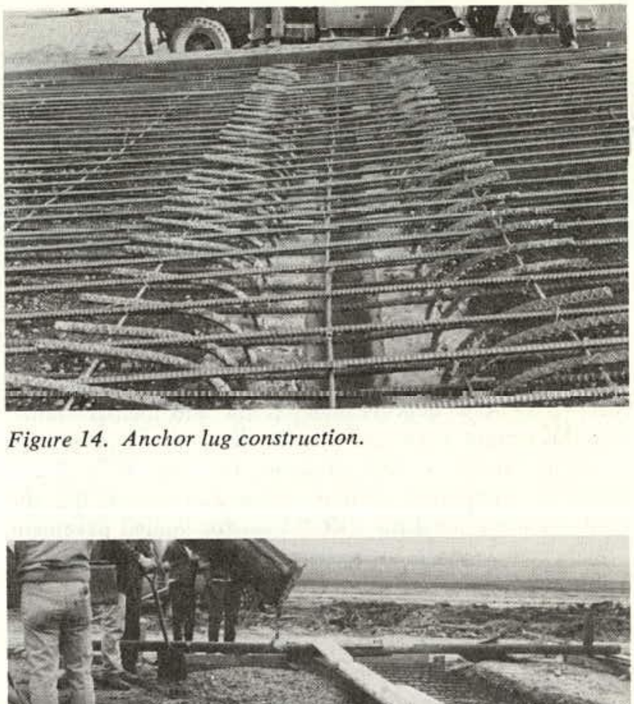

Figure 14. Anchor lug construction.

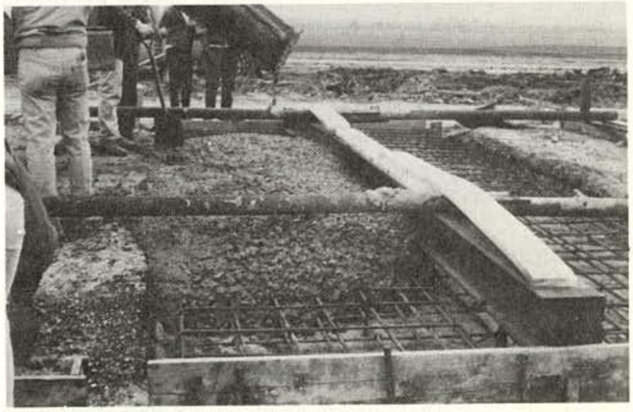

Figure 15. Wide-flange terminal construction.

REPAIRS

Although the performance of CRCP generally has been very good, some local distresses have occurred. Most of these have been attributed to improper lapping of the reinforcement, to construction joints, to inferior concrete (usually caused by inadequate consolidation, but occasionally by poor material), and to saturated or nondurable bases.

The repair techniques for CRCP are somewhat different than for jointed pavement. Not only must the concrete be replaced but the continuity of the reinforcing steel also must be restored.

The minimum size of patch is usually 10 ft (3 m) long by a single traffic lane width. Each traffic lane is repaired separately while the adjacent lane is kept intact. Steel projecting into the patch from the slab ends is not permitted to be bent because the subsequent rebending is likely to leave the steel with a slight "S" shape. This has resulted in a failure of the patch from eccentric forces created when the steel was stretched by movement of the contiguous pavement. The new steel is spliced to the old with double-length laps and tied. Most states do not permit welding of new bars to the old. Supplemental steel bars to increase the area by 50 percent frequently are used.

Because the ends of the pavement may move with changes in temperature, concrete for the patch should be placed in the late afternoon or the early evening. This was shown in one state where five repairs placed in the afternoon were successful while one poured in the morning failed (*19*). On a later repair job, measurements indicated that the patch length decreased by 1 in. (25 mm) as the temperature rose from 72°F (22°C) at 8:30 AM to 90°F (32°C) at 3:20 PM. To reduce movement while the patch cures, the ends of the existing pavement can be kept wet for a distance of at least 100 ft (30 m).

CHAPTER FOUR

GUIDELINES FOR DESIGN AND CONSTRUCTION OF CRCP

The following guidelines are recommended for the design and construction of continuously reinforced pavements.

BASE

CRCP should be constructed on a nonerodible base placed on top of a well-compacted subgrade. This is necessary because a CRCP deflects under traffic and then rebounds, and this action may lead to deterioration of supporting materials. Bases, as well as subgrades, must be well and uniformly compacted; there is evidence to indicate that this need is more critical for CRCP than for jointed pavement.

Stabilized bases are excellent examples of nonerodible bases in current use. Bituminous materials, cement, and lime are ingredients that may be added to base materials to stabilize them and bind the particles in the base together to prevent shifting of the particles under traffic. Such stabilized bases give more uniform support, reduce deflections, and provide a useful working platform for the construction of the pavement. A stabilized base also assists in eliminating the possibility of a reservoir for free water beneath the pavement.

The base should be properly designed for durability. Width of the base should be at least 1½ to 2 ft (0.5 to 0.6 m) greater than the pavement on each side if a slip-form paver is to be used. If possible, the base should be continued through the shoulders. Adequate drainage should be provided to prevent water from accumulating in the base.

CONCRETE

The design procedures currently in use for CRCP are tied to the design of jointed pavements because no other simple method presently is available. Present design procedures available include the "AASHO Interim Guide" (*3*) and the ACI publication on design procedures (*13*). Some states have their own design procedures that incorporate factors other than those in the foregoing methods. It is recommended that each project in a state be designed on its own merits, and that the thickness of concrete be determined for that project. What this really involves is the development of a design procedure that includes separate factors for such geographical variables as climate and subgrade, so that the design procedure may be used for different localities. In the absence of better methods, it is recommended that the thickness design at present be based on the AASHO (*3*) or the ACI (*13*) design procedures, and that the thickness used be adequate to keep deflections to a level that the base can tolerate.

Care should be exercised in the design of concrete thickness, and the practice of determining thickness of CRCP as simply *X* in. less than jointed pavement, or as *Y* percent of jointed pavement may lead to the use of CRC pavements that are too thin, particularly where nonstabilized bases are used.

LONGITUDINAL REINFORCEMENT

Only deformed reinforcement should be used. Smooth wire fabric has given unsatisfactory performance and should not be used. Deformed wire fabric should be used with caution as some reports have indicated problems with its use. Perhaps the real problem in the use of deformed wire fabric is in obtaining wire fabric that has deformations of appreciable size.

The longitudinal reinforcement should be designed to hold the transverse cracks in the concrete close enough together so that at least 90 percent of load transfer is obtained by aggregate interlock. Unfortunately, data from which to determine the maximum allowable crack width are inadequate. However, on the basis of the limited available data (*27, 28*), it is suggested that this crack width be considered as 0.02 in. (0.5 mm) until a better value is established. Where the CRCP is built on a stiff base and deicing salts are not used, a greater opening may be tolerable.

The percentage of steel may be determined from the AASHO (*3*) or the ACI (*13*) design procedures. These existing design procedures do not directly consider a specific or limiting crack width. What is needed is a design procedure that relates allowable crack width, crack spacing, percentage of steel, bond area of steel, and steel strength with temperature, shrinkage, and subgrade or base friction. The AASHO and ACI design procedures for longitudinal reinforcement give steel percentages that have generally proven successful. Through experience, the bond factor has led to widespread use of No. 5 bars, but some theoretical and placement considerations raise the question of whether No. 6 bars might be more desirable. Until better design procedures are developed, it appears wise to use a steel percentage of about 0.7 percent where the temperature drop from placement temperature is great and where deicing chemicals are to be used on the pavement. On the other hand, one state with minor deicing problems and lesser values of temperature drop from construction temperature has had success with steel percentages of as low as 0.5 percent.

The longitudinal steel should be located vertically such that there will be at least 2½ in. (64 mm) of cover, and the resulting placement should not be more than 1 in. (25 mm) below mid-depth of the pavement. A variation of ±1 in. (25 mm) in vertical and horizontal location does not appear to adversely affect pavement performance; therefore, steel placement tolerances should not be set so tight as to add to costs without significantly improving performance.

Control of crack width is the secret of good performance of CRC pavement. Cracks must be held tightly closed by the reinforcement to provide load transfer and to prevent passage of water and infiltration of incompressible materials. Therefore, an extension of steel under load, as well as strength of the material, are considerations that must be taken into account. Experience indicates that steel strengths greater than 60,000 psi (414 MPa) cannot be used. Although higher yield strengths will provide insurance against breakage in cold climates, the higher strength cannot be used in design because elongation of the steel to the higher limit causes wide cracks and loss of aggregate interlock. The designer can be misled into a use of a smaller percentage of steel when using a higher yield point steel if he fails to consider that the unit strains and resulting crack openings may be adversely affected.

Construction joints should have additional longitudinal reinforcement to assist in load transfer across this joint, which has no aggregate interlock. States have recognized this, and one successful practice has been the addition of 50 percent more longitudinal steel at construction joints in the form of steel reinforcement bars 6 ft (1.8 m) long. This amount and length of additional reinforcement should be considered a minimum and should be used whether wire fabric or bars are used as the longitudinal reinforcement.

Construction joints should not be placed at splice areas, insofar as possible, and those splices adjacent to or near a construction joint should have additional lap length beyond the calculated minimum for bond.

TRANSVERSE REINFORCEMENT

With the uniform support provided by a properly designed base, the need for transverse reinforcement is questionable. With the latest construction methods there appears to be no need for the use of transverse reinforcement simply to space and support the longitudinal reinforcement, and there may be cost savings by eliminating transverse steel.

LONGITUDINAL JOINTS

Longitudinal joints should be provided when pavement is built wider than 14 ft (4.3 m), unless local experience permits a greater width without longitudinal joints. Transverse reinforcement should extend through the joint, or tie bars should be used. The joint should be made as narrow as possible if it is not to be sealed. If it is to be made by sawing, such sawing should be done as soon as the concrete is hard enough to prevent raveling of the sawed edges.

TERMINALS

Some type of treatment is required at the ends of CRCP—particularly at bridges where there is a concern for protection of the bridge. Of the various types of expansion devices that have been tried, the wide-flange beam has been the most successful. This device should be used with 1 or 2 in. (25 or 51 mm) of expansion space at the CRCP side of the beam, and with one or more conventional expansion joints in the pavement beyond the beam.

Although some states believe that anchors do not perform their intended function, others are using them successfully. If anchors are to be used, the number of lugs required will depend on the type of soils encountered as well as on the expected friction between the CRCP and the base. Usually, three full-pavement-width anchors will be adequate to restrict end outward movements to 1 in. (25 mm). Conventional expansion joints will be needed beyond the anchors to accommodate the 1-in. movement. Anchors should not be used in cohesionless soils.

OVERLAYS

Experience with overlays of CRC is described earlier in this report. Such overlays definitely appear to have much potential in the future, especially on Interstate and other highways that have good alignment and grade but need resurfacing. Many such overlays are just now being placed in service, and there is really no long-term record of performance on which to base recommendations. It does appear that CRC overlays may be placed as thin as 6 in.

(150 mm) and be successful. A leveling course, preferably of bituminous material, will be necessary in instances where the existing pavement surface is uneven either transversely or longitudinally. A bond breaker may be necessary for overlays on existing PCC pavement if a leveling course is not used.

CONSTRUCTION

Reports from states indicate that although admittedly specific and exact design methods for CRCP are now lacking, many of the problems with existing CRCP projects can be traced to construction. Because CRCP is less forgiving of errors, and because repairs are more difficult to make in CRCP than in jointed pavement, greater care during construction is important. Both the contractor and the inspectors should be made aware of this need, and the supervision of construction of CRCP should be tightened.

Careful attention during construction must be given to the base and subgrade beneath CRCP. Uniform compaction and good drainage of these elements are more necessary for CRCP than for jointed concrete pavement. Localized soft spots in the subgrade must be corrected, and granular bases should be carefully and completely compacted. Stabilized or nonerodible bases, which are recommended, should not be considered as the complete solution to a pumping subgrade situation. Reports already have been received of instances where pumping has been observed to exist together with the use of lime- and cement-treated bases. This has led to erratic crack patterns, with pavement deterioration and failure resulting in some cases. Often during construction, soil and subgrade conditions are found that were unknown during the design stage of the project. The engineer and the contractor should work together to adequately solve such problems when they are encountered. For instance, if free water is found to exist in the subgrade, consideration should be given to the incorporation of longitudinal underdrains or other drainage methods.

Great care must be exercised in placing concrete so as to obtain uniform quality from the beginning to the end of the day's work. In the placement of all concrete, adequate vibration and consolidation must be achieved. This is especially important in areas where splices are made, as well as at construction joints.

Many reports have been made concerning early deterioration and breakup of pavement placed in the last 2 or 3 ft (0.6 or 1.0 m) immediately before the construction joint and of extensive cracking in the pavement immediately beyond construction joints. Much of the problem before the joint stems from poor-quality concrete. This could be solved by careful use of hand vibrators to obtain good consolidation at this critical location. Any segregated concrete should be removed. Consideration should be given to adding extra cement to the first few batches of concrete when paving operations are resumed beyond the construction joint. This will allow mortar to coat the drums, trucks, etc., and also give additional strength to the concrete immediately beyond the joint. Also, depending on the placement method used, the fresh concrete within the first 2 or 3 ft beyond the joint might be placed by hand and carefully vibrated to assure adequate consolidation. Such careful attention at construction joints is warranted in CRCP because these joints frequently have been reported as the location of trouble spots, as far as concrete quality is concerned.

The exact vertical and horizontal placement of longitudinal reinforcement does not appear to be critical. If the contractor can obtain the reasonable tolerances without pre-setting of the steel, he should be allowed to do so. However, regardless of the method used to place steel, great care must be taken to ensure adequate laps. There have been numerous reports of failures that have been traced to a lack of obtaining the proper lap of the reinforcing steel. It has been observed that when deformed fabric was placed on the full depth of concrete and mechanically depressed into position, apparently the depressor at times caught the fabric, pulled it along longitudinally, and therefore reduced or eliminated the lap. So many instances of failures resulting from improper lapping have been reported that this area should receive major attention during construction. Bars or mats that are to be lapped should be securely tied in such a way that they will not become separated during the construction process.

Leave-outs should be avoided if at all possible. At areas where cross traffic must be accommodated, a short section of pavement should be placed in advance, with carefully protected steel projecting through construction joints at each side. Another way to avoid a leave-out is to use a temporary or portable bridge to carry the cross traffic. If this is not possible, and a leave-out must be used, the end movements of the CRCP on both sides of the leave-out should be stabilized until the leave-out is cured. A method of achieving this is to keep the ends covered with wet burlap or wet sand from 72 hr before pouring the concrete until the required strength is attained. Additional steel also may be required in the leave-out area.

REPAIRS

When areas of CRCP must be removed and patches made, it is suggested that such patches be at least 10 ft (3 m) in longitudinal length and not less than a traffic lane in width. A saw should be used to provide a transverse cut to within about ½ in. (13 mm) of the steel at each end of the patch. If the longitudinal steel or the full depth of concrete must be removed, additional full-depth transverse cuts should be made (cutting the longitudinal steel) 3 ft (1 m) from each end of the patch length; this center section of concrete and steel may then be removed by jackhammer or otherwise. The base should not be disturbed. The 3-ft extensions of steel from the patch lines should not be bent out of alignment; the concrete in these areas must be removed carefully so as not to disturb the steel and so as to provide a vertical plane through the concrete at the patch lines. Longitudinal steel, as long as the batch and the same size as the steel in the pavement, should then be placed and tied to the existing longitudinal bars. One state requires that an additional bar be added and tied to every other existing bar. High-early-strength, air-entrained concrete then should be placed through the steel and carefully consolidated and finished.

It is advisable to place the concrete during stable weather conditions when the daily temperature cycle is small. This will minimize cracking of the fresh concrete from temperature changes. If reinforcing steel is to be welded, the welding should be done when the pavement is in its most expanded position (usually late afternoon), and concrete should be placed immediately thereafter.

Repairs should be made in one lane at a time and in one continuous operation.

CHAPTER FIVE

RESEARCH

CURRENT RESEARCH

A few agencies currently are engaged in research into continuously reinforced concrete pavements. These are identified in Table 2. This list is not comprehensive; productive research and evaluation studies may be in initial or continuing stages in many highway agencies, universities, and other research-oriented agencies.

Some research also has been done on concrete pavements with continuous reinforcement and elastic joints (*23*). These pavements use weakened plane transverse joints with the longitudinal steel continuous through the joint. The steel is treated to prevent bond with the concrete for an appropriate distance on either side of the joint. One advantage of this construction is the lesser amount of steel required—from 0.2 to 0.4 percent. Although some research has been done in Europe on this type of continuous pavement, almost none has been done in the United States.

FUTURE RESEARCH

Although much is known about continuously reinforced concrete pavements, much is unknown; in fact, the research effort represented by the listing in Table 2 is actually less than that of five or six years ago, yet many of the problems of design and construction of CRCP are still unsolved. The following areas for research are suggested.

Longitudinal Reinforcement

Although steel percentages between 0.5 and 0.7 percent have been used with success in locations throughout the U.S., many states report that they use a certain percentage of steel for no other reason than that it has proven successful in past projects. It appears that research might refine a method for determining the optimum percentage of steel in continuously reinforced pavements. If it is assumed that the purpose of the steel is simply to hold the cracks tightly together, the research might begin by establishing a maximum crack width (at the surface of the pavement) that could be tolerated for the pavement to still have near 100 percent of load transfer. Such research should include the parameters of steel percentage, steel stress, bond area, steel location, crack width, crack spacing, subgrade friction, concrete strength, and temperature.

States that are now building continuously reinforced pavements or overlays might be encouraged to instrument those pavements so that more data could be obtained relating stress in the steel, surface crack width, and temperature and other climatic conditions. Time of construction of the pavement also should be worked into the analysis. The problem of choosing the optimum percentage of steel appears to have a solution, and undoubtedly much data relating the variables mentioned already are available.

Base

Laboratory data now are available to indicate the difference in the deflection of pavements under wheel loads with stabilized or plain bases. However, field data about the performance of CRCP on different bases are only now being gathered. Such data are needed to assist in determining to what extent stabilized bases assist in limiting pavement deflections. Comparative data are needed, and agencies should be encouraged to instrument and obtain such data as they continue to build CRC pavements and overlays.

Few data are available that would assist one in choosing a minimum thickness or quality of base for a CRCP with given subgrade conditions. Associated with this problem is the need to first determine a limiting deflection that can be tolerated by a CRCP.

Concrete Thickness

There appears to be no well-defined, rational method to determine the thickness of CRCP. There is a tendency to use the best semi-empirical methods at hand to determine the thickness for jointed concrete pavement, and then simply use 1 or 2 in. (13 or 25 mm) less for CRCP. An analytical solution for a CRCP under vertical wheel loads, considering both stresses and deflections, appears feasible. Then, by limiting stresses and deflections to safe values, thickness could be determined. For highway construction,

TABLE 2

SUMMARY OF KNOWN RESEARCH ACTIVITIES RELATED TO CRCP [a]

RESEARCH PROJECT TITLE	RESEARCH AGENCY	HRIP NO.[b]
Continuously Reinforced Concrete Pavement	Illinois Division of Highways	25 007725
Road Pavings with Continuous Reinforcement	Liège University (Belgium)	25 065538
Continuously Reinforced Concrete Pavement	Central Road Research Inst. of India	25 068661
Performance of Experimental PCC Pavement Sections	California Division of Highways	25 091281
Continuously Reinforced Concrete Pavement Observation Program	Mississippi State Highway Department	26 019039
Evaluation of Concrete Pavement Performance in Alberta	Alberta Coop. Hwy. Research Program	26 050185
Condition of the Reinforcing Steel in Continuously Reinforced Concrete	Wisconsin Dept. of Transportation, Division of Highways	26 213704
Continuously Reinforced Concrete Pavement	Kentucky Department of Highways	26 219734
Continuously Reinforced Concrete Pavement	Minnesota Department of Highways	32 003193
Temperature, Shrinkage and Load Effects on Continuous and Jointed Concrete Pavements	Portland Cement Association	32 206929
Design of Continuously Reinforced Concrete Pavements for Highways (NCHRP Project 1-15)	University of Texas	—

[a] As of October 1972. [b] Acquisition number assigned by the Highway Research Information Service of the Highway Research Board; HRIP = publication entitled *Highway Research in Progress* (current issue).

it appears that CRCP pavement thicknesses of 7, 8, and 9 in. (180, 200, and 230 mm) will prevail. Research toward establishing an analytical procedure would be of value in defining not only these pavement thicknesses for new pavements, but also even smaller thicknesses of CRCP that might be used as overlays in the future. This problem appears to be solvable, and analytical work already has been done on stresses. Limiting deflection values must yet be established; little has been done on this subject.

Terminal Movements

Data should be obtained and analyzed on the movements of terminal ends of slabs, and the opening and closing of the commonly used expansion joints placed between plain and RCP slabs adjacent to the terminal ends of the CRCP pavements. More data on such movements where concrete lugs or wide-flange beams are used are needed and could be obtained from future projects in various states with different climatic conditions. At present, many states that are constructing CRC pavements are not making arrangements to obtain such data, yet it would be valuable. The 20-year report on the Illinois pavements (*7*) revealed that lengths of 4,000 ft (1,200 m) or less resulted in growth of as much as 2 in. (51 mm) at the ends when no restraints were used. It is possible that, without more extensive data, highway agencies could build numerous sections of CRCP that would function satisfactorily for a few years and then might present tremendous problems due to excessive end movements that had not been allowed for by the construction of adequate expansion space. Research should focus attention on the wide-flange joint particularly, because it appears to be inexpensive and relatively easy to construct.

Concrete Tensile Strength

The cracking pattern of CRCP depends on the tensile strength of the concrete and the modulus of elasticity. Because there are no standard tests for direct tensile strength of concrete, research in this area is warranted. Information also is needed about the quantitative effects of tensile strength and modulus of elasticity on CRCP.

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APPENDIX A

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APPENDIX B

A SIMPLIFIED ANALYSIS OF ENVIRONMENTAL CRACKING OF CRCP *

The following analysis of cracking in CRCP is presented to show (1) why cracking occurs, and (2) the effects of some of the variables. It is based on the facts that the forces are in equilibrium and the length is constant.

GIVEN (SEE FIG. B-1)

1. Concrete placed at an internal temperature of 100°F (38°C).

2. The following winter the average temperature drops to 0°F (−18°C).

3. Pavement thickness is 8 in. (200 mm).

4. Pavement contains No. 5 bars on 6-in. (150-mm) centers: $A_s = 0.31$ in.^{2} (2.0 cm^2).

5. Concrete tensile strength: $f_t' = 400$ psi (2.8 MPa).

6. Concrete and steel coefficients: $\alpha = 5 \times 10^{-6}$ per °F (9×10^{-6} per °C).

7. Concrete modulus of elasticity: $E_c = 4 \times 10^6$ psi (28,000 MPa).

* By T. J. Pasko, Highway Research Engineer, Office of Research, Federal Highway Administration.

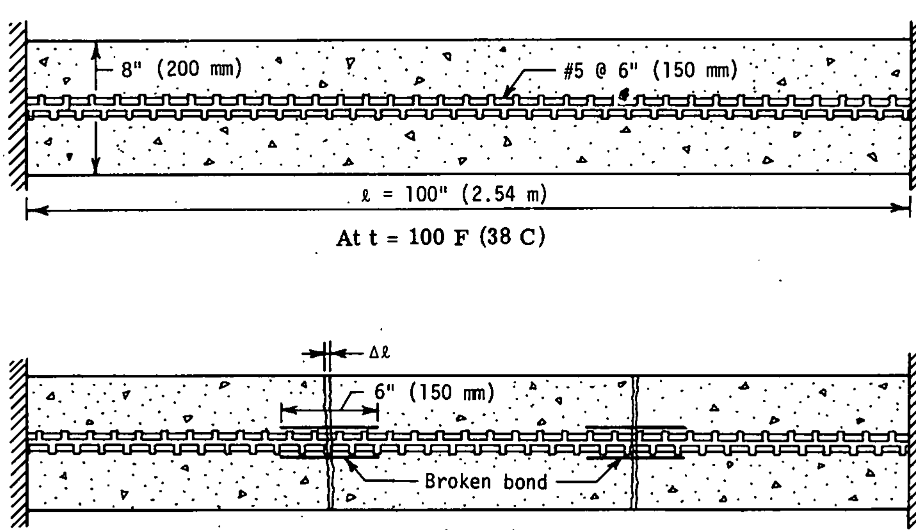

Figure B-1. Analysis of CRCP cracking.

8. Length of pavement for analysis: $l = 100$ in. (2.54 m).
9. Yield strength of the steel: $f_y = 65{,}000$ psi (448 MPa).
10. Steel modulus of elasticity: $E_s = 30 \times 10^6$ psi (207,000 MPa).

BACKGROUND CALCULATIONS

The thermal movement of an unrestrained length of pavement would be:

$$\text{Total } \Delta_{\text{thermal}} = (\alpha)(\Delta t)(l)$$
$$= (5 \times 10^{-6})(100)(100)$$
$$= 0.050 \text{ in. } (1.27 \text{ m})$$

The same length subjected to 400 psi would elongate:

$$\Delta_{\text{tension}} = \frac{(f_t')(l)}{E_c} = \frac{(400)(100)}{4 \times 10^6} = 0.010 \text{ in. } (0.25 \text{ mm})$$

The forces in the longitudinal direction are equal to zero:

$$(f_t')(A_c) - (S)(A_s) = 0$$
$$(400 \text{ psi})(8 \text{ in.})(6 \text{ in.}) - (S)(0.31) = 0$$

and the steel stress, $S = 62{,}000$ psi (427 MPa).

ANALYSIS

At 0°F (−18°C) the tension in the concrete will be approximately 400 psi (2.8 MPa) and several cracks will have opened up, stressing the steel to 62,000 psi (427 MPa). At the cracks the steel will break bond with the concrete. Research in Maryland * showed that bond eventually is broken for 6 to 12 in. (150 to 300 mm) from the crack, but it is assumed here that the bond is completely lost for 3 in. (75 mm) on each side of the crack, for a total of 6 in. (150 mm). Steel stressed to 62,000 psi over a 6-in. length will elongate:

$$\Delta l = \frac{S}{E_s} l = \frac{(62{,}000)(6)}{(30 \times 10^6)} = 0.0124 \text{ in. } (0.31 \text{ mm})$$

A 100-in. (2.54-m) length of concrete wants to contract 0.050 in. (1.27 mm) for a 100°F (56°C) temperature drop, but the concrete can tolerate only 0.010 in. (0.25 mm) of this movement. The remainder—0.04 in. (1.02 mm)—must be accommodated in the steel elongations at the cracks. Because each crack can accommodate only 0.0124 in., the number of cracks that occur in 100 in. is (0.04/0.0124) = 3.23. Hence, the crack spacing is (100 in./3.23) = 31 in., or 2.6 ft (0.8 m).

* Nixdorf, R. H., and Lepper, H. A., Jr., "Maryland Investigation of Continuously Reinforced Concrete Pavement, 1959-1964 Strain Observations." *Hwy. Res. Record No. 112* (1966) pp. 82-105.

APPENDIX C

CRCP MILEAGE AWARDED *

STATE	BUILT TO AUG.'59	AUG.'59 to APR.'60	APR.'60 to APR.'61	APR.'61 to APR.'62	APR.'62 to APR.'63	APR.'63 to APR.'64	APR.'64 to APR.'65	APR.'65 to APR.'66	APR.'66 to APR.'67	APR.'67 to APR.'68	APR.'68 to APR.'69	APR.'69 to APR.'70	APR.'70 to APR.'71	APR.'71 to APR.'72	TOTAL
CALIFORNIA	1.0											9.4			10.4
ILLINOIS	5.6			32.4	23.6	44.7	94.7	147.2	187.4	362.9	108.1	381.2	200.3	260.2	1848.3
INDIANA	0.7					7.2			15.3	92.5	184.2	110.0	175.9	109.7	695.5
MARYLAND	5.3	6.2								14.6	152.9		7.2	22.9	209.1
MICHIGAN	8.3			11.1		11.5	12.2	5.4	1.3		2.5	10.9	6.3	52.2	121.7
NEW JERSEY	2.0														2.0
PENNSYLVANIA	8.4									5.5		11.4	21.8		47.1
TEXAS	22.2	39.4	95.4	238.9	292.5	355.6	260.7	208.3	339.2	306.9	225.2	199.6	234.7	264.6	3083.2
MISSISSIPPI		10.3	13.5	45.4	108.7	86.9	87.6	158.3	80.8	104.7	70.4		20.7	100.2	887.5
CONNECTICUT			3.1						9.5						12.6
MAINE			0.6												0.6
NORTH DAKOTA			1.9			20.4	15.9	69.7	64.6		21.0	122.2	51.3	28.8	395.8
WISCONSIN			13.7			53.6					72.4	18.8		65.4	223.9
RHODE ISLAND				1.0											1.0
OREGON					21.4	5.5		23.8	3.0	49.6	29.1	12.3	16.4	8.0	169.1
SOUTH DAKOTA					1.5					85.6	67.4	33.4	62.9	49.4	300.2
MINNESOTA						11.4			40.9	44.7	50.8	107.4	7.5		262.7
ARKANSAS						0.4			10.2	40.1	30.8	29.2	10.7		121.4
IOWA						6.4		67.1	144.8	19.1	72.6	79.2	62.9	93.6	545.7
OHIO							9.2		27.4	3.2	58.6	34.2	15.0	26.5	174.1
VIRGINIA							14.2	13.8		56.9	8.7	69.9	42.6	1.6	207.7
LOUISIANA									16.0	23.1	12.0		85.5	10.6	147.2
NORTH CAROLINA										2.6	51.8	103.1	36.9	36.3	230.7
ALABAMA										35.0					35.0
KENTUCKY										13.0			6.4		19.4
MISSOURI											9.3				9.3
OKLAHOMA											13.8	29.7	3.7	12.9	60.1
NEBRASKA												6.3			6.3
SOUTH CAROLINA												32.7	85.8	37.4	155.9
GEORGIA												24.4	49.0	39.3	112.7
WEST VIRGINIA												7.2		24.4	31.6
DELAWARE													21.0	6.6	27.6
IDAHO													18.2		18.2
TOTAL	53.5	55.9	128.2	328.8	447.7	603.6	494.5	693.6	940.4	1,260.0	1,241.6	1,432.5	1,242.7	1,250.6	10,173.6

* Compiled by the Continuously Reinforced Pavement Group, April 1, 1972. Mileage is equivalent 2-lane pavement 24' wide. (1 mile = 1.6093 km; 24' = 7.3 m)

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—*	A Critical Review of Literature Treating Methods of Identifying Aggregates Subject to Destructive Volume Change When Frozen in Concrete and a Proposed Program of Research—Intermediate Report (Proj. 4-3(2)), 81 p., $1.80
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