CONTINUOUSLY REINFORCED CONCRETE PAVEMENT
Design & Construction Guidelines
Authors/Contributors

Robert Otto Rasmussen, PhD, INCE, PE (TX)
The Transtec Group, Inc.

Richard Rogers, PE (TX)
The Transtec Group, Inc.

Theodore R. Ferragut, PE (VA)
TDC Partners, Ltd.

Sponsors

Federal Highway Administration
Concrete Reinforcing Steel Institute
ACKNOWLEDGMENTS

This manual is the result of a cooperative effort between the Federal Highway Administration's (FHWA) Office of Pavement Technology and the Concrete Reinforcing Steel Institute (CRSI). The author/contributor team is grateful for the support of these two organizations in developing this much-needed resource.

The team also appreciates the invaluable advice and input provided by several State departments of transportation, academia, and the concrete pavement industry as represented by the American Concrete Pavement Association who participated in an FHWA-CRSI expert task group. Their responses to drafts of the document resulted in a tighter, more focused and technically sound manual.

Members of the task group include the following:

Steve Tritsch and Mike Plei, CMC
Sam Tyson, FHWA
A.J. Jubran, Georgia Department of Transportation
Wouter Gulden, ACPA-SE

Bill Farnbach, Caltrans
Dan Zollinger, Texas A&M
Jeff Roesler, U of IL - Champaign
Mohamed Elfino, Virginia Department of Transportation
Chetana Rao, ARA
Bethany Walker, CRSI
Moon Won, Texas Tech University
Norbert DeLatte, Cleveland State University
Tom Cackler, National Center for Concrete Pavement Technology
Darren Szrom, CRSI
Leif Wathne, ACPA
Bob Risser, CRSI
Jeff Dean, Oklahoma Department of Transportation
Lisa Lukefahr, Texas Department of Transportation
Rene Renteria, Oregon Department of Transportation
Doc Zhang, Louisiana Department of Transportation and Development
Suneel Vanikar, FHWA
Continuous reinforced concrete pavements (CRCP) were introduced in 1921 when the U.S. Bureau of Public Roads built a CRCP section on the Columbia Pike near Arlington, Virginia. Since then CRCP has become standard construction practice in several States, including Illinois, Texas, and Oregon. Many European countries, Japan, and Australia also construct CRCP.

During the 70-plus years that CRCP has been common practice, various lessons learned through research and practical experience have contributed to improved design methods, materials selection, and construction practices.

Today CRCP can be designed and constructed consistently and reliably to provide superior long-term performance with very low maintenance.

This manual provides information about current practices for designing and constructing CRCP. The information has been collected and synthesized from formal research results and from the most knowledgeable technical experts and practitioners in the country. The manual focuses on characteristics and practices unique to CRCP, including general information about concrete pavement design, materials, and construction when necessary to provide context.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ACKNOWLEDGMENTS</strong></td>
<td></td>
<td>iii</td>
</tr>
<tr>
<td><strong>PREFACE</strong></td>
<td></td>
<td>v</td>
</tr>
<tr>
<td><strong>TABLE OF CONTENTS</strong></td>
<td></td>
<td>vii</td>
</tr>
<tr>
<td><strong>LIST OF FIGURES</strong></td>
<td></td>
<td>xi</td>
</tr>
<tr>
<td><strong>LIST OF TABLES</strong></td>
<td></td>
<td>xv</td>
</tr>
<tr>
<td><strong>CHAPTER 1: INTRODUCTION AND OVERVIEW</strong></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>What is CRCP?</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>When and Why is CRCP Used?</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Overview of Key Points for CRCP</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td><strong>CHAPTER 2: CRCP DESIGN OVERVIEW</strong></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Background</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Objectives</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Scope of the Design Guidelines</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td><strong>CHAPTER 3 CRCP DESIGN FUNDAMENTALS</strong></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>CRCP Behavior</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Crack Spacing</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Crack Width</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Reinforcement Stress</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Other Factors affecting CRCP Behavior</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Structural and Functional Performance Indicators</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Punchouts</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Spalling</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>Smoothness</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td><strong>CHAPTER 4: CRCP DESIGN INPUTS</strong></td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Design Criteria</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>Limiting Criteria on Crack Spacing, Crack Width, and Steel Stress</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>Structural Performance</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Functional Performance</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Concrete Properties</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Reinforcement Type and Properties</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>Pavement Support</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>Bases</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>Subgrades</td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>Drainage</td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>Climate</td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>Traffic</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td><strong>CHAPTER 5: DESIGN OF CRCP FEATURES</strong></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>CRCP Design Methods</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>AASHTO-86/93 Design Procedure</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>AASHTO Interim MEPDG</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>Early-Age Behavior Analysis Tools</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>HIPERPAV II</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>PowerPave</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>Evaluation of Critical Stresses</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>Concrete Thickness</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>Longitudinal Reinforcement</td>
<td></td>
<td>30</td>
</tr>
</tbody>
</table>
Joints
Longitudinal Control Joints
Longitudinal Free Joints
Transverse Construction Joints
Blockouts
Construction Techniques for Controlling Crack Spacing
Fast-Track Paving
Environmental Influences during Construction
Hot Weather Conditions
Concrete Placement Time and Season
Using FHWA HIPERPAV and CRSI PowerPave

CHAPTER 10: TERMINAL OR TRANSITION TREATMENTS

Expansion Joints
Wide-Flange Beam Joints
Anchor Lugs
Seamless Transitions

CHAPTER 11: CONSTRUCTING CROSSES

Leave-Ins
Leave-Outs
Temporary Crossovers

CHAPTER 12: CONSTRUCTING SHOULDERS AND RAMPS

Shoulders and Auxiliary Lanes
Concrete Shoulders
Asphalt Shoulders
Widened Lane
Concrete Ramps

CHAPTER 13: CRCP OVERLAY CONSTRUCTION

CHAPTER 14: CONSTRUCTION INSPECTION

CHAPTER 15: GUIDE SPECIFICATIONS FOR CRCP

Materials
Coarse Aggregate
Reinforcement
Bar Specifications
Length of Reinforcing Bars
Size and Spacing of Reinforcing Bars
Equipment
Construction Methods
Placement of Reinforcement
Reinforcing Bars Placed Manually on Chairs
Reinforcing Bars Placed Mechanically Using a Tube Feeder
Placement of Concrete
Joint and Terminal Construction
Longitudinal Joints
Transverse Construction Joints
Wide-Flange Beam Terminal Joints
Anchor Lug Terminal Joints
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Newly constructed CRCP in Virginia</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Reinforcement design is critical to good performance</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Concrete design and mix materials are critical to good performance</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Typical CRCP cross section</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Schematic representation of some of the factors influencing CRCP behavior.</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>Typical CRCP punchout distress.</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>Spalling along transverse crack in a CRCP.</td>
<td>16</td>
</tr>
<tr>
<td>8</td>
<td>Structural performance in terms of punchouts as a function of time or traffic loads.</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>Functional performance in terms of IRI as a function of time or traffic loads.</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>Framework of CRCP design procedure in the AASHTO Interim MEPDG.(29)</td>
<td>28</td>
</tr>
<tr>
<td>11</td>
<td>Conceptual representation of steel design for CRCP.(55)</td>
<td>30</td>
</tr>
<tr>
<td>12</td>
<td>Reinforcement spacing recommendations.</td>
<td>32</td>
</tr>
<tr>
<td>13</td>
<td>Two-layered steel reinforcement mat.</td>
<td>33</td>
</tr>
<tr>
<td>14</td>
<td>Typical layout pattern with laps skewed across pavement.</td>
<td>34</td>
</tr>
<tr>
<td>15</td>
<td>Longitudinal construction joint with multiple piece tiebars</td>
<td>37</td>
</tr>
<tr>
<td>16</td>
<td>Longitudinal contraction (hinged) joint with transverse bars.</td>
<td>37</td>
</tr>
<tr>
<td>17</td>
<td>Transverse construction joint. 38</td>
<td>39</td>
</tr>
<tr>
<td>18</td>
<td>Wide-flange beam joint detail.</td>
<td>39</td>
</tr>
<tr>
<td>19</td>
<td>Layout of reinforcement in leave-out section.(58)</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>Recommended layouts for ramp connections.</td>
<td>42</td>
</tr>
<tr>
<td>21</td>
<td>Jointing details for ramp connections.</td>
<td>42</td>
</tr>
<tr>
<td>22</td>
<td>Design detail for CRCP intersection.(67)</td>
<td>43</td>
</tr>
<tr>
<td>23</td>
<td>Edge punchout in CRCP.</td>
<td>47</td>
</tr>
<tr>
<td>24</td>
<td>Asphalt-stabilized base. (photo courtesy of Zachry Constrution)</td>
<td>51</td>
</tr>
<tr>
<td>25</td>
<td>Placing geotextile interlayer in Germany.</td>
<td>52</td>
</tr>
<tr>
<td>26</td>
<td>Fastener for geotextile interlayer.</td>
<td>52</td>
</tr>
<tr>
<td>27</td>
<td>Core taken showing pavement with geotextile interlayer.</td>
<td>52</td>
</tr>
<tr>
<td>28</td>
<td>Trimming and compacting granular base.</td>
<td>53</td>
</tr>
<tr>
<td>29</td>
<td>Typical vertical moisture barrier configuration.</td>
<td>55</td>
</tr>
<tr>
<td>30</td>
<td>Example of the ASTM marking requirements for a #8, Grade 60 (#25, Grade 420) bar.</td>
<td>59</td>
</tr>
<tr>
<td>31</td>
<td>Mill and coating certifications for rebar.</td>
<td>59</td>
</tr>
</tbody>
</table>
Figure 32. Longitudinal steel reinforcement in Virginia.
Figure 33. Epoxy-coated steel reinforcement.
Figure 34. Lap splices.
Figure 35. Typical lap splice patterns.
Figure 36. Longitudinal sawed joint with tiebars.
Figure 37. Longitudinal construction joint with tiebars.
Figure 38. Multiple-piece threaded tiebars.
Figure 39. Mechanical tiebar inserter. (Photo courtesy of HDR)
Figure 40. Protective coating on tiebars.
Figure 41. Paver with steel on chairs.
Figure 42. Worker walking on reinforcing steel in Virginia.
Figure 43. Example of steel placed on chairs in Texas.
Figure 44. Example with two layers of steel placed on chairs.
Figure 45. Placing longitudinal steel on TBAs.
Figure 46. Checking reinforcement lap.
Figure 47. Checking steel placement.
Figure 48. Checking for steel movement.
Figure 49. Probing the fresh concrete to check the steel depth.
Figure 50. Effect of coarse aggregate size on crack roughness variation with slab depth.
Figure 51. High-speed belt discharge in Virginia.
Figure 52. Longitudinal free joint.
Figure 53. Transverse (start) construction joint.
Figure 54. Transverse construction joint (header).
Figure 55. CRCP Blockout Schematic.
Figure 56. Expansion Joint, CRCP to JCP or a bridge.
Figure 57. Expansion joint, CRCP to HMA.
Figure 58. Expansion joint, CRCP to HMA alternative.
Figure 59. Typical wide flange beam terminal joint system used in Illinois.
Figure 60. Typical anchor lug terminal joint system.(85)
Figure 61. Seamless pavement transition for bridges.
Figure 62. Conceptual approach for CRCP temperature management end-result specification.(48)
Figure 63. Texas design standard for CRCP one layer steel bar placement for slab thicknesses under 14 in (356 mm).
Figure 64. Texas design standard for CRCP two layer steel bar placement for 14 and 15 in (356 and 381 mm) slab thicknesses.

Figure 65. Texas design standard for CRCP terminal anchor lugs.

Figure 66. Texas design standard for bridge approach slab (sheet 1 of 2).

Figure 67. Texas design standard for bridge approach slab (sheet 2 of 2).

Figure 68. Illinois design standard for CRCP bar reinforcement.

Figure 69. Illinois design standard for 24 ft (7.2 m) CRCP with wide flange beam transition joint (sheet 1 of 2).

Figure 70. Illinois design standard for 24 ft (7.2 m) CRCP with wide flange beam transition joint (sheet 2 of 2).

Figure 71. Illinois design standard for bridge approach pavement (sheet 1 of 4).

Figure 72. Illinois design standard for bridge approach pavement (sheet 2 of 4).

Figure 73. Illinois design standard for bridge approach pavement (sheet 3 of 4).

Figure 74. Illinois design standard for bridge approach pavement (sheet 4 of 4).

Figure 75. Chart for estimating wheel load tensile stress.

Figure 76. Minimum percent longitudinal reinforcement to satisfy crack width criterion.

Figure 77. Percent of longitudinal reinforcement to satisfy crack spacing criteria.

Figure 78. Minimum percent longitudinal reinforcement to satisfy steel stress criteria.
LIST OF TABLES

Table 1. Allowable steel working stress, ksi (MPa).(5) 19
Table 2. Weight and dimensions of ASTM standard reinforcing steel bars.(31) 22
Table 3. ASTM standard grades for reinforcing steel bars.(31) 22
Table 4. Friction coefficients for different base materials.(5) 35
Table 5. Wide-flange (WF) beam (weight and dimensions) (56) 39
Table 6. Summary of Inspection Tasks. 97
Table 6. Summary of Inspection Tasks. (continued) 98
Table 6. Summary of Inspection Tasks. (continued) 99
Table 6. Summary of Inspection Tasks. (continued) 100
Table 6. Summary of Inspection Tasks. (continued) 101
Table 7. Typical CTE for concrete made with common aggregate types. 133
Table 8. Approximate relationship between shrinkage and indirect tensile strength of concrete.(5) 133
What is CRCP?

Continuously reinforced concrete pavements (CRCP) contain continuous longitudinal reinforcement, usually steel, and do not have transverse joints except where necessary for construction purposes (e.g., end-of-day construction header joints) or at bridge approaches or transitions to other pavement structures.

Continuous reinforcement is a strategy for managing the transverse cracking that occurs in all new concrete pavements. In new concrete, natural volume changes due to cement-water hydration are restrained by the pavement base and other physical features adjacent to the concrete, causing stresses to develop in the concrete. These stresses build faster than the concrete’s strength so, at some point, full-depth cracks form, effectively dividing the pavement into individual slabs.

Unlike jointed plain concrete pavements (JPCP), where the number and location of transverse cracks are managed by sawing or constructing joints, in CRCP the continuous reinforcement allows transverse cracks to occur relatively closely together and holds them tightly closed for maximum aggregate interlock. As a result, load transfer between pavement slabs is maximized, and flexural (bending) stresses due to traffic loads and curling and warping are minimized.

In CRCP, longitudinal joints may be used to relieve concrete stresses in the transverse direction, for example when the paving width exceeds 14 ft. To hold any longitudinal cracks that may form tightly closed, CRCP commonly contains transverse reinforcement as well.

When and Why is CRCP Used?

Continuously reinforced concrete can be an excellent pavement solution for heavily traveled and loaded roadways, including interstate highways (Figure 1). Well designed and constructed CRCPs accomplish the following:

- Eliminate joint-maintenance costs for the life of the pavement, helping meet the public’s desire for reduced work zones and related traveler delays.
- Provide consistent transfer of shear stresses from heavy wheel loads, resulting in consistently quiet ride and less distress development at the cracks.
Such pavements can be expected to provide over 40 years of exceptional performance with minimal maintenance. These attributes are becoming increasingly important in high-traffic, heavy-truck areas, where delays are costly and a smooth ride is expected. Some of the most highly trafficked roadways in the country—including Interstate 75 in Atlanta, I-90 and I-94 in Chicago, and I-45 in Houston—demonstrate CRCP’s rugged, low-maintenance performance.

Data from the FHWA’s Long Term Pavement Performance (LTPP) program show that the large majority of heavily-trafficked sections of CRCP projects in 22 States have maintained their smoothness for 20 to 30 years and more.

CRCP can be easily widened to provide additional capacity and, after many years of service, can be overlaid with either concrete or asphalt.

Overview of Key Points for CRCP

Some States, including Illinois and Texas, have finetuned their CRCP design and construction techniques, resulting in lower life-cycle costs and increased public satisfaction.

Following is a brief list of key practices that help ensure successful CRCP projects:

- Design, mix, and construction decisions and practices (Figure 2 and 3) should maximize load-transfer efficiency and minimize flexural stresses.
- Cracks that are closely spaced (3-4 ft. maximum is optimum) and tight (0.02 in. at the depth of the reinforcement) help maximize load-transfer efficiency and minimize flexural stresses, maintaining steel stress well below the yield strength.
- Closely spaced, tight cracks result when the project includes
  - Adequate longitudinal steel content (0.6 to 0.8 percent of the slab cross-section area).
  - Optimum reinforcement diameter.
  - Adequate lapping of reinforcement splices.
  - Appropriate depth of reinforcement placement.
  - Thorough consolidation of concrete around the reinforcement,
- Reinforcement design has to consider possible fracture and/or excessive plastic deformation. Stress in the reinforcement is usually limited to a reasonable percentage of the ultimate tensile strength to avoid fracture and limit the amount of plastic deformation.
- Large, abrasion-resistant aggregates promote good aggregate interlock and thus enhance load-transfer efficiency.
- Sufficient slab thickness is required to manage transverse tensile stresses due to truck traffic and curling and warping.
- The foundation must be uniform and stable, provide good drainage, and extend beyond the slab edge through the shoulder area and through transitions at bridge approaches, cuts, and fills.
- Longitudinal construction joints must be tied to adjacent pavement at centerline or shoulder.
- Longitudinal contraction joints at shoulders should be sawed directly over the transverse reinforcement.
- Curing should be thorough and appropriate to each CRCP application, weather conditions, etc.
Many practices from the above list are illustrated in Figure 4, a typical modern CRCP cross section. Ongoing research, field monitoring, and materials innovations will likely result in additional refinements to these practices.

Figure 4. Typical CRCP cross section
CHAPTER 2
CRCP DESIGN OVERVIEW
Background

A recent survey on CRCP design practices in the US indicated that most States that commonly use this pavement type use the AASHTO design procedure published in 1986 (and later in 1993). One exception is Illinois, which uses a modified version of this method.\(^{(4,5)}\) While there are differences in the overlay design, the core of the pavement design procedures found in both the 1986 and 1993 editions is the same. Therefore, the guidelines presented herein refer to this method as the "AASHTO-86/93" design procedure.

Since the development of the AASHTO-86/93 design procedures, a number of new findings have been reported based on research conducted around the world. Some of these findings include improved practices based on a FHWA research study where CRCP sections in several states were evaluated.\(^{(6-12)}\) Additional findings have been reported from evaluation of sections in the LTPP database.\(^{(13,14)}\) Other experimental and field studies performed by individual States and around the world have also contributed to updates in CRCP design.\(^{(15,16,17)}\)

It is important that pavement design engineers in the US are aware of such findings, as they may very likely have an impact on the performance of CRCP that can translate into cost-effective pavement solutions.

Objectives

With the above considerations, this section of the guidelines is intended to provide updated design guidelines based on recent findings. These guidelines address available design methodologies, and include both state-of-the-practice and state-of-the-art recommendations. Guidance is included on the selection of design inputs, pavement performance criteria, and recommendations for different CRCP structural elements.

These guidelines are not in and of themselves a design method, but should instead be considered a synthesis of better design practices. It should be noted that at the time of writing this document, the interim AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) is currently being evaluated by State DOTs. While findings from these evaluations are ongoing, the authors have taken measures to incorporate a reasonable amount of relevant information in order to provide a preview of how this may affect CRCP design.

Scope of the Design Guidelines

The Design Section is divided into the following sections. Section 2 discusses CRCP Design fundamentals; this section provides a brief introduction on CRCP behavior followed by structural and functional criteria that should be considered during design.

Section 3 expands on the factors that should be considered during the design stage that are known to have an impact on CRCP performance, such as reinforcement type, pavement support, climate, and traffic.

Section 4 discusses the design of CRCP features; this section provides recommendations on the selection and sizing of various CRCP features including thickness, reinforcement, joints, and shoulders.
Designing a CRCP involves dimensioning the different geometric pavement features such as thickness, longitudinal and transverse reinforcement, construction joints, slab width, shoulders, and pavement transitions based on site-specific traffic, climatic, and foundation parameters. The designer selects pavement designs that will be suitable to achieve the desired performance level for the design period selected. As in all pavement designs, the goal is to use locally available materials to the greatest extent possible, but without compromising pavement performance.

The crack spacing, crack width, steel stress, and bond development length generated as a function of reinforcement restraint and climatic conditions each affect the CRCP structural integrity in the long term. It is important that precautions are taken during the CRCP design, materials selection, and construction process so that a crack pattern develops that minimizes development of pavement distresses.

It should also be noted that many of these design aspects described herein are common to all concrete pavements - not just CRCP. As a result, for brevity, some aspects of concrete pavement design will not be expanded upon herein. Instead, guidance should be sought from the appropriate design references such as the AASHTO-86/93 Guide. That said, the following sections provide a description of the factors affecting crack patterns that develop in early-age CRCP, and further discuss the impact that this CRCP behavior has on pavement performance. Additional information on structural and functional performance factors are also given.

CRCP Behavior

Following construction of a CRCP, a number of mechanisms influence development of stresses in the slab and thus the formation of cracks. Figure 5 provides a schematic representation of some of the factors influencing CRCP behavior. During the early age, temperature and moisture fluctuations induce volume changes in the concrete that are restrained by reinforcement and base friction, leading to the development of stresses.

Since concrete is weak in tension, whenever the stresses that develop are higher than the tensile strength of the concrete, transverse cracks form to relieve the stresses. Reinforcement serves to keep cracks closed as keeping the cracks tight is essential in maintaining load transfer through aggregate interlock. This, in turn, reduces pavement flexural stresses due to traffic loading.

Tight cracks are also beneficial to avoid water infiltration and intrusion of incompressibles through the cracks. Subsequent drops in temperature and the effect of drying shrinkage in the concrete tend to reduce the transverse crack spacing further. Externally-induced stresses due to wheel loads, and subsequent seasonal (climat) changes, further reduce the crack spacing over time, but at a much slower rate. Overall, it has been observed that the crack spacing decreases rapidly during the early age of the pavement, up until about one or two years. After this stage, the transverse cracking pattern remains constant until the slab reaches the end of its fatigue life.

Figure 5. Schematic representation of some of the factors influencing CRCP behavior.
The primary early-age pavement indicators of performance on CRCP include crack spacing, crack width, and steel stress. The following sections describe these indicators in more detail.

**Crack Spacing**

CRCP slab segments distribute traffic loads in the longitudinal and transverse directions. In the case of short transverse crack spacings with poor load transfer, however, the slab can act more as a beam with its longer dimension in the transverse direction. Significant transverse flexural stresses due to traffic loading can then develop. As a result, longitudinal cracks may subsequently form, progressing into a distress condition commonly known as a punchout (illustrated in Figure 6). On the other hand, larger crack spacings can result in wider cracks that have lower load transfer and are more prone to spalling. Evaluation of long-term performance of CRCP reveals that CRCP with adequate subbase support, and with widened lanes or tied concrete shoulders, provided excellent long-term performance. It appears from these more recent observations that crack spacing does not appear to have as significant an impact on punchouts or other distresses as was previously believed.

To minimize both of CRCP distresses, the AASHTO-86/93 Guide recommends controlling crack spacing to fall between 3.5 and 8 ft (1.1 m and 2.4 m). It has been found, however, that crack spacings of less than 2 ft (0.6 m) have performed well under good soil-support conditions. An analysis of LTPP data has shown some trend for a higher probability of punchouts when crack spacings are present less than 3 ft (1.0 m). The LTPP analysis is based on a limited number of sections, however. Ultimately, control of the number of short slab segments can be achieved through adequate materials selection and the use of good design and construction practices. Because of variability, it is also recommended that crack spacing be characterized in terms of both its average value and its distribution. For a given crack spacing distribution, the percentage of crack spacings that fall outside the recommended range should be determined, as this may be more indicative of the potential for distress during the pavement life.

Although the designer has some control over the crack patterns through the selection of the quantity of reinforcement, there are confounding factors cannot be as readily controlled during the design stage. These include the selection of materials, climatic conditions, and construction practices. It is therefore important that the highway agency ensure that the assumptions made during design are adhered to during the materials selection and construction process. This can be accomplished through use of targeted specifications or special provisions.

Finally, it should be noted that with respect to crack spacing, cluster cracking and Y-cracking are a unique case of short crack spacing that can be problematic in terms of their contribution to localized failures including punchouts. These types of cracking are generally more construction related, however, and not as much a design issue. They are often caused by localized weak support or because of inadequate concrete consolidation.

**Crack Width**

Crack widths have a crucial effect on CRCP performance in several ways. Excessive crack widths may lead to undesirable conditions such as infiltration of water that could later result in corrosion of the reinforcing steel and softening of the support layers. Incompressibles can also enter into wide cracks, and since the pavement is subjected to contraction and expansion as well as traffic loading, this can in turn lead to excessive bearing stresses at the cracks. If unchecked, these stresses can cause crack spalling. Furthermore, wider cracks mean that less contact exists between the faces of the crack, resulting in poor aggregate interlock. The consequence of this is an increase in slab deflections and flexural stresses that, in turn, lead to additional spalling, faulting, secondary cracking, and punchouts.

The AASHTO-86/93 Guide recommends limiting the crack width to 0.04 in (1 mm) at the pavement surface to avoid spalling. However, a crack width of 0.024 in (0.6 mm) or...
less has been found to be effective in reducing water penetration, thus minimizing corrosion of the steel and maintaining a high load transfer efficiency.\textsuperscript{(22,23)} As is done to control crack spacing, the designer may select a reinforcement percentage that achieves a desired crack width. However, it is ideal if the highway agency further ensure that assumptions made in design are adopted during construction.

In general, a higher percentage of longitudinal steel leads to smaller crack widths. The results of field performance evaluations have found that an adequate amount of longitudinal steel in the range of 0.6% to 0.85% effectively keeps crack widths reasonably tight throughout the pavement life.

The depth of the reinforcement is another important factor in controlling crack width. Major experiments in Illinois show that when reinforcement is placed above mid-depth, the cracks are more narrow leading to fewer punchouts and repairs over the long term. For reasons of adequate cover, reinforcement should not be placed closer than approximately 3.5 to 4 in (89 to 101 mm) from the surface of the CRCP.

**Reinforcement Stress**

The level of stress that develop in both the concrete and reinforcement will also influence CRCP performance in the long term. As stated before, the reinforcement serves to restrain volume changes in the concrete, keeping cracks tight. Consequently, significant stresses develop in the reinforcement at the crack locations. Reinforcement design has to consider possible fracture and/or excessive plastic deformation at these locations. Excessive yield or fracture of the reinforcement may lead to wide cracks, corrosion, and loss of load transfer that may later result in undesirable distress.

It is common for a limiting stress criterion to be used for reinforcement design. This is often selected as a fixed percentage of the ultimate tensile strength, thus avoiding fracture, and allowing only a small probability of plastic deformation.\textsuperscript{(5,24)} It should be recognized in design that slightly wider crack openings may result when permanent deformation is allowed to occur.

**Other Factors affecting CRCP Behavior**

It is known that crack spacing, crack width, and reinforcement stress are also a function of other factors. Concrete tensile strength compared to the level of stresses that result from the restraint to volume changes is one example. Any factor that affects the tensile strength, or other factors such as slab restraint will contribute to volume changes (or the restriction thereof). These will also have an effect on the cracking characteristics of CRCP.

**Structural and Functional Performance Indicators**

The following sections expand on CRCP structural and functional performance indicators. These indicators are sometimes used as design criteria. These factors should not only be considered during the design stage, but also controlled through construction specifications if possible. The result will be a pavement structure that is capable of accommodating the expected traffic and environmental loading.

**Punchouts**

A punchout is a type of distress that typically occurs between closely spaced transverse cracks in CRCP. It is defined as a block or wedge of CRCP that is delimited by two contiguous transverse cracks, a longitudinal crack, and the pavement edge. A picture of a typical punchout is presented in Figure 6.

A punchout commonly initiates in conjunction with excessive erosion of the support between two closely spaced transverse cracks. The natural opening and closing of cracks is caused by temperature and moisture changes in the slab. There is also a tendency of the aggregate interlock along the transverse crack to wear out under traffic. This results in a loss of load transfer.

Traffic loads and the curling and warping behavior of the slab segment combined with these circumstances can induce both high transverse shear and flexural stresses leading to the characteristic spalling along the transverse cracks and longitudinal crack formation typically 2 to 5 ft (0.6 to 1.5 m) from the pavement edge between transverse cracks. This combination of behavior describe the prerequisites for a punchout distress. Progression of the punchout distress continues with traffic loads and the formation of severe faulting. Loss of support, pumping of the base material, and the consequent reduction are all factors in the further development of the severity of the punchout distress.\textsuperscript{(25)}

The most important factor in preventing punchouts is use of a non-erodible pavement base material to minimize loss of support. Other factors that can be considered during the design stage to enhance the control of punchouts include:

- Adequate steel reinforcement to maintain tight crack widths.
• Sufficient concrete strength and slab thickness to reduce tensile stresses and cracking.

• Selection of hard and angular aggregates with a low coefficient of thermal expansion (CTE) that can improve load transfer. While most any aggregate can be successfully used in a CRCP, aggregates with these properties will improve the behavior of the cracks.

• The use of a stress relieving interlayer beneath the slab, sometimes referred to as a "bond breaker".

• Specification of curing techniques that allow for concrete hydration without excessive temperatures and subsequent drying shrinkage.

• Specification of mix designs that are suited for the environmental conditions.

• Slab thickness that is adequate given the magnitude of the traffic loading.

• Tied shoulders and widened lanes.

It is ideal for a pavement designer to obtain experience on those factors that influence punchout development under local conditions. For example, the Texas Department of Transportation (TxDOT) has performed extensive investigations into the effect of different aggregate materials on the performance of CRCP. These observations should be used in CRCP design.

Spalling

Spalling refers to a localized fracturing of concrete that occurring along cracks or joints. Several factors contribute to development of spalling in CRCP, but most stem from the presence of pre-existing fractures that are propagated into cracks leading to spall distress. For example, moisture loss and the associated drying shrinkage at the pavement surface, coarse aggregate type, and inadequate curing protection may result in weak concrete near the surface. This concrete is more prone to spalling, especially at transverse cracks in CRC pavement. Early-age horizontally-oriented delamination in combination with slab deflection of the pavement slab under load creates bearing stresses at the crack faces due to the action of load transfer. This can cause the concrete surface to spall in a relatively short period of time, and in turn, lead to spalling that is somewhat independent of traffic level.

One cause of spalling is the type of coarse aggregates, especially those low in quartzite content (<10% by weight). When these conditions exist, other design factors should be considered to minimize the potential for spalling including the selecting an improved curing method to enhance the strength of the concrete to resist delamination. Using a lower water-cement ratio is a measure that can also be used when river gravel coarse aggregates are used. This reduces the availability of surface water to the gravel materials. Another precaution can be made during concrete batching, where the coarse aggregate can be added as the last component. Finally, another measure that has been effective in preventing spalling is to blend calcareous aggregates with gravel sources which essentially increase the overall early-age bond strength of the concrete aggregate, thus reducing the potential for delamination and subsequent spalling.

Smoothness

Achieving a high level of smoothness is important, as it is known to correlate with ride comfort and safety by eliminating driver distractions and fatigue that originate from a rough surface. CRCP is no different from other pavements, where smoothness is an important performance indicator.

Figure 7. Spalling along transverse crack in a CRCP.
CHAPTER 4
CRCP DESIGN INPUTS
This section provides guidelines on the selection of CRCP design inputs. These inputs are divided into six major categories as follows: 1) Design Criteria; 2) Concrete Properties; 3) Reinforcement Type and Properties; 4) Pavement Support; 5) Climate; and 6) Traffic.

**Design Criteria**

Design criteria are pre-established parameters (controls and limits) that are required when designing a pavement structure. Design criteria for CRCP are often no different than other concrete pavements; however, some differences do exist and are worth noting. This section will highlight some of those differences.

**Limiting Criteria on Crack Spacing, Crack Width, and Steel Stress**

The AASHTO-86/93 Guide recommends controlling crack spacing to fall within 3.5 to 8 ft (1.1 m to 2.4 m).(5) However, the new CRCP design procedure described in the AASHTO Interim MEPDG does not provide recommendations on the control of minimum crack spacing due to the numerous factors that affect this variable including reinforcement percentage. A maximum average crack spacing of 6 ft (1.8 m) is however recommended. While it does not specify a minimum crack spacing, the AASHTO Interim MEPDG does instead recommend designing for small crack widths to ensure long-term performance.(29)

The AASHTO-86/93 Guide limits the crack widths to 0.04 in (1 mm) to avoid spalling.(5) However, crack widths of 0.024 in (0.6 mm) have been found to be more effective in reducing water penetration, and thus minimizing corrosion of the steel, maintaining the integrity of the support layers, and ensuring high load transfer efficiency.(22) The AASHTO Interim MEPDG predicts and requires a maximum crack width of 0.020 in (0.5 mm) over the entire design period.(29) Regardless of what procedure is used, the use of corrosive deicing salts should be taken into consideration when selecting the crack width criterion.

Reinforcement design has to consider possible fracture and/or excessive plastic deformation. To accomplish this, the stress in the reinforcement is usually limited to a reasonable percentage of the ultimate tensile strength to not only avoid fracture, but to limit the amount of plastic deformation.(5,24) Table 1 shows the maximum allowable working stress for steel with yield strength of 60 ksi (420 MPa) that is recommended by the AASHTO-86/93 Guide.

It can be noted that in some cases, the AASHTO-86/93 Guide allows a working stress above the yield strength that could result in a possibility of some plastic deformation.(5,24) As a result, it should be noted that slightly wider crack openings may result when permanent deformation is allowed.

With respect to the use of limiting criteria in general, it should be noted that CRCP design is continuing to evolve. Motivation for revised thinking is born out of the new design process inherent with the AASHTO Interim MEPDG. More importantly, however, it is the result of observations of in-service CRCP performance. While design of CRCP in the past might have required the conventional limiting criteria for crack spacing, crack width, and steel stress, these might not be as relevant today. The pavement designer is encouraged to seek out the latest guidance in this evolving practice before taking exception to what could be overly-conservative designs resulting from the current design standards.

<table>
<thead>
<tr>
<th>Indirect Tensile Strength of Concrete at 28 days, psi (MPa)</th>
<th>Reinforcing bar diameter, in (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5 (12.7)</td>
</tr>
<tr>
<td></td>
<td>0.625 (15.9)</td>
</tr>
<tr>
<td></td>
<td>0.75 (19.1)</td>
</tr>
<tr>
<td>300 (2.1) or less</td>
<td>65 (448)</td>
</tr>
<tr>
<td>400 (2.8)</td>
<td>67 (462)</td>
</tr>
<tr>
<td>500 (3.4)</td>
<td>67 (462)</td>
</tr>
<tr>
<td>600 (4.1)</td>
<td>67 (462)</td>
</tr>
<tr>
<td>700 (4.8)</td>
<td>67 (462)</td>
</tr>
<tr>
<td>800 (5.5) or greater</td>
<td>67 (462)</td>
</tr>
</tbody>
</table>

Table 1. Allowable steel working stress, ksi (MPa).(5)
Structural Performance

In mechanistic-empirical design procedures such as those developed for the AASHTO Interim MEPDG, structural performance for CRCP is typically expressed in terms of allowable punchouts per unit of distance (i.e., punchouts/mile) before rehabilitation is needed. Figure 8 conceptually illustrates the structural performance level in terms of punchouts as a function of time or load applications. Recommended threshold values for the allowable number of punchouts are commonly expressed as a function of the functional highway classification or traffic level. The limit that is selected is also a function of the design reliability (risk).

The AASHTO Interim MEPDG recommends a maximum of 10 medium- and high-severity punchouts per mi (6 punchouts/km) for interstates and freeways, 15 punchouts per mi (9 punchouts/km) for primary highways, and 20 (12) for secondary highways. The American Concrete Pavement Association (ACPA) recommends a maximum of 10 punchouts per mi (6 punchouts/km) for Average Daily Traffic (ADT) greater than 10,000 vehicles/day, 24 punchouts per mi (15 punchouts/km) for ADT between 3,000 and 10,000 veh./day, and 39 punchouts per mi (24 punchouts/km) for ADT below 3,000 veh./day.\(^{(29,30)}\)

Functional Performance

Like structural performance, functional performance thresholds are commonly defined based on the functional highway classification or traffic level. Figure 9 conceptually illustrates the functional performance level in terms of international roughness index (IRI) as a function of time or load applications. The AASHTO Interim MEPDG recommends a maximum IRI of 175 in/mi (2.7 m/km) for interstates and freeways, 200 in/mi (3.2 m/km) for primary highways, and 250 in/mi (4 m/km) for secondary highways. The ACPA recommends a maximum IRI of 158 in/mi (2.5 m/km) for ADT greater than 10,000 vehicles/day, 190 in/mi (3.0 m/km) for ADT between 3,000 and 10,000 veh./day, and 220 in/mi (3.5 m/km) for ADT below 3,000 veh./day.\(^{(29,30)}\)

Concrete Properties

In addition to concrete strength and elastic modulus, a number of other concrete properties influence CRCP performance. These include the heat of hydration, coefficient of thermal expansion, and shrinkage potential of the concrete mix. All concrete properties should be optimally selected according to site-specific conditions so that sufficient structural capacity is provided, capable of withstanding the anticipated traffic loads. The concrete should also possess the required characteristics to endure the expected environmental conditions.

Durability factors such as alkali-silica reactivity (ASR) potential, freeze-thaw damage, sulfate attack, and others that can be minimized or even avoided with proper design of the paving mixture. If possible, this should be considered during the design of the pavement through the development of project specifications and/or special provisions. Some of the more relevant concrete properties that should be considered in CRCP design include:

- Strength - Both the tensile strength and the flexural...
strength are the concrete properties of interest for reinforcement and thickness design, respectively.

° The transverse crack pattern in CRCP is related to the tensile strength of the concrete. Higher tensile strength typically results in larger crack spacings. In addition, greater variability in tensile strength can result in shorter crack spacings and vice versa. The 28-day tensile strength used for reinforcement design is determined through the American Standards for Testing and Materials (ASTM) C 496 or AASHTO T 198 splitting tensile tests.

° In addition to the effect of tensile strength on cracking behavior, CRCP also requires sufficient strength to resist traffic loads. Fatigue cracking in concrete is found to correlate with the flexural stress-to-strength ratio. For CRCP, maintaining stresses at a level that is much lower than the concrete flexural strength can minimize punchout development. The 28-day flexural strength is determined using the ASTM C 78 or AASHTO T 97 third-point loading (modulus of rupture) test, and is used in most thickness design procedures.

° The concrete strength used in CRCP design does not have to deviate from that currently used for jointed concrete pavement design.

- Concrete Coefficient of Thermal Expansion - Volumetric changes in the concrete, and thus the level of stresses generated, are governed in large part by the concrete coefficient of thermal expansion (CTE).

° CTE has been found to be one of the most influential factors on the behavior of CRCP.(23)

° All else being equal, selection of aggregate types with low CTE is recommended to achieve adequate cracking patterns minimizing the potential for punchout formation. For economic reasons, however, locally available materials should be used to the greatest degree possible. Improved construction practices including an optimized concrete mixture can often compensate for higher CTE.

- Drying Shrinkage - This is a function of a number of factors including the water-cement ratio, cement type, cement content, admixtures used, type and amount of aggregates, and climatic conditions.

° Should be kept as low as possible to minimize volumetric changes in the CRCP that can lead to wide cracks, adversely impacting performance.

- Heat of hydration - affects the set time, strength development, and modulus of elasticity development. In addition, the heat of hydration contributes to the temperature increase in the concrete during the first hours after placement.

° If possible, take measures to reduce the adverse affects of excessive heat of hydration, as it could affect CRCP performance.

More information on the influence of these and other concrete properties can be found in guidance such as the Integrated Materials and Construction Practices (IMCP) for Concrete Manual, developed by the National Concrete Pavement Technology Center (CP Tech Center).

Reinforcement Type and Properties

Several types of reinforcement have been used in CRCP, but by far the most common is deformed steel bars. Other innovative materials include solid stainless steel, stainless steel clad, and other proprietary materials such as fiber reinforced polymer (FRP) bars. Despite a higher initial cost, these all promise to provide more corrosion resistance than steel bars.(37,38,39) Currently, however, implementation of these materials has been more targeted more for their use as dowel bars.

Deformed steel bars are the most widely accepted type of reinforcement for CRCP. The difference in volumetric changes in the steel and the concrete generates stresses in both materials. Stress transfer from the steel to concrete depends on the steel surface area and the shape of the surface deformations on the reinforcing bar (rebar). It is thus important that the rebar comply with requirements specified in AASHTO M 31, M 42, or M 53 for billet-steel, rail-steel, or axle-steel deformed bars respectively.

Alternatively, ASTM A 615 for billet steel, and ASTM A 996 for rail- and axle-steel deformed bars, may be used. Bar designations as well as requirements for deformations and steel tensile strength or steel grade are provided in both the AASHTO and ASTM specifications. Table 2 shows weight and dimensions of ASTM standard reinforcing steel bars.

The required yield strength of reinforcing steel for use in CRCP is typically 60,000 psi (420 MPa), designated as English Grade 60 (metric Grade 420). Other reinforcing steel grades are presented in table 3. Higher steel grades have been used in some European countries and in some
It is important to note that although higher steel grades may suggest the use of less steel to maintain cracks tight, this may not necessarily be true as long as the elastic modulus of the steel remains unchanged. The use of higher quantities of carbon in steel production typically increases its strength, but often with no significant change in its elastic properties (modulus) which control crack widths. The elastic modulus of steel reinforcing bars is typically in the order of 29,000,000 psi (200,000 MPa).

Another property of interest for CRCP reinforcement design is the coefficient of thermal expansion of the steel. Depending on the difference in the steel and concrete CTE, varying restraint will result, leading to different crack patterns. The AASHTO-86/93 Guide recommends the use of a steel CTE of 5 x 10^-6 in/in/ºF (9 x 10^-6 m/m/ºC) in design. However, steel CTE values provided by the AASHTO Interim MEPDG range from 6.1 to 6.7 x 10^-6 in/in/ºF (11 to 12 x 10^-6 m/m/ºC).

### Pavement Support

#### Bases

Pumping of support layer material through CRCP cracks and joints is a common mechanism contributing to punchout formation. The erosion caused by pumping action may also result in increased pavement deflections that can lead to spalling at the cracks. The use of a base layer constructed with non-erodible, impermeable materials is typically specified on CRCP subjected to heavy traffic loads to minimize pumping. In addition to controlling pumping, the base layer provides a stable platform during construction and may serve other purposes such as controlling frost action and controlling shrink and swell of the subgrade due to moisture changes.

Friction between CRCP and an untreated base is low compared to a treated base. Thus, crack spacing and width will be larger if an untreated aggregate base is used as opposed to a treated (e.g., asphalt, cement) base. Although unbound

### Table 2. Weight and dimensions of ASTM standard reinforcing steel bars.

<table>
<thead>
<tr>
<th>Bar Size US (SI)</th>
<th>Nominal Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter, in (mm)</td>
</tr>
<tr>
<td>#3 (#10)</td>
<td>0.375 (9.5)</td>
</tr>
<tr>
<td>#4 (#13)</td>
<td>0.500 (12.7)</td>
</tr>
<tr>
<td>#5 (#16)</td>
<td>0.625 (15.9)</td>
</tr>
<tr>
<td>#6 (#19)</td>
<td>0.750 (19.1)</td>
</tr>
<tr>
<td>#7 (#22)</td>
<td>0.875 (22.2)</td>
</tr>
<tr>
<td>#8 (#25)</td>
<td>1.000 (25.4)</td>
</tr>
<tr>
<td>#9 (#29)</td>
<td>1.128 (28.7)</td>
</tr>
<tr>
<td>#10 (#32)</td>
<td>1.270 (32.3)</td>
</tr>
<tr>
<td>#11 (#36)</td>
<td>1.410 (35.8)</td>
</tr>
</tbody>
</table>

### Table 3. ASTM standard grades for reinforcing steel bars.

<table>
<thead>
<tr>
<th>Reinforcement Grade</th>
<th>Minimum Yield Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>English (Metric)</td>
<td>psi (MPa)</td>
</tr>
<tr>
<td>40 (300)</td>
<td>40,000 (300)</td>
</tr>
<tr>
<td>60 (420)</td>
<td>60,000 (420)</td>
</tr>
<tr>
<td>75 (520)</td>
<td>75,000 (520)</td>
</tr>
</tbody>
</table>
granular base materials have been used for low-volume traffic roads, typical base types used under most CRCP include non-erodible asphalt treated, cement treated, and lean concrete bases. These have shown to provide better control of pumping on heavily-trafficked highways. When a cement treated or lean concrete base is used, a thin layer of HMA is needed to reduce the potential of erosion and to provide adequate friction to produce proper crack spacing and widths. No attempt should be made to reduce the friction between the CRCP and the HMA layer.

Some performance problems have been reported in the past with the use of open-graded positive drainage systems, and the designer should take into account such risks. For example, problems observed with open-graded drainable bases under CRCP include lime-stabilized subgrades pumping into the permeable base material. Undesirable early-age cracking and poor performance of CRCP on cement-treated permeable bases has also been reported due to the high restraint (bond) at the CRCP/base interface. To help mitigate these problems, some States have recommended the construction of a 25-mm (1-in) dense-graded HMA interlayer directly atop the base, and beneath the CRCP.

The structural support that the base layer provides to the pavement depends primarily on its thickness and stiffness (elastic or resilient modulus). A stabilized base is typically 4 to 6 in (100- to 150-mm) thick as used under CRCP. A minimum base thickness of 4 in (100 mm) is required for constructability considerations. Greater base thicknesses should be provided when unstabilized materials are used and/or to control frost action or shrink-swell subgrade conditions. In these cases, a well-graded granular non-frost susceptible material may be used for the additional required frost susceptible depth.

Subgrades

The performance of any pavement - including CRCP - is affected by the support provided by the subgrade. Subgrades that provide uniform support and that are not affected by moisture variations result in better performing pavements than those with shrinking and swelling changes due to moisture variations. To take advantage of the support capabilities of a subgrade, the designer should provide adequate drainage and stabilization of the subgrade materials as required. In addition, it is convenient to divide the project in sections with similar support characteristics for pavement design purposes. The use of gradual transitions between cuts and fills are needed, especially in bedrock areas or at bridge approaches, to reduce stresses under the slab due to differential support. It has been noted that even in areas that exhibit uniformly poor support (as opposed to intermittent support), CRCP has demonstrated superior performance.

Drainage

While much less than for jointed pavements, water infiltrating through cracks and joints in a CRCP may contribute to moisture-accelerated damage because of erosion and loss of support underneath the pavement slab. While ensuring tight transverse crack widths may reduce the infiltration of water, the use of erosion resistant stabilized bases may be warranted, especially for pavements exposed to high levels of precipitation and/or high traffic volumes.

Climate

The climatic conditions expected during placement and during the service life of the CRCP should be considered during the design stage as they affect the cracking behavior and thus may affect the potential development for punchouts in the long term. For example, the precipitation expected in the region will influence the selection of the drainage system required.

CRCP construction in hot climates causes an increase in the concrete heat of hydration and thus the slab temperature at set. Subsequent temperature drops can result in short crack spacings and meandering cracks, increasing the potential for punchout occurrence. In addition, when paving during hot weather, the pavement is more prone to experience excessive moisture loss from the pavement surface, which may result in subsequent spall development. Besides air temperature, low ambient humidity, and high wind speeds can also contribute to higher moisture loss from the concrete surface.

While climatic effects on early-age CRCP behavior will vary based on the project location and time of year of construction, previous investigations of early-age CRCP behavior have demonstrated that the time of day when the pavement is placed can affect the crack pattern. For example, when constructing CRCP in hot weather and placing in the late afternoon and early evening, the concrete heat of hydration will typically occur at a different time than the peak air temperature. This can result in a lower temperature drop in the concrete, and thus more uniform crack spacing.

Although the designer might not have control over the placement time, specifications or special provisions can be used to limit the maximum temperature of the concrete mix [typically 90 to 95°F (32.2 to 35°C)] during placement of concrete. The heat of hydration and thus maximum temper-
ature in the concrete will be a function of the constituents and proportions of the concrete mix. Therefore, specifications that limit the maximum curing temperature of the concrete rather than the temperature of the mix are more desirable as they provide the designer with a better control of the maximum temperature drop expected. A specification that controls the maximum curing temperature in the concrete has been recently investigated in Texas, and some concepts are provided in Appendix A. (48)

When designing CRCP, adequate selection of the design temperature drop should be made. The design temperature drop is sometimes based on both the average concrete curing temperature after placement and the lowest slab temperature during the year for where the CRCP will be constructed:

\[ \Delta T_D = T_H - T_L \]

where, \( \Delta T_D \) = Design Temperature Drop (°F or °C),  
\( T_H \) = Average concrete curing temperature after placement (°F or °C), and  
\( T_L \) = Average daily low temperature during the coldest month of the year (°F or °C).

Oftentimes during the design stage, little information on when the pavement will be placed is available. Therefore, the average concrete curing temperature is commonly assumed as the average daily high temperature for the hottest month of the year. Historical climatological records can be obtained from the National Oceanic and Atmospheric Administration (NOAA) to estimate the design minimum temperature. The design minimum temperature is typically taken as the average daily low temperature for the coldest month of the year. It should be noted that if the design temperature drop is being used to estimate the critical crack width, a value of 32°F (0°C) may be considered for TL, since water infiltration is not as much of a concern in sub-freezing temperatures.

**Traffic**

The level of traffic to which a pavement structure will be subjected dictates a number of design considerations. All pavements, including CRCP, are primarily designed to withstand the level of traffic loads to which they will be subjected under specific environmental conditions. For this purpose, traffic is characterized based on how it will affect the level of stresses in the pavement structure. Primary traffic characteristics include load configuration, traffic volume, traffic classification, traffic distribution, growth rate, and traffic wandering.
CHAPTER 5
DESIGN OF CRCP FEATURES
All too often, pavement design tends to focus only on thickness design. However, there are numerous other aspects of a CRCP that affect its behavior and performance including the reinforcement, thickness, shoulders, support, and concrete-making materials. The design of the CRCP should therefore consider each of these features, and ideally arrive at an optimum design through an iterative process.

To complete the design, a life-cycle cost analysis is sometimes performed. This allows the designer to take into account the costs associated with various pavement design alternatives along with the benefits in terms of increased pavement performance.

**CRCP Design Methods**

Various design methods for determination of slab thickness and the amount of reinforcement required in CRCP have been developed in the past. The two most relevant due to their common use and/or level of validation include:

1. AASHTO-86/93 Guide for Design of Pavement Structures
2. AASHTO Interim MEPDG

**AASHTO-86/93 Design Procedure**

Although the AASHTO-86/93 Guide procedure does not directly consider one of the primary failure mechanisms in CRCP (punchout development), this procedure has been used for design of CRCP by making similar considerations to those for the design of jointed concrete pavements. In addition, because reinforcement keeps cracks tight in CRCP, a slightly improved load transfer coefficient is typically used, which results in a moderate reduction in thickness for this pavement type under similar traffic and environmental conditions.

The AASHTO-86/93 method also includes design procedures for the selection of reinforcement. These procedures are based on a desired range of crack spacing, maximum crack width, and maximum steel stress. It should be noted that it has been reported that this design procedure tends to underestimate the required steel. A summary of the AASHTO-86/93 design procedure is presented in Appendix B since it is currently the most widely used design procedure for design of CRCP.(4)

**AASHTO Interim MEPDG**

Over the last decade, the National Cooperative Highway Research Program (NCHRP) has undertaken a major effort to develop the next generation of pavement design procedure based on mechanistic-empirical methods. This has been conducted under research project 1-37A, and has resulted in the current AASHTO Interim MEPDG. In this design procedure, specific mechanistic-empirical models for prediction of CRCP performance have been developed.(29,53)

A flow diagram of the AASHTO Interim MEPDG CRCP design process is given in Figure 10. The process begins with the selection of a trial design including layer thicknesses, materials, reinforcement, shoulder characteristics, and construction information. Site-specific conditions including environment, foundation, and traffic are also considered. Performance criteria in terms of punchouts and IRI are then specified, along with the reliability level for each criterion. The MEPDG also has limiting design criteria on crack width (over design period), crack spacing, and crack load transfer efficiency (over design period as well).

The procedure explicitly predicts punchout development as a function of the crack width and load transfer efficiency due to aggregate interlock at transverse cracks. Stresses due to loading are predicted as a function of load transfer efficiency, and continuously evaluated and modified throughout the design period. Fatigue damage as a function of the stress level and strength is evaluated and accumulated, and punchout development is subsequently predicted.

IRI is also predicted throughout the design period as a function of the initial smoothness conditions, punchout development, and site-specific conditions. Once the trial design is evaluated, its predicted performance is checked against design criteria at the specified reliability level. If the design requirements are satisfied, the trial design is considered as a viable alternative that can later be evaluated in terms of life-cycle costing. Otherwise, a new trial design is evaluated.
Figure 10. Framework of CRCP design procedure in the AASHTO Interim MEPDG.(29)
Early-Age Behavior Analysis Tools

In addition to the above design procedures, software tools such as FHWA HIPERPAV (High PERformance concrete PAVing) II and CRSI PowerPave are currently available to engineers for the analysis of CRCP early-age behavior. These tools can be used as a way to fine-tune designs under given site-specific construction scenarios. These tools may be also helpful in developing specifications based on locally available materials and construction procedures.

HIPERPAV II

Developed under sponsorship of the FHWA, this software represents computerized design and construction guidelines for optimization the early-age behavior of CRCP. In HIPERPAV II, the crack spacing, crack width, steel stress, and bond development length are predicted as a function of design, materials, environment, and construction factors, and then evaluated in terms of predefined design thresholds. A sophisticated model for the prediction of concrete pavement temperature is used at the core of the software. The predicted pavement temperature is used for both the prediction of strength and stress development in the concrete. The cracking prediction is based on the CRCP-8 model. Originating from findings under NCHRP research project 1-15, the CRCP-8 model has since been extensively validated through laboratory and field testing.

PowerPave

Developed by CRSI, PowerPave is similar to HIPERPAV II, and is also based on the CRCP-8 model. However, pavement temperature is not predicted but it is rather an input to the software.

Evaluation of Critical Stresses

It is sometimes worth checking the level of stresses of a CRCP in order to evaluate the use of alternate base types. A program based on elastic layered theory (ELSYM5 or BISAR) can be used for this purpose. Alternatively, discrete element (SLAB49) or finite element (ILLISLAB, ISLAB2000, ABAQUS, EverFE2.2) methods can be used. These programs can also be used to model Westergaard's plate theory and develop composite k-values. Additional discussion of stress evaluation can be found in the AASHTO Interim MEPDG documentation.

Concrete Thickness

Thickness design involves the determination of the minimum required CRCP thickness that will produce an acceptable level of stress in the pavement under traffic and environmental loadings. The assumption being that the targeted stress will reduce the potential for punchouts and other structural distresses, while at the same time maintaining an acceptable level of function (e.g., smoothness).

Reduction of stresses in the pavement slab is not only achieved by increasing thickness but by consideration of numerous other factors including:

- High load transfer efficiency - This can be accomplished by keeping transverse cracks tight with the use of an adequate longitudinal steel content to achieve good aggregate interlock. Selecting large size aggregates that are resistant to abrasion will also improve load transfer at the cracks.

- Sufficient lateral support - Tied concrete shoulders or widened lanes that extend beyond the wheelpath into the shoulder at least one foot provide improved lateral support over asphalt shoulders, as well as aid in mitigating punchouts.

- Uniform and stable structural support under the slab - This may be achieved by stabilizing subgrade if swelling is expected and/or by selecting erosion-resistant bases that minimize erosion and pumping of subgrade materials and through accelerated freeze-thaw and wet-dry testing with strength assessment can be demonstrated to have long-term durability.

- Prevention of subgrade or base saturation - This can be achieved by improving drainage features such as selecting non-erodible or permeable moisture insensitive bases.

- Improved concrete structural properties - Although excessively high concrete strengths are not desirable, producing concrete with sufficient strength and a low modulus of elasticity will help in reducing stresses due to traffic loading.

Taking the above measures will minimize potential for punchout development at a minimum required thickness, thus resulting in a more cost-effective design.

In the past, it was common practice by some States to design CRCP thickness based on jointed concrete pavement methodology, and then reduce the thickness by as much as 20 percent to account for the effect of increased load transfer efficiency at the cracks.
In some cases, this resulted in an under-design, which in turn required expensive maintenance and rehabilitation. As a result, this practice is no longer recommended. Today, typical CRCP thicknesses vary from 7 to 15 in (178 to 381 mm) depending on the level of traffic and environmental conditions, although most common practice is between 10 and 12 inches (254 to 305 mm).

**Longitudinal Reinforcement**

Reinforcement design involves selecting the proper percentage, bar size, and bar configuration for optimum CRCP performance. Reinforcement design is focused on providing the minimum reinforcement necessary to develop the desired crack spacings and widths, while at the same time keeping the steel at an acceptable level of stress. States that have been designing CRCP have established standard details for longitudinal layout and bar size.

**Reinforcement Content**

Longitudinal steel reinforcement content is defined as the ratio of the area of longitudinal steel to the area of concrete \( \left( \frac{A_s}{A_c} \right) \) across a transverse section, often expressed as a percentage. As illustrated in Figure 11, higher amounts of steel reinforcement will result in shorter crack spacings, smaller crack widths, and lower steel stresses. An increase in the percent of longitudinal reinforcement will result in an increase in restraint.

As the level of restraint increases, so does the number of cracks that develop, resulting in shorter crack spacings. In addition, as the amount of reinforcement increases, the average steel stresses are reduced, producing less reinforcement elongation.

As previously mentioned in Section 2.1.1, crack spacings between 3.5 to 8 ft (1.1 and 2.4 m) minimize the potential for development of punchouts and spalling. However, it has been observed that crack spacings as short as 2 ft (0.6 m) have shown good performance as long as good support underneath is provided. Crack widths under 0.024 in (0.6 mm) prevent infiltration of water and incompressibles, and ensure adequate load transfer efficiency between the cracks thus reducing load induced stresses. In addition, keeping the steel working at an acceptable stress level minimizes fracture of the steel or excessive yield that may lead to wide cracks with poor load transfer efficiency.

Longitudinal reinforcement should be designed to meet the following three criteria:

1. Produce a desirable crack pattern (spacing),
2. Keep transverse cracks tightly closed, and
3. Keep reinforcement stresses within allowable levels.

![Figure 11. Conceptual representation of steel design for CRCP.](image-url)
Although cracking characteristics in CRCP largely depend on the amount of reinforcement, they are also a function of the climatic conditions during placement, materials properties, and construction factors as discussed in Section 3. When designing for longitudinal reinforcement, all these factors need to be taken into consideration.

Specifications for maximum concrete temperatures, low CTE aggregates, and proper curing procedures can help ensure that the intended performance from the reinforcement design will be achieved.

It is also important to consider the effect that excess thickness can have on CRCP performance. Concrete pavement specifications commonly allow for a pay incentive (bonus) for additional pavement thickness due to the resulting increase in structural capacity. However, for CRCP, increasing the thickness (while maintaining the same amount of reinforcement) results in a reduction of the reinforcement percentage. This, in turn, can result in larger crack spacings, wider cracks, and an increase in reinforcement stress. This effect should be considered when specifying an upper limit for thickness pay incentives. For this reason, CRCP should also not be used as a leveling layer.

**Bar Size and Spacing**

Longitudinal steel is typically designed to meet a minimum spacing in order to achieve good consolidation of concrete during placement. A maximum spacing is also considered to exist in order to ensure adequate concrete bond strength and thus tight crack widths. FHWA Technical Advisory T 5080.14 provides guidelines for minimum and maximum spacing of longitudinal steel as follows:(56)

- The minimum spacing of longitudinal steel should be the greater of 4 in (100 mm) or 2½ times the maximum aggregate size.
- The spacing of longitudinal steel should be not greater than 9 in (230 mm).

Typical bar sizes used in CRCP range from #4 (0.5 in) to #7 (0.875 in) [#13M (12.7 mm) to #22M (22.2 mm)]. Selection of the steel bar size (diameter) is governed by steel percentage and minimum and maximum spacing permitted.

With the required amount of reinforcement and bar size selected, the reinforcement spacing, S, may be computed as follows:

\[
S = \frac{\phi^2 - \pi}{4 \cdot D \cdot p_s} \cdot 100
\]

where,  
- \( S \) = Reinforcement spacing (in or mm),
- \( \phi \) = bar diameter (in or mm),
- \( D \) = Slab thickness (in or mm),
- \( p_s \) = Longitudinal reinforcement percentage (fraction), and
- \( \pi \) = pi (3.141593).

It is recommended that the reinforcement spacing determined with the above equation be considered as the maximum to maintain the required longitudinal reinforcement percentage. If this spacing needs to be adjusted, it should be done so by rounding down to a practical spacing according to pavement geometry.

Another option commonly exercised is to space the bars near the slab edge closer, as indicated in TxDOT standard "CRCP (1) 03" (shown in Appendix A).

Figure 12 provides recommended bar spacing for various slab thicknesses and bar sizes as a function of reinforcement percentage.
Other considerations should be made when selecting the bar size including evaluation of the reinforcement surface (bond) area. It has been observed that the average crack spacing decreases with an increase in ratio of reinforcement surface area to concrete volume. A possible explanation for this is that the high tensile stresses in the steel at crack locations are transferred to the concrete as a function of the reinforcement surface area and deformation characteristics of the longitudinal reinforcement.\(^{(55)}\) On the other hand, the greater the bond area, the more restraint to movement of the concrete is imposed by the steel, and therefore, tighter cracks are expected to result.\(^{(57)}\)

For a given reinforcement percentage, higher surface area is achieved using smaller bar sizes. Therefore, reinforcement design should also consider this. For this reason, the ratio of reinforcement surface area to concrete volume, \(R_b\), is typically controlled to take into account the bar size effect. This ratio can be determined with the following relationship:

\[
R_b = \frac{\phi \cdot \pi}{S \cdot D} \quad (\text{sq. in/cu. in or } m^2/m^3)
\]

Where, \(R_b\) = Ratio of reinforcement surface area to concrete volume,

\[
\phi = \text{bar diameter (in or mm)},
\]

\[
\pi = \text{pi (3.141593)}
\]

\[
S = \text{Reinforcement Spacing (in or mm), and}
\]

\[
D = \text{Slab thickness (in or mm)}.
\]

A minimum ratio of steel surface area to concrete volume of 0.03 sq.in/cu.in (1.2 m\(^2\)/m\(^3\)) is typically recommended for summer construction and of 0.04 sq.in/cu.in (1.6 m\(^2\)/m\(^3\)) for fall or winter construction.\(^{(9)}\)

![Figure 12. Reinforcement spacing recommendations.](Continuously Reinforced Concrete Pavement Design and Construction Guidelines)
Vertical Position of Reinforcement

There are two primary considerations that should be made when selecting the vertical position of the longitudinal reinforcing steel.

On one hand, drying shrinkage and temperature fluctuations are typically more pronounced at the pavement surface, and can result in wider cracks at this location. It is believed that by positioning the reinforcement closer to the surface, narrower crack widths and higher load transfer efficiency can be achieved.

On the other hand, keeping the reinforcement closer to the surface increases the probability of exposure to chlorides from deicing salts, which may lead to corrosion. Future diamond grinding of the pavement surface would further reduce the distance of the reinforcement from the surface. Given these two considerations, it is common to position the reinforcement between one-third and one-half the slab thickness measured from the pavement surface.

To provide sufficient concrete cover, it is typically recommended to specify a reinforcement depth of at least twice the maximum aggregate size. Illinois DOT requires a minimum reinforcement depth of 3.5 inches (8.9 centimeters) from the pavement surface to the top of the longitudinal reinforcement to minimize the possibility of corrosion and to accommodate variations in construction procedures.

It is also recommended that the maximum reinforcement depth be no more than half the slab thickness measured from the surface. As illustrated in Figure 13, placement of reinforcement in two layers has also been used. This is implemented in the TxDOT specifications for pavements thicker than 13 in (330 mm). The TxDOT standard CRCP(2)-03 in Appendix A shows a detail for placement of reinforcement in two layers.

Figure 13. Two-layered steel reinforcement mat.

It is believed that placement of the required reinforcement in this way not only helps to maintain the optimum reinforcement bond area to concrete volume ratio, but also ensures proper spacing while at the same time allowing reinforcement to be positioned closer to the CRCP surface where shrinkage strains tend to produce larger crack widths.

Based on long-term field testing in Illinois and on other projects in Belgium and elsewhere, the depth of reinforcement was a major effect on crack width. The higher the position of the reinforcement, the tighter the transverse cracks. Illinois sections with mid-depth steel had much more full depth repair than those with reinforcement above mid-depth over a 20 year period. Illinois recommends a 3.5 in (89 mm) covering over the reinforcement. The highly successful CRCP pavements in Belgium also place reinforcement above mid-depth.

Lap Splices

Adequate design of the reinforcement lap splices is necessary to maintain reinforcement continuity. Forces induced in the reinforcement by thermal and shrinkage movements are transferred through the lapped splice from one bar to the other by the surrounding concrete bonded to both bars. A minimum lap length of the splices is therefore necessary to ensure sufficient load transfer. Inadequate design and/or construction of the lap splices can result in failure of the reinforcement and poor CRCP performance, ultimately requiring expensive repairs.(58) Typical lap patterns are shown in Figure 14 and also in Figure 68 of Appendix A.

The effectiveness of the splice relies on achieving sufficient bond development length between the concrete and the reinforcement. Special consideration should be given to ensure that the concrete achieves adequate bond strength during the critical early-age period. This is particularly important during cold weather construction when the concrete gains strength at a lower rate.

Guidelines on splicing length among the different States vary from 25 to 33 bar diameters.(32) Some State specifications require the use of a fixed length of lap splicing varying between 16 and 20 in (406 and 508 mm). An experimental study looking at the bond development length for CRCP reported that lap splices of 33 bar diameters provide good performance, and may be the basis for the larger splice length specified.(59)

FHWA Technical Advisory T 5080.14 recommends a minimum splice length of 25 bar diameters if the splicing is performed in a staggered or skewed pattern. For a staggered...
splice pattern, no more than one third of the bars should terminate in the same transverse plane. In addition, the minimum distance between staggers should be 4 ft (1.2 m).

For the skewed splice pattern, the skew angle should be at least 30 degrees from perpendicular to centerline. In practice, an approximate skew configuration may be achieved by skewing the reinforcement by half the pavement width (Figure 14). In any case, it is recommended that a minimum lap splicing of no less than 16 in (406 mm) be provided.

**Corrosion Protection**

Some states require epoxy-coated rebar in CRCP to prevent corrosion of the reinforcement, especially in urban areas where maintenance and rehabilitation activities are strongly discouraged. This step may also be justified in environments with high exposure to chlorides from deicing salts, especially where corrosion has been previously identified as a problem.

The use of solid stainless steel, stainless steel clad, and other proprietary reinforcement non corrosive materials, such as Glass Fiber Reinforced Polymer (GFRP), may be considered in areas with high chloride, with heavy deicer applications, or where long life (50 years or greater) is desired. Corrosion of reinforcing steel in CRCP has been rarely reported though, and is usually attributed to inadequate reinforcement design resulting in wide transverse cracks. (60)

The designer should strive to provide sufficient reinforcement to maintain narrow crack widths and sufficient reinforcement depth. These measures will help to minimize the probability of reinforcement exposure to chlorides from deicing salts. Additionally, increased steel percentages to account for potential corrosion may be also considered during design.

In the case where epoxy-coated bars are employed, the effect of the epoxy coating on the reinforcing steel bond development length should be accounted for. The FHWA Technical Advisory TA 5080.14 recommends an increase of 15 percent in the bond area when epoxy coated rebar is used. (56)

Although, some studies have found no significant difference in cracking patterns between the use of uncoated and epoxy-coated reinforcement. It is believed that additional research is needed in order to better understand the effect of epoxy coatings on CRCP behavior and performance.

![Figure 14. Typical layout pattern with laps skewed across pavement.](image-url)
Transverse Reinforcement

Transverse reinforcement in CRCP serves several purposes, including:

1. To function as tiebars across longitudinal joints (if continuous).
2. To keep uncontrolled longitudinal cracks that may form held tight (which may occur due to shallow saw cuts, late sawing, differential settlement, or heave).
3. To support longitudinal steel in place (ensuring proper spacing and depth according to specifications if mechanical placement of the longitudinal steel is not used).

Illinois and Texas, which both predominantly use CRCP, both use transverse reinforcement - Illinois in urban areas and Texas in all areas. For pavements wider than 7m (24 ft), it is recommended to use continuous transverse reinforcement with an expansion joint adjacent to concrete traffic barriers.

Size and Spacing

As with longitudinal reinforcement, the design of transverse reinforcement consists of determining the required amount of reinforcement per cross sectional area of concrete, and then selecting a corresponding bar size and spacing configuration. The reinforcement design is based on equilibrium of base layer restraint and concrete contraction forces. The required percentage of transverse reinforcement can be obtained with the following relationship:

\[ p_t = \frac{\gamma_c \cdot W_s \cdot F \cdot 100}{2f_s} \]

where, \( p_t \) = Percentage of transverse reinforcement (%),
\( \gamma_c \) = Unit weight of concrete (lb/cu.in or kN/m3),
\( W_s \) = Total pavement width (in or m),
\( F \) = Coefficient of friction (unitless), and
\( f_s \) = Working stress of steel (75% of yield strength) (psi or kPa).

Friction coefficients for different base materials are provided in Table 4.

Once the required percentage of transverse reinforcement is determined, a bar size is selected and the transverse steel spacing is obtained as follows:

\[ Y = 4 \cdot p_t \cdot D \cdot 100 \]

where, \( Y \) = Transverse steel spacing (in or mm),
\( \phi \) = Bar diameter (in or mm), and
\( D \) = Slab thickness (in or mm).

Typical reinforcing recommended in the transverse direction includes # 4 to # 6 (12.7 to 19.1 mm) Grade 60 (Grade 420) deformed bars. It is common for transverse reinforcement to be spaced from 12 in (0.3 m) to 36 in (0.9 m) apart. It should be noted that following this design procedure is very conservative, as the steel stresses are greatest at the tied joints and in the center of the pavement and decrease to zero at the free edges.

Transverse reinforcement may serve a second purpose as tiebars if continuous across the joint. In this configuration, the transverse bars are typically extended half the required tiebar length across the longitudinal joint. For example, for a 24-ft (7.3-m) wide pavement, transverse reinforcement is designed for 12-ft (3.65-m) pavement widths and this reinforcement is extended across the middle longitudinal joint to function as a tiebar.

Since transverse reinforcing bars are typically used to keep longitudinal reinforcement bars in place, they are commonly specified to be positioned below the longitudinal reinforcement.

Tiebars

Tiebars are used along lane-to-lane or lane-to-shoulder longitudinal joints, when placed in separate passes, to keep these joints tight, and to ensure adequate load transfer. The required amount of tiebar reinforcement along longitudinal

<table>
<thead>
<tr>
<th>Type of Material Beneath Slab</th>
<th>Friction Factor (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface treatment</td>
<td>2.2</td>
</tr>
<tr>
<td>Lime stabilization</td>
<td>1.8</td>
</tr>
<tr>
<td>Asphalt stabilization</td>
<td>1.8</td>
</tr>
<tr>
<td>Cement stabilization</td>
<td>1.8</td>
</tr>
<tr>
<td>River gravel</td>
<td>1.5</td>
</tr>
<tr>
<td>Crushed stone</td>
<td>1.5</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1.2</td>
</tr>
<tr>
<td>Natural subgrade</td>
<td>0.9</td>
</tr>
</tbody>
</table>
joints is determined in a similar way as for transverse reinforcement. However, in this case, the length of pavement for analysis corresponds to the distance from the tied joint to the closest free edge.

A shorter distance to the free edge will result in a lesser amount of reinforcement required to hold the longitudinal joint together. The following equations are used to determine the percentage of tiebar reinforcement and tiebar length required:

\[ p_t = \frac{Y_c \cdot W' \cdot F}{f_s} \cdot 100 \]

Where, \( p_t \) = Percentage of tiebar reinforcement (%),
\( Y_c \) = Unit weight of concrete (lb/in\(^3\) or kN/m\(^3\))
\( W' \) = Distance from tied joint to closest free edge (in or m),
\( F \) = Coefficient of friction, and
\( f_s \) = Working stress of steel (75% of yield strength) (psi or kPa).

\[ t = \frac{1}{2} (\frac{f_s \cdot \phi}{f_b}) + 1a \]

Where, \( t \) = Tiebar length (in or mm),
\( \phi \) = Bar diameter (in or mm),
\( f_s \) = Working stress of steel (75% of yield strength) (psi or MPa).
\( f_b \) = Allowable bond stress (typically assumed to be 350 psi (2.44 MPa)),
\( 1a \) = Additional length for misalignment (3 in or 75 mm)

For economy and simplicity, tiebar length is often selected based on available standard manufactured lengths. Typical tiebars consist of Grade 40 or 60 (Grade 300 or 420) steel. Common standard manufactured tiebar lengths include 24, 30, 36, 42, and 48 in (0.61, 0.76, 0.91, 1.07, and 1.22 m). A maximum tiebar spacing of 48 inches (1.22 m) is recommended.

For wide pavements, it is generally more economical to provide an untied longitudinal joint rather than extending transverse bars along the total pavement width. Caltrans, for example, requires at least two lanes but no more than 50 ft (15.2 m) between untied joints. An untied joint may alleviate excessive transverse concrete stresses that could lead to potential longitudinal random cracking. It is recommended that untied joints be located far from the pavement edge to avoid lane separation. Expansion joints adjacent to concrete traffic barriers without providing load transfer are commonly used to prevent the formation of uncontrolled longitudinal cracks in these situations.

For longitudinal construction joints, tiebars are often inserted along the edge while concrete is fresh. It should be emphasized though that bending of the tiebar should be discouraged since it may result in cracking of the steel, and based on experience, there have been several instances where the tiebars have not been unbent prior to placing the adjacent concrete. In addition, when tiebars are epoxy coated, bending may result in damage of the epoxy, giving place to corrosion.

Some State DOTs require the use of multiple-piece tiebars to prevent problems associated with bending bars. This type of tiebar comes in two pieces that are threaded together. Female couplers are inserted along the longitudinal joint in the fresh concrete before paving the adjacent section; the threaded piece is later screwed to form a complete tiebar. With the use of these mechanisms, bending of the tiebar is avoided. Multiple-piece tiebars should conform to ASTM A 615 specifications, and the coupler should be required to develop a failure force of 1.25 to 1.5 times the yield strength of the steel. (2) Another option is to drill and epoxy tiebars and require a pull-out test as per ASTM E 488. Regardless of the tiebar type and method of placement, it is important to ensure that tiebars are securely anchored so that they provide the pull-out resistance required by design.

**Joints**

CRCP does not require transverse joints in the same way that jointed concrete pavements do. However, joints in CRCP are still necessary. Joints in the longitudinal direction are used between traffic lanes, and between traffic lanes and tied concrete shoulders. Transverse joints are also necessary for construction purposes at the start and end of daily operations. Transition or terminal joints are also necessary for approaches to some types of structures and the transition to other pavement types. This section provides design details that should be considered when designing CRCP joints.
Longitudinal Joints

The use of longitudinal joints is recommended for pavements wider than 15 ft (4.6 m). Joints are typically located in between lanes and between a lane and a concrete tied shoulder. Tiebars or transverse reinforcement should be provided along longitudinal joints to prevent separation, and to maintain adequate joint transfer efficiency. Two types of longitudinal joints are commonly used in CRCP: construction and contraction joints.

Better practices for concrete pavement joints can be found in the IMCP manual and elsewhere. However, some typical sections of joints that have been used on CRCP pavements are given herein.

A longitudinal construction joint is illustrated in Figure 15, and is specified when more than one pass is necessary to pave the total pavement width. In the past, it was recommended that trapezoidal or half-round keyways were formed along the longitudinal construction joints to increase its load transfer efficiency. However, some key joints have failed in shear resulting in spalling along the joint. In addition, the area along the keyway may be more susceptible to concrete consolidation problems. It is therefore recommended that tied butt joints be used instead.

Longitudinal contraction (hinged) joints, as illustrated in Figure 16, ensure that longitudinal cracking on wide pavements occur along a fixed (weakened) plane. Longitudinal joints are created by performing a sawcut at the specified joint location to relieve the stresses generated in the transverse direction of the concrete due to volumetric changes. Along these longitudinal joints, either transverse reinforcement or tiebars should be used to tie the adjacent slabs together and to maintain adequate load transfer efficiency. Reinforcement design should follow recommendations provided in Section 4.5.

![Figure 15. Longitudinal construction joint with multiple piece tiebars.](image)

![Figure 16. Longitudinal contraction (hinged) joint with transverse bars.](image)
Transverse Construction Joints

Transverse construction joints are formed at the start and end of paving operations, or whenever paving operations are halted long enough to form a cold joint. Proper design and construction of transverse construction joints is essential to maintain continuity of the CRCP.

Figure 17 shows a transverse construction joint detail. A minimum of 1.0% of longitudinal reinforcement should be provided at transverse construction joints by placing additional reinforcement bars along the joint. Deformed bars 72-in (1.8-m) long and with the same size and grade of the longitudinal reinforcement are typically used to reinforce the transverse construction joint. These tiebars are placed between every other longitudinal bar to provide the required additional reinforcement.

The additional reinforcement is provided to resist the increased shear and bending stresses at the joint, and to provide additional bond area required to accommodate stresses generated during the first few days after construction, before the concrete gains sufficient strength.

In addition, lap splices that fall within 3 ft (0.9 m) behind the construction joint, or lap splices that fall within 8 ft (2.4 m) ahead of the construction joint (in the direction of paving), should be additionally strengthened. It is recommended that the lap either be made double the normal length, or else additional deformed bars 6 ft (1.8 m) long of the same size as the longitudinal reinforcement be spliced in symmetrically with the lap.(2)

This is especially important for transverse construction joints in order to produce high-quality concrete on both ends of the joint. Many transverse construction joints have performed poorly due to inadequate concrete consolidation.

Transition or Terminal Joints

Transition or terminal joints are provided in CRCP to accommodate pavement growth that, if uncontrolled, may close the expansion joint in the approach to structures and induce damage to the adjacent structure. Pavement growth is typically a result of expansion changes in the concrete pavement coupled with intrusion of incompressibles at the cracks. Areas with high precipitation have been found to experience this more frequently since precipitation produces a higher accumulation of incompressibles at the cracks.

Two types of joints are commonly used to prevent excessive CRCP movement: terminal end anchors and wide-flange beams. Terminal end anchors attempt to restrain movement, while wide-flange beams are effective in accommodating movement.

Terminal End Anchor Joints

End anchors were originally developed to restrain movement in jointed pavements. In fact, their use would be more justified on jointed pavements since on this type of pavement there is an increased chance of intrusion of incompressibles at the joints with the consequent pavement growth. The practice of using anchor lugs was carried over from jointed pavements to CRCP.

End anchors are provided by a series of concrete lugs underneath the pavement that anchor to the subgrade and attempt to restrain CRCP movement. The lug depth depends on the soil type and frost conditions. Soil types with low stiffness and thus low resistance to movement may compromise the effectiveness of the end anchors. In such situations, end anchor lugs should not be used. A design standard for terminal end anchors is provided in Figure 65 of Appendix A.
Regardless of the CRCP length, its central portion remains fully restrained by the underlying base and no change in length is experienced with exception of the last few hundred feet [typically 300 to 400 ft (90 to 120 m)] at the ends.

**Wide-Flange Beam Joints**

Wide-flange beam joints are increasing in popularity as a means to control CRCP end movements. Wide-flange beam joints provide room for CRCP expansion and provide a means to maintain joint load transfer efficiency. Figure 18 shows a typical design detail for a wide-flange beam joint. This joint is typically formed by casting a 10-in (250-mm) thick by 10-ft (3-m) long reinforced sleeper slab used to support the ends of the abutting pavements.

A wide-flange beam is embedded 5 to 6 in (127 to 152 mm) into the sleeper slab so that the top flange is flush with the CRC pavement surface. Compressible joint material such as polystyrene is provided on the side of the beam web, adjacent to the CRCP, to allow for expansion. In addition, a bond breaker is used on top of the sleeper slab to allow the pavement ends to move freely. It is important to provide adequate support for the sleeper slab or it may sink at one end.

It is recommended that corrosion protection be provided for the wide-flange beam, commonly using a corrosion inhibitor. To provide room for additional expansion, one or more slabs with doweled expansion joints are typically constructed between the CRCP transition joint and the bridge approach slab.

Some wide-flange beam joint premature failures have been reported in the past. The type of failure observed was separation of the top flange from the beam web. Because of this, it is now recommended to weld stud connectors to the top flange of the beam to prevent this type of failure. Recommended wide-flange beam sizes for various pavement thicknesses are provided in Table 5.

---

**Figure 18. Wide-flange beam joint detail.**

**Table 5. Wide-flange (WF) beam (weight and dimensions) (56)**

<table>
<thead>
<tr>
<th>Slab Thickness in (mm)</th>
<th>Embedment in &quot;Sleeper&quot; slab</th>
<th>Size x Weight in lb/ft (mm x kg/m)</th>
<th>Flange Width in (mm)</th>
<th>Flange Thickness in (mm)</th>
<th>Web Thickness in (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 (203)</td>
<td>6 (152)</td>
<td>14 x 61 (356 x 91)</td>
<td>10 (254)</td>
<td>5/8 (16)</td>
<td>3/8 (9.5)</td>
</tr>
<tr>
<td>9 (229)</td>
<td>5 (127)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>254 (10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 (279)</td>
<td>5 (127)</td>
<td>16 x 58 (406 x 86)</td>
<td>8.5 (216)</td>
<td>5/8 (16)</td>
<td>7/16 (11)</td>
</tr>
</tbody>
</table>
A recent FHWA study looked at the performance of existing CRCP sections in several States. In this study, fewer distresses such as spalling and faulting of the transition joint were observed on wide-flange beam joints than on terminal anchors. This may attributed in part to the younger ages of the wide-flange beams.(8)

Worth noting is that success has been achieved in providing continuity between the CRCP reinforcement and that in continuous span bridge structures,(62, 63) This is accomplished by tying the CRCP to both ends of the bridge, with some jointing modifications. It is believed that by successfully tying the CRCP to the bridge structure, the designer can provide for a smooth transition between these elements. One successful implementation of this technique was recently accomplished on Westlink M7 in Sydney, Australia.(63)

Other Details

The following paragraphs provide information on design details for crossovers, shoulders, ramps, and auxiliary lanes.

Crossovers

Crossovers are often used during construction to provide access to thru traffic. When crossovers are needed, it is recommended to pave the crossover in anticipation of the mainline paving requirement. Leaving gaps in the CRCP to provide room for crossovers is not recommended. When these gaps are paved, they are subjected to excessive movement exerted by the CRCP on both ends due to cyclic temperature changes. During the first days after placing, the leave-out concrete will not have reached its full strength, and will be more susceptible to slippage of the reinforcement.

Figure 19. Layout of reinforcement in leave-out section.(58)
Paving these sections ahead of the mainline paving prevents reinforcement slippage since it is less unlikely that the short length of the paved crossover will exert excessive force on the fresh CRCP. It is recommended that special attention be given to crossovers when planning the paving schedule in order to minimize the need for leave-outs. Some States such as South Dakota include language in their specifications to discourage leave-out gaps.

An option worth considering is the use of a fast-track (high early strength) concrete in areas where a leave in/leave out would otherwise be used. Where this has been tried wet mat curing has been provided for 24 hours. This method would require prior coordination for the delivery of high early strength concrete in a timely manner so that all concrete within the crossover is high early strength.

When leaving a gap in the CRCP cannot be avoided, a minimum of 50 percent additional reinforcement should be required in the leave-out and across the construction joints on both ends of the leave-out. The additional reinforcement should be evenly distributed between every other regular reinforcement bar. Both additional and regular reinforcement bars should extend into the leave-out no less than 7 ft (2.1 m) and should be embedded no less than 3 ft (0.9 m) into the pavement ends adjacent to the leave-out. Splices in the leave-out area should follow the same requirements as those followed at a construction joint.

**Shoulders**

Shoulder types that are commonly used with CRCP include concrete and asphalt shoulders. While asphalt shoulders may have lower initial construction costs than concrete shoulders, the longitudinal joint between the CRCP and asphalt shoulder often requires significant maintenance activities during the life of the pavement. On the other hand, concrete tied shoulders provide enhanced lateral structural support resulting in a reduction in both pavement deflection and stress under traffic loading, leading to improved performance.

In order to provide increased structural support, concrete shoulders should be properly tied to the mainline pavement. While tied concrete shoulders paved in a second pass after the mainline pavement provide good lateral support, additional benefits are obtained from shoulders paved monolithically since a significant improvement in load transfer is achieved by aggregate interlock at the longitudinal joint with the mainline pavement.

Concrete shoulders for CRCP may be designed as either CRCP or JCP. CRCP shoulders can provide a uniform pavement section that can later be fully utilized when additional lanes are required. Jointed concrete shoulders (with no reinforcement) may provide savings in comparison to CRCP shoulders in terms of initial construction cost, although future maintenance of the CRCP to JCP joint may be required. If JCP shoulders are selected, it is recommended to use short joint spacings (< 15 ft (5m)) on the shoulder in order to minimize joint movement that could cause additional cracking in the CRCP mainline pavement.

Other factors that require consideration when selecting the shoulder type include the effect the shoulder will have on drainage as well as the effect that the environment will have on shoulder performance.

As an alternative to shoulders, experience has shown that by extending the outer concrete lane by at least 1 ft (0.3 m) into the shoulder to create a "widened lane," this can significantly reduce edge deflections. The use of a widened lane can provide either additional pavement life or an opportunity to decrease the CRCP thickness. With these considerations, some States have opted to use widened lanes and asphalt shoulders. While this combination may not be as beneficial as monolithic tied concrete shoulders, it provides a trade off between initial construction costs and enhanced performance.

**Ramps and Auxiliary Lanes**

Selection of pavement type for auxiliary lanes between acceleration/deceleration lanes should take into account similar considerations as for shoulders in the previous section. In general, CRCP with the same characteristics as the mainline paving is also recommended for auxiliary lanes.

Pavement ramps, also termed acceleration/deceleration lanes, can be either CRCP or jointed pavement. It is typically recommended that ramps be tied to the mainline paving with the use of tiebars along the longitudinal joint, or by extending the transverse reinforcement from the mainline paving. Reinforcement design along the ramp to lane joint should follow the same guidelines as those provided for conventional longitudinal joints.

Performance of the longitudinal joint between the ramp and mainline paving will also depend on the differential movement between these two elements. If the ramp is constructed with jointed pavement, it is recommended to
provide a short joint spacing similar to jointed concrete shoulders to minimize movement and potential cracking of the CRCP. Furthermore, it is recommended to use jointed concrete pavement on the ramp if the distance between the CRCP end and the gore section of the ramp is less than 200 ft (60 m). This is to prevent excessive movement of the CRCP with respect to the ramp. Recommended layouts for ramp connections and jointing details are provided in Figure 20 and Figure 21.

Figure 20. Recommended layouts for ramp connections.

Figure 21. Jointing details for ramp connections.
Intersections

Intersections present a unique challenge for CRCP design as maintaining continuity of reinforcement in both directions through the intersection may be required if two CRCP pavements are intersecting. A recent TxDOT research report documents best practices for design and construction of CRCP in transition areas, including intersections. As shown in Figure 22, the report provides design details used by TxDOT for maintaining reinforcement continuity in both directions through an intersection.

Note that the longitudinal reinforcement for the pavement in one direction provides the transverse reinforcement for the pavement in the other direction and vice versa. The report also provides design details for isolating intersecting CRC pavements when maintaining reinforcement continuity in only one direction is necessary, as well as intersection details for CRC pavements intersecting non-CRC pavements.

Figure 22. Design detail for CRCP intersection. (67)
To assure the superior performance that is commonly associated with CRCP, construction plans and specifications that properly address critical details are essential. Uniformity and consistency of concrete placement and reinforcement location along the project are also necessary. In addition, climatic conditions encountered during actual placement of the pavement can have a significant effect on future performance. This section of the guide provides information on key aspects of the construction process that is critical in achieving successful CRCP performance.

The key structural performance indicator of CRCP is the width of transverse cracks. If the transverse cracks can be held tightly together over the intended design life, the likelihood of good CRCP performance is greatly enhanced. When cracks are wide, the CRCP loses the ability to transfer shear stresses from heavy wheel loads. This loss of load transfer will quickly lead to the development of punchouts, the primary structural failure in CRCP. As illustrated in Figure 23, punchouts lead a loss of smoothness and require full-depth repairs.

Crack width depends on several design and construction factors. These include depth of reinforcement, proper lap lengths on reinforcement bars, staggering of laps, concrete shrinkage, concrete thermal coefficient of expansion, the effects of moisture on concrete expansion and contraction, concrete consolidation, set temperature of the CRC slab (climate conditions at time of construction), and friction between the base and CRC slab. (69,70,71)

Many CRCP performance problems have been related to inconsistent or inappropriate construction practices that do not meet stated design requirements. For example, CRCP has exhibited distresses due to inadequate consolidation of the concrete at construction joints, inadequate reinforcement laps, delamination due to steel too close to the surface, and loss of ride quality due to differential subgrade settlement along the project, especially in areas where embankments are placed on heavy existing clays.

Construction quality must be consistent throughout the project. Quality construction results in both uniformity (in subgrade, base, slab, and reinforcement) and uniformly spacing and width of transverse cracks that maintain load transfer over the design life).

**Contracting for Innovation**

As knowledge and understanding of CRCP construction and performance increases, innovative contracting procedures may need to be implemented in order to allow the contractor more options for building a high quality pavement. For example, quality assurance testing will allow for improvement of the quality and the performance of the product.

Some States now require contractors to perform quality assurance testing with certified equipment and operators, with only random checks performed by the State. Currently, these efforts are focused on ride quality, but could also include following:

- Deflection testing to evaluate variability and structural behavior;
- Ground penetrating radar to check steel placement, layer thickness, and moisture related issues;
- Visual Condition Survey to document the as-built crack spacing and crack widths;
- Skid testing to document as-built frictional characteristics; and
- Core strengths to document as-built strength and variability.

![Figure 23. Edge punchout in CRCP.](image)
Base Layers

The base course directly beneath a CRCP is a very critical component. The base course must provide the following:

• Smooth construction platform on which to construct a smooth CRCP;
• Permanent support to the CRCP over its design life;
• Non-deforming and smooth surface for accurate reinforcement placement and placement of a uniform CRCP slab thickness; and
• Sufficient friction with the CRCP slab to help form adequate crack spacing.

Several types of bases have been used successfully, including unbound aggregate, cement-treated and lean concrete, asphalt-stabilized, and combinations of the above. Each of these base courses must be designed and constructed properly to avoid contributing to problems in CRCP performance.

It is also common to place a subbase layer, either an unbound granular material or treated subgrade layer, between the base and the subgrade. This subbase layer is extremely important when the subgrade is wet and soft, as it can reduce erosion of the top of the subgrade and provide a construction platform for base construction.

The width of the base course is important during construction. Ideally, it should extend beyond the CRCP slab edge by at least 3 ft (0.9 m) to provide increased edge support and to provide a stable track-line for paving operations. It may be necessary to widen the base further to accommodate some newer paving equipment.

Base thicknesses in the range of 4 to 8 in (100 to 200 mm) are common for highways. Subbase thicknesses are often 6 to 12 in (150 to 300 mm) or greater.

Asphalt-Stabilized Base

Field studies have shown that the addition of asphalt to granular materials to produce a non-erodible stabilized mixture for base construction can improve CRCP performance. (73) An example of an asphalt-stabilized base is illustrated in Figure 24. Proper (as-designed) asphalt content, density, and other mix quality parameters must be achieved during construction. The key benefits include minimizing moisture-related loss of support, providing a smooth construction platform for steel placement and improved ride quality, and supplying an adequate amount of friction with the CRCP to provide proper crack spacing, and to provide stress relief during curling and warping cycles.

Stripping of asphalt binders from aggregates in these bases has been a concern. Stripping is a direct result of moisture...
in the pavement system that brakes down the bond between the aggregate and asphalt binder. Consequently, the use of asphalt stabilized bases in areas with high water tables should be designed with proper additives, and its use, if any, should be used with caution.

**Cement-Treated Base**

A cement-treated base consists of crushed stone base commonly blended through a pugmill with an optimized quantity of cement (typically 5 percent) to achieve a 7 day compressive strength of 500 psi (3.5 MPa) and water at 1 to 2 percent below the optimum moisture content. A strong and non-erodible cement-treated base can be very effective in improving CRCP performance and has been successful in areas with high water tables. Some erosion and deterioration of cement stabilized base courses have occurred in the past, creating loss of support problems for CRCP. However, this can be prevented through proper materials selection and construction, particularly achieving adequate density and consistency of material.

For cement-treated base, the time between mixing, placement, and initial compaction should not exceed 1 hour. Complete bonding between a cement-treated base and concrete slab is not recommended due to potential of reflection cracking and the increase in the effective CRCP slab thickness, which results in the need to increase the amount of steel reinforcement.

An interlayer of some type should be used between the slab and the base to serve as a stress relief layer. Most often, a 1 to 2 in (25 to 50 mm) layer of rich, dense-graded HMA is placed on top of the cement-treated base layer to minimize erosion potential while providing stress relief for curling, warping, expansion and contraction.

While not necessarily for CRCP until recently, contractors in Germany have been using a 0.2 in (5 mm) thick non-woven geotextile as a stress relief layer between concrete pavements and cement stabilized bases. Figure 25 shows the system used for placing the geotextile. The fabric is fastened to the subgrade or base layer with a washer and nail as shown in Figure 26, to secure it during construction. Cores taken in a pavement built in 1981, as shown in Figure 27, noted no deterioration in the geotextile or cement-treated base.

Cement-treated bases should not be placed under freezing or near freezing conditions. It is recommended that the material be placed and cured when ambient air temperatures are greater than 40°F (4°C) (measured in a shaded area) until adequate strength is reached. Cement-treated bases can be cured by covering with polyethylene sheeting for 3 to 5 days or spraying a fine water mist several times a day after placement. At the end of each day’s construction, a straight transverse construction joint should be formed by cutting back into the completed base to form a vertical face.
Lean Concrete Base

Lean concrete, sometimes known as "econocrete", is made of aggregates that have been plant-mixed with a sufficient quantity of cement to provide a strong and non-erodible base. Lean concrete has been used as a base course for many CRCP. It can provide a smooth uniform surface as a construction platform for steel placement and paving. It can be placed using the same equipment that will pave the concrete surface. Lean concrete bases should be cured using white-pigmented curing compound and be left untextured to prevent bonding to the CRCP.

Field studies have shown that a lean concrete base of adequate strength will reduce erosion of the base and loss of support. Some agencies specify sawcut weakened plane joints once the lean concrete base has set to prevent large cracks from forming and reflecting into the CRCP surface. Other agencies successfully placing a layer of asphalt-stabilized base or HMA (1 to 2 inches or 25 to 50 mm thick) on top of the lean concrete base layer to minimize erosion, provide stress relief, and provide a moisture barrier, similar to that recommended for a cement-treated base.

Dense-Graded Granular Base and Subbase

Dense-graded unbound granular materials with low plasticity have been used successfully as a base and subbase for CRCP. To minimize consolidation and settlement problems, a relative density of 95 to 100 percent as determined by AASHTO T 180 (Modified Proctor) is necessary.

Care should also be exercised during construction and fine grading to avoid segregation and minimize loss of density and uniformity. Any of these conditions can result in loss of slab support and subsequent CRCP failures. Specialized equipment is often used to place the granular materials to a uniform depth without segregation, as shown in Figure 28.

It should be noted that some agencies have had significant problems with pumping and loss of support with unbound bases, even on strong dry subgrades. Use of an untreated aggregate base under CRCP will result in much longer crack spacing for the same reinforcement content. This may cause serious problems in crack spacing for the same crack deterioration and punchout development. This can be accommodated by increasing the reinforcement content. The MEPDG provides recommended friction values for unbound base courses calibrated from field conditions.
Because CRCP is normally used for heavily trafficked highways, most agencies utilize a stabilized base to minimize erosion and loss of support, and instead opt for a granular subbase. This combination has helped facilitate construction and provide the uniform foundation needed for long term and high quality performance.

Open-Graded Permeable Base

An open-graded permeable base is a drainable layer with a typical laboratory permeability value of 1000 ft/day (300 m/day) or greater. Permeable asphalt-treated and cement-treated bases have seen limited use as open-graded drainage layers for CRCP.

The primary function of this layer is to collect water infiltrating the pavement and move it to edge drains within an acceptable time frame. However, the permeability of the base should always be balanced with stability. Stability is more critical than permeability in CRCP foundation systems.

The main problem with open-graded bases for CRCP is that concrete mortar often infiltrates the base resulting in additional bonding between the slab and base/subbase, which increases the effective CRCP slab thickness, thereby reducing the steel as a percentage of the slab cross section. These effects can change the crack spacing and lead to performance problems.

In addition, due to the relative "flexibility" of CRCP, the unbound layer just beneath the open-graded layer may pump into and infiltrate the permeable layer causing localized settlements, which has occurred with lime treated subgrades on some projects. For these reasons, permeable bases are not generally recommended for CRCP, unless strong practical measures to prevent these problems are taken, such as the use of geotextiles.

Open-graded permeable bases were very popular in the late 1980s and early 1990s, but due to a number of failures from these mechanisms, many agencies now discourage their use. If deemed a necessary component, however, measures should be taken to reduce the target permeability to 100 ft/day (30 m/day) in order to improve stability.

Edge Drains and Impervious Moisture Barriers

Heavy traffic combined with moisture variations in susceptible materials often leads to erosion in the base and subgrade or shrinkage and swelling that leads to premature concrete pavement failures, including CRCP. Infiltration of water into the CRCP structure can be controlled with proper cross slopes, maintaining a seal that prevents moisture changes in unbound pavement layers, and construction of an edge drainage system to transport water away from the pavement structure.

Edge drains work best in granular soils. However, in cohesive soils, which do not allow water to drain freely, edge drains can accentuate shrinking and swelling by causing the soils to be drier adjacent to the drains, which causes shrinkage. Alternatively, if drains become clogged and fill with water, adjacent soils will become saturated, which can lead to swelling.

To function properly in cohesive soils, edge drains should incorporate a moisture barrier to prevent wetting or drying of adjacent soils under the pavement. In addition, base and subbase layers must be free draining and extend over the edge drain. Care should be exercised during the construction of these systems to:

- Ensure that the as-designed gradation of the drainage layer is obtained to preserve permeability,
- Provide a system that allows access and can readily flush out the system without causing any erosion,
- Ensure that the drainage layer is placed and lightly compacted without fracturing aggregate particles, which create additional fines, and
- Avoid collapsing, breaking, and clogging of the pipes and outlets.

It is also suggested to regularly conduct a video survey of the outlets and longitudinal pipes to ensure they can function.

An impervious moisture barrier can be used to effectively prevent both changes in surface grades and cracking along the pavement edges due to swelling soils. A vertical moisture barrier should be constructed as deep as the zone affected by seasonal moisture variations. Alternatively, a conservative minimum depth of 7 ft (2.1 m) can be used, as illustrated in Figure 29.

Before any drainage feature is added to a pavement system, an assessment should first be made of the cost of the system as it compares to the potential improvement to performance.
Figure 29. Typical vertical moisture barrier configuration.

Polyethylene Membrane
Double layer > 8 mils thick (0.2 mm) each

Sealed with a water-proof mastic

Impermeable & non-expansive fill

Note: The use of TxDOT flowable backfill would expedite installation (Item 401)

PCC

0.3 m (1 ft.) minimum

CTB

LSS

0.3 m (1 ft.) minimum

0.9 m (3 ft.) minimum

2.1 m (7 ft.)

(To accommodate trenching equipment & avoid damaging base material)
Continuous steel reinforcement is the key feature that distinguishes CRCP from jointed concrete pavement.

This section of the guide discusses the construction aspects of longitudinal steel reinforcing bars, transverse steel reinforcing bars, and steel tiebars in CRCP. Steel requirements in construction joints, terminal treatments, and crossover treatments are discussed in Sections 8.4 and 9 of this guide.

Reinforcing steel should be placed as shown on plans; noting that:
• As the thickness increases, both the longitudinal and transverse steel requirements increase, and
• As the pavement width increases, the transverse steel requirements increase.

**Characteristics of Reinforcing Steel**

Only deformed steel bars should be used as reinforcement for CRCP. Reinforcing steel bars are characterized by size and yield strength (or grade). Standard ASTM reinforcing bars are required to be marked distinctively for size and minimum yield strength or grade. Figure 30 shows an example of the ASTM marking requirements for a #8, Grade 60 (#25, Grade 420 metric) bar. ASTM specifications require the bar size number (e.g., #8) to be rolled onto the surface of the bar as shown in the figure.

These specifications also allow a mill to choose to roll the grade number onto the bar, or roll on a single longitudinal rib or grade line to indicate Grade 60. Additional information about steel bar marking and identification is available in ASTM A615/A615M-96a, ASTM A706/A706M-96b, and ASTM A6/A6M-96c. The identification marks on bars delivered to the job site should be checked regularly against those shown on the plans. Certified Mill Tests and/or Bar Coating Reports should accompany shipments of reinforcing steel to the job site as shown in Figure 31.

A light brown coating of rust on reinforcing bars is considered acceptable by industry. Although cited ASTM standard specifications do not consider the presence of mill scale as cause for rejection, a recent ACI paper found that bars with mill scale produced more corrosion compared to other bars investigated.

Reinforcing steel should be stored on platforms off the soil to prevent damage and deterioration.

---

**Longitudinal Reinforcement**

As stated previously, the design basis of CRCP allows the pavement to crack at approximate intervals in the transverse direction, but includes a sufficient amount of longitudinal steel reinforcement to keep cracks closed very tight over the design life. Longitudinal steel placed on grade prior to concrete placement is illustrated in Figure 32.

![Figure 30. Example of the ASTM marking requirements for a #8, Grade 60 (#25, Grade 420) bar.](image)

![Figure 31. Mill and coating certifications for rebar.](image)
Bar Size and Quantity

The amount of longitudinal steel is commonly expressed as a percentage of the total slab cross-sectional area. Longitudinal steel is normally delivered in 40 or 60 ft (12 or 18 m) lengths. It should be noted that the required bar size and percentage of steel should be determined by the design process.

When epoxy-coated steel is specified (see Figure 33), ensure that the coating is not damaged during shipping, handling, or installation. For example, epoxy-coated bars should not be dropped or dragged and should be stored on wooden or padded steel cribbing.

Bar Spacing and Depth

A minimum steel depth of 3.5 in (90 mm) to a maximum of mid-depth of the slab are recommended, as measured from top of slab to top of reinforcement bars. Spacing of longitudinal reinforcement should allow for easy placement of the bars and consolidation of the concrete. The spacing should be no less than 4 in (102 mm) or 2.5 times the maximum size of the aggregate, whichever is greater. To achieve proper load transfer and bond strength, experience indicates that the spacing of longitudinal bars should not exceed 9 in (230 mm). In two-lane construction, an even number of longitudinal bars should be used to avoid locating a bar under a longitudinal joint, where it would interface with sawing.

A placing tolerance of ± 0.5 in (13 mm) vertically and ± 1.0 in (25 mm) horizontally is normally permitted for longitudinal bars. However, this vertical tolerance has often been difficult to achieve and a ±1.0 in (25 mm) may be a more practical vertical tolerance.

Bar Splices

Longitudinal steel must be adequately lapped at splices (see Figure 34). Splices should also be staggered in arrangements that do not cause localized strains in the pavement or a nearby construction joint. Inadequate laps resulting from faulty construction have been direct causes of structural failures in CRCP. The length of splices is related to embedment length and the bond strength developed between the deformities on the bar and the concrete matrix.

Bond strength at early ages is critical to the development of desirable random cracking in CRCP, requiring splices to keep stresses and strains relatively uniform within the slab. Unless adequate bond strength is achieved at lap splices, the continuity of the CRCP slab may be lost and wide cracks that lead to structural failures can occur.
Lap splices must be tied or secured in such a manner that the two bars are held firmly in contact. However, the lap requirements and arrangements differ somewhat among the States to meet this requirement. The recommended minimum lap length of longitudinal steel splices is 25 times the bar diameter. A minimum of two ties per lap is recommended.

These lap treatments apply to all manual and mechanical steel placement methods. If a staggered splice pattern is used, not more than one-third of the bars should terminate in the same transverse line, and the minimum distance between staggerers should be 4 ft (1.2 m). If a skewed arrangement is used, the minimum skew should be 12 ft (3.7 m) in a 24 ft (7.3 m) wide pavement, or a 1:2 ratio. Typical lap patterns are shown in Figure 35.

Transverse Reinforcement

Field studies have found that transverse crack locations often coincide with the location of the transverse steel, particularly when the steel is placed in two layers. Although transverse steel can be omitted, all States that actively build CRCP use transverse steel. When used, transverse steel serves to:

- Support and maintain the specified spacing of longitudinal bars in position. Usually, longitudinal bars are tied or clipped to transverse steel at specified locations.
- Act as tiebars across longitudinal joints in lieu of conventional tiebars (although this is not often done, as transverse steel may terminate prior to reaching the longitudinal joint and a typical tiebar is used across the joint).
- Hold longitudinal cracks closed tightly to mitigate punchouts from forming.

Causes of uncontrolled longitudinal cracking include late sawing, shallow sawing, improperly installed joint inserts, or a swelling subbase or subgrade.

Bar Size and Quantity

Transverse steel reinforcement should be #4, #5, or #6 Grade 60 (#13, #16, or #19 Grade 420) deformed bars meeting the same specifications as the longitudinal reinforcement and normally spaced at standard increments of 12, 24, 36 or 48-in (0.3, 0.6, 0.9, or 1.2 m).

Transverse bars that overlap into the adjacent lane width can be staggered to function as tiebars across the longitudinal joint at a closer spacing along the middle of the paving width. For example, transverse bars spaced at 2 ft (1.2 m) and staggered in adjacent lanes would overlap the center joint by one-half the normal tiebar length and result in effective tiebar spacing of 2 ft (0.6 m).

Figure 35. Typical lap splice patterns.
Transverse Reinforcement

Field studies have found that transverse crack locations often coincide with the location of the transverse steel, particularly when the steel is placed in two layers. Although transverse steel can be omitted, all States that actively build CRCP use transverse steel. When used, transverse steel serves to:

- Support and maintain the specified spacing of longitudinal bars in position. Usually, longitudinal bars are tied or clipped to transverse steel at specified locations.
- Act as tiebars across longitudinal joints in lieu of conventional tiebars (although this is not often done, as transverse steel may terminate prior to reaching the longitudinal joint and a typical tiebar is used across the joint).
- Hold longitudinal cracks closed tightly to mitigate punchouts from forming.

Causes of uncontrolled longitudinal cracking include late sawing, shallow sawing, improperly installed joint inserts, or a swelling subbase or subgrade.

Bar Size and Quantity

Transverse steel reinforcement should be #4, #5, or #6 Grade 60 (#13, #16, or #19 Grade 420) deformed bars meeting the same specifications as the longitudinal reinforcement and normally spaced at standard increments of 12, 24, 36 or 48-in (0.3, 0.6, 0.9, or 1.2 m).

Transverse bars that overlap into the adjacent lane width can be staggered to function as tiebars across the longitudinal joint at a closer spacing along the middle of the paving width. For example, transverse bars spaced at 2 ft (1.2 m) and staggered in adjacent lanes would overlap the center joint by one-half the normal tiebar length and result in effective tiebar spacing of 2 ft (0.6 m).

Tiebars

Both traditional (Figure 36 and Figure 37) and multiple-piece (Figure 38) tiebars can be used at longitudinal joints to tie adjacent lane slabs together or to tie concrete shoulders to the mainline slab similar to jointed concrete pavements. As mentioned before, transverse reinforcement may be used in lieu of conventional tiebars. Tiebars are usually placed at mid-depth of the CRCP slab, but must be low enough to avoid damage if longitudinal joints are formed by sawing.
If slipform pavers are used, multiple-piece tiebars, bent tiebars, or mechanically inserted tiebars are inserted into the concrete while still within the confines of the slipform paver. Bent tiebars are not recommended due to joint separation failures caused either by the weakened steel or failure to bend the tiebar straight before paving adjacent lanes. Mechanical tiebar inserters work well when located in the zone of vibration and should be allowed as long as the edge does not slump.

If fixed-form pavers are used, multiple-piece tiebars (or bent tiebars) are often attached to side forms. Another option is to drill and epoxy tiebars in place. Tiebars should be tested to ensure they develop a pullout resistance equal to a minimum of three-fourths of the yield strength of the steel after 7 days, as determined by ASTM E 488, Standard Test Methods for Strength of Anchors in Concrete and Masonry.

Where tiebars are to be bent and later straightened, reinforcing bars of ASTM designation A 615 Grade 40 (Grade 300) should be used to prevent fatigue cracking in the bars. This requires the spacing to be somewhat less than that for Grade 60 (Grade 420) bars used as transverse reinforcement.

Good practice is to place tiebars approximately parallel to the grade, perpendicular to the longitudinal joint, and at the specified spacing. For example, a common arrangement of tiebars consists of 30 in (760 mm) long #4 or #5, Grade 40 (#13 or #16, Grade 300) deformed steel bars, if bending is allowed, or Grade 60 (Grade 420) when no bending is allowed, spaced at 30 in (760 mm) center-to-center, and placed with half of the length on each side of the joint.

Tiebars should be placed at the design position within a tolerance of ± 1.0 in (25 mm) vertically (or within the center 2/3 of the slab but lower than the joint saw cut) and ± 2.0 in (50 mm) horizontally.

Where corrosion is a concern, consideration should be given to the use of corrosion resistant steel or by coating the steel with a protective layer (see Figure 41).

### Placing Reinforcement

Proper placement of reinforcing steel is an extremely critical aspect of CRCP construction. Detailed schematics should be provided by the contractor, approved by the engineer, and inspected in the field prior to paving to assure compliance with project standards and specifications. Longitudinal alignment and depth of the steel relative to the slab surface have a significant effect on CRCP performance.
Field studies have shown no significant difference in the performance of CRCP with steel placed on chairs and CRCP with steel placed using tube feeders as long as both are done properly. However, chairs are used far more frequently than tubes because of the demonstrated benefits of using transverse steel, and due to the perception that they are more likely to result in accurate placement of the steel.

Regardless, some quality assurance measures are needed to assure the steel has not shifted during the construction process. Some states are experimenting with the use of magnetometers and ground penetrating radar for this purpose.

**Manual Steel Placement (Chairs or Transverse Bar Assembly)**

In this method, reinforcing bars are attached to support assemblies prior to construction. These can consist of a variety of chair and support combinations, often tied to the transverse bars in some fashion. The supports must be sturdy enough to hold the bars within tolerances during placing and consolidating the concrete. For example, a recent project experienced problems when the plastic chairs proved to have inadequate stability and required strengthening and additional ties at steel intersections. In addition, supports should have a base configuration that provides adequate support for the weight of the steel and concrete as well as workers walking on the steel (see Figure 42) without collapsing, sinking into the base, or impeding the flow of concrete during placement and consolidation.

![Figure 41. Paver with steel on chairs.](image)

![Figure 42. Worker walking on reinforcing steel in Virginia.](image)
Using pins to anchor the reinforcing steel mat to prevent movement during paving is an item of contention. While some believe pinning the mat may cause horizontal cracking and/or a weakened bond between the concrete and steel, others believe the procedure is acceptable.

The arrangement and spacing of the steel supports should be such that the reinforcing bars are supported uniformly and in the specified position and do not move when concrete is placed. Bars should not permanently deflect or be displaced. Spacing of the supports is a function of the size and spacing of the reinforcing steel, the support provided by the pavement base layer, and the design of the chairs. As a general guideline, the spacing should not exceed 3 ft (0.9 m) transversely or 4 ft (1.2 m) longitudinally.

Usually, transverse bars are first placed on the individual chairs, or else a prefabricated transverse bar assembly is used. The longitudinal bars are then arranged in position (staggered for lapping, as discussed in Section 7.2.3). Next, the longitudinal bars are tied and secured to the transverse bars to maintain specified tolerances. Experience indicates that tying or clipping the longitudinal bars to the transverse bars at 4 to 6 ft (1.2 to 1.8 m) intervals along the longitudinal bars produces satisfactory results. States that are experienced with CRCP do not allow welding of longitudinal and transverse bars. Examples of steel placed on different types of supports are shown in Figure 43 and Figure 44.

A Transverse Bar Assembly (TBA) is sometimes used in place of a chair support system and separate transverse reinforcing bars. A TBA consists of a transverse reinforcing bar and triangular metal legs with metal u-shaped clips that are welded to the transverse bar. TBAs are custom manufactured to project specifications, such as paving width and horizontal and vertical bar location.

The number and spacing of the triangular metal legs is determined by the requirements of support and rigidity for the bar mat. The triangles of the legs are oriented in the longitudinal plane to avoid overturning of the mat during slipform paving.

The metal u-shaped clips are welded along the transverse bar at the accurate spacing position required by the longitudinal reinforcing bars, creating a uniform separation between them. The clips are sized to hold the longitudinal bars in place and allow a bit of give in the paving direction. The longitudinal bar is snapped quickly into the clip (see Figure 45). Sometimes the clips are omitted from every other transverse bar. Wire tying at rebar intersections is not required; tying is only required at the splice areas.

One key advantage of the TBA is that it saves labor and time, mainly in the tying required at rebar intersections. A six person crew using TBAs can typically lay one-lane mile of bar mat per 8 hour shift. While the TBA itself is more expensive compared to the traditional method, the bar mat installation using TBAs is most cost-effective in areas where labor rates are high.

Figure 43. Example of steel placed on chairs in Texas.

Figure 44. Example with two layers of steel placed on chairs.
Steel Placement (Tube-feeding)

When tube feeding steel, the longitudinal bars are distributed on the base, approximately spaced, lapped, and tied manually. During placement, the longitudinal bars are raised up on rollers and threaded through bell-ended tubes within the concrete spreader where they are held at the specified vertical and horizontal positions as the concrete is placed between the tubes.

Few, if any, contractors use the tube feeding method for steel placement. A number of problems have been reported with tube feeding, primarily related to ensuring the steel is at the proper depth in the pavement. Steel too high in the pavement has resulted in corrosion of the reinforcement and spalling of surrounding concrete, and even exposed steel in some instances. Steel too low in the pavement can result in undesirably wide crack widths. While tube feeding does eliminate the labor required for placing the steel on chairs, and permits access to the base in front of the paving operation (although not for concrete placement), the potential problems associated with this technique may far outweigh the benefits.

Inspection

Steel reinforcement should be properly inspected to ensure that spacing, splice lengths, and patterns are consistent with design requirements. At a minimum, the following checks should be performed and documented prior to concrete placement:

- Ensure all longitudinal lap and ties of all splices to assure that the minimum lap of the reinforcing steel is maintained (see Figure 46).

- While it is important to check the distance between longitudinal reinforcement bars (see Figure 47), it is even more important to ensure the correct number of bars is in place.

- Periodically check that the reinforcing steel is placed within the specified vertical tolerance. When chairs or transverse bar assemblies are used, this is accomplished prior to concrete placement by pulling a string line transversely across the roadway at the grade of the new pavement and measuring down to the reinforcing steel and checking the steel for movement as the paver passes (see Figure 48).

- Although the supports are designed to hold the steel at the correct depth, the midpoint between the chairs should be checked for possible sags. When tube feeders are used, a probe, or ruler, is inserted to determine the depth to steel from the surface of the slab at several locations across the paving width.

- Ensure there are no broken steel chair welds or plastic chair joints, bars are properly aligned, there are a sufficient number of wire ties on lap splices, and bars are lapped properly. Special precautions should be taken to prevent bar bending and displacement at construction joints.

- Remove foreign materials prior to placing concrete. At a minimum, the following inspection techniques should be employed as the concrete is being placed:

- Monitor the reinforcing steel at either the spreader or paver to ensure that reinforcement is not displaced by the fresh concrete.

- Regularly check the depth of the reinforcing steel behind the paver, which can be accomplished when the concrete is plastic or hardened (see Figure 49).
The depth of reinforcing steel in plastic concrete may be determined as previously mentioned or by excavating to the steel and directly measuring the depth from the slab surface. Should the location not be correct, paving operations should stop until the problem is corrected. Generally, movement of reinforcement occurs more often with tube placement than when presetting steel on chairs.

For hardened concrete, either a Ground Penetrating Radar (GPR) or magnetometer can be used to locate the position and depth of steel (after calibration with coring results). However, at this point, remedial measures are limited, unlike a check during construction.

**Troubleshooting and Precautions**

- When placing CRCP on asphalt bases, both chairs and transverse bar assemblies need base plates to prevent sinking into the base during warm weather.
- Pinning the steel mat to the base should not be necessary and may adversely affect long-term performance.
- Longitudinal reinforcement should be spaced to avoid longitudinal sawcut joints directly above a reinforcing bar.
- Epoxy coated rebar should only be tied with coated tie wires and any damage to the epoxy coating should be repaired according to the manufacturer's written instructions before construction.
- Mechanical insertion of tiebars should be allowed as long as edge slumping is not a consistent problem.
- Tack welding of reinforcing bars in the field should not be allowed, as it can embrittle the steel.
- Manholes and drop-inlets should be isolated from the CRCP, and a reinforcing bar should be placed around the perimeter of the obstruction.
- Any increase in pavement thickness should be accompanied by an increase in reinforcement to maintain desired steel percentages.
- CRCP should not be tied to noise walls, retaining walls, or other structures without the pavement engineer's approval. Typically, this is rarely if ever done on a given project.
- Paving should not be allowed until reinforcement schematics have been approved and reinforcement has passed field inspection.
The combination of the concrete material and placement operations directly influence the performance of a CRCP. Specifically, mixture properties and construction features during the first 72 hours after placing the concrete have a significant impact on short- and long-term performance.

Guidance included in the IMCP Manual and elsewhere should be adhered to. However, in this section, additional guidance specific to CRCP is provided.

## Aggregates

Aggregates constitute about 60 to 75 percent of the concrete mixture. Aggregate properties—including the coefficient of thermal expansion (CTE), surface texture, and coarse aggregate size—affect crack spacing and width for a CRCP. As these are critical properties in CRCP performance, aggregates should be selected carefully and not be changed in the field before consulting with pavement engineers and concrete mix designers.

The following characteristics should be considered when selecting aggregates for a CRCP mixture:

- **Coefficient of Thermal Expansion** - The CTE of the coarse aggregate affects crack spacing and crack width in CRCP. Use of a lower CTE coarse aggregate, and thus lower CTE concrete, will reduce crack width opening for the same crack spacing.

- **Size** - Generally, a larger coarse aggregate results in better aggregate interlock across cracks and thus a higher Load Transfer Efficiency (LTE) of transverse cracks (see Figure 50). The maximum size of coarse aggregates should not be less than 1.0 in (25 mm), and preferably larger, to achieve adequate crack LTE. However, the maximum aggregate size must allow for proper placement and consolidation of concrete. It is recommended that the maximum coarse aggregate size be less than half the spacing between longitudinal bars. Currently, States observe this recommendation by specifying maximum coarse aggregate size to be 1.5 in (38 mm).

## Placing

In CRCP paving, haul vehicles cannot drive on to the base due to reinforcing steel. Therefore, the concrete is generally discharged onto a high-speed belt placer from the side (see Figure 51). This method allows rapid and efficient unloading and places the concrete in the proper location.

Another less desirable option is to discharge on grade using the chutes on transit mix trucks or agitators. This practice greatly increases the possibility of displacing reinforcing steel and segregating the concrete.

Figure 51. High-speed belt discharge in Virginia.

![Figure 51. High-speed belt discharge in Virginia.](image_url)

Figure 50. Effect of coarse aggregate size on crack roughness variation with slab depth.
Consolidation

Concrete is consolidated to achieve required strength and durability, reduce entrapped air, and ensure bonding between the concrete and steel. Thus, adequate consolidation is a critical factor in achieving desirable long-term performance of CRCP. Like all concrete paving, concrete used in CRCP is consolidated using mechanical vibrators. Though rare, over-vibration can cause aggregate segregation, excessive bleeding, and reduction in entrained air. Furthermore, vibrator trails indicate failing vibrator equipment. Either over-vibration or under-vibration can reduce bonding strength between steel and concrete and thus result in poor CRCP performance. It should be noted that problems associated with under-vibration of concrete appear more frequently than those associated with over-vibration. Vibrators must not come in contact with reinforcing steel bars for extended periods of time because this can cause weakened mortar to concentrate around the steel bars. Also, contact between vibrators and joint assemblies, base material, and side forms must also be avoided for the same reason. Extra care should be taken to attain sufficient consolidation by manually vibrating at construction joints and leave outs.

Joints

Longitudinal Control Joints

Longitudinal control joints, otherwise known as contraction, hinged or warping joints are necessary to relieve stresses caused by concrete shrinkage and temperature gradients and changes in monolithically placed slabs that are wider than 14 ft (4.3 m) to control longitudinal cracking (see Figure 36 for a typical photo). These joints are generally formed by sawing the hardened concrete, but early entry saws have proven to work as well.

The recommended sawing depth is one-third of the as-constructed slab thickness to ensure an adequate weakened plane. Longitudinal control joints must be spaced to avoid sawing directly over a longitudinal steel bar. Care must be taken not to cut the tiebars across control joints. Saw cuts less than one-third the slab depth may not be adequate to form a crack at the planned location and can lead to random longitudinal cracking.

If random cracking should occur, the CRCP transverse reinforcement will aid in holding the cracks together. In some cases, cross-stitching can possibly be used to ensure that longitudinal cracks will remain tight. If any tiebars are damaged during saw cutting operations, cross-stitching should be done at those locations.

Longitudinal Free Joints

Longitudinal free joints are used to reduce the amount of steel needed in the transverse direction, to facilitate construction, and to isolate structural elements from the CRCP (see Figure 52). These joints are typically placed at the edge of median concrete traffic barriers, at the top of wingwalls, mechanically stabilized earth walls, or cast-in-place retaining walls to isolate the pavement movement from the movement of the structures. Since the amount of transverse steel needed is based on subgrade drag theory, a longitudinal free joint at the centerline of the pavement may reduce the amount of transverse steel needed by one-half. Longitudinal free joints should only be placed where load transfer and joint movement in the horizontal or vertical directions is not a critical consideration.

Transverse Construction Joints

Transverse construction joints are installed at the end of each day’s paving operation or other placement interruptions (whenever the placing of concrete is suspended for more than 30 minutes). In early CRCP construction, these joints often failed. However, proper design and construction proved these non-working transverse joints could perform as well as random transverse cracks.

Transverse construction joints are formed by means of a suitable split header board conforming to the cross section of the pavement. The header board should be secured vertically in place perpendicular to the surface of the pavement. Longitudinal reinforcing bars should extend through the split in the header board and be supported beyond the joint by chairs. On the leave side of the header, reinforcing steel should be covered with plates of wood so as to allow easy
removal of the concrete that is carried over the header (see Figure 54). Before resuming paving, the header board is removed. Figure 53 and Figure 54 show paving operations beginning and ending at transverse construction joints.

Transverse construction joints are typically smooth faced butt joints that do not benefit from aggregate interlock. These joints should not be edged or sealed. An important factor in good CRCP performance is continuity of load transfer; thus, special reinforcing bar arrangements are needed to replace load transfer capacity lost because of the smooth joint face and to handle early stress concentrations. Several States require adding 72 in (1.8 m) long tiebars at the construction joints, placed adjacent to every other longitudinal bar. These additional bars typically have the same diameters, grade, and depth of the regular longitudinal steel bars. This additional reinforcement prevents movement and reduces the possibility of cracks developing in the adjacent slabs.

Pavement areas adjacent to both sides of the joint should receive additional consolidation from hand vibrators inserted into the concrete along the entire length of the joint. These areas should extend at least 10 ft (3 m) from the joint. Ensure vibrators do not excessively contact steel, forms, or base.

A recent report by the Texas Transportation Institute provides additional details for CRCP transitions, including details for transverse construction joints. (123)
Blockouts

Blockouts are needed to allow for obstructions in the CRCP, such as drop-inlets, manholes, and foundations for luminaries. These types of obstructions in CRCP should be avoided if possible or otherwise limited to outer edges of shoulders. Typically, the perimeter of the blockout is an isolation joint where the width of the joint is 1.5 in (40 mm). Whereas an isolation joint in normally constructed with preformed fiberboard material, the blockout joint should instead use a compressible material that does not absorb water. In addition, approximately 3 in (75 mm) outside the perimeter of the blockout should be two concentric reinforcing bars of the same size and grade as the longitudinal reinforcing steel in the CRCP. A schematic detail is shown in Figure 55.

Construction Techniques for Controlling Crack Spacing

Field studies in Texas and elsewhere have investigated the control of crack spacing by inducers at prearranged locations. The Texas study was conducted on CRCP that was constructed in hot weather (90 to 100°F or 32 to 38°C). Crack induction was achieved by the use of two different methods: sawcutting a shallow notch in the pavement surface and metallic crack inducers. Early-age sawcutting techniques (consisting of a portable, light saw) were used for surface notching. Notches were made roughly 4 hours after concrete placement and resulted in cracks that initiated at the surface. Metallic crack inducers were placed in both single and stacked layer configurations and were anchored to the double layer of longitudinal reinforcement to provide support against the flow of fresh concrete during paving operations. Crack inducers initiate cracks at the interior of the pavement thickness.

Based on the limited data from these research studies, it appears that surface crack initiation (using the early-age notching technique) is more effective than interior crack initiation (using inducers) in controlling the crack pattern. New studies also show that plastic tape inserts can be effective in initiating transverse cracks. However, more work needs to be done to prove the viability of this technique.

Fast-Track Paving

Fast Track paving is a process of using proven techniques for concrete paving that will allow the pavement to be open to traffic at an earlier that normal age, generally in less than 12 hours. The necessary early strengths are normally achieved with an optimized mixture and thermal insulation.

The following special considerations need to be accommodated when fast tracking CRCP construction:

- Steel Stresses - High early strength gains and the possibility of increased shrinkage in the concrete need to be evaluated to ensure that excessive steel stresses do not develop.
- Steel Corrosion - Corrosive accelerators like CaCl should never be used to achieve high early strength because they may result in corrosion and structural failure. Finer cements are often used but cause decreased workability.

Figure 55. CRCP Blockout Schematic.
that requires additional water or a water reducing admixture. By adding more water, permeability will increase creating a greater risk for corrosion. Permeability is also increased by plastic shrinkage cracks that may result from heat caused by faster hydrating cements.

- **Temperature Control** - Software like FHWA HIPERPAV or CRSI PowerPave coupled with maturity sensors, should be used to ensure temperature controls are adequate to achieve the desired strength within the desired time constraints and that the removal of the thermal blankets do not cause thermal shock.

### Environmental Influences during Construction

Climatic conditions such as ambient temperature, relative humidity, and wind speed during construction affect both crack formation and pattern in CRCP through a built-in thermal gradient and set temperature. Shrinkage and contraction stresses, which are the result of restrained movement caused by temperature and moisture changes and slab friction with base layers, cause cracks to develop at early ages. These cracks are likely to occur at an early age if the temperature rise of the concrete is not held to a minimum and the heat is not allowed to dissipate at a reasonable rate, or if the concrete subjected to a severe temperature gradient.

### Hot Weather Conditions

Hot weather concreting is that when temperatures are above 90°F or 32°C. Particular concern exists when these conditions are accompanied by higher wind speeds and low relative humidity. Concrete temperatures will generally be high as a result, and there is therefore an increased loss of water due to evaporation and an increased potential for early-age cracking. Early-age cracking due to hot weather tends to be wider than cracks that develop at later ages and can thus be more damaging to CRCP performance. In addition, rapid initial or false set may reduce the effectiveness of vibration in consolidating concrete around steel reinforcing bars.

### Concrete Placement Time and Season

Early-age crack formation is related to both season and time of the day at which the concrete is placed. Recent CRCP studies in Texas indicate that concrete placed in warmer temperature experience more cracking over time and poorer crack pattern than concrete placed in cooler temperature. Also, concrete placed during daytime experienced crack formation much more quickly than concrete placed at night.(71) The FHWA HIPERPAV software can be used to identify the optimum time of day for paving to fit the current and forecasted environmental conditions to improve the performance of a CRCP. While night paving may not be desirable in urban areas (e.g., due to construction noise) the demonstrated improved performance and reduced congestion may help to justify paving at night.

Generally, CRCP placed in cool weather conditions performs better (longer crack spacing and smaller crack width) than CRCP placed in hot weather conditions. However, adverse weather conditions must be considered under these circumstances as well. Guidance provided in the IMCP Manual and elsewhere should be sought.

### Using FHWA HIPERPAV and CRSI PowerPave

Both FHWA HIPERPAV and CRSI PowerPave are software analysis tools that predict the early-age performance of CRCP. These analyses are based on support layer restraint, concrete materials and quantities, environmental conditions (both existing and predicted), and construction methods. These tools can be used for the following:

- Determining optimum paving times.
- Evaluating mixture changes that could be used to either reduce or increase the heat of hydration.
- Optimizing mixture designs as they interact with expected paving conditions.
- Determining the window for sawing operations of the longitudinal joints.
- Determining when and what additional curing may be needed.
- Estimating opening times for traffic. Recent advancements in concrete maturity and on site weather monitoring now allow this to be done in real time (FHWA SmartCure).
- Reducing the risk of thermal shock cracking.
- Determining when it is safe to stop or start paving due to adverse weather.(115)
CHAPTER 10

TERMINAL OR TRANSITION TREATMENTS
The free end of a CRCP can be expected to move up to 2 in (50 mm) longitudinally due to environmental changes in temperature and moisture depending on the frictional resistance or the viscoelastic properties of the underlying layer. To mitigate this, terminal (or transition) joints are placed where a CRCP abuts a structure or another pavement type. These joints facilitate the movement of the CRCP without damaging the adjacent structures.

An ideal terminal joint system would be one that fully allows or constrains the expected movement of CRCP while fulfilling the requirements of maintaining a smooth riding surface, preventing intrusion of water into the base, and providing necessary load transfer across the joint. There are three commonly used CRCP terminal/transitiojoints, and a fourth type has been used in Texas and Australia:

1. Expansion joints,
2. Wide flange beam joints,
3. Anchor Lugs, and
4. Seamless pavement transition at bridges.

Use of these transitions varies depending on the supporting layers, importance, and location of controlling the movement of CRCP.

Expansion Joints

When transitioning to a bridge, as illustrated in Figure 56, there are two key lessons that have been learned to help prevent the proverbial "bump at the bridge". First is to continue the CRCP base layers under the bridge approach slab to the bridge cap. Terminating the CRCP surface and base layers at one point has been shown to be problematic. The second lesson is that if there are fat clays in the sub-grade where an embankment for an overpass will be placed, then the clays should undergo a geotechnical evaluation to determine anticipated movements and treated accordingly. Pavement smoothness and structure can be significantly affected by as little as 1 in (25 mm) of differential settlement in 30 ft (10 m).

Expansion joint systems are designed to accommodate expected CRCP end movements and are the least expensive to construct of the various terminal joint systems. Maintenance may be required to clean out the joint and replace the seal, but construction is relatively simple, inexpensive, and quick.

Performance of expansion joints is significantly improved by incorporating a sleeper slab and extending base layers under the sleeper slab. Experience has shown that sleeper slabs have a tendency to tilt when base layer(s) do not extend under the sleeper slab. Multiple expansion joints may be needed, as shown in Figure 56, when it is critical for the abutting pavement not to move (e.g., in a jointed pavement toll section). Note that base layers were carried under both sleeper slabs.

Figure 57 and Figure 58 show two types of typical expansion joint systems at a CRCP transition to a HMA pavement. Note that transition in the base layers is provided away form the transition in the surface layers.
Wide-Flange Beam Joints

Wide-flange beam joint systems are also designed to accommodate CRCP end movements. Figure 59 shows a typical drawing of a wide-flange beam terminal joint system. The wide-flange beam joint is cast in a reinforced concrete sleeper slab that supports the end of the abutting pavement or structure. The steel flange helps protect the pavement edges against spalling and aids in load transfer across the joint. Beam size depends upon slab thickness and embedment in the sleeper slab. Generally a polyethylene foam that is compressible and will not absorb water is placed on the side of the web adjacent to the CRCP to accommodate end movements and prevent the intrusion of fines and moisture. A wide-flange system costs more than an expansion joint system, but less than an anchor lug system.

The system must be maintained to prevent incompressible materials from accumulating in the joint and restricting pavement movements. If the system is not maintained, repairing the wide-flange can be expensive and will take more time than an expansion system without the wide-flange beam.

Figure 57. Expansion joint, CRCP to HMA.

Figure 58. Expansion joint, CRCP to HMA alternative.

Figure 59. Typical wide flange beam terminal joint system used in Illinois.
In corrosive environments (e.g., where chloride deicing agents are applied), the beam must be protected against corrosion. Careful workmanship is critical to the performance of wide-flange terminal joint systems. The following guidelines are particularly important for installing these systems:

- The subgrade in the joint area should be compacted thoroughly, similar to the rest of the CRCP project before excavating for the sleeper slab.
- The sleeper slab must be cast with the wide flange beam in place and should be allowed to gain sufficient strength before the pavement is placed.
- The base/subbase quality in the joint area should be similar to the rest of the project; including the support under the sleeper slab. If the subgrade is considered a quality material this may not be necessary.
- The steel beam should match the cross slope and road profile of the pavement.

**Anchor Lugs**

Anchor lug terminal treatments generally consist of heavily reinforced, rectangular, transverse, concrete lugs placed in the subgrade to a depth below frost penetration prior to the placement of the pavement. This system is by far the most expensive to construct and repair. Anchor lug systems are installed at the end of CRCP sections to restrain most of the terminal movement by transferring movement forces into the soil mass through passive and shear resistance of the soil. Since this system relies on passive resistance of the soil, it may not be effective where cohesionless soils are encountered.

It is important that reinforcing steel in these systems be adequate to prevent shear failure and the system be designed to resist rotation. Field studies indicate that "lug rotation" roughness has occurred in designs that include four lugs at 40 ft (12 m) spacing, but no significant rotation is known to have occurred in designs that have three lugs spaced at 20 ft (6 m). Lugs are typically 4 ft (1.2 m) deep and 2 ft (0.6 m) wide. Figure 60 shows a typical drawing of an anchor lug terminal joint system. The following guidelines are particularly important for installing these systems:
The subgrade in the joint area should be compacted thoroughly, similar to the rest of the CRCP project before excavating for the lugs. It is desirable to continue base/subbase placement through the lug-anchor area and to excavate through the base/subbase to form lug trenches.

Lugs should be cast directly into trenches in the embankment without forms to achieve maximum resistance. However, concrete must not be contaminated by earth falling from trench sidewalls.

Reinforcing bars must be held securely in place during concrete placement.

Concrete must be consolidated effectively throughout the lug area.

Seamless Transitions

The seamless CRCP-to-structure transition is an enhancement that eliminates the need for transverse joints by connecting CRCP longitudinal steel directly into bridge deck reinforcement. This creates continuous reinforcement through the CRCP, the transition zone between the CRCP and bridge deck, and through the bridge deck itself.

The concept is similar to the process being used to reduce the number of joints in bridge decks through the use of link slabs at internal piers and has the following advantages: reduced maintenance, improved smoothness, simplified construction and cost savings (see Figure 61).(121) Although only used on a limited basis thus far in Australia, Europe, and Texas it has the potential to greatly improve the efficiency CRCP construction and performance of CRCP at bridge transitions.

Figure 61. Seamless pavement transition for bridges.
CHAPTER 11
CONSTRUCTING CROSSOVERS
CRCP design procedures and specifications are developed around the concept of continuity in load transfer and thermal stress resistance in a monolithic pavement slab. Thus, temporary gaps in CRCP should be avoided as much as possible. Giving proper consideration to the paving schedule can minimize the necessity for these gaps. However, temporary gaps are necessary in some paving situations, such as providing a haul road crossing or an intersection where cross traffic must continue to flow.

These gaps are referred to as leave-ins or leave-outs. If paving in the gap area precedes mainline construction, the gap pavement is referred to as a leave-in; if it follows mainline construction, the gap is referred to as a leave-out.

**Leave-Ins**

If the concrete is placed in the gap before paving the mainline, the crossover is referred to as leave-in. Leave-ins are preferred to leave-outs because movement of the hardened concrete of the short pavement section is not likely to have a damaging effect when abutting freshly placed concrete of the mainline section. Crack spacing in the leave-in may be greater than what develops in the mainline due to free movement of the ends. However, additional cracks will develop over time after it is connected to the mainline pavement.

Normal lap staggering and construction joint procedures can be used in leave-ins. Extra care should be taken to provide high quality concrete, effective consolidation, proper reinforcement placement, and a smooth surface. If the leave-in is in the form of an intersection, the two sides of the intersection can be constructed separately, or the entire intersection can be constructed at once.

**Leave-Outs**

If the concrete is placed in the gap after paving the mainline, the crossover is referred to as leave-out. A major concern with leave-outs is that the movement of the mainline hardened concrete can overstress the fresh concrete in the gap, causing cracking, crushing, and permanent loss of bond between concrete and steel in the leave-out area. Thus, this type of crossover should not be used unless it is the only practical method of gap construction. In fact, some agencies do not permit the use of leave-outs.

In the event a leave-out does become necessary, the following precautions should be taken to reduce distress in the leave-out concrete:

- Leave-out should be at least 100 ft (30 m) in length.
- Leave-outs require 50 percent more longitudinal deformed bars of the same nominal size as the regular reinforcement. The additional reinforcement should be spaced evenly between every other regular longitudinal reinforcing bar and should be bonded at least 3 ft (1 m) into the pavement ends adjacent to the leave-outs. All regular longitudinal reinforcement should extend into the leave-out a minimum of 8 ft (2.5 m). Required splices should be made the same as those in normal construction.
- Leave-outs should be paved during stable weather conditions when the daily temperature range is small. This condition is likely to exist when the sky is cloudy and the humidity is high.
- If it becomes necessary to pave a leave-out in hot weather, the temperature of the concrete in the free ends should be stabilized by placing an adequate layer of insulating material on the surface of the pavement to minimize movement. Curing compound should be applied to new concrete in a timely manner. Insulation material should remain on adjacent pavement until the design modulus of rupture of the leave-out concrete is attained.
- Because of the shortness of the steel spacing, extreme care should be exercised in placing and consolidating concrete to prevent honeycombing or voids under reinforcement.
- Place terminal treatments at each end of the leave-out.

**Temporary Crossovers**

This type of crossover is sometimes needed to accommodate truck movement across the grade after reinforcing steel is in place. These crossovers can be installed by placing wooden mats over the steel after temporary removal of bar supports. The wooden mats can be designed so that cleats underneath are spaced to fit between longitudinal and transverse reinforcing members.
CHAPTER 12
CONSTRUCTING SHOULDERS AND RAMPS
Concrete and asphalt shoulders, auxiliary lanes, and ramps can be constructed in conjunction with a mainline CRCP. The design and construction of these components will affect the cost of CRCP construction, maintenance requirements and can significantly impact long-term performance of the mainline CRCP.

**Shoulders and Auxiliary Lanes**

Typical shoulder designs for CRCP traffic lanes include:

- Jointed plain concrete pavement placed after the mainline traffic lanes without dowels (when not expected to carry traffic). Tiebars are used to provide load transfer.
- HMA placed adjacent to an extended outside lane of the mainline CRCP slab. The mainline slab should extend at least 2 ft (0.6 m) into the shoulder area to provide an interior loading condition for traveled lanes.
- CRC with the same cross-section as main lanes. Often times a State will widen the shoulder so that it may serve as a traffic lane when needed.

Key features to consider in the design and construction of shoulders and auxiliary lanes include the following:

- Amount of load transfer provided by the shoulder (or auxiliary lane) through the design life of the pavement.
- Ability to prevent the intrusion of moisture to susceptible layers under the loaded area of the pavement.
- Maintenance requirements.
- Ability to use shoulder for regular traffic (emergencies, increased capacity, and/or parking).

**Concrete Shoulders**

Concrete shoulders should be tied to the mainline by either extending the transverse steel from the mainline CRCP into the shoulder with a longitudinal contraction joint provided at the juncture of the traveled lane and the shoulder, or through a longitudinal construction joint with properly spaced, aligned, and sized tiebars. Tiebars are required between the mainline slab and concrete shoulder to provide designed load transfer and prevent water infiltration into the pavement and base structure.

Tiebar installation at the shoulder follows the same construction practice as provided in Section 7.4 at longitudinal mainline construction joints. Almost all states have abandoned the use of Grade 40 (Grade 300) tiebars and the practice of bending the bars, due to joint separation issues.

Some agencies are now using a multi-piece threaded tiebar as was shown in Figure 38. One half of the bar is tied to the reinforcement in the CRCP traffic lane. After concrete is placed, the other half is threaded into this bar. Keyed longitudinal joints are not recommended and should never be used for pavements less than 10 in (250 mm) thick. If used for pavements 10 in (250 mm) or greater in thickness, keyways should be placed at mid-slab depth to ensure maximum strength. Proper concrete consolidation, both above and below the keyway, is essential and the joint must be tied with reinforcing steel as previously recommended.

Where plain jointed concrete shoulders are used adjacent to CRCP, the tied concrete shoulder should be sawed transverse to the direction of traffic to a depth of one-third the pavement thickness at no more than 15 ft (5 m) intervals. If the shoulder will be used for mainline traffic, or substantial parked truck traffic, consideration should be given to use of dowels at these joints to prevent faulting and provide additional load transfer. Plain jointed concrete shoulders should not be constructed integrally with or before the mainline CRCP, as the transverse saw cuts in the integrally constructed shoulders would propagate as cracks across the mainline CRCP.

Corrugations that are impressed in plastic concrete have proven to be an effective contrast between shoulder and mainline pavements alerting drivers they are moving onto the shoulder. The width and depth of the corrugations are dependent on roadway average speed. In a 50 to 70 mph (80 to 110 kph) range, a width of 4 to 6 ft (1 to 2 m), and a spacing of 60 to 100 ft (18 to 30 m) are appropriate. Care should be taken to make certain that the impressed corrugations meet the plan details throughout the hardening process and that the concrete is not weakened by late disturbance.

**Asphalt Shoulders**

The FHWA Technical Advisory T5040.29 recommends that shoulders be constructed of the same materials as the mainline pavement to facilitate construction, improve performance, and reduce maintenance costs. The Advisory explains that tied concrete shoulders in lieu of flexible shoulders will minimize problems associated with infiltration of surface water into foundation through lane-shoulder longitudinal joints. However, if HMA shoulders are selected, the following guidelines should be considered:

- Include anti-stripping agents in the HMA mixture used on the shoulder.
• Include proper subdrainage such as edge drains beneath the lane/shoulder joints, or daylighted treated permeable bases, so as to drain water infiltrating the lane-shoulder joint and to keep the entire base structure free of moisture. Sub-drainage is discussed in Section 6.2 of this guide.

• Ensure that the HMA is compacted to adequate density, particularly at lane-shoulder interface.

**Widened Lane**

The use of full-width CRC paved shoulders is desirable for many reasons. However, the additional cost of this design may not be warranted on all projects. Some agencies build widened outside lanes instead of using full-width paved shoulders. A monolithic widening of at least 1 ft (0.3 m) outside of regular painted edge strips is commonly used. Widened lanes are only effective when travel lanes are striped at 1 ft (0.3 m) to help guide vehicles within the traffic lane and not on the widened area. Widened lanes reduce the number of edge loadings; thereby reducing development of edge punchouts. Placement of rumble strips on the shoulder portion of a widened lane should also be considered.

**Concrete Ramps**

Concrete ramps adjacent to mainline CRCP can be constructed as CRCP or jointed concrete pavement. Longitudinal joints between the ramp and mainline CRCP should be designed and tied as the lane-lane or lane-shoulder tied longitudinal joints that are discussed in Section 8.4 of this Guide.

When the ramp is constructed as CRCP or as a jointed concrete pavement with a joint spacing of 15 ft (5 m) or less; tiebars can be placed uniformly at the same spacing used in the adjacent longitudinal joint. If the ramp is constructed as a jointed concrete pavement with a joint spacing greater than 15 ft (5 m), only the middle third of each slab between joints should be tied because excessive stresses in the CRCP can result from large thermal movements of the tied ramp near transverse joints. (89)

Take extra care in the ramp concrete consolidation (especially around construction joints) and finishing to achieve concrete uniformity and satisfactory ride quality.

CRCP ramps will require terminal treatments at their point of transition to the adjoining roadway.
CRCP has been effective as an overlay for deteriorated composite, rigid, and flexible pavements. CRCP overlays have also been effective over pavements in good condition for the purpose of adding capacity or structure when traffic loads are heavier than expected. Only in cases where separation layers or overlay thicknesses were inadequate (e.g., less than 7 in (178 mm)) did CRCP overlays not perform well.

CRCP overlays are similar to new CRCP in terms of mechanical behavior and primary distress (e.g., wide cracks and punchouts). Generally, all concrete and reinforcement construction guidelines that have been discussed previously for new CRCP apply to CRCP overlays. CRCP overlays are designed and constructed as bonded or unbonded overlays depending on the existing pavement type and condition.

Additional guidance for CRCP Overlays can be found in the Guide to Concrete Overlays developed by the National Concrete Pavement Technology Center. An additional reference is the "Concrete Overlays for Pavement Rehabilitation" guidance, published as ACI document 325.13R-06.
CHAPTER 14
CONSTRUCTION INSPECTION
Quality construction is a key factor in the long-term exceptional performance of CRCP and does not happen by chance.

In addition to guidance found in the Materials and Construction Optimization (MCO) Guidelines and elsewhere, the following items should be checked on CRCP projects:

- Crack widths that exceed the design criteria, which would be in the range of greater than 0.02 in (0.5 mm) and punchouts caused by:
  - Insufficient steel lap length,
  - Steel placed too low in the slab,
  - Less-than-design slab thickness,
  - More-than-design slab thickness, resulting in a reduced steel percentage,
  - Poor bonding of the steel to the concrete caused by:

- Insufficient consolidation of the concrete,
- Sudden temperature drops greater than 20°F (10°C) during construction, and/or
- Steel heavily rusted, soiled, or coated with curing compounds, grease, or oils without adequate cleaning.

- Surface delaminations caused by steel too high in the slab, large temperature swings, or inadequate vibration.
- Punchouts in CRCP overlays due to a lack of repairs to serious underlying pavement deteriorations.

Construction related distress can be greatly minimized or even eliminated with proper attention to detail, care during construction, and sound quality control. Several DOT's have constructed quality CRCP that have shown excellent performance. Examples of inspection tasks are listed in Table 6, which summarizes the items that need special attention during the construction of CRCP. The details of these items are discussed throughout this guide.

Table 6. Summary of Inspection Tasks.

<table>
<thead>
<tr>
<th>Critical Inspection Item</th>
<th>Importance</th>
<th>Suggested Precautionary Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subgrade</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uniformity of subgrade support</td>
<td>Minimize differential localized settlements along CRCP project over time.</td>
<td>Use heavy roller to proof roll length of pavement, identify, and correct soft areas. Use DCP or GPR at regular intervals to identify location of very soft soils. Measure the density and moisture content after compaction of each layer.</td>
</tr>
<tr>
<td>Grading of subgrade</td>
<td>Any abnormality in the subgrade will likely be reflected in the CRCP surface. Proper subgrade grading helps achieve proper thickness and smoothness in the base and surface of CRCP.</td>
<td>Check for stringline sag. Check the beginning and ending of the stringlines. Continually &quot;eyeball&quot; the stringline for straight grades and smooth transitions. Continually check if the sensors are connected and operating properly.</td>
</tr>
<tr>
<td><strong>Base/Subbase(s)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction between CRCP slab and support</td>
<td>Affects crack spacing. Using a push-off test, verify that the as-constructed friction between CRCP and the support layer is consistent with as-designed friction (e.g., do not reduce this friction during construction unless it was explicitly designed).</td>
<td>Evaluate mixture as constructed, and conduct stripping tests to ensure adequate film thickness around the aggregates.</td>
</tr>
<tr>
<td>Binder content in asphalt treated base</td>
<td>Asphalt base needs to provide adequate support over the entire design life and thus must avoid stripping. Critical to minimize development of punchouts and loss of smoothness.</td>
<td></td>
</tr>
<tr>
<td>Critical Inspection Item</td>
<td>Importance</td>
<td>Suggested Precautionary Measures</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Base/Subbase(s) (continued)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stability and uniformity of unbound aggregate base</td>
<td>Unbound aggregate base needs to provide adequate support over the entire design life. Critical to minimize development of punchouts and loss of smoothness.</td>
<td>Measure gradation and density of base course and avoid segregation.</td>
</tr>
<tr>
<td>Cement treated base (CTB) or lean concrete base</td>
<td>Generally used over weak or variable subgrades to provide uniform support that is not subject to water damage support over the entire design life. Critical to minimize development of punchouts and loss of smoothness. Erosion related to strength of base.</td>
<td>In the field, use density as a check for moisture content and strength. Use appearance to check for consistency. Initially and when density and visual check indicate the need take cores and check strengths (compression or indirect tensile). At the plant, regularly check compressive or indirect tensile strength for consistency and compliance. • Longitudinal joints should match those in the CRCP slab. • Pave during proper climatic conditions and use proper curing process.</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td>Affects crack spacing, crack width, punchouts of CRCP</td>
<td>Sample at site prior to or during placement of concrete and check to assure that unwanted water is not being added.</td>
</tr>
<tr>
<td>Deviation of as-constructed slab thickness from as-designed value</td>
<td>Affects crack spacing, crack width, punchouts of CRCP. Thicker as-built slab results in lower percentage of steel and thinner slab results in punchouts. Consistent thickness is important to achieving smooth surface.</td>
<td>• Constantly monitor in plastic concrete using depth checker. • If necessary, verify with cores after hardening.</td>
</tr>
<tr>
<td>Consolidation</td>
<td>To provide sufficient bonding between steel and concrete and concrete durability that is necessary to protect the steel from corrosion.</td>
<td>• Check the density of the concrete. • Check the frequency, amplitude, centrifugal force, and radius of action of the mechanical vibrators or require continuous recording with time, temperature, and distance. • If necessary, visually inspect concrete from cores.</td>
</tr>
<tr>
<td>Aggregate</td>
<td>Aggregate properties—including the CTE, surface texture, and size of the coarse aggregate—affect the crack spacing and width in CRCP.</td>
<td>Select the aggregates carefully and do not change in the field before consulting with the pavement and concrete mix designers.</td>
</tr>
<tr>
<td>Concrete placement</td>
<td>Uniformity of concrete affects surface smoothness.</td>
<td>• Maintain consistent concrete delivery. • Maintain consistent concrete slump (significant changes in temperature may require a change in the mix design to maintain the same consistency). • Maintain consistent head in front of the paver. • Maintain consistent paver movement.</td>
</tr>
</tbody>
</table>
### Table 6. Summary of Inspection Tasks. (continued)

<table>
<thead>
<tr>
<th>Critical Inspection Item</th>
<th>Importance</th>
<th>Suggested Precautionary Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concrete (continued)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete texturing</td>
<td>Tining affects surface texture and thus noise level and skid resistance. Also, improper tining may result in spalling.</td>
<td>• Begin tining when the concrete surface loses its water sheen and just before the concrete becomes nonplastic. • If texturing operations are delayed, consider fog applications of an evaporation retardant until they can be resumed. • Begin the curing process as soon as possible after texturing has occurred.</td>
</tr>
<tr>
<td>Concrete curing</td>
<td>Curing is particularly important in CRCP because of its effect on the formation of transverse cracking.</td>
<td>• Apply curing immediately after the finishing and texturing operations are complete. • Cure for at least 72 hours.</td>
</tr>
<tr>
<td>Placing concrete in hot weather (over 90 °F or 32°C)</td>
<td>In hot weather, especially when accompanied by wind and low humidity, concrete sets at an increased rate and there is an increased water demand. Thus, there is an increased potential for early-age cracking. Also, rapid initial set may reduce the effectiveness of vibration in consolidating concrete around the steel reinforcing bars.</td>
<td>• Cool the mixing water and/or aggregate. • Fog the base, steel reinforcement, and side forms (if used). • Use water-reducing retarders. • Consult the design and materials engineers when taking these precautions. • Use a Class F fly ash to replace cement. • Use liquid nitrogen shots to reduce the mix temperature.</td>
</tr>
<tr>
<td>Placing concrete in cold weather (less than 40 °F or 4°C)</td>
<td>In cold weather concrete will take longer to set and gain strength. Concrete that freezes before it has gained at least 1500 psi (10.3 MPa) in compressive strength can be permanently damaged.</td>
<td>• Heat the mixing water and or aggregate. • Adjust the mix design (increase the cement content, change the cement type, add water-reducing agents or air entrainment). • Consult the design and materials engineers when taking these precautions. • Use a Class C fly ash instead of a Class F fly ash.</td>
</tr>
<tr>
<td><strong>Reinforcement</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth of longitudinal steel</td>
<td>Placing reinforcement closer to the surface can result in tighter cracks and fewer punchouts. However, the steel should have sufficient cover to preclude the development of cracks over the longitudinal bars and resist steel corrosion caused by chloride deicing agents.</td>
<td>• Check the depth of steel (top of slab to top of steel) on a continuing basis by means of probing. • Use sturdy supports that have a base configuration that provides adequate support for the weight of the steel and concrete without sinking into the base. • Verify that the design depth of steel is met (between 3.5 in (90 mm) and mid-depth of the slab).</td>
</tr>
<tr>
<td>Splicing</td>
<td>Splices should be installed so they do not create a transverse plane of weakness across the CRCP (which may result in crack opening).</td>
<td>• Use a minimum lap length of longitudinal steel splices of 25 times the bar diameter is recommended. • Use at least two secure wire ties for each lap splice. • If a staggered splice pattern is used, not more than one-third of the bars should terminate in the same transverse plane, and the minimum distance between staggers should be 4 ft (1.2 m) (If a skewed arrangement is used, the minimum skew should be 12 ft (3.6 m) in a 24 ft (7.2 m) width pavement, or 1:2.</td>
</tr>
<tr>
<td>Critical Inspection Item</td>
<td>Importance</td>
<td>Suggested Precautionary Measures</td>
</tr>
<tr>
<td>-------------------------</td>
<td>------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td><strong>Reinforcement (continued)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tiebars and transverse steel</td>
<td>Transverse steel control longitudinal cracks that develop due to problems with forming the lane-to-lane joint or settlements along the highway. If transverse steel is not carried through longitudinal joint locations, tiebars or multiple-piece threaded bars are used to hold the adjoining slabs together.</td>
<td>Note that satisfactory transverse steel installations have been made with #4 (#13) bars at 36 in (900 mm), #4 bars (#13) at 48 in (1200 mm), #5 (#16) bars at 36 in (900 mm), #5 (#16) bars at 44 in (1000 mm), #5 (#16) bars at 48 in (1200 mm), and #6 (#19) bars at 36 in (900 mm). When tiebars are to be bent and straightened, use reinforcing bars of ASTM designation A 615 Grade 40 (Grade 300). Tiebars are usually placed near mid-depth of the concrete slab. They must be low enough to avoid cutting if the longitudinal joint is formed by sawing, or to avoid interference if a ribbon insert is used to form the joint. They may be attached to the regular reinforcement.</td>
</tr>
<tr>
<td>Lateral spacing longitudinal steel</td>
<td>Lateral spacing should allow for proper vibration of the concrete.</td>
<td>Verify that the spacing is no less than 4 in (100 mm) or 2.5 times the maximum size of the aggregate, whichever is greater; but is not greater than 9 in (225 mm).</td>
</tr>
<tr>
<td><strong>CRCP Overlays</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction between CRCP slab &amp; the separation layer</td>
<td>Friction is important as it affects crack spacing and base. No need to try to reduce friction.</td>
<td>Verify that the as-constructed friction between CRCP slab and the separation layer is consistent with as-designed friction.</td>
</tr>
<tr>
<td>Localized failed areas in the existing pavement</td>
<td>Affects reflection cracks in the CRCP.</td>
<td>Identify and correct high deflection areas of existing pavement to be overlaid and provide adequate thickness of separation layer.</td>
</tr>
<tr>
<td><strong>Joints</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sawing time and depth of longitudinal joints</td>
<td>Properly formed longitudinal joints relieve stresses caused by concrete shrinkage and temperature differentials in monolithically placed slabs.</td>
<td>• Sawing must be completed before the slab begins to shrink, and started when only minor raveling occurs. Note that typically, the sawing depth is one-third of the specified slab thickness; however, the saw cut must not be so deep that the tiebars across the control joint are weakened.</td>
</tr>
<tr>
<td>Steel installation and concrete consolidation at construction joints</td>
<td>Critical factors to prevent joint failures.</td>
<td>• Note that typically, additional 72 in (1.8 m) long tiebars at the construction joints are placed adjacent to every other longitudinal bar. • Apply additional consolidation from hand vibrators to the pavement areas adjacent to both sides of the joint 10 ft (3 m).</td>
</tr>
<tr>
<td>Installation of wide flange terminal joints</td>
<td>Critical to allow these joints to facilitate the movement of the CRCP without damaging the adjacent structures.</td>
<td>• Use high quality concrete. • Protect the wide flange beam against corrosion. • Cast the sleeper slab with the wide flange beam in place and allow it to gain strength before the pavement is placed.</td>
</tr>
<tr>
<td>Installation of anchor lug terminal joints</td>
<td>It is important that the reinforcing steel in these systems be adequate to prevent shear failure and system be designed to resist rotation.</td>
<td>• Do not use in cohesionless soils. • Cast the lugs directly into the trenches (without contaminating the concrete) in the embankment without forms to achieve maximum resistance. • Consolidate the concrete effectively throughout the lug area.</td>
</tr>
<tr>
<td>Critical Inspection Item</td>
<td>Importance</td>
<td>Suggested Precautionary Measures</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Installation of leave-ins</strong></td>
<td>The performance of these systems affects CRCP smoothness.</td>
<td>Take extra care to provide high quality concrete, effective consolidation, and smooth surface.</td>
</tr>
<tr>
<td><strong>Installation of leave-outs</strong></td>
<td>The performance of these systems affects CRCP smoothness.</td>
<td>• Pave during stable weather conditions when the daily temperature cycle is small.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Note that leave-out should be at least 100 ft (30 m) in length.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Use 50 percent more longitudinal deformed bars in leave-outs, of the same nominal size and splices as the regular reinforcement.</td>
</tr>
</tbody>
</table>
Introduction

This guide specification for field installation has been developed by the Concrete Reinforcing Steel Institute (CRSI) as part of their Cooperative Agreement with the Federal Highway Administration. The guide specification was reviewed by various state DOTs, industry, and academia and is intended for educational purposes only.

Continuously reinforced concrete pavements do not require transverse joints except where necessary for construction purposes (e.g., end of day construction header joints) or in the approach to bridges or transitions to other pavement structures). Natural volume changes in the concrete (caused by hydration and seasonal movement), combined with the restraint imposed by steel reinforcement and the pavement base, will lead to transverse cracks that develop at regular intervals. These cracks, which occur as the pavement ages, are kept tight by the longitudinal reinforcement. These cracks are natural and intended; they do not constitute defects.

Longitudinal joints are used on continuously reinforced concrete pavement to relieve concrete stresses in the transverse direction and/or when the paving cannot be performed in a single pass.

Guide Specification

1.0 DESCRIPTION. Work shall consist of constructing a continuously reinforced Portland cement concrete pavement on a prepared subgrade or subbase in close conformity with the lines, grade, thicknesses, and typical cross-sections shown on the Project Plans and in accordance with the Standard Specifications except as modified herein.

All specification references shall be the latest copy at the time of bid release. Project plans shall include type of steel, spacing, etc.

2.0 MATERIALS. Materials shall conform to the requirements of the Standard Specifications, and the requirements given hereinafter.

- Coarse Aggregate
- Protective Coatings
- Steel Reinforcing Bars
- Tie Bars
- Steel Wide Flanges

2.1 COARSE AGGREGATE. The maximum size of coarse aggregate shall be not greater than one-half the minimum nominal clear opening between longitudinal reinforcing bars as computed from Project Plan dimensions.

2.2 CONCRETE STRENGTH LIMITS. The concrete strength shall be as designated in the Project Plans.

**GUIDE NOTE:** Plan concrete strengths should show values and test methods for either flexural or compressive with values at both 7 days and 28 days.

2.3 STEEL.

2.3.1 STEEL REINFORCING BAR SPECIFICATION. Reinforcing bars shall consist of deformed steel reinforcing bars and the material delivered to the site shall conform to one of the following requirements:

- Deformed common (black) reinforcing bars conforming to ASTM A615/A615M (AASHTO Designation M31M/M31) Grade 60.
- Deformed common (black) reinforcing bars conforming to ASTM A706/A706M Grade 60.
- Epoxy-coated reinforcing bars shall conforming to ASTM A775/A775M. Epoxy-coated reinforcing bars shall be provided from a plant certified by CRSI in accordance with the CRSI Voluntary Certification Program for Fusion-Bonded Epoxy Coating Applicator Plants.
Stainless-steel bar shall conform to ASTM A 955/A 955M Grade 60.

Deformed reinforcing bars conforming to ASTM A1035/A1035M.

Transverse Bar Assembly conforming to minimum W5 wire size number specified in ASTM A 82/A 82M for clips, minimum W2 wire size number specified in ASTM A 82/A 82M for chairs, and welded under Section 7.4 of A

STM A 185/A 185M.

Transverse bars to which supports are to be welded, bars that cross the longitudinal joint, or bars which are to be bent and later straightened shall be ASTM A615/A615M Grade 40 or ASTM A706/A706M.

Wide flange beams if used in the anchor slab terminal joint of continuously reinforced pavement shall conform to the requirements of ASTM A36/A, 36M or structural steel in ASTM A572/A 572M.

2.3.2 LENGTH OF REINFORCING BARS. The longitudinal bars shall be not less than 30 feet (10 m) in length except where shorter bars are required for the purpose of starting or ending a staggered lap pattern or at a construction joint. The maximum length of longitudinal bars shall be that which can be placed in a proper manner, or as shown on the Project Plans.

2.3.3 SIZE AND SPACING OF STEEL REINFORCING BARS. Longitudinal bars shall be of the dimensions and spacings as shown on the Project Plans or shall be governed by the minimum permissible spacing of the bars and the percentage of longitudinal steel specified or shown on the Project Plans. The longitudinal bars shall be spaced not less than 4 inches (10 cm) and not more than 9 inches (23 cm) center-to-center. Transverse bars shall be of the size, dimensions and spacings as shown on the Project Plans.

2.3.4 PROTECTING MATERIAL. Reinforcing steel shall be stored on platforms, skids, or other supports that will keep the steel above ground, well drained, and protected against deformation. When placed in the work, steel reinforcement shall be free from dirt, paint, oil, or other foreign substances.

2.3.5 BLACK BAR. Steel reinforcement with rust or mill scale will be permitted provided samples wire brushed by hand conform to the requirements for weight and height of deformation.

2.3.6 EPOXY COATED BARS. Epoxy coated bars shall be handled in accordance with Appendix X1 of ASTM A 775 or Appendix X2 of ASTM A 934.

2.3.7 STAINLESS STEEL. Stainless steel reinforcement shall be stored separately or above conventional steel reinforcing to prevent contamination from mill scale or other ferrous metals. Steel chains, bands and lifting devices should not be in direct contact with stainless. Synthetic straps and slings are preferred. Stainless steel reinforcing bar which is stored outdoors shall be off the ground, covered with tarpaulin and not in direct contact with steel storage racks or stored below steel bars. Non-ferrous cribbing shall be separate the two materials.

3. CONSTRUCTION METHODS. The construction of continuously reinforced concrete pavement shall conform in all respects to the requirements of the Standard Specifications with the following revisions and modifications.

3.1 PLACEMENT OF REINFORCING BARS. Reinforcing bars shall be preset such that the longitudinal bars shall be placed to meet the tolerances, locations and clearances shown on the Project Plans.

The arrangement and spacing of the supports shall be such that the reinforcing bars will be supported in proper position without permanent deflections or displacement of no more than 0.1 in. (2.5 mm) occurring during the placement of the concrete in excess of the tolerances specified herein. They shall have

GUIDE NOTE: It is not recommended to use tube feeding of reinforcing steel. While some state DOT specifications do allow it, it has been found that steel location is much too variable and can lead to excessive vertical and horizontal variations. It is strongly recommended.
sufficient bearing at the base to prevent overturning and penetration into the subbase. They shall be designed so as not to impede the placing and consolidation of the concrete or otherwise interfere with its performance. Continuous supports should not be set so close to other transverse bars as to make placing of the concrete between bars difficult. This is particularly important in areas where there is a concentration of lap-spliced reinforcing bars. Welding of individual supports to transverse bars will be permitted.

At the time the concrete is placed, the reinforcement shall be free of mud, oil or other non-metallic coating that may adversely affect or reduce the bond. Common (black) reinforcement with rust, seams, surface irregularities or mill scale shall be considered as satisfactory provided the weight, dimensions, cross-sectional area, and tensile properties of a hand wire brushed test specimen are not less than the applicable ASTM specification requirements. Stainless steel should be protected from carbon steel surface contamination by using equipment exclusively dedicated to stainless steel, or by covering all contact points with clean neoprene, wood, or synthetic materials. If contamination of the stainless steel surface occurs it should be removed with a stainless steel wire brush or pickling paste. Bars shall be free from kinks or bends that may prevent proper assembly, placement or performance. Forms, if used, shall be oiled prior to placement of reinforcing bars.

A sample of the individual or continuous supports proposed for use shall be submitted for review. Unless a specific spacing of supports is designated on the Project Plans, a drawing showing the proposed layout with supports shall be developed and approved. If the support system does not maintain the reinforcing bars in the position required herein during placing and finishing of the concrete, the number of supports will need to be increased or steps taken as required to assure proper positioning of the reinforcing bars.

GUIDE NOTE: The Contractor may select the method of support to be used. However, if the required horizontal and vertical tolerances for placement of the reinforcing bars are not met, the Contracting Agency reserves the right to require changes in the placement or equipment operations.

Longitudinal bars shall be secured to the transverse bars by wire ties or clips at sufficient intersections to maintain the horizontal and vertical tolerances specified on the Project Plans. Welding of the longitudinal bars to the transverse bars shall not be permitted.

Steel reinforcement shall be firmly held during the placing and setting of concrete. Bars shall be tied at every intersection where the spacing is more than 12 inches in any direction. Bars where the spacing is 12 inches or less in each direction shall be tied at every intersection or at alternate intersections provided such alternate ties accurately maintain the position of steel reinforcement during the placing and setting of concrete. Stainless tie wires should be used for stainless steel. Tie wires used with epoxy-coated steel shall be plastic coated or epoxy coated. Following placement of epoxy-coated reinforcement and prior to concrete placement, the reinforcement will be inspected. All visible damage of the epoxy coating shall be repaired in accordance with Appendix XI of ASTM A 775 or ASTM A 934.

3.2 STEEL LOCATION CHECK PRIOR TO PAVING. The vertical location of the reinforcing steel shall be checked prior to concrete placement. This may be accomplished by pulling a stringline transversely across the roadway at the grade of the new pavement and measuring down to the reinforcing steel.

3.3 STEEL LOCATION CHECK DURING PAVING. To verify the depth of the reinforcing steel, a probe can be used to check the depth of the reinforcing steel while the concrete is still plastic.

GUIDE NOTE: A cover meter may be used to periodically check the depth of the reinforcing steel behind the paver while the concrete is plastic or hardened.
3.4 LAP SPLICES IN LONGITUDINAL REINFORCING BARS. Lap splices in the longitudinal reinforcing bars shall be placed in a pattern (skewed or staggered) across the pavement width as shown on the Project Plans. A minimum lap length of 25 bar diameters shall be used. No more than one-third of the longitudinal bars within a single traffic lane shall terminate in the same vertical plane at right angles to the pavement centerline. All lap splices in the longitudinal reinforcing bars shall be fastened securely with a minimum of two ties.

The longitudinal lap of all splices shall be checked to assure that the minimum lap of the reinforcing steel is maintained as shown in the plan details.

3.5 STEEL LOCATION CHECK DURING PAVING. A cover meter may be used to periodically check the depth of the reinforcing steel behind the paver while the concrete is plastic or hardened. Another option used to verify the depth of the reinforcing steel is to actually probe down to the reinforcing steel while the concrete is still plastic, and measure the depth.

GUIDE NOTE: The length of the lapped splices of the longitudinal reinforcing bars is critical to good performance. It is imperative that the minimum length requirements be observed carefully and enforced strictly during construction.

3.6 PLACING AND PAVING OPERATION.

Place, pave and finish concrete so as to:

- avoid segregation or loss of materials,
- avoid premature stiffening,
- produce a uniform dense and homogeneous product throughout the pavement,
- expel entrapped air and closely surround all reinforcement and embedments, and
- provide the specified thickness and surface finish.

Extreme care should be exercised to prevent honeycombing in the concrete, especially around the immediate area of construction joints where hand spud vibrators shall be used to assure good consolidation of the concrete. The surface shall be given one pass for the full pavement width with a pan type or gang spud vibrator prior to the passage of the finishing machine.

GUIDE NOTE: Thickness measurements of the concrete slab can be determined by rod/level on a grid system, coring, or edge measurements.

For transverse bar reinforcement in a curve with a radius under 2,500 feet, the reinforcement shall be placed in a single continuous straight line across the lanes and aligned with the radius point. If the curve does not allow the specified spacing between transverse bar reinforcement and tie bars, space them a distance that is between one half the specified spacing and the specified spacing. The tie bars shall be placed on the same alignment as the transverse bar reinforcement.

Thickness Measurement - Under Thickness. A slab which is more than 0.50 in. (13 mm) below the specified thickness shall be removed and replaced in accordance with the Standard Specifications. A slab which is 0.50 in. (13 mm) or less below the specified thickness may be accepted providing that it represents isolated sections within a lot and such sections comprise less than 5 percent of the area of the lot. Such concrete shall be subject to a deduction in accordance with the Standard Specifications.

Thickness Measurement - Excess Thickness. Where the thickness of the slab exceeds the specified thickness, conformance of the slab is dependent on both thickness and strength. Deductions shall be applied in accordance with the Standard Specifications.

3.7 FINAL STRIKE-OFF, CONSOLIDATION, AND FINISHING. The vibrating impulse shall be applied in a manner by which the concrete is consolidated throughout its entire depth and width. Special care shall be taken to assure thorough consolidation of the concrete under and around lapped bars to avoid segregation and honeycombing in the concrete. The pavement vibrator shall not be allowed to operate for more than 10 seconds while the machine is standing still. Only one pass of the vibrator equipment shall be made.
3.8 TRANSVERSE CONSTRUCTION JOINTS. A transverse construction joint shall be placed at the end of each day’s work or whenever paving operations are interrupted for more than 30 minutes, provided the length of pavement laid from the last joint is 12 feet (3.5 m) or more and the distance from the construction joint to the nearest bar lap splice is at least 3-1/2 feet (1 m). Sections less than 12 feet (3.5 m) in length are not permissible.

At any location where a “leave out” is necessary for a detour, at least 100 feet shall be maintained between transverse construction joints.

The transverse construction joint shall be formed by a split header board conforming to the cross-section of the pavement. The header shall consist of two sections, one being placed above and one being placed below the reinforcing mat, and shall be furnished with openings to accommodate the longitudinal steel. It shall be accurately set and held securely in place in a plane perpendicular to the surface of the pavement. The longitudinal reinforcing bars shall extend continuously through the split in the header board, supported beyond the joint by supports to prevent undue deflections, and afforded positive protection against excessive movement and bending until concrete placement resumes. A hand vibrator shall be used along the entire length of the joint. The header board shall be kept clean and not oiled.

The construction joint shall be strengthened by the addition of supplementary reinforcing bars of the same size, strength and type as the longitudinal bars. The supplementary bars shall be centered at the joint and at a uniform spacing along the joint as shown on the Project Plans. No lap splices in the longitudinal bars shall be within 3-1/2 feet (1 m) of the stopping side or closer than 8 feet (2.5 m) from the starting side of a construction joint.

Before paving operations are resumed, the header board shall be removed, any concrete that may have leaked through the holes or split in the header chipped away from the face of the joint, all surplus concrete on the subbase shall be cleaned away, and any irregularities in the subbase shall be corrected.

The fresh concrete shall be deposited directly against the old. Use hand-held immersion vibrators to consolidate the concrete adjacent to all formed joints. If more than 5 days elapse before construction continuation, the temperature of the completed slab shall be stabilized to reduce potential high tensile stresses in the longitudinal steel. This shall be accomplished by placing insulation material on the completed slab for a distance from the free end for a period of at least 72 hours prior to placing the adjacent concrete.

Tie bars located within 18 inches of the transverse construction joint should be omitted.

Paving in the area of a transverse construction joint will not be permitted for 12 hours after installation.

3.9 LONGITUDINAL JOINTS. Longitudinal joints between adjacent slabs shall be tied together to prevent separation by using either tie bars of the type, length, size and spacing shown in the Project Plans, or transverse bars extending across the full width of each slab, as specified in the Project Plans.

For adjacent slabs constructed separately (i.e., construction joints), deformed tie bars, of the type, length, size and spacing shown in the Project Plans, shall be placed mid-depth and centered across the two slabs. These bars may be supported on approved assemblies or securely tied to the undersides of the longitudinal bars or placed manually or mechanically during the paving of the first slab or placed in preformed or drilled holes in the first slab after it has sufficiently hardened. Holes for the latter type of installation shall be blown clean and dry prior to placing the tie bars, and the bars shall be secured inside the holes using an approved non-shrink grout or chemical adhesive.

Monolithically placed slabs widths of more than 15 ft (4.5 m) shall have a longitudinal joint (contraction or construction). These joints shall be located within 6 in. (15 cm) of the lane line unless the joint location is shown on the Project Plans.

Longitudinal joints shall be formed or sawed to a depth of one-third of the slab thickness. It is important that the reinforcing steel be placed and surveyed accurately in order to avoid conflict with the longitudinal sawn joint.

Longitudinal construction and contraction joints shall be cleaned and sealed in accordance with the contract specifications and Project Plans.

3.10 TERMINAL JOINTS. Terminal joints shall be constructed in accordance with details shown on the Project Plans.
Terminal joints shall be constructed normal to the control line, to the dimensions and at the locations shown on the Project Plans or where directed by the Superintendent.

Terminal joints shall extend over the full width of the base and the associated transverse expansion joint shall not be placed closer than 8 ft (2 m) to other transverse joints. Where necessary, the Superintendent shall authorize a change in the spacing of transverse joints to ensure that this minimum clearance is obtained.

Excavation of trenches shall be to the dimensions and details shown on the Project Plans.

The structural steel components and/or reinforcing steel shall be checked to assure they meet material requirements of the specifications and the details shown in the Project Plans.

All surfaces that are required to be coated in the Project Plan details shall be done so completely.

3.10.1 LUG ANCHORAGE SYSTEM TERMINAL JOINT. The number and location of lugs shall be as shown on the Project Plans. The lugs shall be constructed in trench. All loose material shall be removed and the vertical faces trimmed to neat lines. The bottom of the trench shall be recompacted, where required, to the degree of consolidation of the adjacent undisturbed material and to the satisfaction of the Superintendent. The use of forms will not be permitted. Secure reinforcement in position before concrete placement in accordance with the Project Plans. Lug concrete shall be poured separately from the continuously reinforced concrete pavement. Membrane curing will not be permitted. The surface of the concrete shall be finished rough and shall be free of any dust, dirt or other foreign material at the time the continuously reinforced concrete pavement is placed.

3.10.2 WIDE FLANGE BEAM TERMINAL JOINT. Construct subgrade, base, and pavement layers in accordance with the Project Plans. Restore subgrade and base layers damaged by overexcavation. The sleeper slab shall be constructed to the same slope and cross section as the pavement. The top surface of the sleeper slab shall be given a smooth finish with a steel trowel on the pavement side of the wide flange beam and a rough finish on the terminal joint side. Membrane curing of the sleeper slab will not be permitted. Shop-fabricate wide-flange beams in accordance with the plans. Unless otherwise shown on the plans, wide-flange beams are not required to be welded or spliced at longitudinal construction joints. Accurately secure wide flange beam in position in accordance with the Project Plans and with sufficient supports to safely maintain alignment during concrete placement and finishing. The concrete in the groove on the expansion side of the wide flange beam shall be carefully finished across the top and at the edges of the pavement to facilitate unrestrained pavement expansion. The concrete on the fixed side shall be thoroughly vibrated to prevent voids occurring under the flange of the beam.

3.11 ISOLATION JOINTS. Isolation joints shall be provided at the locations and to the details shown on the Plans. The line of the isolation joint shall not deviate from the specified position by more than 0.5 in. (10mm). The line of the joint shall not deviate from a 10 ft (3 m) straight-edge by more than 0.5 in. (10nm). The joint filler shall consist of preformed jointing material of bituminous fiberboard or equivalent approved by the Superintendent and sealant shall comply with the requirements listed in Table 250.7. They shall be installed in accordance with the Project Plans and in a manner conforming to the manufacturer's recommendations.

The surface of the pavement shall be finished in accordance with the Standard Specifications.

3.12 METHOD OF MEASUREMENT. Continuously reinforced concrete pavement shall be measured in square yards of pavement in place, completed and accepted. For this purpose, the width shall be that shown on the Project Plans. The area paid for shall be equal to the square yards of concrete pavement specified or required to be reinforced with no allowance for necessary lap splices.

3.13 BASIS FOR PAYMENT. This work shall be paid for at the contract unit price per square yard for Continuously Reinforced Concrete Pavement and Pavement Reinforcing Bars measured as specified herein. The unit price shall include the cost of bars, bar supports, wire, ties, clips, and all other accessories necessary for installing the reinforcing bars complete in place.

Terminal joints shall be paid for at the contract unit price per linear foot for the pavement width specified, which price shall include all excavation, concrete, reinforcement and all other appurtenances necessary to construct the lug system complete as shown on the plans.

References
This guide specification is based on specifications from the states of IL, VA, OR, OK, GA, TX, and CA. It also drew from Roads and Traffic Authority, New South Wales, Australia. The guide specification is in harmony with guidance provided by the CRSI-FHWA Design and Construction Manual.
This appendix begins with some information on innovative specifications for CRCP temperature management. It also includes design standards specified by both the Texas and Illinois DOT. Finally, recent developments in the use of composite pavements in some European countries are briefly discussed.

**Specifications for CRCP Temperature Management**

Previous investigations on the behavior of CRCP sections in the field have demonstrated that the time of day when the pavement is placed affects the crack pattern. By placing at night during hot weather, the concrete heat of hydration occurs at a different time than the peak air temperature that usually occurs during the afternoon hours. This results in a lower temperature drop and thus a more uniform crack spacing.

Although the designer rarely has direct control over the selection of placement season or time, various States specifications have limitations on the maximum temperature of the concrete mix (typically 90 to 95 °F (32 to 35°C)) during hot weather placement. In addition, the heat of hydration and thus maximum temperature in the concrete will be also a function of the constituents and proportions of the concrete mix. Therefore, specifications that limit the maximum curing temperature of the concrete rather than the temperature of the mix are more desirable as they provide the designer with a better control of the maximum temperature drop expected.

A specification that controls the maximum curing temperature in the concrete has been recently investigated in Texas. As depicted in Figure 62, an end-result specification for control of the concrete temperature during construction would ensure that construction procedures and materials selection follow considerations made during design. With the use of a temperature prediction program (such as FHWA HIPER-PAV) and the required information on materials and site-specific conditions, the designer could use the prediction program for reinforcement design and specification development.

The contractor could also use such a tool for their ideal selection of materials. For example, they can assess the use of supplementary cementitious materials to reduce the heat of hydration, along with aggregates that possess desirable thermal properties (low CTE). Likewise, selection of construction procedures could ensure meeting the specification such as lowering the temperature of the concrete mix and employing optimum curing procedures could be adopted. Temperature sensors could even be installed in the pavement at frequent intervals for quality assurance purposes. 

![Figure 62. Conceptual approach for CRCP temperature management end-result specification.](image-url)
Texas DOT Design Standards
Figure 63. Texas design standard for CRCP one layer steel bar placement for slab thicknesses under 14 in
Figure 64. Texas design standard for CRCP two layer steel bar placement for 14 and 15 in (356 and 381 mm) slab
Figure 65. Texas design standard for CRCP terminal anchor
Figure 66. Texas design standard for bridge approach slab (sheet 1)
Figure 67. Texas design standard for bridge approach slab (sheet 2)
Continuously Reinforced Concrete Pavement Design and Construction Guidelines

Figure 68: Illinois design standard for CRCP bar reinforcement.
Figure 69. Illinois design standard for 24 ft (7.2 m) CRCP with wide flange beam transition joint (sheet 1)
Figure 71. Illinois design standard for bridge approach pavement (sheet 1 of 4).
Figure 72. Illinois design standard for bridge approach pavement (sheet 2 of 4).
Figure 73. Illinois design standard for bridge approach pavement (sheet 3 of 4).
Figure 74. Illinois design standard for bridge approach pavement (sheet 4 of...
Composite Pavements

Rigid composite pavements are defined as a concrete pavement (commonly CRCP) overlaid with a thin HMA wearing course. Rigid composite pavements are not new in the US. In fact, many existing CRCP have been rehabilitated with a HMA overlay to improve ride quality and skid resistance, and to provide additional structural support in the past. However, a stricter definition of rigid composite pavements includes an HMA overlay on a newly-placed concrete pavement. Use of this pavement type has recently become common practice in the Australia, the United Kingdom, and other European countries. Their popularity has increased over the years as a means to provide both structural and functional performance.(19,32) Benefits of composite pavements that have been cited include:

- Improved ride quality and skid resistance.
- Reduction in tire-pavement noise generation.
- Reduction in water infiltration.
- Possible reduction in corrosion of reinforcement in CRCP.
- Thermal insulation to prevent large temperature changes in the CRCP.

In the UK, a HMA surfacing of at least 4 in (100 mm) is commonly used on top of what is termed a Continuously Reinforced Concrete Roadbase (CRCR). Overlays are scheduled at later stages during the pavement life. Rigid composite pavements are commonly designed for a 40-year life. Transverse reinforcement in the CRCR is required for ease and consistency of construction. Typical designs range from 6 to 10 in (150 to 240 mm) of CRCR and 4 in (100 mm) of HMA surfacing.(19) A minimum of 1.2 in (30 mm) of wearing course is allowed in the UK on top of the CRCP. If a 4-in (100-mm) wearing course is used, a reduction in thickness of the CRCR is allowed. The structural contribution and thermal insulation provided by the wearing course is accounted for in the CRCR thickness design.

Porous asphalt (PA) can be used as the surface course on CRCR. However, 2 in (50 mm) of PA surface course on top of 3.5 in (90 mm) binder course are required, otherwise, 2 in (50 mm) of PA on top of 2.4 (60 mm) of binder course is allowed as long as the CRCR is increased in thickness by 4 in (10 mm). When a PA surface course is used, it is modified with a polymer or fiber additive.(19) While 0.6% of longitudinal reinforcement with #5 (16 mm) bars on CRCP without wearing course is specified in the UK, 0.4% with #4 (12 mm) bars is allowed for CRCR with a minimum of 100 mm (4 in) asphalt surface course.

Transverse reinforcement is typically specified with 0.5 in (12 mm) diameter deformed bars at 24 in (600 mm) spacings. Although a separation membrane (bond breaker) is used for jointed pavements, this layer is omitted from CRCR to provide a higher level of friction between the concrete slab and the base. A layer with uniform properties such as a lean concrete or asphalt base is recommended under the CRCR. Whenever a 1.2-in (30-mm) thin wearing course is used, a bond coat is specified to ensure adhesion between the CRCR and this layer.(19)

It is important to note that while composite pavements provide one solution to improving ride quality and reducing tire-pavement noise, other treatments such as diamond grinding can provide similar benefits for CRC pavement. Diamond grinding may in fact be a more economical solution for improving functional characteristics of new and existing CRCP.
APPENDIX B:
AASHTO-86/93 GUIDE
REINFORCEMENT DESIGN
Longitudinal Reinforcement Design Inputs

The inputs required in this procedure include:

- Concrete tensile strength, \( f_t \)
- Concrete CTE, \( \alpha_c \)
- Concrete shrinkage at 28 days, \( z \)
- Reinforcing bar diameter, \( \phi \)
- Steel CTE, \( \alpha_s \)
- Design temperature drop, \( \Delta T_D = T_H - T_L \)
- Wheel load tensile stress, \( \sigma \)

Concrete Tensile Strength

The concrete tensile strength determined through the ASTM C 496 or AASHTO T 198 splitting tensile test performed at 28 days is used in this procedure. A correlation of 86% of the third-point loading flexural strength used for thickness design may be assumed to determine the concrete tensile strength.

Concrete Coefficient of Thermal Expansion

Table 7 provides typical values of CTE for concrete made with different aggregate types. This information is derived from "Mass Concrete for Dams and Other Massive Structures," Proceedings, Journal of the American Concrete Institute, Vol. 67, April 1970, as referenced in AASHTO, 1993.(5)

Concrete Drying Shrinkage

Values for 28-day concrete shrinkage as a function of splitting tensile strength may be obtained from Table 8.

Reinforcing Bar Diameter

Typical bar sizes used in CRCP range from # 4 (0.5 in) to # 7 (0.875 in) [#13 (13 mm) to # 22 (22 mm)].

Steel Coefficient of Thermal Expansion

A steel CTE of 5 ± 10⁻⁶ in/in/°F (9 ± 10⁻⁶ m/m/°C) is recommended for longitudinal reinforcement design unless information on the steel CTE is available.

Design Temperature Drop

The design temperature drop is determined based on the average concrete curing temperature after placement and the lowest temperature of the year expected in the region where the CRCP will be constructed. The guidance provided in Section 3.5 may be used for this purpose.

Wheel Load Tensile Stress

Wheel load tensile stresses due to construction traffic during the early age may impact the crack spacing pattern and are therefore accounted for in longitudinal reinforcement design. The wheel load stress may be obtained from Figure 75 as a function of the design slab thickness, magnitude of wheel load, and effective k-value.

Longitudinal Reinforcement Design Procedure

The AASHTO-86/93 Guide includes design of the longitudinal reinforcement based on a desirable range of crack spacing, maximum crack width, and maximum steel stress. Longitudinal reinforcement is designed to meet the following three criteria:

1. Amount of reinforcement required to produce desirable crack spacings. Recommended crack spacings to Table 8. Approximate relationship between shrinkage and indirect tensile strength of concrete.(5)

<table>
<thead>
<tr>
<th>Indirect Tensile Strength psi (MPa)</th>
<th>Shrinkage in/in (m/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 (2.07) or less</td>
<td>0.000000</td>
</tr>
<tr>
<td>400 (2.76)</td>
<td>0.000060</td>
</tr>
<tr>
<td>500 (3.45)</td>
<td>0.000045</td>
</tr>
<tr>
<td>600 (4.14)</td>
<td>0.000030</td>
</tr>
<tr>
<td>700 (4.83) or greater</td>
<td>0.000020</td>
</tr>
</tbody>
</table>
minimize potential for development of punchouts and spalling range between 3.5 and 8 ft (1.1 and 2.4 m).

2. Amount of reinforcement required to keep transverse cracks tightly closed. Maximum allowable crack widths applicable to this procedure should not exceed 0.04 in (1.0 mm) to prevent spalling and water infiltration (although better practices would limit this to 0.02 in (0.5 mm).

3. Amount of reinforcement required to keep reinforcement stresses within allowable levels. Keeping the steel working at an acceptable stress level minimizes fracture of the steel or excessive yield that may lead to wide cracks with poor load transfer efficiency. Maximum allowable working stress for steel Grade 60 (Grade 420) recommended by AASHTO-86/93 as a function of indirect tensile concrete strength and reinforcing bar diameter is provided in Table 9.

With the design inputs obtained following the guidelines in Section 3, and the above limiting criteria, the longitudinal reinforcement design is accomplished following the procedure described below:

Figure 75. Chart for estimating wheel load tensile stress.
• The amount of longitudinal steel reinforcement to satisfy each limiting criterion is obtained using the design charts in Figure 76, Figure 77, and Figure 78. The minimum required steel percentage \( P_{\text{min}} \) corresponds to the largest obtained among the crack spacing of 8 ft (2.4 m), crack width, and steel stress criteria. The maximum required steel percentage \( P_{\text{max}} \) corresponds to the crack spacing of 3.5 ft (1.1 m). The design charts are accessed by drawing a continuous line intersecting the selected design values on the various scales to determine the percent steel. (In some cases, it may be necessary to extend the turning lines to the top or bottom of the chart.)

• If \( P_{\text{max}} \) is greater than or equal to \( P_{\text{min}} \), proceed to the next step. However, if \( P_{\text{max}} \) is less than \( P_{\text{min}} \), the design is considered unsatisfactory and revision of the selected inputs should be made until \( P_{\text{max}} \) is greater than \( P_{\text{min}} \).
• Use the following equations to determine the range in the number of reinforcing bars or wires required:

\[
N_{\text{min}} = \frac{0.01273 \cdot P_{\text{min}} \cdot W_s \cdot D}{\varphi^2}
\]

\[
N_{\text{max}} = \frac{0.01273 \cdot P_{\text{max}} \cdot W_s \cdot D}{\varphi^2}
\]

where, \(N_{\text{min}}\) = Minimum number of reinforcing bars required,

\(N_{\text{max}}\) = Maximum number of reinforcing bars required,

\(P_{\text{min}}\) = Minimum required steel percentage,

\(P_{\text{max}}\) = Maximum required steel percentage,

\(W_s\) = Total width of pavement section (in or mm),

\(D\) = Slab thickness (in or mm), and

\(\varphi\) = Reinforcing bar or wire diameter (in or mm).

(1 in = 25.4 mm, 1 ft = 0.3048 m, 1 psi = 6.98 KPa)

Figure 77. Percent of longitudinal reinforcement to satisfy crack spacing criteria.
• The total number of bars, \( N_{\text{design}} \), is determined by selecting a whole number between \( N_{\text{min}} \) and \( N_{\text{max}} \). The final design is checked against the limiting criteria by converting \( N_{\text{design}} \) to percent of steel and working backwards through the design charts.

Figure 78. Minimum percent longitudinal reinforcement to satisfy steel stress criteria.
• Aggregate - Granular material, such as sand, gravel, crushed stone, crushed hydraulic-cement concrete, or iron blast furnace slag, used with a hydraulic cementing medium to produce either concrete or mortar.

• Aggregate Interlock - The projection of aggregate particles or portion of aggregate particles from one side of a joint or crack in concrete into recesses in the other side of the joint or crack to effect load transfer in compression and shear and maintain mutual alignment.

• Air Content - The amount of air in mortar or concrete, exclusive of pore space in the aggregate particles, usually expressed as a percentage of total volume of mortar or concrete.

• Air Void - A space in cement paste, mortar, or concrete filled with air; an entrapped air void is characteristically 0.4 in (1 mm) or more in size and irregular in shape; an entrained air void is typically between 3.93 x 10^-4 and 0.39 in (10 m and 1 mm) in diameter and spherical (or nearly so).

• Air Entraining - The capabilities of a material or process to develop a system of minute bubbles of air in cement paste, mortar, or concrete during mixing.

• Alkali-Aggregate Reaction (AAR) - Chemical reaction in mortar or concrete between alkalis (sodium and potassium) released from cement or from other sources, and certain compounds present in the aggregates; under certain conditions, harmful expansion of the concrete or mortar may be produced.

• Alkali-Silica Reaction (ASR) - The reaction between the alkalis (sodium and potassium) in cement and certain siliceous rocks or minerals, such as opaline chert, strained quartz, and acetic volcanic glass, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

• ACPA - American Concrete Pavement Association

• Area of Steel - The cross-sectional area of the reinforcing bars in or for a given concrete cross section.

• ASTM - American Society for Testing and Materials

• Bar Chair - An individual supporting device used to support or hold reinforcing bars in proper position to prevent displacement before or during concreting.

• Bar Spacing - The distance between parallel reinforcing bars, measured center to center of the bars perpendicular to their longitudinal axis.

• Blanking Band - A plastic scale, or computer-generated scale, 1.7 in (43 mm) wide and 21.12 in (0.5 m) long representing a length of 0.1 mi (161 m) on a profilograph trace. The opaque blanking strip, running the length of the scale and located at its midpoint, covers the profile trace. Typically, a bandwidth of 0.0 to 0.2 in (0 to 5 mm) is used.

• Bleeding - The self-generated flow of mixing water within, or its emergence from, freshly placed concrete or mortar.

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

• Bond Strength - Resistance to separation of mortar and concrete from reinforcing steel and other materials with which it is in contact; a collective expression for all forces such as adhesion, friction due to shrinkage, and longitudinal shear in the concrete engaged by the bar deformations that resist separation.

• Bond Stress - The force of adhesion per unit area of contact between two surfaces such as concrete and reinforcing steel or any other material such as foundation rock.

• Burlap - A coarse fabric of jute, hemp, or less commonly flax, for use as a water-retaining cover for curing concrete surfaces; also called Hessian.

• Burlap Drag - Surface texture achieved by trailing moistened coarse burlap from a device that allows control of the time and rate of texturing.
California Profilograph - Rolling straight edge tool used for evaluating pavement profile (smoothness) consisting of a 25-ft (7.6-m) frame with a sensing wheel located at the center of the frame that senses and records bumps and dips on graph paper or in a computer.

Coefficient of Thermal Expansion (CTE) - Change in linear dimension per unit length or change in volume per unit volume per degree of temperature change.

Compressive Strength - The measured resistance of a concrete or mortar specimen to axial loading; expressed as pounds per square inch (psi) of cross-sectional area.

Concrete - See Portland Cement Concrete.

Concrete Overlay - Overlay of new concrete placed onto existing concrete pavement; it is unbonded when an interlayer is used between the new and old concrete surface to separate them; it is bonded if there is no interlayer.

Consistency - The relative mobility or ability of fresh concrete or mortar to flow. The usual measures of consistency are slump or ball penetration for concrete and flow for mortar.

Consolidation - The process of inducing a closer arrangement of the solid particles in freshly mixed concrete or mortar during placement by the reduction of voids, usually by vibration, centrifugation, tamping, or some combination of these actions; also applicable to similar manipulation of other cementitious mixtures, soils, aggregates, or the like.

Construction Joint - A joint made necessary by a prolonged interruption in the placing of concrete.

Continuously Reinforced Concrete Pavement (CRCP) - Portland cement concrete pavement with no transverse joints and containing longitudinal steel in an amount designed to ensure holding shrinkage cracks tightly closed. Joints exist only at construction joints and on-grade structures.

CRSI - Concrete Reinforcing Steel Institute.

Curing - The maintenance of a satisfactory moisture content and temperature in concrete during its early stages so that desired properties may develop.

Curing Blanket - A built-up covering of sacks, matting, Hessian, straw, waterproof paper, or other suitable material placed over freshly finished concrete. See also Burlap.

Curing Compound - A liquid that can be applied as a coating to the surface of newly placed concrete to retard the loss of water or, in the case of pigmented compounds, also to reflect heat so as to provide an opportunity for the concrete to develop its properties in a favorable temperature and moisture environment.

Deformed Bar - A reinforcing bar with a manufactured pattern of surface ridges that provide a locking anchorage with surrounding concrete.

Drainage - The interception and removal of water from, on, or under an area or roadway; the process of removing surplus ground or surface water artificially; a general term for gravity flow of liquids in conduits.

Durability - The ability of concrete to remain unchanged while in service; resistance to weathering action, chemical attack, and abrasion.

Early Strength - Strength of concrete developed soon after placement, usually during the first 72 hours.

FHWA - Federal Highway Administration

Final Set - A degree of stiffening of a mixture of cement and water greater than initial set, generally stated as an empirical value indicating the time in hours and minutes required for a cement paste to stiffen sufficiently to resist to an established degree, the penetration of a weighted test needle; also applicable to concrete and mortar mixtures with use of suitable test procedures. See also Initial Set.

Finishing - Leveling, smoothing, compacting, and otherwise treating surfaces of fresh or recently placed concrete or mortar to produce desired appearance and service.
• Fixed Form Paving - A type of concrete paving process that involves the use of fixed forms to uniformly control the edge and alignment of the pavement.

• Floating - Process of using a tool, usually wood, aluminum, or magnesium, in finishing operations to impart a relatively even but still open texture to an unformed fresh concrete surface.

• Grooving - The process used to cut slots into a concrete pavement surface to provide channels for water to escape beneath tires and to promote skid resistance.

• Hairline Cracking - Barely visible cracks in random pattern in an exposed concrete surface which do not extend to the full depth or thickness of the concrete, and which are due primarily to drying shrinkage.

• Hardening - When cement is mixed with enough water to form a paste, the compounds of the cement react with water to form cementitious products that adhere to each other and to the intermixed sand and stone particles and become very hard. As long as moisture is present, the reaction may continue for years, adding continually to the strength of the mixture.

• Honeycomb - Concrete that, due to lack of the proper amount of fines or vibration, contains abundant interconnected large voids or cavities; concrete that contains honeycombs was improperly consolidated.

• Initial Set - A degree of stiffening of a mixture of cement and water less than final set, generally stated as an empirical value indicating the time in hours and minutes required for cement paste to stiffen sufficiently to resist to an established degree the penetration of a weighted test needle; also applicable to concrete or mortar with use of suitable test procedures.

• Jointed Plain Concrete Pavement (JPCP) - Pavement containing enough joints to control all natural cracks expected in the concrete; steel tiebars are generally used at longitudinal joints to prevent joint opening, and dowel bars may be used to enhance load transfer at transverse contraction joints depending upon the expected traffic.

• Jointed Reinforced Concrete Pavement (JRCP) - Pavement containing some joints and embedded steel mesh reinforcement (sometimes called distributed steel) to control expected cracks; steel mesh is discontinued at transverse joint locations.

• Keyway - A recess or groove in one lift or placement of concrete which is filled with concrete of the next lift, giving shear strength to the joint.

• Load Transfer Efficiency - The ability of a joint or crack to transfer a portion of a load applied on side of the joint or crack to the other side of the joint or crack.

• Longitudinal Cracking - Pavement cracking predominantly parallel to the direction of traffic.

• Longitudinal Joint - A joint placed parallel to the long dimension of the pavement to control longitudinal cracking.

• Longitudinal Reinforcement - Reinforcement essentially parallel to the long axis of a concrete member or pavement.

• Longitudinal Tine - Surface texture achieved by a hand held or mechanical device equipped with a rake-like tining head that moves in a line parallel to the pavement centerline.

• Longitudinal Profile - The perpendicular deviations of the pavement surface from an established reference parallel to the lane direction, usually measured in the wheel tracks.

• Maximum Size Aggregate - The largest size aggregate particles present in sufficient quantity to affect properties of a concrete mixture.

• Mechanistic-Empirical - A design philosophy or approach wherein classical mechanics (physics) is used in conjunction with empirically derived relationships to accomplish the design objectives.

• Membrane Curing - A process that involves either liquid sealing compound (e.g., bituminous and paraffinic emulsions, coal tar cut-backs, pigmented and non-pigmented resin suspensions, or suspensions of wax and drying oil) or non-liquid protective coating (e.g., sheet plastics or "waterproof" paper), both of which types function as films to restrict evaporation of mixing water from the fresh concrete surface.
• Modulus of Elasticity (E) - The modulus of any material is a measure of the stress-strain behavior of the material.

• Modulus of Rupture - An indicator of tensile bending strength of concrete, is the maximum tensile stress at the bottom at rupture during a flexural test of a simply supported concrete beam.

• Modulus of Subgrade Reaction (k) - Westergaard's modulus of subgrade reaction for use in rigid pavement design (the load in pounds per square inch on a loaded area of the roadbed soil or subbase divided by the deflection in inches of the roadbed soil or subbase, psi/ in.).

• Moisture Content of Aggregate - The ratio, expressed as a percentage, of the weight of water in a given granular mass to the dry weight of the mass.

• Paving Train - An assemblage of equipment designed to place and finish a concrete pavement.

• Pavement Condition - A quantitative representation of pavement distress at a given point in time.

• Pavement Management - The effective and efficient direction of the various activities involved in providing and sustaining pavements at a condition acceptable to the traveling public at the lowest life-cycle-cost.

• Pavement Performance - Measure of accumulated service provided by a pavement (i.e., the adequacy with which it fulfills it purpose). Often referred to the record of pavement condition or serviceability over time or with accumulated traffic.

• Pavement Rehabilitation - Work undertaken to extend the service life of an existing facility. This includes placement of additional surfacing material and/or other work necessary to return an existing roadway, including shoulders, to a condition of structural or functional adequacy. This could include the complete removal and replacement of a portion of the pavement structure.

• Pavement Structure - A combination of subbase, base course, and surface course placed on a subgrade to support the traffic load and distribute it to the roadbed.

• PCA - Portland Cement Association

• Percent Fines - Amount, expressed as a percentage, of material in aggregate finer than a given sieve, usually the No. 200 (0.075 mm) sieve; also, the amount of fine aggregate in a concrete mixture expressed as a percent by absolute volume of the total amount of aggregate.

• Performance-Related Specifications (PRS) - Specifications that describe the desired levels of key materials and construction quality characteristics that have been found to correlate with fundamental engineering properties that predict performance. These characteristics (for example, strength of concrete cores) are amenable to acceptance testing at the time of construction.

• Permeable Subbase - Layer consisting of crushed aggregates with a reduced amount of fines to promote drainage and stabilized with Portland cement or bituminous cement.

• Placement, Concrete - The process of placing and consolidating concrete; a quantity of concrete placed and finished during a continuous operation.

• Portland Cement Concrete (PCC) - A composite material that consists essentially of a binding medium (Portland cement and water) within which are embedded particles or fragments of aggregate, usually a combination of fine aggregate course aggregate.

• Profile Index - Smoothness qualifying factor determined from profilograph trace. Calculated by dividing the sum of the total counts above the blanking band for each segment by the sum of the segment length.

• Punchout - In continuously reinforced concrete pavement, the area enclosed by two closely spaced (less than 3 ft or 1m) transverse cracks, a short longitudinal crack, and the edge of the pavement or longitudinal joint, when exhibiting spalling, shattering, or faulting. Also, area between Y cracks exhibiting this same deterioration.
• Quality Assurance (QA) - Planned and systematic actions by an owner or his representative to provide confidence that a product or facility meet applicable standards of good practice. This involves continued evaluation of design, plan and specification development, contract advertisement and award, construction, and maintenance, and the interactions of these activities.

• Quality Control (QC) - Actions taken by a producer or contractor to provide control over what is being done and what is being provided so that the applicable standards of good practice for the work are followed.

• Random Cracking - Uncontrolled and irregular fracturing of a pavement layer.

• Reinforcement - Steel embedded in a rigid slab to resist tensile stresses and detrimental opening of cracks.

• Resilient Modulus - A standardized measurement of the modulus of elasticity of roadbed soil or other pavement material.

• Rideability - A subjective judgment of the comparative discomfort induced by traveling over a specific section of highway pavement in a vehicle.

• Sawcut - A cut in hardened concrete utilizing diamond or silicone-carbide blades or discs.

• Select Material - A suitable native material obtained from a specified source such as a particular roadway cut or borrow area, of a suitable material having specified characteristics to be used for a specific purpose.

• Setting of Cement - Development of rigidity of cement paste, mortar, or concrete as a result of hydration of the cement. The paste formed when cement is mixed with water remains plastic for a short time. During this stage it is still possible to disturb the material and remix without injury, but as the reaction between the cement and water continues, the mass loses its plasticity. This early period in the hardening is called the "setting period," although there is not a well-defined break in the hardening process.

• Setting Time - The time required for a specimen of concrete, mortar or cement paste, prepared and tested under standardized conditions, to attain a specified degree of rigidity.

• Shrinkage Cracking - Cracking of a slab due to failure in tension caused by external or internal restraints as reduction in moisture content develops.

• Skid Resistance - A measure of the frictional characteristics of a surface.

• Slipform Paving - A type of concrete paving process that involves extruding the concrete through a machine to provide a uniform dimension of concrete paving.

• Slump - A measure of consistency of freshly mixed concrete, equal to the subsidence measured to the nearest ¼-inch of the molded specimen immediately after removal of the slump cone.

• Strength - A generic term for the ability of a material to resist strain or rupture induced by external forces. See also Compressive Strength, Fatigue Strength, Flexural Strength, Shear Strength, Splitting Tensile Strength, Tensile Strength, Ultimate Strength, and Yield Strength.

• Stress - Intensity of internal force (i.e., force per unit area) exerted by either of two adjacent parts of a body on the other across an imagined plane of separation; when the forces are parallel to the plane, the stress is called shear stress; when the forces are normal to the plane the stress is called normal stress; when the normal stress is directed toward the part on which it acts it is called compressive stress; when it is directed away from the part on which it acts it is called tensile stress.

• Strikeoff - To remove concrete in excess of that required to fill the form evenly or bring the surface to grade; performed with a straightedged piece of wood or metal by means of a forward sawing movement or by a power operated tool appropriate for this purpose; also the name applied to the tool. See also Screed and Screeding.

• Surface Texture - Degree of roughness or irregularity of the exterior surfaces of aggregate particles or hardened concrete.

• Subgrade - The top surface of a roadbed upon which the pavement structure and shoulders are constructed.
• Subgrade, Improved - Any course or courses of select or improved materials between the subgrade soil and the pavement structure.

• Tensile Strength - Maximum stress that a material is capable of resisting under axial tensile loading based on the cross-sectional area of the specimen before loading.

• Terminal Joint - Joint used in continuously reinforced concrete pavement at the transition to another pavement type or to a bridge structure.

• Tiebar - Deformed steel bar extending across a longitudinal joint in a rigid pavement to prevent separation of abutting slabs.

• Transverse Cracking - Pavement cracking predominantly perpendicular to the direction of traffic.

• Vibration - Energetic agitation of concrete produced by a mechanical oscillating device at moderately high frequency to assist consolidation and compaction

• Vibration, External - External vibration employs vibrating devices attached at strategic positions on the forms and is particularly applicable to manufacture of precast items and for vibration of tunnel-lining forms; in manufacture of concrete products, external vibration or impact may be applied to a casting table.

• Vibration, Internal - Internal vibration employs one or more vibrating elements that can be inserted into the concrete at selected locations, and is more generally applicable to in-place construction.

• Vibration, Surface - Surface vibration employs a portable horizontal platform on which a vibrating element is mounted.

• Vibrator - An oscillating machine used to agitate fresh concrete so as to eliminate gross voids, including entrapped air but no entrained air, and produce intimate contact with form surfaces and embedded materials.

• Water-Cement Ratio - The ratio of the amount of water, exclusive only of that absorbed by the aggregates, to the amount of cement in a concrete or mortar mixture; preferably stated as a decimal by weight.
4 Concrete Reinforcing Steel Institute, Summary of CRCP Design and Construction Practices in the US, Research Series No. 8, 2001.


Continuously Reinforced Concrete Pavements, Permanent International Association of Road Congresses, 1994.


Verhoeven, K., Cracking and Corrosion in Continuously Reinforced Concrete Pavements, Proceedings of the 5th International Conference on Concrete Pavement Design and Rehabilitation, Purdue, 1993.


Concrete Reinforcing Steel Institute, "Continuous Reinforcement Makes a Good Pavement Better".


98 Concrete Reinforcing Steel Institute, "Field Inspection of Reinforcing Bars", Engineering Data Report No. 54, 2004.


