Concrete Pavement Field Reference

Paving

A practical guide to understanding and troubleshooting:

Quality control
Producing concrete
Placing concrete
Texturing & curing
Jointing
Opening to traffic

American Concrete Pavement Association
Concrete Pavement Field Reference

Paving

This publication includes, at the outset, a series of checklists aimed at guiding and assisting with proper procedures. These checklists precede the main content of the field reference to provide a preview of what appears in each section and also to provide some quick references to the entire publication.

You can also find these checklists in a printer-friendly layout at:

www.acpa.org/fieldreference

These are available free of charge for distribution to your paving crews or others who may benefit from these quick and easy-to-use checklists. Again, the checklists are intended to help you with proper procedures.

This field reference also includes several cross-references intended to help you find information quickly. General topics are organized by chapters and may be found either by chapter number or in the table of contents. Also, key words are included in an index at the end of this field reference.

Of course, if you are looking for information, but still cannot find it, please call on any ACPA office for help.
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# Table of Contents

**Introduction** ................................................................. 1

**Proper Procedures Checklists** ......................................... 3
  - Quality Control ......................................................... 3
  - Producing Concrete .................................................. 6
  - Placing Concrete ...................................................... 8
  - Texturing and Curing .................................................. 14
  - Jointing .................................................................. 15
  - Opening to Traffic ..................................................... 17

**Quality Control (QC)** ....................................................... 19
  - 1.1 Standard QC Tests .................................................. 21
  - 1.2 Coordination .......................................................... 24
  - 1.3 Testing Crew and Laboratory Training/Certification ........... 24
  - 1.4 Plant, Truck, Plant Operator, and Other Certifications ........ 25
  - 1.5 QC Testing Programs ............................................. 26
  - 1.6 Handling and Curing Concrete Test Specimens ................. 26
  - 1.7 Reporting Protocols for Test Data ................................ 27
  - 1.8 Contingencies for Hot/Cold Weather ............................ 27
  - 1.9 Checks for Proper Grade and Thickness ........................ 28
  - 1.10 Time Series Plots (Control or Run Charts) .................... 28
  - 1.11 Parameters for Mixture Adjustments due to QC Results .... 28
Producing Concrete .................................................. 31
  2.1 Stockpile and Materials Management ...................... 31
  2.2 Mixing Concrete ............................................. 33
    2.2.1 Obtaining a Consistent Concrete Mixture ................ 33
    2.2.2 Mixing Operations ...................................... 34
  2.3 Hauling/Delivery ........................................... 38
    2.3.1 Methods of Transport .................................. 38
    2.3.2 Rate of Delivery ....................................... 41

Placing Concrete .................................................... 43
  3.1 Access and Placement of the Concrete Mixture .......... 44
  3.2 Placement of In-Pavement Steel ............................ 45
    3.2.1 Location of Dowels, Baskets, DBI. ................... 47
    3.2.2 Location of Tiebars, Chairs, Inserters ............... 50
    3.2.3 Leave Tiebar Out Near Dowel Basket ................. 51
  3.3 Wetting the Grade .......................................... 51
  3.4 Fixed Form Paving .......................................... 52
    3.4.1 Spreading the Mixture ................................ 55
    3.4.2 Consolidation .......................................... 55
    3.4.3 Thickness Verification ................................ 56
    3.4.4 Finishing .............................................. 56
    3.4.5 Form Removal .......................................... 56
  3.5 Slipform Paving ............................................. 57
    3.5.1 Components of a Typical Slipform Paving Machine and Their Functions ............................................. 59
    3.5.2 Continuous Operations ................................ 64
    3.5.3 Thickness Verification ................................ 65
    3.5.4 Finishing .............................................. 65
    3.5.5 Resuming Paving at a Header ......................... 69
    3.5.6 Paving on Steep Grades ............................... 69
  3.6 Paving in Inclement Weather ................................ 70
Table of Contents

3.6.1 Cold Weather Paving ........................................ 70
3.6.2 Hot Weather Paving ........................................ 71
3.6.3 Rained on Pavements ...................................... 72
3.7 Night Paving .................................................. 76

Texturing and Curing .............................................. 79
4.1 Texturing ...................................................... 79
4.1.1 Methods ................................................... 81
4.2 Curing ........................................................ 84
4.2.1 Methods ................................................... 85

Jointing .............................................................. 91
5.1 Sawcut Joints .................................................. 91
5.1.1 Sawcut Window ............................................ 91
5.1.2 Joint Location Identification ............................ 97
5.1.3 Sawing Equipment and Procedures ................... 98
5.1.4 Unsealed Joints ........................................... 103
5.1.5 Sealed Joints .............................................. 103
5.2 Construction Joints (Headers) ............................. 109
5.2.1 Header in Fresh Concrete ................................. 109
5.2.2 Sawed Header ............................................. 110
5.2.3 Continuing Paving and Opening to Traffic .......... 112
5.3 Terminal Joints in Continuously Reinforced Concrete Pavement (CRCP) ........................................ 112

Opening to Traffic ................................................ 115
6.1 Strength Requirements ....................................... 116
6.2 Determining Strength ....................................... 117
6.3 Concrete Mixture Considerations ......................... 119
6.4 Insulating Blankets .......................................... 120

References ......................................................... 123
Index ............................................................... 135
Introduction

Concrete is one of the most abundant and versatile construction materials in the world. It is also somewhat forgiving, which means that handling, placing, and curing conditions do not have to be absolutely perfect for the final product to perform well over time.

Still, constructing a quality concrete pavement requires planning before paving so that the highest quality and most uniform concrete pavement can be constructed for the owner. Of course, the human factor also is a key variable as it is integral to every step of the pre-paving, construction, and repair of a concrete pavement. From delivery of the concrete mixture to curing the slab, concrete paving operations should proceed at a consistent pace. Everyone at the jobsite should have a basic understanding of the entire operation.

The human factor certainly cannot be underestimated, particularly given the number of people, as well as their knowledge, training, skill levels, experience, and other considerations, that guide what is done and how it is done on a given project. Given this level of dependence on human ability, it is imperative that all parties involved in the planning and construction of a concrete pavement be cognizant of all other parties and the effects their decisions might have on each other.

This reference is not intended to be the final word in paving considerations. Rather, it is a common-sense guide to paving considerations that will aid in constructing a quality concrete pavement. It represents some current best-practices, as well as a good-faith representation of methods, materials, machines, and instruments currently available for quality control, concrete production, concrete placement, texturing and curing, jointing, and opening to traffic requirements.

This document serves to educate, guide, and inform all parties involved in any construction considerations for concrete pavements, from contractors to consultants to agencies/owners. Although nothing can replace experience, skill, and sound judgment, it is our hope that this guide will augment those “human factors.”
Last, but not least, it is likely that as this guide is printed and distributed, some new or even currently existing paving products or processes may be brought to market (or simply brought to our attention). In advance, we humbly offer that, although we have attempted to capture the breadth and depth of best practices, such disclosures are a normal and healthy part of process improvement and advancement of technology.
Proper Procedures Checklists

NOTE: All proper procedure checklists contained herein can be downloaded for free at: www.acpa.org/fieldreference.

■ Quality Control

Standard QC Tests (Section 1.1)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
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<tbody>
<tr>
<td>1</td>
<td>Consider all relevant quality control (QC) tests in Table 1.2 of this document in the contractor’s and/or producer’s QC plan(s).</td>
<td>□</td>
</tr>
</tbody>
</table>

Coordination (Section 1.2)

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<thead>
<tr>
<th>No.</th>
<th>Task</th>
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<tbody>
<tr>
<td>1</td>
<td>Ensure that the contractor’s and/or producer’s QC plan(s), procedures, and reporting protocol(s) are discussed with all parties involved (e.g., all members of the project team, including the owner/agency, project engineer, inspector, plant manager, etc.) during a pre-paving meeting.</td>
<td>□</td>
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</tbody>
</table>

Testing Crew and Laboratory Training/Certification (Section 1.3)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Obtain all necessary or desired testing/laboratory crew and construction site personnel training/ certification well before construction begins.</td>
<td>□</td>
</tr>
</tbody>
</table>
Plant, Truck, Plant Operator, and Other Certifications (Section 1.4)

No. Task Complete
1. Obtain all necessary or desired plant, truck, and plant operator certifications well before construction begins.

QC Testing Programs (Section 1.5)

No. Task Complete
1. Ensure that the QC plan includes all necessary and desired tests, and that the proper procedures and testing equipment for each test are in place before paving.

Handling and Curing Concrete Test Specimens (Section 1.6)

No. Task Complete
1. Check that all personnel who might be required to produce or handle test specimens know the proper sampling, casting, and handling procedures and are aware of the consequences of mishandling.

Reporting Protocols for Test Data (Section 1.7)

No. Task Complete
1. Review the necessary reporting protocols for test data with the appropriate members of the paving crew and/or the individual or company responsible for the testing immediately prior to paving.

Contingencies for Hot/Cold Weather (Section 1.8)

No. Task Complete
1. If thought that hot or cold weather might be a potential concern, ensure that all necessary hot/cold weather contingencies are put into place prior to paving.
2. If any hot or cold weather contingencies are to be implemented into the work plan before paving, communicate the details of the contingencies to all parties involved during a pre-paving meeting.
### Checks for Proper Grade and Thickness (Section 1.9)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>Because they typically are not part of a formal QC plan, ensure that proper grade and thickness checks will be made regularly during the paving process, and that any problems with grade or thickness will be quickly communicated to the appropriate personnel.</td>
</tr>
</tbody>
</table>

### Time Series Plots (Control or Run Charts) (Section 1.10)

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<thead>
<tr>
<th>No.</th>
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<tbody>
<tr>
<td>1.</td>
<td>Quickly communicate any abnormalities with time series plots to the appropriate personnel.</td>
</tr>
</tbody>
</table>

### Parameters for Mixture Adjustments due to QC Results (Section 1.11)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>Confirm that the appropriate personnel have ample experience with or knowledge of troubleshooting problems with test results or abnormalities with time series plots by making necessary adjustments to the paving mixture and/or equipment.</td>
</tr>
</tbody>
</table>
### Producing Concrete

#### Stockpile and Materials Management (Section 2.1)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>Ensure that the stockpile/bin location is taken under consideration and that all stockpiles/bins have appropriate separation and drainage.</td>
<td>[ ]</td>
</tr>
<tr>
<td>2.</td>
<td>Check that the aggregate loader operator is adequately trained so that he/she is capable of managing aggregate properties such as gradation and moisture content, and that he/she is aware of the potential for aggregate contamination or segregation and means by which to prevent them.</td>
<td>[ ]</td>
</tr>
</tbody>
</table>

#### Mixing Concrete (Section 2.2)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Confirm that all scales are calibrated, approved by the necessary agency, and tested with weights throughout the range to be used; the water meters are checked for their accuracy and water lines checked for leakage; the capacity of boilers or chillers, if used, are verified; all admixture dispensers are checked for accuracy; the mixing drum is examined for hardened concrete buildup inside or on the fins; the mixing flights or fins inside the drum(s) are checked; the generator trailer, if used, is properly maintained and in operating condition; haul times are considered for stationary mixed concrete batching; and any other aspect of the mixing process that needs checking is checked.</td>
<td>[ ]</td>
</tr>
<tr>
<td>2.</td>
<td>Only use certified and/or approved ingredients/ materials in the concrete mixture.</td>
<td>[ ]</td>
</tr>
<tr>
<td>3.</td>
<td>Batch the ingredients in the proper sequence and closely control the mixing time for each load so that the most uniform and consistent concrete mixture can be produced load after load.</td>
<td>[ ]</td>
</tr>
</tbody>
</table>
### Hauling/Delivery (Section 2.3)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Establish the delivery route (and ensure that this route is well communicated) prior to construction.</td>
<td>☐</td>
</tr>
<tr>
<td>2.</td>
<td>Ensure that all concrete hauling vehicles are checked/approved and inspected regularly for cleanliness.</td>
<td>☐</td>
</tr>
<tr>
<td>3.</td>
<td>For central mixed concrete, note all high-early strength loads and conduct random checks of discharge within the pre-determined time limits.</td>
<td>☐</td>
</tr>
<tr>
<td>4.</td>
<td>For stationary mixed concrete, ensure that the concrete batch ticket is delivered with each load (and that it has the required information), that any addition of water in the field is documented on the ticket for that batch, that the mixers used the correct number of revolutions, and that high-early strength loads are noted.</td>
<td>☐</td>
</tr>
<tr>
<td>5.</td>
<td>Ensure that the rate of delivery is properly calculated and enforced.</td>
<td>☐</td>
</tr>
</tbody>
</table>
Placing Concrete

Access and Placement of the Concrete Mixture (Section 3.1)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Give all concrete delivery trucks immediate access to the paving site and direct all delivery traffic down the predetermined delivery route.</td>
<td>☐</td>
</tr>
<tr>
<td>2.</td>
<td>Before discharging the concrete mixture from the delivery vehicle, check that the temperature of the concrete is with specification and there are no signs of segregation or other problems.</td>
<td>☐</td>
</tr>
<tr>
<td>3.</td>
<td>Discharge the mixture from each delivery vehicle within specified time limits.</td>
<td>☐</td>
</tr>
<tr>
<td>4.</td>
<td>If placing the concrete mixture directly onto the grade, place it such that minimum re-handling is required.</td>
<td>☐</td>
</tr>
<tr>
<td>5.</td>
<td>Ensure that the slump (consistency) is similar between subsequent loads and that it is within the anticipated range for each load.</td>
<td>☐</td>
</tr>
<tr>
<td>6.</td>
<td>If non-agitating delivery trucks are used, confirm that all concrete is removed from them before sending them back for more concrete.</td>
<td>☐</td>
</tr>
<tr>
<td>7.</td>
<td>Conduct all applicable QC tests to the concrete mixture as it is delivered and per the schedule for that QC test. Also, cast all necessary cylinder/beam specimens from the freshly delivered concrete mixture and ensure that all necessary maturity meters are already installed or are ready to be inserted into the freshly placed pavement.</td>
<td>☐</td>
</tr>
</tbody>
</table>
**Placement of In-Pavement Steel (Section 3.2)**

1. If dowel baskets will be used, mark reference lines on the subgrade/subbase before paving to identify the location where transverse sawcuts will be made.

2. Install (e.g., place and stake down by the required means) all reinforcing steel, mesh reinforcement, dowel baskets, and tiebars that must be installed on chairs or in baskets prior to paving.

3. Confirm that all in-pavement steel is within tolerance (for steel dimensions, spacing/depth/location, and alignment) and securely fastened to the subgrade/subbase, if applicable, and that the proper lubricant/corrosion inhibitor, if applicable, is properly applied.

**Wetting the Grade (Section 3.3)**

1. If necessary, wet the grade with water shortly before placing the concrete; do not begin placing the concrete and paving until the water has soaked adequately into the grade.

**Fixed Form Paving (Section 3.4)**

1. See ACPA’s, “Concrete Pavement Field Reference: Pre-Paving,” for details on setting a stringline and forms.

2. Check that all forms used are mortar-tight, sufficiently rigid to prevent excessive deflections, and set at a height to ensure adequate thickness.

3. Check that the form surfaces are smooth and clean of all dirt, mortar, and foreign materials, and that an acceptable form release oil has been applied (for wooden forms, it might also be necessary to moisten the forms prior to paving).

4. Ensure that all fixed forms are placed such that joints at the boundaries of the forms will align properly.
<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
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<tbody>
<tr>
<td>5.</td>
<td>Check that all embedded items (e.g., conduits, utility block-outs, anchoring devices, etc.) are placed and adequately secured.</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Ensure that all hand/spud vibrators are operating properly and per the appropriate specification.</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Evenly deposit the concrete onto the grade in front of the fixed form placement machine and work the concrete around the grade as necessary, being sure not to pile too much or too little concrete in front of the placement machine (use the fixed forms as a reference for concrete placement height).</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Properly consolidate the concrete, ensuring that proper vibration is performed around embedded items.</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Strike off the concrete with an acceptable device or machine.</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>Mark and account for all gaps in the paving and specialty locations, such as driveways.</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>If necessary, finish the surface by the appropriate methods. Add minimal or no water to the surface to assist the finishing.</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>If high-early strength concrete will be used, mark the areas where it will be used.</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>See the “Texturing and Curing” and “Jointing” checklists for those details.</td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>Remove forms after the concrete has hardened sufficiently to prevent damage but within 24 hours; properly cure all newly exposed edges.</td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>Ensure that all paving equipment is properly cleaned and maintained before reuse.</td>
<td></td>
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</tbody>
</table>
## Slipform Paving (Section 3.5)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>See ACPA’s, “Concrete Pavement Field Reference: Pre-Paving,” for details on setting a stringline, if used, and paving equipment setup.</td>
<td>□</td>
</tr>
<tr>
<td>2.</td>
<td>Prior to paving, ensure that the slipform paving machine is set up properly; hydraulic vibrators are checked for oil leaks; all vibrators are working properly; the dowel bar inserters, if used, are correctly located; sensor wands, if used, are working and adjusted properly; and any other necessary paver setup and maintenance is completed.</td>
<td>□</td>
</tr>
<tr>
<td>3.</td>
<td>Eyeball and, if necessary, adjust the stringline, if used, immediately prior to paving, and frequently during the paving process; instruct all members of the paving crew to use caution around the stringline.</td>
<td>□</td>
</tr>
<tr>
<td>4.</td>
<td>Check that all embedded items (e.g., conduits, utility block-outs, anchoring devices, etc.) are placed and adequately secured.</td>
<td>□</td>
</tr>
<tr>
<td>5.</td>
<td>Deposit the concrete directly onto the grade or into a spreader.</td>
<td>□</td>
</tr>
<tr>
<td>6.</td>
<td>Ensure that concrete is delivered at the pre-determined delivery rate to foster continuous operations of the slipform paving machine.</td>
<td>□</td>
</tr>
<tr>
<td>7.</td>
<td>Spread and consolidate the concrete as it is slipped to the proper thickness, checking thickness at the appropriate, regular interval.</td>
<td>□</td>
</tr>
<tr>
<td>8.</td>
<td>If a dowel bar inserter is used, mark reference lines on the subgrade/subbase after the paver has passed but before the dowel bar insertion marks are closed to identify the locations where transverse sawcuts will be made.</td>
<td>□</td>
</tr>
<tr>
<td>9.</td>
<td>Finish the concrete by the appropriate methods, being sure to close imprints from dowel bar insertion, footprints, etc. Minimize hand finishing as much as possible. Add minimal or no water to the surface to assist the finishing.</td>
<td>□</td>
</tr>
<tr>
<td>10.</td>
<td>Use a straight-edge to roughly determine if smoothness is within tolerance.</td>
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### Paving in Inclement Weather (Section 3.6)

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<tr>
<th>No.</th>
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<tbody>
<tr>
<td>1.</td>
<td>If possible, do not pave when a very high probability of inclement weather exists.</td>
<td>☐</td>
</tr>
<tr>
<td>2.</td>
<td>When paving in cold or hot weather, follow all applicable procedures and specifications; consider running a HIPERPAV (<a href="http://www.hiperpav.com">www.hiperpav.com</a>) analysis, if it is not otherwise required, before commencing paving in immanent cold or hot weather.</td>
<td>☐</td>
</tr>
<tr>
<td>3.</td>
<td>If a high risk for precipitation exists, ensure that enough materials are available to protect any freshly placed pavement.</td>
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</table>
**Night Paving (Section 3.7)**

<table>
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<th>No.</th>
<th>Task</th>
<th>Complete</th>
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<tbody>
<tr>
<td>1.</td>
<td>Ensure that all applicable or necessary precautions are taken to ensure safe and trouble-free nighttime paving operations.</td>
<td>□</td>
</tr>
<tr>
<td>2.</td>
<td>Communicate project details and schedule to the owner, all levels of the contractor workforce, and any local businesses or residents that might be affected by the nighttime paving operations.</td>
<td>□</td>
</tr>
<tr>
<td>3.</td>
<td>Ensure that any potential initial curing procedures that might be necessary after night paving but before sawing of the joints are ready to be implemented, if necessary.</td>
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## Texturing and Curing

### Texturing *(Section 4.1)*

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
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<tbody>
<tr>
<td>1.</td>
<td>If tining is used, ensure that the tining rake meets specifications for width, depth, and spacing of the tining grooves, and that the tines are clean; if a drag texture is being applied, ensure that the drag material meets specification(s).</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Ensure that the texturing medium is leaving an acceptable texture (e.g., to the proper depth and uniformity) and that, if applicable, the texturing medium is properly waited and wetted.</td>
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### Curing *(Section 4.2)*

<table>
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<tr>
<th>No.</th>
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<tbody>
<tr>
<td>1.</td>
<td>Ensure that all initial and final curing materials and methods that might be used are approved, and that ample amounts of curing materials meeting the appropriate specification(s) are available.</td>
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</tr>
<tr>
<td>2.</td>
<td>If a membrane forming curing compound is used, ensure that it is applied within the specified time or distance behind the paving operation.</td>
<td></td>
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<tr>
<td>3.</td>
<td>If a white-pigmented membrane forming curing compound is used, ensure that it is applied such that the surface of the pavement is uniformly as white as a sheet of paper.</td>
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<tr>
<td>4.</td>
<td>If insulating blankets might be used as part of the curing regiment during cold weather, ensure that the contractor and owner/agency agree on the basis for determining what temperature triggers the use of insulating blankets, and that all insulating blankets are placed and removed per the requirements.</td>
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### Jointing

**Sawcut Joints (Section 5.1)**

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<th>No.</th>
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<tbody>
<tr>
<td>1.</td>
<td>Ensure that every member of the sawing crew is aware of the sawing window and the impact that curing, ambient conditions, and other variables have on it.</td>
<td>☐</td>
</tr>
<tr>
<td>2.</td>
<td>Make any necessary field adjustments to intersect manholes, utilities, etc. whose location might vary slightly from that on the original saw cutting plan.</td>
<td>☐</td>
</tr>
<tr>
<td>3.</td>
<td>Saw all necessary crack-controlling cuts (initial sawcuts) at the proper locations (and within the proper tolerance with respect to embedded steel), to the proper depth/width, and within the sawcut window (e.g., after raveling might occur during sawing operations but before uncontrolled random cracking occur); if allowable and planned, also construct tooled crack-controlling joints in shoulders or non-traffic areas.</td>
<td>☐</td>
</tr>
<tr>
<td>4.</td>
<td>If sealing the joints, ensure that all saw cut residue is flushed from the joint and removed from the surface of the pavement by an approved method.</td>
<td>☐</td>
</tr>
<tr>
<td>5.</td>
<td>If the joints are to be sealed, ensure that the concrete is properly cured; saw the sealant reservoir, if applicable, per the appropriate specification or manufacturer's recommendation; ensure that the joint faces are free of latent dust, debris, or other contaminants and, if not, clean the joint faces by an approved method; and seal each joint using the appropriate, approved materials, being careful not to overfill or underfill the joint. Also, ensure that any non-extruding pre-molded compressible material used in isolation joints or backer rod used in contraction or construction joints meets specification and is installed properly prior to sealing.</td>
<td>☐</td>
</tr>
</tbody>
</table>
Construction Joints (Headers) (Section 5.2)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Discuss during the pre-paving meeting if there is a preference by any party for formed or sawed headers, and plan accordingly to account for headers to end at transverse joints in an adjacent concrete pavement.</td>
<td>☐</td>
</tr>
<tr>
<td>2.</td>
<td>If using a formed header, ensure that any necessary embedded steel is placed at the proper location (using either a dowel basket in conjunction with the form or by drilling and installing the necessary dowel bars after form removal but before resuming paving) in the header, that the concrete is properly poured, vibrated, finished, edged, textured, and cured, and that the form is removed before resuming paving.</td>
<td>☐</td>
</tr>
<tr>
<td>3.</td>
<td>Alternatively, if using a sawed header, use a full-depth sawcut to remove the overpaved section of the pavement and install any necessary embedded steel before resuming paving.</td>
<td>☐</td>
</tr>
<tr>
<td>4.</td>
<td>If using the maturity method for estimating in-place concrete strength of the project, remember to check the strength of the in-place concrete at a header before allowing any heavy construction loads (e.g., paving machine, concrete delivery trucks, or other construction vehicles), otherwise allow a sufficient amount of strength to develop before placing heavy construction loads on the header.</td>
<td>☐</td>
</tr>
</tbody>
</table>

Terminal Joints in Continuously Reinforced Concrete Pavement (Section 5.3)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Ensure that any terminal joints in continuously reinforced concrete pavements (CRCPs) are constructed per specification(s).</td>
<td>☐</td>
</tr>
</tbody>
</table>
Opening to Traffic

Strength Requirements (Section 6.1)

No. Task Complete
1. Determine and agree upon the required opening strength for construction or public traffic and for each thickness of concrete pavement being constructed at the site during a pre-paving meeting, and ensure that these values are communicated to all necessary paving and testing personnel. □

2. Do not open the pavement to construction or public traffic until the appropriate strength requirement is met. □

Determining Strength (Section 6.2)

No. Task Complete
1. If cylinder specimens are used for testing the early-age strength of the concrete, ensure that the opening strength cylinders are sampled, cast, handled/transported, cured and tested by the appropriate means, and per specification. □

2. If a maturity meter is used to estimate the early-age strength of the concrete, ensure that the maturity curve was constructed using cylinders that used the same materials/mixture design as will be used on the job, that the cylinders were cured in conditions similar to those in the field at the time of construction, and that maturity testing is conducted properly. □

Concrete Mixture Considerations (Section 6.3)

No. Task Complete
1. If early opening to traffic is necessary and a conventional strength concrete mixture is used, confirm that the mixture is capable of obtaining the necessary early-age strength under the ambient conditions at the job; if not, consider switching to a high-early strength concrete mixture. □
<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>If a high-early strength concrete mixture is used, ensure that the many ancillary material properties such as durability, early stiffening potential, autogenous shrinkage, drying, temperature rise, etc., and not just strength, were considered and/or tested when designing the mixture.</td>
<td>☐</td>
</tr>
<tr>
<td>3.</td>
<td>Ensure that, if used, ample insulating blankets are available prior to paving, and place and remove the insulating blankets per the requirements.</td>
<td>☐</td>
</tr>
</tbody>
</table>
## Overview

Quality control (QC, also known as process control) is defined as the actions and considerations taken by a producer and/or contractor to assess, document, and adjust production and construction processes so as to control the level of quality being produced in the end product; by following proper QC procedures, a producer and/or contractor ensures that all specifications (e.g., strength, smoothness, etc.) detailed in the contract documents are met. QC is not the same as quality assurance (QA); in fact, QC is a component of QA, and the overall QA process typically is the responsibly of the specifying agency.

To clarify the differences between QC and QA, consider the comparisons presented in Figure 1.1 and Table 1.1.

## Key Points:

- **Quality control (QC) is not the same as quality assurance (QA); QC, being the responsibility of the producer and/or contractor, is a component of QA, the responsibility of the agency.**
- **The QC plan should be discussed during a pre-paving meeting.**
- **The level of QC, and the number of required tests, is dependent on the size and scope of the project.**
- **The testing crew, laboratory personnel, plant, and plant and truck operators should obtain the appropriate training and/or certification prior to paving.**
- **Specimens should be handled and cured appropriately.**
- **The required reporting protocols of a QC plan vary from agency to agency so the reporting protocols should be discussed during a pre-paving meeting.**
- **Contingencies for hot and cold weather paving should be discussed during a pre-paving meeting, when appropriate.**
- **Though not typically part of a formal QC plan, proper grade and thickness should be checked at regular intervals during paving.**
Table 1.1. Quality Assurance (QA) versus Quality Control (QC)

<table>
<thead>
<tr>
<th>Quality Assurance (QA)</th>
<th>Quality Control (QC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ensures that the end product is of the proper quality (checks that things are done properly)</td>
<td>Makes the product of the proper quality through QC processes (ensures that things are done properly)</td>
</tr>
<tr>
<td>Responsibility of the specifying agency</td>
<td>Responsibility of the producer and/or contractor</td>
</tr>
<tr>
<td>Motivates proper QC practices</td>
<td>Motivated by QA and acceptance procedures</td>
</tr>
</tbody>
</table>
Being a component of proper QA, the QC procedures for any project should be discussed with the specifying agency before construction to aid in acceptance of the newly constructed concrete pavement.

**Motive for Proper QC** – Although QC is motivated by QA and acceptance procedures, it is not the goal of QC to simply comply with specifications; rather, QC is a tool that a producer and/or contractor can use to minimize their own risks. Risk to the producer and/or contractor is minimized by using results of QC tests to modify steps in the construction of a concrete pavement to ensure that the concrete material production and placement/paving operations are as uniform as possible.

**Use of QC Testing for QA** – Some agencies allow QC test results to be used for acceptance of the final product. Although acceptance tests are conducted on random samples and at a regular interval, it should be noted that, even if an agency allows a contractor to use QC test results for acceptance, additional testing may be necessary for a thorough QC program. Acceptance testing typically is not required at a high enough frequency to provide enough data for a QC program to effectively make any necessary adjustments to the batching, mixing, placing, and constructing procedures.

### 1.1 Standard QC Tests

**Tests to Consider** – The various tests that might be conducted during mixture design/proportioning and pre-construction mixture verification are detailed in ACPA’s, “Concrete Pavement Field Reference: Pre-Paving.” Although many of these tests are routinely repeated as part of a proper QC plan, the entire suite of QC tests that might be considered for various roadway classifications is shown in Table 1.2.
Table 1.2. QC Tests that Might be Considered for Various Roadways Classifications*

<table>
<thead>
<tr>
<th>Test</th>
<th>Procedure(s)</th>
<th>Testing Frequency</th>
<th>Streets and Roads</th>
<th>Highways (&lt;100,000 AADT)</th>
<th>Highways (&gt;100,000 AADT)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WORKABILITY</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined Grading</td>
<td>ASTM C136/ AASHTO T27/ CSA A23.2-2A</td>
<td>1,500 yd³ (1,150 m³)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Aggregate Moisture Content</td>
<td>ASTM C566/ AASHTO T255</td>
<td>1,000 yd³ (765 m³)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Slump and Loss of Workability</td>
<td>ASTM C143/ AASHTO T119/ CSA A23.2-5C</td>
<td>500 yd³ (380 m³)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Vibrator Monitoring</td>
<td>Manufacturer’s recommendation</td>
<td></td>
<td>Continuous monitoring</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Cementitious Heat Generation</td>
<td>Testing guide*</td>
<td>1,500 yd³ (1,150 m³)</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>False Set</td>
<td>ASTM C359/ AASHTO T136/ CSA A3000</td>
<td>Only when early stiffening is detrimental</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td><strong>STRENGTH DEVELOPMENT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microwave Water Content</td>
<td>AASHTO T318/ CSA A23.2-18C</td>
<td>500 yd³ (380 m³)</td>
<td>Optional (AASHTO T318/ CSA A23.2-18C or strength testing)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Signature (Calorimetry)</td>
<td>Testing guide*</td>
<td>1 per day</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Concrete Strength (3 and 7 day)</td>
<td>ASTM C39/ AASHTO T22/ CSA A23.2-9C, ASTM C78/ AASHTO T97/ CSA A23.2-8C, ASTM C239/ AASHTO T177</td>
<td>500 yd³ (380 m³)</td>
<td>Optional (AASHTO T318/ CSA A23.2-18C or strength testing)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AIR ENTRAINMENT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (Unit Weight)</td>
<td>ASTM C138/ AASHTO T121/ CSA A23.2-6C</td>
<td>500 yd³ (380 m³)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
### Table 1.2. QC Tests that Might be Considered for Various Roadways Classifications*

(Continued)

<table>
<thead>
<tr>
<th>Test</th>
<th>Procedure(s)</th>
<th>Testing Frequency</th>
<th>Streets and Roads</th>
<th>Highways (&lt;100,000 AADT)</th>
<th>Highways (&gt;100,000 AADT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Content</td>
<td>ASTM C231/ AASHTO T152/ CSA A23.2-4C, ASTM C173/ AASHTO T196/ CSA A23.2-7C</td>
<td>500 yd³ (380 m³)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Air-Void Analyzer</td>
<td>Testing guide*</td>
<td>1,500 yd³ (1,150 m³)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardened Air Properties</td>
<td>ASTM C457</td>
<td>Only when AVA results indicate potential durability issues</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SHRINKAGE**

| HIPERPAV                    | Testing guide*                                                               | Two stress-strength analyses/day | X                 | X                        |

**OTHER PROPERTIES**

<table>
<thead>
<tr>
<th>Concrete Strength (Maturity Curve)†</th>
<th>ASTM C1074/ AASHTO T325</th>
<th>Optional (place two sensors every day)</th>
<th>Optional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Incompatibilities</td>
<td>Testing guide*</td>
<td>Each project stage noted</td>
<td>Whenever air-void property or early stiffening issues arise</td>
</tr>
<tr>
<td>Concrete Temperature</td>
<td>ASTM C1064/ AASHTO T309M/ CSA A23.2-17C</td>
<td>500 yd³ (380 m³)</td>
<td>X</td>
</tr>
</tbody>
</table>

* This table is adapted from the National Concrete Pavement Technology (CP Tech) Center’s publication, “Testing Guide for Implementing Concrete Paving Quality Control Procedures,” 2008, which is available for free here: http://www.cptechcenter.org/publications/mco/testing_guide.pdf.

† Concrete strength using the maturity curve is optional for all roadway classifications and typically is used as a means to estimate strength for early opening to traffic.
More Information on the Tests – Titles of each ASTM, AASHTO and CSA specification listed here and detailed descriptions of each of these testing procedures and the impact that the results from any procedure might have on the concrete mixture or final product can be found in some of the references for this chapter.

1.2 Coordination

Overview – The QC plan, as with all details of a project, should be discussed during a pre-paving meeting. This ensures that all parties involved (e.g., all members of the project team, including the owner, project engineer, inspector, plant manager, etc.) are familiar with the contractor’s QC plan and are comfortable that all appropriate steps are being taken to ensure the highest quality, and most consistent, final product.

Regardless of whether the roadway is a small hand pour at an intersection that might require just a few QC tests such as air content, slump, temperature, and compressive strength, or if the project is an 8 lane highway that has every potential QC test listed in Table 1.2 planned as part of the QC procedures, coordination within the QC team and with everyone else involved during the paving operations is critical to the success of the implementation of the QC plan. Without effective implementation, a QC plan serves no purpose.

Communication is Key – Well before paving begins, lines of communication and decision-making between the QC team, as well as a defined reporting protocol, must be established so that any necessary adjustments can be made during construction with minimal delay. Effective cross-communication about something as seemingly meaningless as a high variation in slump might impact each of the parties involved differently: it might mean that adjustments to the mixture are necessary to minimize variation in slump, which must be relayed to the plant manager, or that adjustments to the frequency of the vibrators are necessary to ensure proper consolidation, which must be relayed to the paving foreman and his crew. Such integration of the QC plan into the operation of each aspect of the paving project is necessary to provide the client the best possible product.

1.3 Testing Crew and Laboratory Training/Certification

Overview – Training and/or certification for the testing (and paving) crew(s) is available from sources such as the ACPA, the American Concrete Institute (ACI), and the American Association of State Highway and Transportation Officials (AASHTO). Even still, many state Departments of Transportation (DOTs) and local specifying agencies might have optional or required training/certification to compliment training from other organizations. Thus, the contractor should be aware of what training/certification might be necessary before constructing a concrete pavement.
**ACPA Training Offerings** – The ACPA offers many classroom and web-based training opportunities throughout the year on every aspect of concrete pavement construction and repair. On-demand, web-based training also is available in the ACPA’s online bookstore (www.acpa.org/bookstore).

**ACI Training/Certification Offerings** – The ACI offers a variety of classroom and hands-on training/certification programs that are conducted through a national network of sponsoring groups. Some of the ACI offerings that are most appropriate to concrete paving include:

- Concrete Field Testing Technician – Grade I
- Concrete Flatwork Finisher/Technician
- Concrete Strength Testing Technician
- Concrete Laboratory Testing Technician – Grade I
- Concrete Laboratory Testing Technician – Grade II
- Field Aggregate Testing Technician
- Laboratory Aggregate Testing Technician
- Concrete Transportation Construction Technician
- Concrete Construction Special Inspector

**AASHTO Certification Offerings** – The AASHTO offers a laboratory Accreditation Program that recognizes the competency of a testing laboratory in construction materials testing.

**Other Trainings/Certifications** – Because the focus of most of the ACI and AASHTO offerings is on laboratory and field testing of specimens for acceptance, many local agencies oftentimes supplement these training programs with more concrete-paving specific trainings/certifications. Locally required or optional trainings/certifications can range from topics as broad as concrete pavement construction to topics as specific as smoothness testing equipment operation; again, the contractor must check with the local specifying agency to ensure that all required training/certification is completed prior to construction.

### 1.4 Plant, Truck, Plant Operator, and Other Certifications

**NRMCA Training/Certification Offerings** – The required (or optional) plant and truck certifications, much like the testing/paving crew training/certifications, vary from agency to agency. The National Ready Mixed Concrete Association (NRMCA) offers a variety of certifications for ready-mixed and portable batch plants, ready-mixed and transit trucks, plant managers/operators, and concrete delivery professionals. The NRMCA also offers certifications for pervious concrete contractors,
concrete sustainability professionals, and even compliance with the Occupational Safety and Health Administration (OSHA) requirements. Again, the contractor should be aware of and obtain any necessary certifications prior to construction of the concrete pavement.

1.5 QC Testing Programs

Selection of Appropriate QC Tests – As shown in Table 1.2, there are many different QC tests that can be conducted on any paving project. However, the suite of tests that is selected for any specific project should balance the costs of a very detailed and comprehensive QC testing program with the reality that every project has a budget. An agency might require a certain number of tests for a project and, often times, a contractor will opt to perform additional tests or test at a higher frequency than might be required by the agency to ensure that the pavement being constructed is uniform and of the highest quality. A quality QC plan might also allow a contractor to mitigate risk when constructing a pavement that has incentives/disincentives in the contract.

All Involved Parties Impact the QC Plan – The QC plan that is appropriate to any specific project is something that should be dictated by the contractor, with input from the other involved parties. The agency might have specific tests it would like the contractor to conduct for QA purposes or the producer might have specific tests they would prefer to have conducted to ensure that they can provide a consistent concrete mixture. Such concerns should be discussed at a pre-paving meeting.

1.6 Handling and Curing Concrete Test Specimens

Importance of Handling/Curing – Many of the QC tests (e.g., air content, unit weight, etc.) are conducted with fresh, randomly sampled concrete in the field. Although such tests are dependent on the sampling technique, ambient temperature conditions, concrete temperature, and many other variables, the results arguably are not as sensitive to such variables as those of hardened samples (e.g., strength, hardened air, etc.). Thus, special care must be given to the preparation, handling, transportation, and curing of such test specimens to ensure that a representative sample is provided. It is especially important to understand that anything that happens to a concrete test specimen after it has been cast typically will have a negative response on the test results; for example, too much movement can cause excessive consolidation of the aggregate and a redistribution of the air void system, likely impacting the tested strength of the specimen.

Compressive Strength Test Specimens – Although flexural test specimens are oftentimes used for QC and/or acceptance, it is more desirable for compressive test specimens to be used for such purposes. Compressive strength testing is not as
sensitive to handling and curing of test specimens. The specimens are also smaller in size and weight, which eases handling. Compressive test specimens should be made in approved forms (ASTM C470). The cylinder form should be placed on a level, rigid, and smooth surface to avoid distortion of the shape of the form. Compressive test specimens should be made and cured per ASTM C31, AASHTO T23, of CSA A23.2-3C. Typically this involves placing the specimens out of direct sunlight and placing a moisture barrier over the specimens to prevent moisture loss. Between 24 and 48 hours after casting, testing specimens are transported to a laboratory for further curing (ASTM C192, AASHTO M201, or CSA A23.2-3C) prior to strength testing (ASTM C39, AASHTO T22, or CSA A23.2-9C).

1.7 Reporting Protocols for Test Data

**Overview** – The necessary reporting protocols for test data varies from agency to agency and from test to test, so it is best to check and discuss the necessary requirements during a pre-paving meeting and to review those details immediately prior to paving with the appropriate members of the paving crew and/or the individual or company responsible for the testing.

**Who Conducts QA Testing?** – Some agencies allow the contractor to perform all the necessary QA testing, also making the contractor responsible for reporting the results back to the agency, while others outsource the testing to a third party or have an employee of the agency do the testing.

1.8 Contingencies for Hot/Cold Weather

**Overview** – The impact of extremely hot or cold weather on the properties of the mixture (e.g., slump, finishability, strength gain, etc.) may or may not have been investigated as part of the pre-paving mixture analysis (see ACPA’s, “Concrete Pavement Field Reference: Pre-Paving”). Regardless, changes can be made to the concrete mixture batching and placing procedures, and the paving operations, to accommodate severe weather. For example, ice can be added to the mixture in lieu of water in hot weather and accelerators can be added to the mixture in cold weather. These techniques help provide a mixture that will still meet the required workability, strength, etc., and these and other methods to combat the effects of paving in hot or cold weather are discussed in depth in Chapter 3.

**Inclusion of Contingencies in a QC Plan** – Requirements for mixture modifications should be included in any QC plan for a project that will be constructed during a time (or in a location) where severe weather or changing conditions are of concern.
1.9 Checks for Proper Grade and Thickness

**Overview** – While typically not part of a formal QC plan, regular checks are necessary to ensure that the pavement is being constructed at the proper grade and to the proper thickness. If it is discovered that the proper grade and thickness are not being constructed into the pavement, adjustments must be made immediately to paving operations.

**Checking Grade** – The grade typically is checked using a total station prior to paving.

**Checking Thickness** – Procedures for checking the concrete thickness are included in the sections about fixed form and slipform paving in Chapter 3.

1.10 Time Series Plots (Control or Run Charts)

**Overview** – Time series plots (also known as control or run charts) are a graphical representation of a series of test results in chronological order. They are particularly useful in checking data for compliance with specifications and determining trends. Typically, individual values or lot-by-lot statistics are plotted along the time series plot and such plots can be constructed for testing results for density (unit weight), slump, strength, etc., and even for the standard deviation of a lot of tests. These time series plots are not meant to quantify passing or failure of test results but rather to indicate when/where unusual test results occur so that corrective action may be taken as part of the QC plan. Thus, it is important to actively watch the time series plots to detect any abnormalities along the grade as early as possible so that any applicable corrective measures can be taken quickly.

**Notes on Analysis of Time Series Plots** – When significant changes occur over time, the data must be organized to separate populations for analysis. If using a running average rather than individual values or lot-by-lot statistics in a time series plot, be aware that such a practice creates a lagging indicator effect so abnormalities may not be apparent as quickly.

1.11 Parameters for Mixture Adjustments due to QC Results

**Parameters to Adjust** – With so many variables factoring into the workability, finishability, etc., of a fresh concrete mixture, the test results from any single QC test might not be enough to isolate which of the many variables is undesirably altering the concrete mixture. See the “Integrated Materials and Construction Practices for Concrete Pavement (IMCP): A State-of-the-Practice Manual,” available for free download at the National Concrete Pavement Technology (CP Tech) Center’s website at www.cptechcenter.org, for details on how you might interpret test results and appropriately adjust the mixture.
**Variability of the Aggregate Moisture Content** – The variable that tends to have the most variability, while also having a great impact on the fresh properties of a concrete paving mixture, is the moisture content of the aggregates. The moisture content of both the fine and coarse aggregates must be periodically measured during batching operations. Sometimes this is done at the stockpiles, sometimes it is done with a portable moisture meter, but it is becoming increasingly more common for moisture meters to be integrated into the conveyor belts that are part of the aggregate delivery system so that the moisture content is determined for each batch of aggregate and the mixture water automatically adjusted to ensure that the proper amount of mixture water is provided in the batch, in turn ensuring a consistent mixture. Regardless of the method by which moisture content is determined, the batch plant operator should always be cognizant of this important variable.
CHAPTER 2
Producing Concrete

Key Points:

- Variability of the production process must be minimized to produce concrete of consistent quality and uniformity.
- Material variations must be recognized and accounted for with planned and permitted field adjustments.
- The plant must have the capacity to meet production requirements of the project, and specifically the paving equipment.
- Critical aspects of aggregate stockpile management include maintaining uniform grading and moisture content, and preventing aggregate contamination.
- Dry ingredients should be batched by weight.
- The order in which materials are introduced into the mixer must be consistent and conform to the trial batch sequence.
- Sufficient mixing time must be allowed to ensure a homogeneous mixture and to entrain the required air-void system.

2.1 Stockpile and Materials Management

Overview – Stockpile management is the coordination of the aggregate delivery and storage as well as the charging of the mixing plant. This is a vital aspect of consistent quality concrete production. Locating the stockpiles is an important first consideration. A relatively flat area is preferred to facilitate unloading and stockpiling of the aggregates. Typically, a pad or aggregate separation layer is placed in the stockpile area to minimize contamination of the aggregate from the soil below and to prevent material loss. The site also must facilitate drainage to prevent undue delays in concrete production after precipitation due to mixture consistency problems stemming from aggregate moisture variability or to prevent recementing of coarse or fine recycled concrete aggregate (RCA) stored in uncovered stockpiles.
It is desirable to maintain uniform gradation and moisture content, and to prevent aggregate contamination, through proper stockpile management. Consistent aggregate properties, such as gradation and moisture content, will contribute to consistent concrete properties, such as slump, strength, etc. A few basic stockpiling concepts include the following:

- Pile the material in lifts.
- Complete each lift before beginning the next.
- Do not dump material over the edges of a stockpile.
- Minimize free-fall heights of aggregates to avoid segregation.
- Only stockpile as much material as practical.
- Minimize crushing of the aggregate by the loader.

**Dirty or Contaminated Aggregate** – In some cases, the aggregates may be contaminated with clay or soil before arriving on the plant site. Dirty aggregates require washing or cleaning, or alternatively, should be rejected. In addition to increasing the probability of strength problems or durability-related distresses (e.g., clay balls) in the finished concrete pavement, dirty aggregates can lead to placement problems (e.g., inconsistent air content) and even concrete material problems (e.g., low strength). The aggregate loader operator has a key role in preventing clay or mud from being deposited into the plant’s feed hoppers (Figure 2.1), while the materials manager needs to ensure dusty aggregates are cleaned effectively.

![Figure 2.1. The aggregate loader operator is an important person in the production of consistent quality concrete.](image-url)
Loader Operations – The aggregate loader operator must control the elevation of the loader blade to prevent picking up contamination from below the aggregate stockpile. The primary responsibilities of the aggregate loader operator include the following:

- Working the stockpile to provide uniform moisture content and gradation, while avoiding segregation.
- Minimizing contamination of the aggregates.
- Observing and reporting moisture variations.
- Adding material to the feed hopper(s) when appropriate.
- Notifying the plant foreman of anticipated aggregate shortages.

Required Number of Stockpiles – Although two stockpiles (one for coarse aggregate and one for fine aggregate) were traditionally used in the production of concrete, common and best practice is to employ three stockpiles (and in some cases more). This is mostly due to the benefits derived from using concrete mixtures with optimized gradations (uniform combined aggregate gradation). See ACPA’s, “Concrete Pavement Field Reference: Pre-Paving” for more details on the impact the aggregate gradation has on workability, water demand, strength development, etc. The increasing use of fine and coarse RCA also is a contributing factor to the necessity of more than two stockpiles for modern concrete paving mixtures.

2.2 Mixing Concrete

Overview – This section focuses on the physical mixing of the concrete paving mixture and not on mixture design. Proper mixture analysis and approval (which includes topics such as determining the maximum cementitious materials content and optimizing aggregate gradations) is covered in ACPA’s, “Concrete Pavement Field Reference: Pre-Paving.”

2.2.1 Obtaining a Consistent Concrete Mixture

Factors to Consider for Consistent Concrete – Effort and care are required to ensure that the components of a concrete mixture are combined in a manner that results in uniformity within a single batch of concrete and consistency between batches of concrete; the mixing process must completely coat aggregate particles with paste. The order in which the ingredients are batched and the batch mixing time are important to the uniformity of the finished concrete pavement. Different concrete mixtures might require different sequencing of mixture constituents, a different time of water addition, a different mixing time, or a different speed of mixing. Other factors to consider in mixing the concrete are the relative size of the batch to the mixer capacity, the time between batching and mixing, and design, configuration, and condition of the mixing drum/blades.
2.2.2 Mixing Operations

Overview – Concrete is produced for delivery to the contractor typically using one of the following two methods:

- Central mixed concrete (e.g., portable batch plant)
- Truck mixed concrete (e.g., ready-mixed)

Regardless of the product method, it is imperative that any mixer used to produce concrete is in proper operating order so that it will produce the most consistent concrete possible. This includes regular maintenance and regular inspection for things like blade/fin wear.

Central Mixed Concrete (Portable Batch Plants)

Overview – Central mixed concrete plants are also known as portable batch plants or wet batch plants. In a central mixed concrete plant (Figure 2.2), the batched ingredients are charged into a mixer and then thoroughly mixed prior to discharge into the delivery unit. The use of a central mixed concrete plant offers the contractor increased production rates and direct control of the production of the concrete.

Mixing Time – Mixing times may vary depending on the mixture properties and mixing equipment but most central mixed concrete plants require a minimum mixing time of one minute; some modern plants can operate with shorter mixing times. If a shortened cycle is desired it is best to run a comparison test of the different mixing
cycle times. It is also important to factor in the necessary mixing time to allow chemical admixtures to perform properly. In some cases, mixing times might be increased to ensure a uniformly blended mixture but the mixing time should not exceed about two minutes or air entrainment may be adversely affected.

**Hauling Vehicles** – Contractors can use dump trucks and/or agitating trucks to deliver the concrete to the paving equipment. Ready-mix trucks also can be used to haul central-mixed concrete, although the drums on these trucks are primarily used for agitation instead of mixing because the drum in the plant would have already fully mixed the concrete prior to discharging it into the ready-mix truck.

**Plant Considerations** – The operator of a central mixed concrete plant is responsible for measuring (batching) the ingredients and monitoring the batch into, through, and out of the central mixer. Again, the order in which the ingredients are batched (Figure 2.3) and the batch mixing time are important to the uniformity of the finished concrete pavement. Central mixed concrete is considered a completely mixed product ready for acceptance by the user when discharged from the central mixer.

![Figure 2.3](image)

*Figure 2.3. Typical sequence of adding materials in a central mixed concrete mixture.*

Plant location and setup depend primarily on site factors like zoning, access to utilities, storage of materials, water source, mixing plant design, adjacent land use, accessibility to construction site, materials delivery, and amount of both construction and public traffic (urban or rural). The plant must have the capacity required to meet the production requirements for the project and the location of the central mixer should be selected to accommodate traffic flow to, from, and around both the central mixer and the construction site.
The central mixed concrete plant needs to be calibrated, in good condition, operated reliably, and produce acceptable concrete uniformly from batch to batch. Plants should be inspected prior to the start (or re-start) of each paving project, and when uniformity or strength problems are encountered during production. Inspection is not limited to the mixing area of the plant itself; all components of any central mixed concrete plant should be inspected during a general inspection, including aggregate bins, admixture storage, the mixing drum, the generator trailer, the control trailer, the various material measuring devices, and the cement and supplementary cementitious material (SCM; e.g., fly ash) pigs. See the section titled, “Plant, Truck, Plant Operator, and Other Certifications” for more information on the inspection of central mixed batch plants.

**Stationary Mixed Concrete (Ready-Mixed or Truck-Mixed)**

**Overview** – Stationary mixed concrete is also known as ready-mixed, truck-mixed, or dry-batched concrete. At a ready-mix plant (Figure 2.4), the various components of the concrete mixture are batched directly into a ready-mix truck (or transit mixer) by the plant operator. The plant operator is responsible for batching and the truck driver is responsible for mixing the concrete. Again, the order in which the ingredients are batched (Figure 2.5) and the batch mixing time are important to the uniformity of the finished concrete pavement. The concrete mixture is not ready for acceptance until the truck has completed the mixing.

*Figure 2.4. Stationary dry-batch (ready-mix) plant.*
Revolution Counter, Slump Meter, and Ready-Mix Truck Capacity – Each ready-mix truck is equipped with a revolution counter and a slump meter. A minimum of 70 revolutions at mixing speed is typically required to ensure proper consistency; a maximum of 300 revolutions at mixing and/or agitating speed is typically allowed. The slump meter allows the ready-mix truck driver to estimate the slump to within about ½ in. (12 mm) but the readings from a slump meter are for quality control purposes only, not for acceptance. A standard ready-mix truck can mix and deliver about 8 yd$^3$ (6 m$^3$) to 10 yd$^3$ (7.5 m$^3$) of material, depending on the truck.

Transit Time – The transit time of stationary mixed concrete transported to a construction site is critical to meeting the production requirements for a project. Because haul times for stationary mixed concrete can be significantly longer than central mixed concrete, scheduling and constant communication with regard to dispatching more/less delivery vehicles are necessary to ensure that the concrete paving operations proceed at the desirable rate and without the formation of a long queue of delivery vehicles.

Plant Inspection – Many ready mixed concrete plants are inspected or certified to meet agency specifications or the criteria of the NRMCA plant certification. This helps ensure that the material produced is within specification, although certification does not ensure quality and consistency. Diligent control and quality production practices must be maintained by plant personnel and truck mixer drivers.
2.3 Hauling/Delivery

**Uniform Delivery Rate is Key** – The hauling of the fresh concrete mixture from a central mixed concrete plant to the paving site, or the delivery of the fresh concrete mixture using stationary mixed concrete vehicles, at a uniform rate is a key factor to producing a quality concrete pavement. After a route has been planned for trucks to take, it is the responsibility of the hauling/delivery vehicle operators to deliver a concrete mixture that is properly mixed and workable, and to do so within the delivery time limit and at a uniform rate. Delivering the fresh concrete mixture in such a manner will result in optimum productivity and placement.

2.3.1 Methods of Transport

**Overview** - There are many different vehicles available for hauling and delivering a fresh concrete mixture, the selection of which is best for a specific project is dependent on the specific circumstances of the paving project, availability, and which mixing operation is used. Typical vehicles include open bed dump trucks, agitating trucks (agitators), and ready-mixed truck (transit mixers); the main difference between these various transport methods is the delivery time available.

**Dump and Agitating Trucks** – Dump trucks (Figures 2.6 and 2.7) and agitating trucks (Figure 2.8) generally have 30 minutes after the concrete is mixed to deliver and place it at the job site. The use of the agitator paddle in agitating trucks can extend the delivery time up to 90 minutes, as can the use of retarding admixtures. The delivery time limit may also be dependent on the ambient temperature. For example, some specifications allow a delivery time of up to 60 minutes for agitating trucks if the agitator paddle is constantly moving and the ambient temperature is 60°F (16°C) or greater and 90 minutes if the ambient temperature is less than 60°F (16°C), both without the addition of retarding admixtures.

**Ready-Mix Trucks** – Ready-mix trucks (Figure 2.9) can be used for both mixing and delivery. They are most commonly used for dry batch operations and street or road paving projects. They generally have up to 90 minutes from initial mixing to delivery. The mixing of the materials is typically done in accordance with the specific project specifications. A number of agencies limit both the number of mixing revolutions and the total allowable revolutions. Many concrete producers require that the material be thoroughly mixed and inspected by the driver before leaving the plant. After mixing is completed, the truck mixer agitates the concrete according to the concrete producer’s recommendation.

The contractor should receive a batch ticket from the ready mix truck driver when the truck mixed concrete is delivered to the project site. Once the contractor is satisfied that the batch ticket indicates that the concrete is in accordance with the order, the concrete can be discharged at the project site.
Delivered Quality in Ready-Mixed Trucks – If the contractor is not satisfied with the slump of the concrete, one addition of water may be permitted to bring the concrete to the desired level, provided the maximum allowable water-cementitious materials ratio is not exceeded. When water is added, 30 revolutions of the drum at mixing speed are required to completely mix the water into the batch. Depending on project procedures, this might be done at the plant if needed or at a staging area on the project.

Figure 2.6. Batching into end-dump truck.

Figure 2.7. Side-dump truck discharging concrete into spreader.
Figure 2.8. Agitating truck discharging concrete on grade in front of slipform paving machine.
2.3.2 Rate of Delivery

Have Enough Delivery Trucks – Regardless of truck type used to haul the concrete, make sure that an adequate number of trucks are available to supply the required amount of concrete to keep the paving operations moving forward at a fairly constant rate.

Variables Impacting Delivery Rate – Variables that have potential impact on the rate of delivery include but are not limited to:

- Type and capacity of batch plant.
- Type of haul road.
- Hauling restrictions.
- Non-construction related traffic impacts.
- Distance from plant to paving operations.
- Air temperature.
- Placement rates.
- Placement and/or equipment requirements.

Placement/Unloading Rate – The placement rate can be defined as the paving speed in feet (meters) per minute times the material needed per foot (meter) of length. The unloading time can be found as follows:
Unloading time = Paving Speed x Placement Width x Placement Thickness x (1 + Grade Yield Loss)  
[Eqn. 2.1]

Thus, at a paving speed of 6 ft/min (1.8 m/min), a section width of 24 ft (7.3 m) and thickness of 8 in. (200 mm), and a grade yield loss of 5 percent, the material needed is 3.7 yd$^3$ (2.8 m$^3$) per minute:

\[
\text{Unloading time: } 6 \text{ ft/min.} \times 24 \text{ ft} \times 8 \text{ in.} \times 1.05 = 3.7 \text{ yd}^3/\text{min}
\]

(Unloading time: 1.6 m/min. x 7.3 m x 0.2 m x 1.05 = 2.8 m$^3$/min)

For that placement rate, the unloading time has to be just over 2 minutes for an 8 yd$^3$ (6 m$^3$) ready-mixed truck to assure continuous forward movement of the paving operations at a constant speed. Thus, it is clear how paving operation speed and material delivery/unloading speed are interdependent.

Because the placement and finishing operations are so dependent upon delivery/unloading speed, the maximum delivery time may become critical if the paving site is a significant distance from the mixing operations or if any delays in paving occur due to mechanical problems of placement/finishing machines. Thus, the maximum delivery time of the intended transport vehicles must be considered to optimize placement operations and minimize losses in the form of material that could not be delivered within its allowable delivery time.

**Unloading Rate with Low-Slump Concrete** – Although unloading time is a small part of the overall cycle time, low-slump concrete has different unloading characteristics than high-slump concrete and this increased time for unloading must be considered. Therefore, to match the required placement rate with low-slump concrete, consider using open-bed dump trucks or truck mixers specifically designed with wider discharge openings.
CHAPTER 3
Placing Concrete

Key Points:

- Ensure that the dowel baskets are affixed to the grade at the proper locations or the dowel bar inserter is in proper operating condition.
- Do not place or insert tiebars within 6 in. (150 mm) of the tip of the nearest dowel bar.
- Wet the grade such that it is moist but does not have any standing water on it immediately prior to paving.
- To build a smooth pavement, the contractor must be able to control:
  - The prepared grade.
  - The paver.
  - The stringline, if one is used.
  - Concrete consistency.
  - Vibration energy (do not over-vibrate).
  - Embedded items in the pavement.
  - Finishing, texturing, and curing operations.
- If fixed form paving, follow proper placing, spreading, consolidating, thickness verification, finishing, texturing, curing, and form removal techniques.
- If slipform paving, operate the slipform paver at a consistent speed with the proper amount of concrete (“head”) in front of the paver and follow all proper placing, spreading, consolidating, thickness verification, finishing, texturing, and curing techniques.
- If a problem such as surface chatter or edge slump occurs, immediately take the necessary steps to resolve the issue.
- Pay special attention to headers and when paving on a steep grade.

Difference Between Fixed Form and Slipform Paving – Fixed form paving typically is used for smaller placements, hand-pour areas, and low-volume or light-
traffic facilities. Slipform paving is used when large amounts of concrete must be placed efficiently. Unlike fixed form paving, where stationary forms are placed to hold the concrete mixture, slipform pavers form and consolidate the fresh concrete as they travel along. Regardless, there are some considerations for access and staging, wetting of the subgrade/subbase, and paving in inclement weather that might be common to both fixed form and slipform paving operations.

### 3.1 Access and Placement of the Concrete Mixture

**Overview** – When transporting the mixture from plant to construction site, the goal is to deliver well-mixed, workable concrete to the construction site. It is essential that the mixture be uniform and consistent from batch to batch.

**Delivery and Delays** – Generally, concrete mixtures are transported by dump trucks, agitating trucks, or ready-mix trucks (see the section titled, “Hauling/Delivery”). One factor affecting choice of transport methods is the time available for delivery. Exceeding the appropriate delivery times affects the concrete’s workability. Extensive delays may make it necessary to shut down paving operations and construct a header joint (see the section titled, “Construction Joints (Headers)”).

**Access** – If the grade provides adequate space, delivery vehicles should deliver the concrete from a haul road adjacent to the area being paved. If there is no room for a haul road, prepare the grade so that it is stable enough such that the concrete trucks and other construction vehicles do not rut the surface of the subbase material (Figure 3.1). If an unstabilized subbase does become rutted or damaged due to hauling vehicles (differential compaction of the subbase can compromise drainage...)

*Figure 3.1. Unbound subbase with enough fines to be stable during construction and provide permeability of about 200 ft/day (60 m/day).*
if the unstabilized subbase was designed to be a drainage layer), it must be re-graded and re-compacted. Stabilized subbases (asphalt- and cement-treated, lean concrete) will typically hold up well under construction traffic without damage.

**Placement** – On fixed form projects, ready mix trucks typically are used, and the chutes are moved during discharge to spread out the mix. For slipform paving, the concrete can be directly deposited in front of the paving machine by direct discharge from the trucks, or a belt placer or spreader (Figure 3.2) may be used. A belt placer conveys concrete from the delivery trucks to the middle of the paving area just in front of the paver. A spreader uses an auger or plow to spread out the concrete to a fairly uniform thickness in front of the paver.

![Figure 3.2. A belt placer and spreader being used to place the concrete in front of a slipform paving machine. Note that the pre-placement of dowel baskets in the paving lane requires the haul road to be outside of the stringline; the belt section of this machine can be raised to allow delivery vehicles to pass on the haul road.](image)

### 3.2 Placement of In-Pavement Steel

**Overview** – Continuous reinforcing steel, mesh reinforcement, and dowel baskets that are tacked in place prior to paving may disrupt the consolidation pressure during the passage of the slipform paver.

**Tiebars** – When two or more lanes are placed, tiebars typically are placed across the centerline or lane lines to prevent the slabs from moving apart over time. If the paver does not install tiebars mechanically, a crew member rides on the paver and inserts them manually. In either case, a timing device – usually a wheel of a specific circumference riding on the paver track – is used to ensure the correct spacing.

**Dowel Bar Inserters** – The alternative to placing dowel bars in basket assemblies is to use automatic dowel insertion equipment (also known as a dowel bar inserter...
(DBI)). The key to controlling the location and positioning of inserted dowel bars is the concrete mixture. Well-graded mixtures with an appropriate workability produce excellent results with dowel insertion, while gap-graded mixtures tend to allow the dowels to migrate within the concrete mass. Figure 3.3 shows a dowel bar inserter.

![Figure 3.3. Dowel bar inserters on paving machines place dowel bars in fresh concrete.](image)

**Prevent Roughness due to Embedded Steel** – Of the four causes of reinforcement-related roughness described in the inset box on the next page, damming and reinforcement ripple are thought to be the most common. These effects were studied in England after problems were noted on continuously reinforced pavement (CRCP). Similar problems have been experienced in the U.S. but have been largely eliminated through paving train adjustments and the use of improved finishing techniques. Some contractors find that placing some concrete over dowel assemblies before passage of the paving machine eliminates dowel assembly shoving and extrusion pressure effects. Others find the use of properly adjusted oscillating beam floats helpful in removing spring-back and rippling effects.
Lack of Consolidation – Lack of uniform consolidation within the dowel basket area may create a rough surface because concrete may settle or slough over the dowels. In extreme cases where high-slump concrete is used, this effect may cause a crack to form directly above the dowel as the dowel causes uneven settlement of the fresh concrete. This phenomenon is termed subsidence cracking.

Reinforcement Ripple – Reinforcement ripple occurs when concrete is restrained by the reinforcing bars, resulting in a ripple in the surface with the surface slightly lower near each bar than in the area between bars. This occurs in one of two ways:

1. Longitudinal depressions are caused when longitudinal bars limit the restitution of surface level behind the profile pan by restraining the rebound of concrete beneath the bars.

2. Transverse ripples are caused by the transverse bars in the same way, except that transverse ripple has been found to be less noticeable than the prominent ridge caused by the damming effect of transverse bars upon the upsurge flow of concrete behind the profile pan. (Note: the prominence of surface rippling depends upon the finishing techniques and depth of cover to the reinforcement, with less cover producing more prominent rippling.)

Spring-Back – Spring-back is a term to describe an extrusion pressure problem affecting the dowel basket assemblies. It occurs when the basket assembly deflects and rebounds after the profile pan passes overhead and the extrusion pressure is released. The result is a slight hump in the concrete surface just ahead of the basket. Spring-back is more apt to occur on steeper grades and when there is too much draft in the pan. It is thought that the spring-back effect is more pronounced where agencies require dowel basket spacer wires to be cut before paving, thereby weakening the assembly.

3.2.1 Location of Dowels, Baskets, DBI

Overview – Dowels can be placed and aligned either prior to concrete placement using dowel bar assemblies (dowel baskets) or during concrete placement using a DBI (see Figure 3.3). Both of these methods provide satisfactory results, but, because a properly functioning DBI and a satisfactory concrete mixture for use with DBI placement essentially take all of the guess work out of positioning dowels, the remainder of this section focuses solely on placing dowel baskets.
Dowel Bar Location and Alignment – The location and alignment of dowel bars is important. After the subbase has been properly trimmed and inspected, dowel baskets, if used, are set on the roadbed, perpendicular to the pavement edge. The bars should be parallel to the pavement centerline AND surface within a reasonable tolerance (this will inherently make all dowels parallel to each other) in order to ease opening and closing of the joint during temperature cycles. Dowel bars should be located near the mid-depth of the slab and carefully aligned to within the specified horizontal and vertical tolerances. If the dowel baskets are too close to the edge of the paving operation, the paving equipment may snag them and disrupt paving.

Securing Dowel Baskets – When the baskets are correctly aligned, they must be adequately secured with stakes, pins, nails, and/or clips. Practices vary by contractor or state requirement, but typically a minimum of eight fasteners (for 12 or 14 ft [3.7 or 4.3 m] lane widths) are placed on the leave side of the basket wire to secure the basket against movement (Figure 3.4 and 3.5).

Marking Dowel Bar Locations – The location of the dowel centers is then marked on both sides of the roadbed, either by setting colored pins or by painting marks (Figure 3.6). The markers indicate where joints should be sawed, ensuring that they will be sawed along the center of the dowel assembly.

Figure 3.4. Staking/pinning dowel baskets to grade.
Figure 3.5. Nailing dowel baskets to grade with clips.

Figure 3.6. Dowel baskets hold dowel bars in the desired alignment and position during paving operations. The spray-painted line on the subbase indicates the location where a joint will be sawed over the center of the dowels.
Not Cutting Dowel Basket Tie Wires – Dowel basket tie wires (or shipping wires) do not need to be cut. Leaving the tie wires intact will not adversely affect joint formation, joint opening, or long-term pavement performance. Rather, it will help stabilize the dowel assembly, making it more rigid and thereby keeping the dowels properly aligned during and after passage of the slipform paving machine.

Dowel Baskets for Skewed Joints – For pavements with skewed joints, special baskets are required to keep the dowels parallel to the pavement centerline, while keeping the bars centered on the skewed joint. The basket manufacturing process, placement/alignment procedures, and subsequent joint sawing are all more complicated with skewed joints.

3.2.2 Location of Tiebars, Chairs, Inserters

Overview – A timing device such as a wheel measuring the distance between the bars typically is used to ensure the correct spacing. Check specifications of the owner/agency for the maximum allowable grade and bend for bent tiebars.

Tiebars in Contraction Joints – When paving two lanes or more in width, tiebars may be mechanically inserted or pre-placed along the planned longitudinal contraction joint location(s) using chairs (Figure 3.7). The tiebars should be properly spaced and either implanted or fastened to chairs that locate the bars at the correct depth in the slab.
**Tiebars in Construction Joints** – Where tiebars are used along longitudinal construction joints, they are typically placed during paving operations. Such tiebars are either placed mechanically by the paving machine or manually by a paving crew member.

### 3.2.3 Leave Tiebar Out Near Dowel Basket

**No Tiebars too Close to a Transverse Joint** – If a tiebar is placed too close to a transverse joint, it may interfere with joint opening and closing and the effectiveness of the dowel bar load transfer at the joint. To keep the slab corner from being too restrained, no tiebar should be placed within 6 in. (150 mm) of the tip of the nearest dowel bar in the transverse joint (see Figure 3.7). The operator may have to use a specific sequence where tiebars are omitted while paving. Depending on the joint and tiebar spacing design requirements, this may be every fourth or fifth bar.

### 3.3 Wetting the Grade

**Wetting Helps Mitigate Drying Shrinkage Stresses** – A dry subbase draws water from the bottom of the concrete mixture. This can potentially cause uneven curing and cracking due to differential stresses resulting from moisture gradients through the slab depth. To help prevent these stresses, thoroughly spray the subbase with water shortly before placing the concrete, allowing the water to soak in adequately (Figure 3.8). The subbase should be noticeably moist but should not have standing water. Wetting may not be necessary after a recent rain.

![Figure 3.8. Wetting the grade prior to concrete placement.](image-url)
3.4 Fixed Form Paving

**Pre-Paving Setup** – Please refer to ACPA’s, “Concrete Pavement Field Reference: Pre-Paving,” for details on pre-paving setup of forms for fixed form paving applications.

**Fixed Form Paving Machines** – There are a variety of fixed form paving machines. The less complex equipment, such as hand-operated and self-propelled vibratory screeds (Figure 3.9), single-tube finishers (Figure 3.10) and revolving triple tubes (Figure 3.11), are useful for many complex paving areas. The external (surface) vibration that this equipment produces is adequate to consolidate most non-reinforced concrete slabs thinner than about 8 in. (200 mm), depending on the concrete mixture being used. If the slab is greater than 8 in. (200 mm), however, supplementary internal vibration with hand-operated spud vibrators is recommended for adequate consolidation. A combination of internal- and surface-vibration is preferable for reinforced slabs at any thickness. Because surface vibration of concrete is least effective near the forms, it is beneficial to consolidate concrete along the forms with a spud vibrator.

![Figure 3.9. A vibratory screed can be used in many situations, including hand pours.](image-url)
Figure 3.10. A roller screed (i.e., single tube finisher) can be used to strike off the concrete in fixed form placements.

Figure 3.11. A triple tube finisher is being used in combination with a straightedge on this project.
Larger, form-riding machines such as bridge deck finishers (Figure 3.12) can place and consolidate the concrete between forms in one pass. These machines ride either on the forms or on pipes laid outside the forms. Because form-riding paving equipment cannot produce acceptable results riding on wooden forms, most of the curved areas joining intersecting pavements require use of hand-placement equipment, such as vibratory or roller screeds.

**Figure 3.12.** A bridge deck finisher can also be used for paving within fixed forms or, as shown in this photo, pre-placed curb and gutter sections [photo courtesy of Terex Bid-Well].

**Paving Width Precaution** – Another consideration for fixed form paving is the width of the section to be placed; some fixed form paving machines can pave widths upwards of 50 ft (15 m) but the agency and contractor must recognize the limitations of such machines and design the concrete mixture such that it is compatible with this type of construction.

**Fixed Form versus Slipform** – If a pavement placement is large enough, some contractors may select a slipform paver because this method typically produces desirable consolidation and ride quality more efficiently than fixed form methods. Agencies may also require slipform construction on certain projects.
3.4.1 Spreading the Mixture

Overview – Evenly depositing concrete onto the grade in front of the fixed form placement machine eases paving. Piling too much concrete in front of the machine leads to strikeoff difficulty. The concrete should not be excessively higher than the forms. However, piling too little concrete in front of the machine may produce low spots in the pavement surface.

Spreading with Hand Tools – Although it is ideal to distribute the concrete evenly with the chute from the ready mix or other concrete hauling truck, some distribution of the concrete with hand tools is usually necessary. Shovels are preferable because they do not cause concrete segregation, although raking is a reasonable alternative.

3.4.2 Consolidation

Overview – When necessary, supplemental vibration with handheld spud vibrators should precede the placement screed (Figure 3.13). Standard practice calls for vertical plunges of the vibrator head roughly every foot (0.3 m). Operators should neither drag spud vibrators through the concrete nor attempt to move the concrete laterally with a vibrator, as either will segregate the mixture. Consolidation for fixed form paving might also be performed using a system of gang mounted vibrators on the spreader, comparable to the gang mounted system employed on a typical slipform paver.

Figure 3.13. In fixed form construction, consolidation is usually achieved through the use of handheld (spud) vibrators, such as the one held by the worker in the center of this photo; this operation is being followed by a roller screed for finishing.
How Long to Vibrate – In general, proper consolidation of air-entrained concrete takes less time than non air-entrained concrete, even when both mixtures are prepared with the same consistency (slump). The vibration time necessary to achieve adequate consolidation also depends upon the size and type of vibrator. For most equipment, leaving the vibrator head inserted for 5 to 15 seconds is usually adequate. For very thin pavements, as little as 2 or 3 seconds may be adequate. Ensure that the minimum and maximum times are enforced to prevent segregation.

3.4.3 Thickness Verification

Verification During Construction – Thickness verification for fixed form paving is very straightforward because, as long as the concrete is struck off and finished with a fairly rigid piece of equipment (thus preventing sag in thickness across the width of the pavement), the concrete pavement will have been constructed to the same thickness as the form and/or adjacent pavement on which the finishing equipment rides. Thus, as long as it is assured that the forms are properly set to the necessary height before paving, the proper thickness during construction is ensured.

Post-Construction Verification – Although typically carefully monitored during construction, thickness verification might be necessary after construction is complete. In such cases, core sampling might be necessary or one of the various non-destructive testing methods, such as ground-penetrating radar, might be employed to estimate the thickness of the concrete pavement.

3.4.4 Finishing

Methods of Finishing – Concrete pavements constructed with fixed forms may be finished by a variety of machines, including a vibratory screed (see Figure 3.9), a roller screed (see Figure 3.10), a clary screed, a laser screed, or a bridge deck finisher (see Figure 3.12). Depending on what surface texture might then be applied, subsequent finishing may or may not be necessary. If necessary, this final finishing often is completed in the same method as with slipform paving, with a straightedge (see Figure 3.11).

3.4.5 Form Removal

Removal and Curing – To ensure proper curing, any fixed forms should be removed carefully within 24 hours of concrete placement, after the concrete has hardened sufficiently to prevent damage (or stiffened enough to prevent sagging at the edge), and the proper curing procedure should be applied to the edges of the pavement. It is critical that the contractor properly time form removal because proper and timely curing is of the utmost importance, but the contractor also will be liable for any damage caused to the pavement from pre-mature form removal.
3.5 Slipform Paving

Pre-Paving Setup – This section will focus on the construction-related details of the various components of a slipform paving machine; please refer to ACPA’s, “Concrete Pavement Field Reference: Pre-Paving,” for more details on pre-paving setup.

Slipform Paving Machines – A slipform paving machine must spread and consolidate the concrete as it moves forward. It cannot produce desired results if it is not well-maintained, must stop often, or has to push a large pile of concrete. When operating properly, a well-consolidated and properly shaped slab is extruded from behind the paving machine as it moves steadily forward.

Because a slipform paver forms the surface of the pavement, all factors except straight-edging and hand finishing influence its operation. Controlling the concrete consistency (see the section titled, “Obtaining a Consistent Concrete Mixture”); delivery (see the section titled, “Hauling/Delivery”); and/or loading (see the section titled, “Placing Concrete”) will result in a steady operation and a smooth, consistent surface.

Stringless Slipform Paving – Because of its potential to reduce staking time and the associated costs, reduce clutter in the workzone, improve safety and mobility in the workzone, increase the speed of construction, and improve control of placement, especially for concrete overlays, the use of stringless slipform paving (Figure 3.14) is increasing. More information on stringless slipform paving machines and other state-of-the-art paving technologies such as GPS guided sawing equipment is available from the various manufacturers of such equipment.

Figure 3.14. A stringless slipform paving operation [photo courtesy of National CP Tech Center].
**Operating at a Consistent Speed** – Slipform pavers should be operated at a consistent speed. This helps provide steady productivity and a smooth pavement. Maintaining a consistent speed is tied to scheduling the appropriate number of concrete delivery trucks. If there are too few trucks, the paver will have to slow down or stop. If there are too many trucks, they may get backed up at the construction site (Figure 3.15) and risk exceeding concrete placement time limits or otherwise impact the consistency of the mixture.

![Figure 3.15. Ready-mix trucks lined up waiting their turn to discharge concrete in front of the paver.](image)

The crew should avoid stopping a slipform paving machine if at all possible – even if it means slowing the machine to a mere crawl. The operator and crew must understand that dips and bumps occur in the surface wherever the machine stops or slows significantly because of breakdowns or lack of concrete supply. It is helpful to record the location and time of any stops to help pinpoint surface problems and correlate the operational activities with smoothness results.

If problems arise and the supply of concrete is delayed, constant communication between the plant and the paving operation allows the slipform operator to match the paver speed to available concrete delivery. If the paver is slowed to match the delivery of concrete, reduction of the vibration frequency is also likely to be necessary to maintain consistent extrusion pressure. This will depend upon the vibration frequency and paving speed considered to be “normal” for the operation.
**Paver Maintenance** – Maintenance of the paving machine is extremely important. As a machine’s hours of operation increase, the components may stick and not move smoothly. This decreases the smoothness in superelevation transitions or any place where the hydraulic systems on the machine react to changing elevations or cross slope.

**Paver Operations** – During operation, the primary adjustment a slipform paving machine operator can make is to the machine’s speed and the frequency of its internal vibrators. If the concrete’s plastic properties vary widely, requiring frequent adjustments of the placing speed or vibration frequency, the result will be roughness in the surface.

**How the Pavement is Formed** – Slipform pavers operate by extruding the concrete into the shape of the slab. All slipform paving equipment contains molding components. These components consist of the “profile pan” or “forming plate” and the side forms. The subbase is the bottom of the mold. All of these elements confine the concrete and create the mold for its shape in the same manner that a caulking gun nozzle confines and defines the shape of the caulk bead.

### 3.5.1 Components of a Typical Slipform Paving Machine and Their Functions

**Overview** – Although specific design and operation details vary between slipform paving machines, the principle steps of slipforming a concrete pavement are (Figure 3.16):

1. The fresh concrete mixture is placed on the grade ahead of the slipform paving operations.

2. An auger or spreader plow distributes the fresh concrete uniformly across the width of the paving operation. A head of concrete will typically build in front of the auger as it distributes the concrete.

3. The volume of concrete passing into the side formed section of the paving machine is regulated by the strike off if one is included on the slipform paving machine.

4. The vibrators fluidize the concrete and the fluid concrete is contained by side forms.

5. The slipform mold constructs the final shape of the pavement cross section.
Augers/Plows – Augers, large horizontal screws in front of the paver (Figure 3.17), or plows traveling back and forth across the width of the paver (Figure 3.18) spread the concrete sideways to create uniform depth ahead of the pan. A uniform head of concrete (not too big and not too small) should be maintained. A large head of concrete can cause the paver to rise, creating a bump in the finished pavement. On the other hand, too little concrete can leave gaps at the edge of the pavement. If this happens, the paver may have to be stopped and the gaps filled.

Figure 3.17. On some slipform pavers, an auger spreads the concrete sideways to ensure even distribution across the entire width.

Figure 3.16. Components of a typical slipform paving machine. See ACPA’s, “Concrete Pavement Field Reference: Pre-Paving,” for a detailed discussion of each component.
**Vibrators** – Vibrators consolidate the concrete as it passes under the paver (Figure 3.19). If there is not enough vibration energy it may result in large pockets or voids in the concrete. Over-vibration may cause segregation of the mixture, which may in turn possibly result in variations in strength and consistency throughout the concrete slab. It can also cause loss of entrained air in the slab, which can reduce pavement life and durability. Typical vibrator spacing is anywhere from 12 to 24 in. (305 to 610 mm), with the specific spacing dependent on mixture design, paver speed, vibrator speed, and other factors.

Vibrator frequencies should not be increased to attempt to solve other mixture problems. The crew should watch the vibrators to identify a concrete mixture problem such as segregation. Some adjustment to vibrator frequency is helpful, but increasing the frequency will not overcome poor equipment set-up, poor alignment, or poor mixtures.

When operating at too high of a frequency, vibrators may cause undesirable results, such as loss of air entrainment or vibrator trails (Figure 3.20). Research has found that specified air contents and uniform air void distributions can be achieved by operating within the paving machine speeds of about 4 to 6 ft/min (1.2 to 1.8 m/min) and with vibrator frequencies from about 5,000 to 8,000 vibrations per minute.
Figure 3.19. Array of vibrators (and auger on left) underneath a slipform paver.

Figure 3.20. Vibrator trails evident on the surface of a concrete pavement.
(vpm), although some agencies have had success with minimum vibrator frequency specifications of about 7,500 vpm. Higher frequencies or paver speeds, or a combination of both, can result in discontinuities and a lack of desirable air content in the upper portion of the concrete pavement. This in turn provides a greater opportunity for water and ice-melting chemicals to enter the concrete and reduces the durability and life of the pavement. Experience shows that vibrator frequency might also need to be reduced if the paver speed falls below 3 ft/min (0.9 m/min).

Changes in the frequency of the vibrators and forward speed of the paver may influence the surface as follows:

- The combination of low frequency (5,000 vibrations per minute) and low paver speed 4 ft/min (1.2 m/min) may create the potential for open surfaces behind the paving machine if the consistency of the concrete varies.

- Higher frequency vibration (8,000 vibrations per minute) and consistency in concrete delivery to maintain a paving speed of 6 ft/min (1.8 m/min) usually results in a surface free of voids, requiring less hand finishing.

**Monitoring the Vibrators** – Vibrator monitoring systems are available to provide real-time readout of frequency for all of the vibrators on a slipform paving machine. These units improve the uniformity of paving through features such as:

- Alarm settings to alert the operator of high or low frequencies, or out-of-range frequencies.

- Ambient temperature and relative humidity readings.

- Programmable vibration frequency that self corrects to changes in the concrete mixture.

- Programmable paver speed settings for automatic reduction or increase of vibrator frequency with slowing or acceleration of the paving machine.

- Recording and downloading of vibration data.

**Slipform Mold (Profile Pan)** – The profile pan is located behind the augers and vibrators. It trims excess concrete (also called screeding or strikeoff) at the proper elevation and smooths the surface. It can be adjusted to trim a straight grade or construct superelevations (i.e., cross slope). The paver may include finishing equipment, such as oscillating screeds or floats (Figure 3.21).
Extrusion Pressure – In extrusion, pressure is necessary to force the material through the mold. In slipform paving, the mold is forced through concrete that remains static on the grade. However, the vibrators are essential to fluidize the concrete (lower face-to-face contact of particles) and make it easier to mold. The slipform paver can pass over fluidized concrete, its mass keeping the pan and side forms steady to confine and shape the material. Extrusion pressure is influenced by:

- Weight of the machine.
- Taper of side forms relative to the desired pavement edge planes (width and height of edge overbuild).
- Angle of the profile pan relative to the desired pavement surface plane.
- Vibrator power and frequency.
- Paver speed.
- Head of concrete (use of augers).
- Concrete consistency.

3.5.2 Continuous Operations

Overview – Even when the subgrade/subbase provides a uniform support for paving operations, when all materials flow to the paving operation in a consistent and uniform fashion, and all other aspects of the slipform paving process go according to plan, continuous operation of the slipform paver is still the final key to constructing a uniform and smooth pavement. Unlike fixed form paving where the finishing procedures can back track a short distance to provide some consistency across a necessary stop in the paving operations, slipform pavers cannot. Thus, any problem that might result in a halting of forward motion of the slipform paver (e.g., equipment breakdown, disruption in the timing of delivery of the fresh concrete, a shortage of embedded steel or curing compound, etc.), results in a location where a break must form in the continuity of the pavement surface, which increases the likelihood of roughness in the final product.
All Activities Affect Operations – Every activity that leads up to the final slipping of the concrete pavement, including the slipform paving itself, that is discussed in this document could potentially have some bearing on the likelihood of a disruption in continuous operations. Thus, this section is not meant to serve as a note to achieving continuous operation of the slipform paver but, rather, as a reminder that all activities leading up to the final forming of the concrete pavement are interrelated and equally important and no detail should be overlooked.

3.5.3 Thickness Verification

Verification During Construction – Thickness typically is verified for slipform paving by using the probe method. Probing typically is conducted by randomly selecting a longitudinal location along the pavement and inserting a measuring probe at two transversely adjacent points per lane. Depending on the subbase below, metal plates might be secured to the grade at these locations ahead of the paving operations to provide a base for the bottom of the pavement; this might be necessary when paving on an unstabilized or very open-graded subbase but typically is not necessary when paving on a typical asphalt-treated, cement-treated or lean concrete subbase. The measuring probe typically has a locking device to serve as a constant gauge for measurement. This form of thickness verification typically is conducted by the inspector at least once per half-day of paving and may be done more frequently by the paving crew to ensure thickness down the grade.

Post-Construction Verification – If required for acceptance, coring might also be necessary after the concrete has hardened to ensure that the concrete pavement was constructed at the proper thickness. Depending on the subbase material, this method sometimes is challenging because of difficulty in establishing where the slab and subbase meet, particularly when they are bonded.

3.5.4 Finishing

Overview – Immediately after the paving equipment passes, the surface is normally finished to close holes and create a tight surface. Crews standing along the slab edge run finishing tools (floats and straightedges) across the surface.

Finishing is critical because of its effects on the durability of the concrete surface. Proper finishing involves skill, knowledge, and experience to deal with various concrete mixtures and field conditions. Having the proper equipment and manpower available is also essential for a successful project. A large factor in the finishing operation is timing. Delays in any part of the concrete hauling or placement can disrupt the flow of the entire construction operation.
**Hand and Mechanical Finishing** – Hand finishing of the pavement surface using bull floats is only necessary where the surface left from the paving equipment contains voids or excessive imperfections. Overuse of mechanical longitudinal floats directly behind the screed or slipform equipment may be detrimental to long-term durability and smoothness of the surface. In general, it is best to limit the amount of hand and mechanical finishing. If longitudinal floating is the only method to produce an acceptably “closed” surface, this is an indication that some corrections are needed for the concrete mixture and/or paving equipment or processes. The agency and contractor should review and adjust their design and operations to improve the results achieved by the paving machine alone.

**Using a Straightedge** – Checking the surface behind the paving equipment with a 10- to 20-ft (3- to 6-m) hand-operated straightedge is a recommended procedure (Figure 3.22); the straightedge can be used to smooth out the surface but not to move the concrete. Successive straight edging should overlap by one-half the length of the straightedge to ensure that the tool removes local high spots and fills local low spots in the surface. Experienced finishers can use the straightedge to remove or reduce noticeable bumps by employing a scraping motion.

![Figure 3.22. Scraping and smoothing with a 20-ft (6.1-m) straightedge.](image)

**Overfinishing** – Overfinishing or excessive finishing can be reduced or prevented by selecting a workable concrete mixture designed for the placement method and/or properly consolidating and striking off the concrete.
Workability/Finishability Issues – If the concrete is not workable/finishable, crews tend to overwork the surface or add water in an effort to close the surface. However, both overfinishing and adding water can lead to a weak surface layer and eventual surface scaling caused by freeze-thaw damage. If workability/finishability issues arise, notify the project manager so the concrete mixture and/or the paver can be adjusted for better concrete workability. Other problems often associated with finishing are surface chatter and edge slump.

Water should not be sprayed on the surface as a finishing aid; adding and finishing additional water into the surface will increase the water to cementitious materials ratio at the surface, which may impact long-term durability. If some additional moisture is necessary to aid in finishing, add it by fogging, not spraying, over the surface. Problems closing up the surface are usually indicative of the fine to coarse aggregate ratio or paste volume being too low or the vibration/consolidation method needing adjustment. Bubbles on the surface of the slab usually indicate overworking the surface too soon after strikeoff; floating should begin after most of the bleed water has evaporated.

If the surface tears or pulls during the finishing operation, the screed or bull floating operation may be starting too soon or too late, or the concrete mixture may be oversanded or contain an excessive amount of fine sand. Other possible causes are low-slump (dry) concrete, under-vibration, or the inclusion of supplementary cementitious materials.

Surface Chatter – Methods to avoid chatter in the surface of concrete pavement have been established by experience contractors. Chatter is defined as bumps and dips with a wavelength of no more than about 8 ft (2.5 m) and an amplitude of as much as 0.2 in. (5 mm). This type of roughness is not often detected by profile measuring equipment that employs a 0.2-in. (5-mm) blanking band.

Sources attributed to creating surface chatter in a slipform paving operation include:

1. Reinforcement ripple from bars embedded in the pavement.
2. Pulsations in the hydraulic system of the slipform paving equipment. The pulsations cause a physical cycling of the equipment that result in small wavelength surface chatter.
3. Use of automatic floating equipment that leaves a 0.04 to 0.08 in. (1 to 2 mm) trace of grout on the surface.
4. Sagging of the stringline between stakes.
5. Improperly adjusted dampening of the elevation sensor on the paving machine.
6. Uneven pressure on the transverse tining rake, if used for texturing, causing one side of the rake to impart deeper striations than the other.
Common solutions for surface chatter include:

1. Careful control of the set-up and operation of equipment,
2. Monitoring of the stringlines, particularly tensioning with changes in weather conditions (temperature), and
3. Checking the surface behind the paving equipment with a straightedge. For more details on straightedges, see earlier portions of this “Finishing” section.

**Edge Slump** – Edge slump occurs when the top edge of a freshly-placed, slip-formed concrete pavement sags down after the slab is extruded. A small amount of edge slump is usually acceptable when the longitudinal joint will have some traffic moving across it. When the slab edge forms the absolute extent of the pavement, a larger amount of edge slump is acceptable.

The factors that affect edge slump are:

- Concrete consistency.
- Concrete mixture compatibility with placement techniques.
- Paver adjustments and operation.
- Excessive finishing.

In general, most agencies specify 1⁄4 in. (6 mm) of edge slump in the outer 6 to 12 in. (150 to 300 mm) of the slab edge as the trigger for corrective action. This usually involves the finishers behind the paver re-working the edge to remove the irregularity. However, continual correction of excessive edge slump in fresh concrete can lead to unacceptable levels of joint spalling in the finished concrete. If such a problem develops, paving should be stopped and measures determined to correct excessive edge slump.

In most cases, edge slump can be corrected immediately behind the paver. Either the mixture’s consistency is adjusted to prevent recurrence, or the paving pan is adjusted to account for the sloughing. If the edge slump is not detected in time, it may require patching and/or diamond grinding to correct the irregularity. The effect of a larger edge slump left in place is generally not known because most specifications require immediate correction of anything greater than 1⁄4 in. (6 mm).

Edge slump is generally more common in thicker pavements, which have to stand higher, and are therefore more susceptible. The most common form of edge slump is when the top edge slumps down (Figure 3.23). The bottom edge slumping out usually indicates a more serious problem with the mixture design, and is often associated with higher slump mixtures that are not intended for slipform paving. When this type of edge slump occurs, paving should be suspended until the concrete mixture has been modified to work more effectively with slipform paving.
3.5.5 Resuming Paving at a Header

**Overview** – To resume paving at a header, the forms must first be removed for a formed header (see Figure 5.15) or the excess concrete must be removed and any necessary dowel bars or tiebars installed for a saw-back header (see Figures 5.16 and 5.17). Once the header is prepared, the slipform paving machine is typically backed against or slightly over the existing pavement and typical slipform paving operations will resume.

3.5.6 Paving on Steep Grades

**Potential Adjustments** – It may be more difficult to construct a pavement with a smooth surface on grades exceeding 3% than on flatter grades. There is no known difference in the final grade of the pavement when using the proper paving mixture and paving uphill or downhill, but for steep grades, it may be necessary to make one or more of the following adjustments:

1. Decrease the slump if it exceeds 1.0 in. (25 mm). The need to make this adjustment depends upon whether or not it is difficult to maintain a uniform head of concrete in front of the paver.

2. Adjust the profile pan attitude, draft, or angle of attack. On flat grades and if stringlines are used, most operators position the profile pan as close to parallel with the stringline as possible but a draft might be necessary when constructing on a steep grade.
3. Adjust the profile pan elevation. When paving up a steeper grade, the pan elevation may be adjusted to about 1.0 in. (25 mm) below the surface grade. When paving down a steeper slope the pan may be adjusted to about 1.0 in. (25 mm) above the surface grade. This adjustment must be made carefully to avoid reinforcement ripple, particularly spring-back of embedded dowel baskets.

4. Adjust the staking interval. When paving on grades for vertical curves, the stringline, if used, is set on chords and the paving elevation is on a semi-chord. Closely follow grade and staking calculations for these circumstances to reduce the semi-chord effect enough to produce a smooth surface. The semi-chord effect is perceived to be worse on sag vertical curves than on crest vertical curves.

5. Use stringless paving grade control to remove the chord effect that introduces roughness to paving on steep grades and tight vertical curves.

3.6 Paving in Inclement Weather

Overview – Although it might be possible to constrain paving operations to only the most ideal ambient conditions, this is not a practical option in most regions, and contractors must be capable of paving during inclement weather (e.g., excessively cold or hot weather, or during threat of a rain event). The unpredictable nature of weather, coupled with stringent construction schedules required of paving contractors by their agency clients, means that encountering adverse conditions are a reality from time to time. With proper consideration for the precautions and means to mitigate associated challenges, however, most inclement weather can have little, if any, effect on the progression of paving and the final quality of a concrete pavement.

3.6.1 Cold Weather Paving

Defining Cold Weather – Any concrete paving operations conducted when the air temperature is 50°F (10°C) or less for more than half of any 24-hour period, or when the average daily air temperature is less than 40°F (5°C) for three consecutive days, are considered cold weather paving.

Potential Problems – During cold weather, cement hydration slows, slowing concrete strength development. Concrete cools faster at the surface than inside the slab, causing stresses in the slab. If the stresses are severe enough, the slab will crack randomly.

Mitigating Steps – Here are some precautions/requirements for cold weather paving:
- Do not pave on frozen subgrade; for smaller paving areas, the subgrade might be kept warm through the use of temperature-controlled heating/curing blankets.
- Do not use aggregates with frozen lumps.
- Heat materials to raise concrete temperature and promote hydration.
- Consider using a higher portland cement content to help the concrete gain strength in adequate time or, alternatively, minimize the use of supplementary cementitious materials (e.g., amount of fly ash and slag cement) if they are not included in the mixture for their potential long-term performance benefits because these materials have a slower strength gain than portland cement.
- Use a non-chloride accelerating admixture conforming to ASTM C494 Type C or E, provided its performance has been previously verified by trial batches.
- Do not pave if the concrete cannot reach adequate strength before it freezes.
- For the first two to three days after placement, protect concrete from freezing with insulating material such as insulating curing blankets (see section titled, “Insulating Blankets”), single or double layers of polyethylene, temperature-controlled heating/curing blankets, or a layer of dry, loose straw or hay between two layers of polyethylene. Allow the slabs to cool completely before removing insulating blankets to avoid a thermal shock that might induce contraction cracking. To saw contraction joints, temporarily roll insulating blankets aside and replace them after joint sawing.

**Verify Strength Gain** – If it is known that the strength gain will be slowed down, verify the in-place concrete strength and delay sawing operations and opening to traffic if necessary.

### 3.6.2 Hot Weather Paving

**Defining Hot Weather** – Any concrete paving operations conducted when the air temperatures are above 90°F (32°C), there is a low relative humidity, wind speeds are high, and/or solar radiation is high (e.g., it is very sunny) are considered hot weather paving.

**Potential Problems** – Hot weather concrete paving presents many challenges, including:

- Concrete loses moisture more rapidly during hauling and placing.
- Aggregate stockpiles dry out, affecting moisture consistency between batches.
- The pavement subgrade/subbase dries out before the mixture is placed, and then absorbs water from the mixture.
- Asphalt or other dark surfaced stabilized subbases or overlay interlayers may become very hot and transfer heat to the bottom of freshly placed concrete causing uneven hydration.

- Rapid water evaporation at the pavement surface can result in shrinkage cracks.

- It is more difficult to entrain air when temperatures are high. Entrained air is important for pavement durability.

- Concrete sets more rapidly, perhaps twice as fast, making finishing more difficult.

- Sawing operations must proceed more rapidly. Additional saws may be required.

**Mitigating Steps** – Some precautions for hot weather paving are:

- If possible, do not pave in very hot, dry weather.

- Pave in the morning, evening, or night (see section titled, "Night Paving") when air temperatures are cooler.

- Maintain uniform moisture in stockpiles.

- Use retarding admixtures in the mixture to slow hydration.

- Use Class F fly ash and/or slag cement in the mixture. These materials hydrate more slowly and generate lower heats of hydration than portland cement, reducing tendencies toward slump loss, premature stiffening, and thermal cracking.

- Increase the dosage of air-entraining admixture. Better or longer mixing may allow maintenance of a constant air void spacing factor without a greater air content. Use of additional water reducer may also be helpful.

- Keep the subgrade/subbase, forms, and equipment damp and cool.

- Use whitewash or white-pigmented curing compound to paint dark-colored subbase or interlayer surfaces white, which will reflect sunlight and reduce heat absorption.

- Apply curing compound to the new pavement slab surface and edges as soon as possible. Additional compound may be required.

- Utilize temporary sunshades and/or windbreaks to reduce the impacts of ambient temperature and wind.

### 3.6.3 Rained on Pavements

**Rainy Conditions Might Not Be Bad** – Ironically, climatic conditions during a rain event can be conducive to concrete curing. During rain, the relative humidity is at or near 100% and, thus, there is little chance for evaporation of mixture water. Temperatures generally are very moderate during rain, which is also beneficial. In these situations, the rain essentially provides a beneficial “moist” curing environ-
ment, which assists with strength development and decreases the chance for uncontrolled cracking. However, any additional water on the pavement surface before the material has set and/or been properly finished will elevate the surface water-cementitious materials ratio, potentially reducing durability.

**Rain Damage** – Before final set, rain can damage the new pavement surface by leaving imprints or washing away paste at the surface. After final set, rain can induce rapid cooling at the surface, leading to rapid development of thermal restraint stresses and possibly early-age, uncontrolled cracking.

**Protection with Plastic Sheeting** – Have plastic sheeting and steel side forms or wooden boards available at all times to protect the surface and edges of the newly placed concrete pavement when it rains (Figure 3.24). If rain is expected on newly placed concrete pavement that has not set/hardened, cover the surface with plastic sheeting. The sheets must be weighted down to prevent them from blowing in the wind. When it starts raining, a “rule of thumb” to determine how much of the pavement to cover is to go back to the point where the rain is not indenting the pavement surface. The covering does not need to be extended to areas where the rain is only washing the curing membrane from the pavement without indenting the surface.

![Figure 3.24. Plastic sheeting ready for placement to protect the fresh surface from rain.](image)

**Surface Marring from Plastic Sheeting** – Some marring of the concrete surface may occur from the plastic sheeting used to protect the slabs from rain (Figure 3.25). Except for an undesirable appearance, there is nothing wrong with surfaces affected by plastic sheeting. A similar appearance can occur when using plastic sheeting to cure concrete.
**Finishing the Concrete during Rain** – Do not finish rainwater into the concrete surface. This elevates the water-cementitious materials ratio, creating a non-durable top surface, susceptible to crazing, scaling, and dusting (Figure 3.26).

*Figure 3.25. Marring of the pavement surface due to plastic sheeting. Does not require remediation unless ride quality or skid resistance is unduly affected.*

*Figure 3.26. Typical scaling of concrete pavement due to non-durable paste on surface.*
**Mitigating Steps** – For slipform paving operations, it is advantageous to install forms where severe erosion of the fresh concrete edge occurs. After the forms are set, place fresh concrete and finish prior to texturing and curing.

If it starts to rain during operations, take the following actions:

- Stop batching and placing operations and cover the fresh concrete immediately with protective coverings like polyethylene sheeting or burlap. (Do not try to remove extra surface water first. Do not add dry portland cement to the surface.)
- As soon as the surface has dried, texture and apply curing membrane.

If the rain is extremely hard and occurs soon after concrete placement, such that the surface mortar is seriously damaged, it is likely that the rain has increased the water-cementitious materials ratio near the surface (within about 0.25 in. [6 mm]). If the surface layer is adversely affected, corrective action is necessary – the affected surface should be diamond-ground.

**Repairing Rained on Pavements** – The primary method to repair a rain-damaged surface is diamond grinding (see ACPA’s, “Concrete Pavement Field Reference: Preservation and Repair”). Areas where water diluted the surface paste should be ground to remove the weak surface layer. As long as minimum thickness requirements are still met after grinding, no structural deficiencies are introduced by this corrective measure. Grinding can commence when the pavement has reached the strength specified for opening to construction traffic.

The only instance requiring repair other than diamond grinding for a rained-on pavement is when severely eroded edges cannot be corrected prior to the concrete hardening (Figure 3.27). Where pavement lanes, concrete shoulders, or curb and gutter are to be constructed adjacent to the eroded edges, a new existing edge can be created by making a full-depth saw cut parallel to the planned pavement edge and a sufficient distance in from the edge to remove all unsatisfactory concrete. Where there is no adjacent concrete section, it may be necessary to remove all or a portion of a lane and reconstruct it. If a portion of a lane width is to be removed, make a full-depth saw cut parallel to the planned edge and a minimum of 2 ft (0.6 m) from it, while keeping in mind the location of any embedded steel (e.g., dowel bars). Drill holes and install tiebars using an expanding grout or epoxy to tie new lanes to the existing lane(s).
Conduct Petrographic Examination before Removing/Replacing – A petrographic examination of cores taken from the pavement is usually not necessary for rained-on pavement situations, but it does provide helpful information to determine the extent of the damage. A petrographer can indicate how deep any damage extends and provide recommendations for effective repair, such as diamond grinding. Before considering removal and replacement of rain-damaged pavement, it is advisable to send a few cores to an experienced petrographer for analysis of the concrete’s water-cementitious materials ratio, air content, air-void spacing factor, and general appearance using ASTM C856.

If a general petrographic evaluation does not answer all of the questions on the concrete’s durability, consider a more detailed analysis of the air-void system using ASTM C457. Surface scaling tests can also be conducted in accordance with ASTM C672. Rain damaged concrete needs to be removed only if it has been determined to be non-durable in terms of abrasion, skid resistance, or freezing and thawing.

### 3.7 Night Paving

**Why Pave at Night** – Concrete pavements might be constructed at night for reasons including:

- As a mitigation step during hot weather.
- To minimize traffic congestion.
- To maximize production rates (e.g., some large projects might include night paving to ensure that a concrete producer has enough trucks to accommodate
the paving operations or so that haul trucks do not have as much traffic congestion to navigate through).

- To increase production rates to complete the project on time (e.g., due to delays) or early.

**Precautions** – Common precautions employed during night paving include:

- Frequent safety meetings to ensure employee awareness of work zone safety.
- Special attention given to traffic control devices such as the work zone’s cones and/or barricades, flaggers, police cars, pilot cars, etc.
- The use of ample lighting (Figure 3.28), while ensuring that no lighting devices shine directly towards traffic.
- Subscription to a weather service; although paving contractors are accustomed to watching the sky for signs of inclement weather, darkness precludes this.
- Construction/maintenance of haul roads during daylight because it is difficult to do so at night.

![Figure 3.28. Nighttime paving operation with ample light being provided.](image)

**Communication is Key** – As with daytime paving operations, communication is key to trouble-free paving operations. Frequent exchanges of ideas and work schedules (e.g., if the night paving will begin on Sunday or Monday night) between the owner and contractor, and throughout all levels of the contractor’s workforce, helps mitigate problems during nighttime paving. Sometimes shifts are intentionally overlapped to keep communication problems to a minimum on the jobsite. Although visitors are less frequent during nighttime paving, any visitor making the effort to visit a night paving operation might require assistance to safely get onto and off of the project, so procedures should be in place (and well communicated) for such an occurrence before construction begins. When paving in an urban area, communicate the reasons for paving at night and when the project is expected to be finished to any local business or residents.
**Special Consideration for Sawing** – Because joints typically are not sawed into pavement constructed during the night until the next morning/afternoon, the likelihood of uncontrolled cracking might increase due to the ambient conditions the day after paving. Initial curing methods such as the application of evaporation retarders or fogging/misting might be necessary to minimize the likelihood of uncontrolled cracking (see the section titled, “Initial Cure”).
CHAPTER 4
Texturing and Curing

Key Points:

- The effectiveness of a texture application is dependent on the timing of texturing relative to concrete hardening and the amount of downward pressure on the texturing tool.

- Regardless of the texturing technique used, the texturing process should be closely monitored so that a uniform texture is produced both across the pavement width and along the grade.

- The importance of curing cannot be overemphasized; proper curing (initial and/or final curing) is crucial to the prevention of plastic, thermal, and drying shrinkage cracks, proper strength development and adequate durability.

- When applying a white-pigmented curing compound, the curing compound should be applied such that the surface of the pavement is uniformly as white as a sheet of paper.

4.1 Texturing

Overview – Various tools or materials may be dragged across fresh concrete to produce a surface texture. Available tools and materials include moistened burlap, brooms, tining rakes, and artificial turf. Each tool produces a unique texture that is distinct in its skid resistance, friction, and noise generation. Drag textures, such as burlap and broom, are adequate for low-speed facilities, with design speed less than 45 mph (72 km/h). More aggressive textures such as turf drag and tining typically are adequate for higher-speed facilities such as freeways and Interstate highways.

Texture Variability – The following items are known to influence variability in textures:

- Consistency of concrete properties.
- Time of texturing related to concrete placement and hardening.
Presence of bleed water on the fresh concrete surface.
Total pressure on texturing tools.
Evenness of the tool on the surface.
Angle of tines, if used, to the surface.
Cleanliness of burlap, turf, or tines.

**Texture Depth and Timing** – The average (mean) texture depth primarily depends upon the pressure applied to the texturing tool and the time at which it is applied (relative to when the concrete was first placed and finished). Therefore, it is important to determine the optimum time to begin texturing to achieve the desired depth, and then consistently apply the texture at that time after placement. It is preferred to conduct texturing sooner rather than later, so that curing can be applied early. Drag textures that are longitudinal in nature help the curing operation stay closer to the paving operation because they are applied faster and do not require an incremental process, such as with a transverse texture.

The amount of down pressure applied to the tool or material can also be adjusted. Drag textures such as burlap drag and artificial turf drag can be weighted down to improve texture depth by piling sand or rock on the material used (Figure 4.1).

![Figure 4.1. Artificial turf drag texturing rig, weighted with sand.](image)

The amount of down pressure applied to tining rakes also is important (Figure 4.2). The depth of the grooves in the concrete will affect not only skid resistance during rainfall events, but will also affect tire/pavement noise generation. Shallower textures will generate less noise.
Impact of Texture on Pavement Roughness – The surface texture should not influence the roughness of the pavement. Vehicle tires bridge the relatively small striations mechanically imparted into a concrete pavement surface. However, in at least one case, transverse tining equipment was determined to have contributed to surface roughness. In this rare case, the rake on the tining machine was adjusted poorly and did not run over the surface evenly. Individual tines were deeper at one side of the rake than the other, inducing chatter detected on a California profiograph trace of the surface.

4.1.1 Methods

The following is a brief summary of each common texture.

Burlap Drag – Created by dragging moistened, coarse burlap across the surface of a plastic concrete pavement surface to create a shallow longitudinal texture (typically 0.008 in. [0.2 mm] deep) (Figure 4.3). The texture depth varies with burlap coarseness, concrete mixture design characteristics, and finishing conditions. Burlap drag textures are constructed easily and inexpensively and are relatively quiet, but may not provide adequate wet weather friction at high speeds unless combined with other features.
Broom (Transverse and Longitudinal) – Created by dragging a hand broom or mechanical broom, either transversely or longitudinally, along the plastic concrete pavement surface to create shallow surface ridges (typically 0.008 to 0.012 in. [0.2 to 0.3 mm] deep). Like burlap drag, broomed surface textures are constructed easily and inexpensively and are relatively quiet, but may not provide adequate wet weather friction at high speeds unless combined with other features.

Tining – Created by drawing a tining head along the plastic concrete pavement surface to create relatively deep textures (typically up to 0.24 in. (6 mm) deep). Due to the depth of the grooves and the improved wet weather friction, longitudinal tining (Figure 4.4) currently is the most commonly recommended texture for higher-speed (50 mph [80 km/h] or greater) concrete pavements in the U.S. Longitudinally tined surfaces generally report lower overall noise levels and comparable wet weather friction characteristics as transversely tined textures.
Artificial Turf Drag – Created by dragging an inverted section of artificial turf along the plastic concrete pavement surface. Early versions of this process produced textures that were similar to those produced by burlap drag and longitudinal brooming, with typical texture depths of 0.03 to 0.04 in. (0.7 to 1.0 mm). As these early artificial drag textures were similar to burlap drag and longitudinal broomed surfaces, they were also constructed easily and inexpensively and are relatively quiet, but there were again concerns about wet weather friction at high speeds.
Developments in the 1990’s resulted in modified artificial turf drag techniques that produce a much deeper (typically 0.04 in. [1.0 mm] or more in depth) and more durable texture. Due to the ability to more reliably obtain a desirable texture depth with the modified techniques, artificial turf drag textures are now being used on many higher-speed (50 mph [80 km/h] or greater) concrete pavements in the U.S.

**Diamond Grinding (Post-Curing)** – Diamond grinding removes a thin layer of hardened concrete pavement surface (usually 0.1 to 0.8 in. [3 to 20 mm] in depth) using closely spaced diamond saw blades mounted side-by-side on a rotating shaft. This surface texturing technique is recognized as a highly effective means to improve pavement profile and ride quality, and to restore surface friction and reduce tire-pavement noise in existing concrete pavements. Although typically used as a preservation technique, diamond grinding occasionally has been used on newly constructed concrete pavements since it was first done so on a military base runway in Arizona in 1956. Such tactics might be employed in current new construction if the concrete pavement is constructed in stages and/or if it proves economical to diamond grind an entire project upon completion to ensure compliance with smoothness specifications.

**Additional Details on the Texturing Methods** – More details on the characteristics of the various surface texture types are available in ACPA’s, “Pavement Surface Characteristics: A Synthesis and Guide” and more details on diamond grinding, a means to establish (as part of new pavement construction) or re-establish (as part of a pavement preservation) a desired surface texture into the surface of an already hardened concrete pavement, can be found in ACPA’s, “Concrete Pavement Field Reference: Preservation and Repair.”

### 4.2 Curing

**Overview** – Curing is defined as the maintenance of a satisfactory moisture content and temperature in concrete during some definite period immediately following placing and finishing so that the desired properties may develop. Thus, the objectives of curing are to prevent (or replenish) the loss the moisture and to maintain a favorable temperature for a predefined period of time.

**Importance of Curing** – The importance of managing moisture in concrete immediately after placement cannot be overemphasized. Concrete moisture is managed through proper curing procedures. This is typically accomplished by applying curing compound uniformly to the entire surface and exposed edges of the concrete to slow the evaporation of water from the concrete, but other forms of curing also might be necessary depending on the concrete mixture characteristics and the ambient conditions.
Curing preserves water for hydration, maximizing pavement strength and durability. It also helps prevent the surface from drying out more quickly than the rest of the slab, reducing the possibility of surface damage due to differential shrinkage. (The appearance of small plastic shrinkage cracks on the concrete surface is a sign that moisture has evaporated too quickly.)

4.2.1 Methods

Curing Categories and Methods – The types of curing methods that are typical to concrete pavements fall into two broad categories: initial cure and final cure. Initial curing procedures might be employed when evaporation rates are very high, such as in very dry and/or windy conditions. Procedures that are considered initial cures are the application of evaporation retarders and misting/fogging of the plastic surface. Final curing procedures are what are considered traditional curing procedures such as application of a membrane forming curing compound, the use of insulating blankets, or placement of wet burlap, impervious paper, or plastic sheets on the pavement surface.

Initial Cure – The initial curing period is the window between when the concrete pavement has been placed and when final curing procedures may be applied (typically after evaporation of the bleed water). Final curing procedures typically cannot be applied during the initial curing period because one or more of the concrete material properties inhibits their application (e.g., concrete material has not set enough to resist damage of the pavement due to placement of a wet burlap sheet on the surface). The purpose of initial curing is to control evaporation of bleed water, thus preventing plastic shrinkage cracking. Thus, initial curing procedures typically are only necessary when evaporation rates are very high.

Evaporation Retarders – These materials are water-based, spray-on liquid that form a monomolecular film over the plastic concrete surface. Evaporation retarders may be applied before or during bleed water evaporation and they will not retard the setting characteristics of the concrete, but they will minimize the amount of water loss in the concrete due to evaporation. They are useful in very dry or windy conditions, when evaporation rates are high.

Evaporation retarders should not be used as finishing aids because they elevate the water-cementitious materials ratio at the surface as they are worked into the surface of the concrete. This may lead to lower strengths at the surface, poor air content or air-void structure, and nondurable surface mortar.

Because evaporation retarders do not effectively seal the surface of the concrete pavement, a curing compound (or other curing method) must still be applied.
**Fogging/Misting** – The application of water in the form of fogging or misting of the surface to prevent excessive loss of bleed water generally is acceptable by most regulatory agencies but caution must be warranted so as to not over-water the surface, which may lead to lower strength at the surface, poor air content or air-void structure, and nondurable surface mortar. The proper application rate of a fogging or misting procedure is heavily dependent on the evaporation rate, which is dependent on the ambient air temperature and relative humidity, the concrete temperature, and the wind velocity.

**Final Cure** – The final curing period is the window between application of a final curing procedure(s) and the cessation of any scheduled curing procedures. The purpose of final curing procedures is to ensure that the water that is necessary for proper hydration is retained, preventing drying shrinkage, and/or that temperature is controlled to foster proper hydration, preventing excessive early-age thermal gradients.

**Membrane-Forming Curing Compound** – By far the most common concrete pavement curing procedure in the U.S., this involves the application(s) of a liquid-membrane-forming compound to the concrete surface. For curing compound to be of benefit, it should be applied as soon as possible after the water sheen has left the surface and texturing is complete. If the curing regiment is inadequate or applied too late, the concrete is susceptible to plastic shrinkage cracking, excessive curl, and scaling.

The initial application of curing compound should coat both the top and edges of slipformed concrete (Figure 4.5). For fixed form paving, the curing compound should initially coat the exposed concrete surface. A second application is necessary to any exposed vertical edges of the slab after the forms are removed to provide a complete seal. Timely application is important; curing compound should be applied as the water sheen is disappearing on the surface. In some circumstances it may be difficult to detect, particularly where a stiff mixture is being employed for slipform construction. In these cases it is recommended that a maximum timeframe be established by the paving crew to coordinate and control the curing application in relation to placement.
Membrane forming curing compounds should be applied by hand-operated or power-driven spray equipment immediately after final finishing of the concrete. Hand operated equipment should only be used for small areas. On dry, windy days, or during periods when adverse weather conditions could result in plastic shrinkage cracking, application of an evaporation retarder immediately after final finishing and before all free water on the surface has evaporated will help prevent the formation of cracks (see the “Initial Cure” section for more on evaporation retarders). Power-driven spray equipment is recommended for uniform application of curing compounds on large paving projects. Spray nozzles and windshields on such equipment should be arranged to prevent wind-blown loss of curing compound. Regardless of which method is used, ensure that all spraying nozzles are clean and well maintained to ensure proper distribution of the curing compound.

Normally only one smooth, even coat is applied. If two coats are necessary to ensure complete coverage, the second coat should be applied at right angles to the first as soon as the first coat becomes tacky. Complete coverage of the surface must be attained because even small pinholes in the membrane will increase the evaporation of moisture from the concrete. Curing compounds might prevent bonding between hardened concrete and a freshly placed concrete overlay. Consequently, they should either be tested for compatibility, or not used when a bonded overlay is used.
White pigmentation in the compound is preferable to a clear compound because the amount of coverage is easy to see; when the surface is adequately covered, it should appear as white as a sheet of paper. The pigment also reflects solar radiation that may otherwise heat the concrete surface undesirably.

When properly applied, curing compounds limit the evaporation to about 20 percent of unprotected concrete. A liquid-membrane-forming compound that meets ASTM C309/AASHTO M148 or ASTM C1315 material requirements is adequate for most situations when applied at the following rates:

- 200 ft²/gal (5.0 m²/L) for normal paving applications.
- 150 ft²/gal (3.75 m²/L) for fast-track concrete.
- 100 ft²/gal (2.5 m²/L) for thin overlays.

Under most curing conditions, a white-pigmented Type 2/Class A curing compound will suffice but a Type 2/Class B curing compound might also be used under very harsh or arid conditions.

Recommendations for curing compound application include:

- Apply liquid curing compounds using spray equipment mounted on a self-propelled frame that spans the paving lane.
- Limit hand-held sprayers for curing application on small areas.
- Even though a visual check is feasible with white-pigmented curing compound, measure the volume on a given area and compare it to the specified or recommended application rate. Although no standard application rate test exist, some testing methods such as California Test 535, “Method of Test for Determining Application Rate of Concrete Curing Compound in the Field,” are available.
- Apply curing compound to all exposed faces (Figure 4.6) of the concrete after slipforming or after forms are removed.
- When moist curing, maintain the moist condition over the entire concrete surface for the entire curing period (typically seven days) or until a curing compound is applied.
Insulating Blankets – Meant to reduce the loss of hydration heat to aid in proper strength development, insulating blankets (Figure 4.7) shield the concrete pavement from relatively low air temperatures, preventing excessive thermal gradients from potentially causing early-age cracking. Because they do not seal the surface of the concrete pavement to prevent moisture loss, insulating blankets should only be placed on the pavement surface after another curing procedure seals the surface (such as the application of a curing compound). Insulating blankets might also be used to prevent thermal cracking at early-ages due to solar radiation; if a pavement becomes excessively cool overnight and the sun’s energy causes the surface to become extremely warm relative to the subbase then extreme thermal gradients might develop at early-ages.

Experience indicates that an insulating blanket with a minimum thermal resistance (R) rating of 0.5 hr ft² °F/Btu (0.035 m² °K/W) is adequate for most conditions. The blanket should consist of a layer of closed-cell polystyrene foam with another protective layer of plastic film. See Table 4.1 for recommendations on when insulating blankets might be used as part of final curing procedures. Additional blankets may be necessary for placement temperatures below about 40°F (4°C).
Other Curing Covers (Plastic Sheets, Wet Burlap, etc.) – Various other final curing procedures might be used to prevent moisture loss. These include the application of plastic sheets, wet burlap, and impervious paper. The effectiveness of each of these curing methods is greatly dependent on the time of application. In the case of wet burlap, it might also be necessary to occasionally rewet the surface of the burlap to ensure that excessive moisture loss does not occur.

Additional Details on the Curing Methods – More details on curing procedures are available in the FHWA’s “Guide for Curing of Portland Cement Concrete Pavements.”
CHAPTER 5
Jointing

Key Points:
- Proper location, sawcut timing, and sawcut depth are critical to preventing uncontrolled cracking in concrete pavements.
- It is essential that the location of dowel bars be clearly marked on the grade during paving operations to aid in proper location of transverse joints.
- Early-entry sawing methods require a lesser sawcut depth than conventional sawing methods.
- If sealing joints, proper construction and preparation of the sealant reservoir is crucial to sealant performance.
- Headers and other specialty joints require special attention during construction.

5.1 Sawcut Joints

Purpose of Sawing Joints – Joints help relieve stresses in concrete pavements in a controlled fashion. An effective, well-constructed pattern of joints allows concrete to crack at predetermined locations, prevents random cracking and other potential problems, and enhances pavement performance. Because the aim of this publication is to focus on construction related details of jointing, please refer to ACPA’s, “Concrete Pavement Field Reference: Pre-Paving,” for details on joint types and joint layout procedures.

5.1.1 Sawcut Window

What Creates the Sawcut Window – There is a brief period of time – the “sawing window” – during which joints can be sawed successfully. This window is primarily related to the strength of the concrete, but it is affected by many factors. Concrete will start to gain compressive strength almost immediately after being placed; even before a significant amount of cementitious material has hydrated, there is already some interlocking of the aggregate to provide some strength. Internal stresses
(those that may induce cracks), however, will not start to build up in the pavement until the cementitious materials have hydrated enough that the concrete can start to withstand a tensile force. As the pavement starts to dry out or cool off, internal stresses build because the pavement wants to shrink but it is restrained due to friction with the subbase, and the continuity of the unsawed pavement. If sawing does not occur in time, the internal stresses might surpass the concrete strength, resulting in a random crack wherever the tensile stresses are highest. This defines the end of the sawing window. The other extreme, the beginning of the sawing window, occurs when the concrete strength is at the minimum level necessary to avert excessive saw cut raveling. These two boundaries of the sawing window are illustrated in Figure 5.1.

The Impact of Curing on the Sawcut Window – Proper curing procedures can have a profound impact on the sawing window by either providing or trapping in the moisture that is necessary for proper hydration of the cementitious materials, and/or by providing a beneficial temperature and minimal temperature gradient (difference in temperature from the top to the bottom of the slab). Curing procedures aid in proper hydration of the cementitious materials, which increases the concrete strength level and uniformity relative to a concrete that is not properly cured. At the same time, drying shrinkage is offset because moisture is trapped in the pavement, and/or the temperature is not allowed to drop, so internal stresses do not develop as quickly. The net effect of proper curing is the development of a longer sawing window, as shown in Figure 5.2.
When the Sawing Window Begins — With conventional walk-behind concrete saws, the window generally begins 8 to 12 hours after placement, depending on weather conditions, mixture properties, and the effectiveness of curing procedures. If light, early-entry saws are used, the window begins much sooner (as soon as walking on the pavement is permitted) generally within about 3 hours of placement. Regardless of the sawing equipment, sawing cannot begin if doing so causes too much raveling. Therefore, rather than simply planning to start sawing operations at some period after placement, it is best to consider each mixture and each day of paving uniquely, monitoring the concrete to determine when the window opens (conditions are right). The sawing window conditions change often because of the many factors that come into play.

Raveling — Sawing too early causes a saw blade to break aggregate particles free from the pavement surfaces along the cut. The resulting jagged, rough edges are termed raveling. Some raveling is acceptable where a second saw cut would be made for a joint sealant. If the raveling is too severe then it will affect the appearance and/or the ability to maintain the joint. Figure 5.3 shows different degrees of raveling.

One study found that raveling was within acceptable limits when the concrete compressive strengths were between 300 and 1,015 psi (2.1 and 7.0 MPa) depending upon the type of aggregate used in the mixture. Refinement of a specific strength threshold number to be used on a project would require trial and error testing of the job materials using the concrete maturity principle.
Raveling usually occurs when sawing too soon, but it can also be caused by the saw equipment or saw blade. A saw blade must be compatible with the power output of the saw, the concrete mixture, and the application. An improper saw blade will dull rapidly and can dislodge aggregate while trying to cut. In some cases, switching to a different saw blade will correct the problem.

Plugging or clogging of the cooling water tubes on a diamond-bladed saw also may cause a raveled cut. Therefore it is important for saw operators to monitor the sawing equipment to determine if it is creating a raveled cut in concrete that is otherwise ready for sawing.

**The Scratch Test** – Short of using maturity testing, defining the sawing window starting and ending times in the field requires some experience. Experienced saw operators rely on their judgment and the scratch test to qualify whether the concrete is ready for sawing (Figure 5.4). The simple test requires scratching the concrete surface with a nail or knife blade, and then examining the depth of the scratch. As the surface hardens, the scratch depth decreases. In general, if the scratch removes the surface texture it is probably too early to saw without raveling problems.
Length of Sawing Window – The length of the sawing window depends upon many factors and is likely to be different for each project and each day of construction. Certain design features, materials or weather conditions can considerably shorten the window (Table 5.1). Under most weather conditions and for typical pavement designs, the window will be long enough to complete sawing with excellent results. In extreme conditions, the window can be so short as to be impracticable for crack control.

Of most importance is to know that the internal temperature and moisture of concrete influences the time available for joint sawing. The temperature relates to the concrete’s strength gain and (in part) controls the ability to start sawing and to finish sawing before the onset of cracking. The simplest way to determine the end of the sawing window is to monitor the concrete surface temperature. It is preferable to complete sawing before the concrete pavement surface temperature begins to fall because thermal contraction begins as the concrete temperature falls.

Higher concrete tensile strength should enable the concrete to withstand more tensile stress when it first cools and undergoes temperature differentials. However, concrete mixtures that gain strength rapidly may actually have a shorter window for sawing than normal mixtures if the heat from hydration is high. In certain weather or ambient conditions, these mixtures may experience a larger surface temperature drop than mixtures that gain strength more slowly and do not become as warm. It is not uncommon for concrete pavement surface temperatures to exceed 115°F (45°C) in summertime, particularly for fast-track concrete paving.
Contractors should become familiar with the heat development potential of job mixtures. Concrete maturity testing is a valuable tool for this purpose. By monitoring the surface temperature, a contractor will know the approximate concrete strength and also the point when surface temperature begins to decline and sawing should be completed. More explanation is provided in Chapter 6 and ACPA’s, “Maturity Testing of Concrete Pavements: Applications and Benefits.”

Cracking During Sawing – To finish sawing joints before the window ends, it may be necessary to continue sawing operations regardless of weather or daylight conditions.

Table 5.1. Factors that Shorten the Sawing Window

<table>
<thead>
<tr>
<th>Weather</th>
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<tbody>
<tr>
<td>Sudden temperature drop or rainshower</td>
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<tr>
<td>Sudden temperature rise</td>
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<tr>
<td>High winds and low humidity</td>
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<tr>
<td>Cool temperatures and cloudy</td>
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<tr>
<td>Hot temperatures and sunny</td>
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<table>
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<tr>
<th>Subbase</th>
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<tbody>
<tr>
<td>High friction between the subbase and concrete slab</td>
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<tr>
<td>Bond between the underlying subbase and concrete slab</td>
</tr>
<tr>
<td>Dry surface</td>
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<tr>
<td>Stabilized open-graded (permeable) subbase materials</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Concrete Mixture</th>
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<tbody>
<tr>
<td>High water demand</td>
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<tr>
<td>Rapid early strength</td>
</tr>
<tr>
<td>Retarded set</td>
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<tr>
<td>Fine aggregate (fineness and grading)</td>
</tr>
<tr>
<td>Coarse aggregate (maximum size and/or percentage)</td>
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<table>
<thead>
<tr>
<th>Miscellaneous</th>
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<tbody>
<tr>
<td>Paving against or between existing lanes</td>
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<tr>
<td>Saw blade selection</td>
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<td>Delay in curing protection</td>
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</table>
There are adjustments that can be made to the sawing operations if uncontrolled cracks occur during or before sawing. Four possible alternatives exist:

- Omit the saw cut if a crack forms at or near the planned location for a joint before sawing starts.
- Stop sawing the joint upon noticing a pop-off crack (to prevent creation of a potential spall between the saw cut and the crack).
- Saw every third transverse joint if uncontrolled cracking is imminent (for example, in the event of unexpected weather changes, like storms or cold fronts).
- Switch to early-entry saws in the event that extreme conditions make it impractical to prevent uncontrolled cracking with conventional saws.

When skipping saw cuts to prevent cracking, the initial contraction joints may open much wider than the 2 or 3 joints sawed between the skip sawcuts. However, these gaps close in time and this is a relatively minor drawback to this excellent method of avoiding uncontrolled cracking.

If problems with early-age uncontrolled cracking are not solved with timing or process adjustments to sawing operations, then it is best to gain better insight into the project conditions using a HIPERPAV analysis (www.hiperpav.com). HIPERPAV is a free computer program used to analyze the impact of project materials and conditions on stress development within the slab. It is very useful for forensic analysis, but it also is useful to avoid problems when applied as a quality management tool. Before continuing paving on a project with known problems, consider running a HIPERPAV analysis to determine what factors, such as mixture design, curing, etc., might be changed to prevent problems.

### 5.1.2 Joint Location Identification

**Preparing Dowel Baskets** – It is important to recognize that in order for the jointing saw cuts to be accurate (within tolerance) relative to dowel baskets, the dowel baskets must be secured to the grade so they do not shift or move during concrete placement. As part of the paving operations it is important to check that the baskets are secured just ahead of the placement and paving operation.

Each dowel must also be lubricated to allow movement as the concrete slabs expand and contract. Most dowels now come with a factory-applied debonding medium, but in some cases a thin film of form oil is applied to the entire length of the dowel. It is good practice to check the dowels ahead of the paving train to ensure they have been oiled properly if a factory lubricant was not used.

Further details of placing, securing and preparing baskets are included in ACPA’s, “Concrete Pavement Field Reference: Pre-Paving.”
Marking the Location of the Dowel Bars – When dowel bars are included in transverse joints, whether with the use of dowel baskets or with a dowel bar inserter, the location of the center of the dowel bars must be marked on the grade during paving to ensure that the transverse joint is cut within the tolerance limits allowable in the specifications (ideally over the middle of the dowels). Most states specify standard dowel lengths of 18 in. (460 mm); the required embedment length for dowel effectiveness is 6 in. (150 mm) to either side of the joint, leaving a ±3 in. (±75 mm) saw cut tolerance.

Basket locations are typically marked with spray paint immediately outside of the pavement edge when placing dowel baskets (see Figure 3.6), or while the paving train progresses along the project when using a dowel bar inserter. Colored marking nails may also be used for this purpose. Referencing the paint marks or nail heads, rope is used to create a mark in the fresh concrete (Figure 5.5) or chalk lines are snapped on the hardened concrete for the saw operator(s) to follow.

5.1.3 Sawing Equipment and Procedures

Saw and Blade Types – There are a variety of saws and saw blades available for cutting concrete pavements. Figures 5.6 through 5.8 show different equipment, although the most common type is the conventional diamond-bladed, walk-behind saw (Figure 5.8). Each saw has its advantages and disadvantages and becomes an important tool to the paving or sawing contractor.
Figure 5.6. Span saw used for transverse joints.

Figure 5.7. Early-entry saw ("green saw").
Saw blades are equally important for a quality project. The most common blades use industrial diamonds as the cutting medium and usually require water cooling while in use. Abrasive blades (carborundum) are also available for dry sawing applications.

It is important to match the saw blade to the concrete on the project. Blades are selected based primarily on aggregate hardness, but the blade also must be compatible with the power output of the saw. An improper saw blade will dull rapidly and may cause the operation to lag and the quality of the cutting to be poor. It is also costly to use blades that are not suitable for the situation.

Like other aspects of concrete pavement construction, operation of concrete saws requires attention and focus on safety. Refer to the necessary Department of Occupational Safety & Health Administration (OSHA) and local safety regulations for saw cutting safety regulations.

**Order of Saw Cuts** – Because concrete pavements generally are significantly longer than they are wide, internal stresses at early ages are generally higher in the transverse direction than the longitudinal direction; that is to say, the probability of early-age random transverse cracking is somewhat greater than random longitudinal cracking. Therefore it is common practice that transverse joints are sawed...
before longitudinal joints to alleviate internal stresses and prevent random transverse cracking. However, it is a best practice to keep all sawing (longitudinal and transverse) as close to the paving operation as possible within the sawing window. Contractors who wait 24 hours or for a crew shift before sawing longitudinal joints are more likely to encounter cracking problems.

**Importance of Sawcut Depth** – It is important to check the contract documents for the specified width and depth of joints, and set the saws up to meet these requirements. The design depth of the initial saw cut is the minimum depth required to create a properly functioning joint. Cuts that are too shallow may not relieve stresses adequately, allowing random cracks to occur. Cuts that are unnecessarily deep require additional effort and expense (take longer and use more blades), cause unnecessary equipment wear, and reduce aggregate interlock. Saw operators should factor some blade wear into the set-up of the sawing equipment to ensure that as the blade diameter decreases with use the cut still meets the design requirements. Wear may be significantly greater with dry, abrasive blades.

**Depth of Sawcuts** – The influence of sawcut depth on early cracking depends primarily upon the time of sawing. Early-entry sawing methods with sawing depths of $T/6$ to $T/5$ (where $T =$ slab depth), but at least 1 in. (25 mm) deep, may provide better crack control than conventional methods with typical depths of $T/4$ or $T/3$. Studies have shown the effectiveness of early-entry sawing methods with field experience on plain concrete pavement up to 13 in. (330 mm) thick. Figure 5.9 shows a properly activated doweled transverse joint that was sawed to a depth of $T/3$ using conventional sawing equipment at the location indicated on the subbase.

**Sawing Speed** – Proper speed of sawing is also important in controlling saw cut depth. The speed of sawing is generally controlled by the saw's self-propelling mechanism. Saw operators that attempt to speed up cutting may tend to push a saw too fast, causing the saw blade to ride up out of its full cut.

**Effect of Aggregate on Saw Cutting** – Hard aggregates like river gravel, quartzite, or granite do not cut easily and can dull or damage saw blades more quickly than other aggregates. Proper blade selection is vital. Sawing concrete made with hard aggregate will require more time, so sawing should begin as soon as possible and may require additional sawing equipment and operators.

**Starting and Stopping a Cut** – Starting and stopping each saw cut may require some special attention. For example, early-entry saws may require that the saw cut be stopped about $\frac{1}{2}$ in. (12.5 mm) short of the pavement edge to prevent “blowing out” the slab edge.
In windy conditions, the slab edge exposed to the wind may dry quickly. Under these conditions it is best to orient the direction of sawing with the wind to the extent possible. There is a higher tendency for pop-off cracks if a high wind is blowing against the edge of the slab, accelerating evaporation and shrinkage.

Figure 5.9. A properly activated transverse joint sawed with a conventional saw to a depth of T/3. Note that the joint was sawed at the location indicated on the subbase and that a conventional saw made a clean cut completely through the edge of the slab.
5.1.4 Unsealed Joints

The No-Seal Option – Despite the long-standing practice to seal all concrete pavement joints to prevent water and incompressibles from entering, and although research into this topic is still ongoing, some owners/agencies no longer require this practice under certain conditions. These agencies omit sealing of joints in their newly constructed, dowelled concrete pavements and some specialty concrete pavement types where erosion of the subbase is not of concern (e.g., undoweled bonded concrete overlays of asphalt pavements). It is therefore important to review the contract documents carefully and understand jointing details for each project. When unsealed joints are specified, the depth of the initial saw cut is generally the same as for a sealed joint, but the width is controlled by the saw blade. The blade width must match the width required by the design.

5.1.5 Sealed Joints

Reasons for Sealing – Traditional joint sealing practices are meant to improve and maintain joint and pavement performance. By preventing water from entering the pavement structure through the joints, it is theorized that there is less risk of erosion of the subbase and the associated faulting of the slabs. Sealing also is meant to minimize incompressible materials from getting lodged in the joint space, which may cause spalling or even pavement migration, leading to blow-ups.

Necessity of a Sealant Reservoir – If joints are to be sealed, a second pass with a conventional concrete saw may be necessary. Such an action will widen the initial sawcut to provide the necessary sealant reservoir, if applicable, but some agencies simply saw and seal the initial saw cut. It is important to review the contract documents carefully and understand these details.

Sealant Materials – There are many acceptable liquid and preformed materials available for sealing joints and cracks in concrete pavements. Liquid sealants depend on long-term adhesion to the joint face and sealant cohesion for successful sealing, whereas preformed compression seals depend on lateral rebound for long-term performance. Regardless of the sealant type, ensure that the sealant conforms to appropriate specifications and is acceptable for use under the construction conditions. If using two component sealants, verify the correct mixing proportions to within the tolerances specified by the manufacturer. If using hot-applied sealants, use calibrated thermometers to verify acceptable application temperatures, as well as insulated application hoses to prevent heat loss during installation.

Shape Factor and Recess – The dimensions of the joint reservoir (Figure 5.10) are set by a shape factor (D/W), defined as the ratio of the depth of the sealant (D) to its width (W). Shape factors generally range from 0.5 to 2.0; the dimensions specified by the agency should match the recommended values of the sealant manufac-
However, the depth of the reservoir saw cut may be greater than the specified sealant depth. For example, if a sawed joint for a silicone sealant is 1/2 in. (13 mm) wide and the shape factor is 0.5, then the required sealant depth is 1/4 in. (6 mm). However, the design of the seal might also be required to allow approximately 1/8 to 1/4 in. (3 to 6 mm) to account for a recess below the pavement surface to prevent contact between the sealant and tires, as well as 5/8 in. (16 mm) to accommodate the backer rod; recommended recess depths and backer rod diameters also will be supplied by the sealant manufacturer. The net result will be a sawed joint almost 1.25 in. (30 mm) deep.

**Cleaning before Sealing** – All joints that are to be sealed typically must be cleaned immediately behind saw cutting or joint widening operations and immediately prior to sealing operations to remove residue and incompressibles like saw-cut slurry, soil, sand, or gravel. These materials in joints can prevent closure and proper sealant adhesion, resulting in joints that do not function properly. Cleanliness of both joint faces is extremely important. Improperly prepared joint faces are a major cause of adhesion loss between the sealant and crack faces, resulting in failure of the seal. If wiping a finger along the crack face picks up dirt or dust (Figure 5.11), recleaning of the joints is likely necessary before sealing. Joint cleaning or recleaning should be completed using methods specified by the manufacturer and/or owner/agency and might include methods such as sand, water, or air blasting.

**Backer Rod Overview** – Backer material, also known as backer rod, typically is placed in sawed joint reservoirs that are to be sealed to minimize excess stress on sealant material from improper shape factors, to provide support for the tooling of the surface if necessary, to prevent self-leveling sealants from filling the entire joint, and to prevent three-sided adhesion, which inhibits the ability of the sealant to expand and compress under thermal stress. Be sure the backer material is chemically inert to prevent reaction with the sealant; non-absorptive to prevent water retention; non-shrinkable; and wide enough to fit snugly, but compressible to allow for easy installation. See the manufacturer’s recommendations for the backer rod diameter appropriate for the specified reservoir width. (Backer materials are not used in joints sealed with preformed compression seals.)
Notes:
A – Initial cut to a depth of T/4 or T/3 as required for conventional sawing.
B – Initial cut to a depth of T/6 to T/5 (minimum of 1 in. [25 mm]) as required for early-entry sawing.
C – As required to accommodate sealant and backer rod.
D – As required by the manufacturer.

Figure 5.10. Typical sealant reservoir details and shape factors.
Backer Rod Materials – Typical backer materials are polychloroprene, polystyrene, polyurethane, and polyethylene closed-cell forms. Do not use paper, rope, or cord. Be sure the melting temperature of the backer material is at least 25°F (14°C) higher than the sealant application temperature to prevent damage during sealant placement. The backer rod material must be compatible with the sealant material and placement method being used. The use of backer rod is especially recommended when there is a history of tears developing within the sealant material. For silicone sealants, the use of separating tape is not recommended in lieu of backer rod. Immediately prior to sealing the joint/crack, be sure the backer rod is placed at the proper depth for the shape factor of the sealant being used (Figure 5.12).
Pre-Sealing Checks – Conduct the joint sealing operation only when pavement temperatures are above the application temperature recommended by the manufacturer for the sealant being used. Monitor application temperatures constantly for hot-applied joint sealants to ensure compliance with manufacturer specified ranges. Be sure joint faces are clean and moisture-free. The joint faces must be dry before sealing to develop proper bonding.

Applying Sealant – Fill the joint from the bottom up to prevent air from becoming trapped under the sealant, which may cause bubbling. Whenever practical, fill the joint from beginning to end in one smooth operation (Figure 5.13). For hot applied sealants, follow the manufacturer's recommendations.

Installing Preformed Seals – Preformed seals should be installed per the manufacturer's recommendations (Figure 5.14).
Figure 5.13. Applying silicone sealant in one smooth operation along a longitudinal joint.
5.2 Construction Joints (Headers)

Reason for Headers – Header joints (also called transverse construction joints) are built at the end of a section of pavement where subsequent pavement construction will continue. Header joints must be constructed at the end of a pour or day’s run, or if paving is delayed by a significant amount of time such that a cold joint might form due to an interruption in the paving process.

5.2.1 Header in Fresh Concrete

Construction of Formed Headers – Formed headers, or headers placed by hand with fresh concrete, are formed by placing a header board just beyond the line where the paver has pulled away from the slab. Two methods are available to include dowels or tie bars in the header construction joint:

- A two-part form is used that allows the dowels or tie bars to protrude through the form (Figure 5.15). (The protruding ends will be incorporated into the next pavement section.)
- False-dowels are attached to the inside of a header board and embedded in the concrete. The false dowels are removed with the header board after the concrete hardens and steel dowels or tie bars are secured in the holes left by the false dowels with either epoxy or grout.
Tiebars are generally specified if the header location is not at a planned joint, while smooth dowel bars are used if the header is at a planned joint location. The header area is hand-poured, vibrated, finished, textured, and cured. Concrete should be well consolidated against the header board and finished with an edging tool.

5.2.2 Sawed Header

Construction of Sawed Headers – Headers that are placed into concrete that has already hardened are called sawed headers. To create a sawed header, the paving machine paves beyond the header location and leaves an irregular pavement end by paving out the remaining concrete (Figure 5.16). The next day, a full-depth saw cut is made at the desired header location and the excess material is removed. Plastic sheeting (placed ahead of time in the area beyond the header location) will make removing the excess concrete easier, particularly with stabilized subbase materials, where some bonding may develop.

Once a clean joint face is exposed, holes are drilled into the sawed face of the pavement and tiebars (if the header location is not a planned joint) or dowel bars (if the header is at a planned joint) are secured in the slab with epoxy or grout (Figure 5.17).
Figure 5.16. Saw-back headers allow the slipform to run out of concrete, resulting in a smoother transition.

Figure 5.17. A doweled sawed header.
**Sawed versus Formed Headers** – The sawed method of header construction is generally preferred because it typically results in a smoother transition at the header joint, and consists of machine-placed and -consolidated concrete. It is also less labor intensive.

**5.2.3 Continuing Paving and Opening to Traffic**

**Preparing to Resume Paving** – If the header is a formed header, wait at least six hours before resuming paving at that location. Remove header boards, supports, and false dowels before installing any necessary dowels or tiebars. For sawed headers, make sure that the concrete has hardened enough (attained adequate strength) before securing dowels or tiebars.

**Resuming Paving** – The paving equipment must then be repositioned over the joint to start the next placement. Some hand placement and hand vibration will be necessary on the start-up side of the header. It is important to finish the pavement using the previously-placed header as a guide for the surface finishing in order to create as smooth a transition across the header as possible.

**Opening to Traffic** – If heavy loads (paving machine, concrete delivery trucks, other construction vehicles) are expected to traffic the previous placement, check the strength of the in-place concrete before allowing them access.

**5.3 Terminal Joints in Continuously Reinforced Concrete Pavement (CRCP)**

**Joints in CRCP** – Continuously reinforced concrete pavement (CRCP) typically is not designed to have transverse joints introduced during construction. It is most common for CRCP to be allowed to develop the necessary stress-relieving cracks at a natural crack spacing with the understanding that the reinforcing steel will keep these cracks from opening significantly. In some rare occasions, transverse joints have been sawed into a CRCP (or formed as construction joints using a slotted headboard, which allows for the longitudinal steel to pass through the joint) to aid in the development of a desirable transverse joint spacing. Even still, where a CRCP section begins and ends (such as when it meets another pavement type or a bridge structure), a specialty joint called a terminal joint is necessary to anchor the CRCP section.

**Types of Terminal Joints** – The most common terminal joint treatments are the doweled sleeper slab type, the wide-flange (WF) steel beam type and the lug anchor type. Sleeper slab and WF steel beam terminal joints are designed to accommodate movement while lug anchor terminal joints are designed to restrict movement. Because of their more extraneous and more costly design, construction, and inspection requirements, and because there has been no conclusive evidence
that they are more cost effective in the long-term, WF and lug anchor terminal joints have become less commonly used than doweled sleeper slab terminal joints.

**Sleeper Slab Terminal Joints** – A doweled sleeper slab terminal joint consists of a doweled isolation joint between the CRCP and the approach/existing slab that it abuts placed atop a reinforced concrete sleeper slab (Figure 5.18).

![Figure 5.18. A typical doweled sleeper slab terminal joint for CRCP](image)

**Wide Flange Terminal Joints** – A WF steel beam terminal joint consists of a WF beam partially set into a reinforced concrete sleeper slab. The WF beam is positioned so that the top flange will be flush with the CRCP surface once the CRCP is constructed. An expansion joint is formed between the flanges by the inclusion of a 1 in. (25 mm) expansion material against the beam’s web and a bond breaker is used on top of the sleeper slab to prevent the CRCP from bonding to it. Design details for a WF terminal joint are available in the FHWA’s T5080.14, “Continuously Reinforced Concrete Pavement.”

**Lug Anchor Terminal Joints** – A lug anchor terminal joint consists of three to five heavily reinforced rectangular transverse concrete lugs that are anchored into the subgrade/subbase to below the frost penetration line. Once placed, these lug anchors are tied to the CRCP with reinforcing steel. Because a lug anchor terminal joint will restrict movement, an expansion joint is usually included if the lug anchor terminal joint abuts a bridge approach. Design details for a lug anchor terminal joint also are available in the FHWA’s T5080.14, “Continuously Reinforced Concrete Pavement.”

**Construction Considerations for CRC Terminal Joints** – Because terminal joints require special details not necessary with jointed plain pavements, the contractor must factor positioning of terminal joints into the construction phasing plan. Construction of sleeper slabs and excavation for lugs must be coordinated with the steel placement and the paving sequence. Once the preparation work is completed, slipform paving operations are the same as for plain pavement construction.
Overview – The concrete pavement needs to gain enough strength to prevent unwanted distresses prior to the application of loads. The strength used to calculate opening time should be the actual strength of the concrete pavement, instead of the strength of a cylinder or beam that cured and gained strength under different conditions than that of the pavement. For this reason, the maturity method is recommended to determine in-place strength of the concrete prior to opening to traffic. Many conventional strength concrete mixtures are capable of obtaining the required opening strength within a desired timeframe but, if not, high-early strength concrete mixtures might be used. Insulating blankets might also be used to foster a more rapid strength gain.

Key Points:

- The concrete material must meet the necessary strength before opening to construction equipment or public traffic.
- Strength, for the purposes of opening to traffic, can be verified by beam or cylinder tests in a laboratory or estimated using the maturity method in the field.
- All beam or cylinder test specimens should be cured in the same manner as and in the same ambient environment as the concrete pavement to ensure accurate strength measurements.
- Many modern conventional strength concrete mixtures can be modified to satisfy early opening strength requirements; if necessary, a high early-strength mixture can be used to further expedite opening to traffic.
- Insulating blankets can be used as part of the curing procedures to foster proper hydration and increase the rate of strength gain to expedite opening to traffic.

Overview – The concrete pavement needs to gain enough strength to prevent unwanted distresses prior to the application of loads. The strength used to calculate opening time should be the actual strength of the concrete pavement, instead of the strength of a cylinder or beam that cured and gained strength under different conditions than that of the pavement. For this reason, the maturity method is recommended to determine in-place strength of the concrete prior to opening to traffic. Many conventional strength concrete mixtures are capable of obtaining the required opening strength within a desired timeframe but, if not, high-early strength concrete mixtures might be used. Insulating blankets might also be used to foster a more rapid strength gain.
6.1 Strength Requirements

Minimum Strength before Construction Traffic – Table 6.1 lists recommendations on minimum strength before opening to construction equipment traffic such as span saws or concrete hauling/delivery trucks (e.g., ready-mixed trucks, agitating trucks, dump trucks, etc.), water trucks, and other construction vehicles. Light equipment (e.g., walk-behind saws, profilers, motorized carts, etc.) may be operated as needed before reaching these strength requirements as long as the equipment does not mar or damage the surface of the pavement or, in the case of sawing, does not cause excessive raveling along the cut (see section titled, “Sawcut Window”).

Table 6.1. Required Flexural Strength for Opening Concrete Pavements to Construction Equipment Traffic*

<table>
<thead>
<tr>
<th>Thickness, in. (mm)</th>
<th>Foundation k-value, pci (MPa/m)</th>
<th>To Support Span Saw, psi (MPa)</th>
<th>To Support 34,000 lb (151 kN) Tandem Axle Loads, psi (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10 Reps</td>
<td>50 Reps</td>
</tr>
<tr>
<td>6 (150)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 (27)</td>
<td>210 (1.5)</td>
<td>410 (2.8)</td>
<td>460 (3.2)</td>
</tr>
<tr>
<td>200 (54)</td>
<td>190 (1.3)</td>
<td>360 (2.5)</td>
<td>390 (2.7)</td>
</tr>
<tr>
<td>500 (135)</td>
<td>100 (0.8)</td>
<td>300 (2.1)</td>
<td>300 (2.1)</td>
</tr>
<tr>
<td>≥ 7 (175)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 (27)</td>
<td>150 (1.0)</td>
<td>300 (2.1)</td>
<td>340 (2.3)</td>
</tr>
<tr>
<td>200 (54)</td>
<td>150 (1.0)</td>
<td>300 (2.1)</td>
<td>300 (2.1)</td>
</tr>
<tr>
<td>500 (135)</td>
<td>150 (1.0)</td>
<td>300 (2.1)</td>
<td>300 (2.1)</td>
</tr>
</tbody>
</table>

*Details on the origin of the recommendations in this table and required flexural strengths for additional concrete pavement thicknesses are available in ACPA, “Fast-Track Concrete Pavements.”

Minimum Strength before Public Traffic – Table 6.2 lists recommendations on minimum strength requirements for opening to public traffic.
6.2 Determining Strength

**Flexural versus Compressive Strength Requirements** – For most concrete pavement applications, flexural strength is the most appropriate structural strength criterion to evaluate load capacity. Flexural strength values provide an assessment of the tensile strength at the bottom of the slab where wheel loads induce tensile stresses. For that reason, this document lists opening criteria in third-point flexural strengths. However, flexural strength tests from ASTM C78/AASHTO T97/CSA A23.2-8C are very sensitive to the test beams and testing procedures, especially at

Table 6.2. Required Flexural Strength for Opening Concrete Pavements to Public Traffic*

<table>
<thead>
<tr>
<th>Thickness, in. (mm)</th>
<th>Foundation k-value, pci (MPa/m)</th>
<th>To Support Estimated ESAL Reps, psi (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100 Reps</td>
</tr>
<tr>
<td>6 (150)</td>
<td>100 (27)</td>
<td>490 (3.4)</td>
</tr>
<tr>
<td></td>
<td>200 (54)</td>
<td>410 (2.8)</td>
</tr>
<tr>
<td></td>
<td>500 (135)</td>
<td>340 (2.3)</td>
</tr>
<tr>
<td>7 (175)</td>
<td>100 (27)</td>
<td>370 (2.6)</td>
</tr>
<tr>
<td></td>
<td>200 (54)</td>
<td>310 (2.1)</td>
</tr>
<tr>
<td></td>
<td>500 (135)</td>
<td>310 (2.1)</td>
</tr>
<tr>
<td>8 (200)</td>
<td>100 (27)</td>
<td>370 (2.6)</td>
</tr>
<tr>
<td></td>
<td>200 (54)</td>
<td>310 (2.1)</td>
</tr>
<tr>
<td></td>
<td>500 (135)</td>
<td>300 (2.1)</td>
</tr>
<tr>
<td>9 (225)</td>
<td>100 (27)</td>
<td>300 (2.1)</td>
</tr>
<tr>
<td></td>
<td>200 (54)</td>
<td>300 (2.1)</td>
</tr>
<tr>
<td></td>
<td>500 (135)</td>
<td>300 (2.1)</td>
</tr>
<tr>
<td>10 (255)</td>
<td>100 (27)</td>
<td>300 (2.1)</td>
</tr>
<tr>
<td></td>
<td>200 (54)</td>
<td>300 (2.1)</td>
</tr>
<tr>
<td></td>
<td>500 (135)</td>
<td>300 (2.1)</td>
</tr>
<tr>
<td>≥ 11 (280)</td>
<td>100 (27)</td>
<td>300 (2.1)</td>
</tr>
<tr>
<td></td>
<td>200 (54)</td>
<td>300 (2.1)</td>
</tr>
<tr>
<td></td>
<td>500 (135)</td>
<td>300 (2.1)</td>
</tr>
</tbody>
</table>

*Details on the origin of the recommendations in this table and required flexural strengths for additional concrete pavement thicknesses and load repetitions are available in ACPA, “Fast-Track Concrete Pavements.”

6.2 Determining Strength

**Flexural versus Compressive Strength Requirements** – For most concrete pavement applications, flexural strength is the most appropriate structural strength criterion to evaluate load capacity. Flexural strength values provide an assessment of the tensile stress at the bottom of the slab where wheel loads induce tensile stresses. For that reason, this document lists opening criteria in third-point flexural strengths. However, flexural strength tests from ASTM C78/AASHTO T97/CSA A23.2-8C are very sensitive to the test beams and testing procedures, especially at
very early ages. Many agencies realize this shortcoming and use the more consistent compressive strength test (ASTM C39/AASHTO T22/CSA A23.2-9C) to evaluate concrete for acceptance and opening.

**Estimating Compressive Strength From Flexural Strength** – To use the flexural strength opening criteria in this publication, it may be necessary to develop a correlation between compressive strength and flexural strength in the laboratory for each unique concrete mixture. The following equation, however, is commonly used to estimate compressive strength from third-point flexural strength:

\[
f'_c = \left(\frac{f_f}{C}\right)^2
\]

Where:

- \(f'_c\) = Compressive strength, psi (MPa)
- \(f_f\) = Flexural strength, psi (MPa)
- \(C\) = a constant; between 8 and 10 (0.66 and 0.83 for metric equivalent), with 9 (0.75) recommended, for normal-strength concrete mixtures and between 7.5 and 12 (0.62 and 1.0), with 11.7 (0.97) recommended, for high-early strength concrete mixtures

**Opening Strength Cylinders** – Field cured opening strength cylinders are commonly used to determine when traffic will be allowed on new concrete pavements. When used, opening strength cylinders are required to be field-cured in the same manner as the concrete pavement. Although field-cured cylinder specimens can be tested at any age (e.g., if early-opening is targeted), 7-day test cylinders are often made for comparison with laboratory tests at the same time; testing at 7-days is useful in judging if curing and protection during cold weather paving was adequate. The field cured opening strength cylinders typically are cast, field cured, and tested by the contractor.

**The Maturity Method** – The maturity method (ASTM C1074/AASHTO T325) is a means of estimating in-place concrete strength by correlating internal concrete temperature histories in the field to laboratory developed maturity and strength data. The basis of maturity is that each concrete mixture has a unique strength-time-temperature relationship. The strength of a given concrete mixture that has been properly placed, consolidated, and cured, is a function of both its age and temperature history.

The maturity-strength relationship is valid only for the mixture design and materials used during its development; if there are changes in material sources or mixture proportions, development of a new maturity-strength curve is necessary. The details of developing maturity curves for concrete mixtures to use for estimating in-place strength are included in ACPA’s, “Concrete Pavement Field Reference: Pre-Paving.”
To implement a maturity curve for a concrete mixture in the field, a temperature sampling device is installed in the freshly placed concrete and the temperature is measured periodically (Figure 6.1). Installation of such a device is a relatively simple matter. Shortly after placement of the pavement, thermocouple wires can be attached to a small wooden dowel and inserted to the desired depth in the fresh concrete. Alternatively, maturity sensors can be affixed to an item embedded in the pavement, such as a dowel basket wire or reinforcing bar. The lead wires are then attached to a datalogging device, which may be located some distance away. Integral temperature sensors/dataloggers can be used as well, eliminating the need to leave a costly maturity meter alongside the pavement, vulnerable to damage and theft.

Using either of the aforementioned methods to gather the thermal history, the strength of the pavement can be estimated at any time by calculating the time-temperature factor (TTF) and reading the strength from a laboratory constructed maturity plot.

### 6.3 Concrete Mixture Considerations

**Conventional Strength Concrete Mixtures** – Oftentimes it is possible to obtain the necessary opening strength within a reasonable time using conventional strength concrete mixtures. In fact, many of the concrete mixtures that are currently considered “conventional” were considered “high-early strength” a few years ago.
The primary means of obtaining the necessary opening strength using conventional concrete mixtures are through using a different portland cement type (particularly Type III), using an increased portland cement content, using helpful admixtures, using a uniform aggregate gradation, and/or keeping the water-cementitious ratio below about 0.43. If, however, the required opening strength cannot be met within a desired timeframe, a high-early strength concrete mixture might be used.

More details on mixture design for conventional strength concrete mixtures are available in the references for this chapter.

**High-Early Strength Concrete Mixtures** – When necessary, high-early strength concrete mixtures can be used to achieve a specified opening strength at an earlier age than conventional strength concrete mixtures.

The primary means of obtaining a high-early strength are:

- Using a Type III or HE high-early-strength portland cement.
- Using a high portland cement content (675 to 850 lb/yd³ [400 to 500 kg/m³]).
- Lowering the water-cementitious ratio to as low as 0.37.
- Using a higher concrete mixing temperature through the use of heated water and/or aggregate.
- Using accelerating admixtures.
- Using insulating curing practices to retain the heat of hydration.
- Using hydraulic non-portland cements that have rapid strength gain.

When designing a high-early strength concrete mixture, strength development is the primary consideration but other criteria should be evaluated, including durability, early stiffening, autogenous shrinkage, drying shrinkage, temperature rise, etc.

High-early strength concrete mixtures might also be used in several special applications, such as cold weather construction (see the section titled, “Cold Weather Paving”), in fast-track paving, during rapid repair of pavements to reduce traffic downtime, and several other instances.

More details on mixture design for high-early strength concrete mixtures are available in the references for this chapter.

### 6.4 Insulating Blankets

**Overview** – In certain scenarios, such as cold-weather paving (see section titled, “Cold Weather Paving”) or just when expedited strength development is desirable, insulating blankets (Figure 4.7) might be used to entrap heat generated from the hydration reaction to speed the reaction up, thus speeding up the rate of strength
gain in an attempt to meet a desired opening to traffic strength requirement; alternatively, temperature controlled heating/curing blankets might also be used to provide additional heat to the system, increasing the heat of hydration and speed of strength gain. It should be noted, however, that although these are viable means of speeding up strength gain, an increase in early-age strength might result in a decrease in long-term strength of the material. If it is known prior to paving that insulating or heating blankets might be used to foster the hydration reaction, an investigation into the potential long-term strength implications should be conducted on laboratory specimens during the mixture design testing.

**When to Place Insulating Blankets** – Contractors usually will place insulating blankets soon after applying curing compound. However, if conditions are warm, it may be acceptable to wait several hours and instead place the blankets as the joint sawing operations progress. In any case, it is advisable to wait until after finishing all joint sawing to start placing insulating blankets.
References

The publications in this list of references, organized by Chapter, can be downloaded or purchased at the following websites:

- **AASHTO Standards** [https://bookstore.transportation.org/](https://bookstore.transportation.org/)
- **ACPA Publications** [www.acpa.org/bookstore](http://www.acpa.org/bookstore)
- **CSA Standards** [http://www.csa.ca/](http://www.csa.ca/)
- **FHWA Publications** [http://www.fhwa.dot.gov/pavement/pub_listing.cfm?areas=Concrete](http://www.fhwa.dot.gov/pavement/pub_listing.cfm?areas=Concrete)

**Chapter 1. Quality Control (QC)**

**ACPA References**

IS257P, “Maturity Testing of Concrete Pavements – Applications and Benefits.”


TB006P, “Constructing Smooth Concrete Pavements.”

SR990P, “Understanding Statistically Based Strength Specifications for Portland Cement Concrete Pavements.”

**Other References**


AASHTO T22, “Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens.”

AASHTO T23, “Standard Method of Test for Making and Curing Concrete Test Specimens in the Field.”


AASHTO T97, “Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading).”

AASHTO T119, “Standard Method of Test for Slump of Hydraulic Cement Concrete.”

AASHTO T121, “Standard Method of Test for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete.”


AASHTO T152, “Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method.”

AASHTO T177, “Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading).”

AASHTO T196, “Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method.”

AASHTO T255, “Standard Method of Test for Total Evaporable Moisture Content of Aggregate by Drying.”

AASHTO T309M, “Standard Method of Test for Temperature of Freshly Mixed Hydraulic-Cement Concrete.”

AASHTO T318, “Standard Method of Test for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying.”

AASHTO T325, “Standard Method of Test for Estimating the Strength of Concrete in Transportation Construction by Maturity Tests.”

ASTM C31, “Standard Practice for Making and Curing Concrete Test Specimens in the Field.”

ASTM C78, “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading).”


ASTM C138, “Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete.”


ASTM C173, “Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method.”

ASTM C192, “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.”

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Index

**A**
AASHTO 22-25, 27, 88, 117-118, 123-124, 130, 132
ACI 24-25
admixture 6, 35-36, 38, 71-72, 120, 129
   chemical 35, 129
aggregate 6, 22, 25-26, 29, 31-33, 36, 67, 71, 91, 93-94, 96, 100-101, 120, 124-126, 128
   coarse 29, 31, 33, 67, 81, 96, 124-125, 128
   fine 29, 31, 33, 67, 96, 124-125
gradation 6, 32-33, 120
particles 33, 64, 93
recycled 313, 126, 128
well-graded 46
agitor, see *haul vehicles, agitating truck*
   air
   content 24, 26, 32, 63, 72, 76, 85-86, 124-129
   entrained, 61, 72
   entrainment 35, 56, 61
   void analyzer 23, 12
   void structure 85-86
   void system 26, 31, 76, 125, 129
alignment 9, 48-50, 61
asphalt 45, 65, 72, 103, 131
   treated subbase 45, 65

**B**
backer rod 15, 104, 106-107
basket, see *dowel basket*
batching 6, 21, 27, 29, 33, 35-36, 39, 75
bleed water 67, 80, 85-86
blockout, see *utility blockout*
bonding 87, 107, 110, 113
broom, see *surface texture, broom*
bull float 66-67
burlap drag, see *surface texture, burlap drag*
butt joint, see *joint, construction*

**C**
calorimetry, see *heat signature*
cement 36, 45, 65, 70-72, 75, 90, 120, 123-133
   slag 70-72, 127
   treated subbase 45, 65
cementitious
   materials 33, 39, 67, 71, 73-76, 85, 92, 126
   heat generation 22
centerline 45, 48, 50
central mixed concrete 7, 34-38
   portable batch plant 25, 34
certification 3, 19, 24-25, 37
chemical admixture, see *admixture, chemical*
compressive strength, see *strength requirements, compressive*
concrete
conventional strength 17, 115, 119-120
high-early strength 7, 10, 12, 17-18, 115, 118-120
high-slump 42, 47
low-slump 42, 67
material 21, 32, 85, 115
mixing 6, 21, 31, 33-39, 42, 72, 103, 120, 124
mixture 1, 6, 8, 17-18, 24, 26-28, 33, 35-38, 44, 46-47, 51-52, 54, 57, 59, 61, 63, 66-68, 81, 84, 94, 96, 118-120
paving 1, 23, 25, 29, 33, 37, 70-71, 95, 125, 127-129, 131-133
placement 1, 10, 47, 51, 56, 58, 75, 79, 97
production 1, 19, 21, 31-37, 76-77
ready-mixed 25, 34-39, 41-42, 116
strength 115
temperature 23, 26, 71, 86, 95, 118
truck-mixed 36
consistency 8, 31, 33, 37, 43, 56-58, 61, 63-64, 68, 71, 79
construction 1, 3-4, 7, 15-17, 19-21, 24-26, 28, 35, 37, 41, 44-45, 51, 54-58, 65, 70, 75, 77, 83-84, 86, 91, 95, 100, 103, 109-110, 112-113, 115-116, 120, 124, 126-132
construction joint, see joint, construction
contamination 6, 31-33
continuously reinforced concrete pavement (CRCP) 16, 46, 112-113, 132
contraction joint, see joint, contraction
corrosion inhibitor 9
cracking 15, 47, 51, 71-73, 78, 85-87, 89, 91, 95-97, 100-101, 129, 131-132

curing 1, 4, 10, 12-15, 26-27, 43, 51, 56, 64, 71-73, 75, 78-81, 83-90, 92, 93, 96, 97, 115, 118, 120-121, 124-126, 130, 131
compound, see final cure, curing compound
density 22, 28, 124
diamond grinding, see surface texture, diamond grinding
dowel
bar 11-2, 16, 43, 45-49, 69, 75, 91, 98, 110
bar inserter (DBI) 11, 43, 45-47, 98
basket 9, 16, 43, 45, 47-51, 70, 97-98, 119, 129, 131
edge slump 43, 67-69
embedded steel 15-16, 46-47, 64, 75
dowel bar, see dowel, bar
tiebar, see tiebar
end-dump truck, see hauling vehicles, end-dump truck
entrained air, see air, entrained
evaporation rate 86
evaporation retarder, see initial cure, evaporation retarder
false set 22
final cure 85-86
curing compound 14, 64, 72, 79, 84-89, 121
membrane-forming 86, 88, 130
white pigmentation 14, 72, 79, 88
impervious paper 85, 90
insulating blankets 14, 18, 71, 85, 89-90, 115, 120-121
plastic sheet 73, 74, 81, 110
wet burlap 85, 90
finishing 10-11, 42-43, 46-47, 55-57, 63-68, 72, 74, 81, 84-85, 87, 112, 121
fixed form paving, see paving, fixed form
flexural strength, see strength requirements, flexural
fly ash 36, 71-72
fogging, see initial cure, fogging

■ G

grooves 13, 80, 82

■ H

handling 1, 4, 8, 26-27
haul vehicles 7, 35, 44
agitating truck 40
end-dump truck 39
ready-mix truck 25, 34-39, 41-42, 116
side-dump truck 39
header, see joint, construction
heat signature 22
high-slump, see concrete, high-slump
HIPERPAV 12, 23, 97
hydration 70-72, 85-86, 90, 92, 95, 115, 120-121

■ I

incompatibility 23, 126, 128
initial cure 78, 85, 87
evaporation retarder 78, 85, 87
fogging 67, 78, 85-86
misting 78, 85-86
insulating blankets, see final cure, insulating blankets
isolation joint, see joint, isolation

■ J

joint 1, 9-10, 12, 13, 15, 16, 44, 48, 50-51, 71, 78, 90-91, 93, 95-101, 103-105, 107, 109, 111-113, 131-132
construction 15-16, 44, 51, 109, 112
contraction 50, 71, 97
isolation 15
longitudinal 101
sealant 15, 91, 93, 103-108
sealed 103
spalling 68
transverse 16, 90-91, 98-100, 112
unsealed 103

■ L

longitudinal joint, see joint, longitudinal
longitudinal tining, see surface texture, longitudinal tining
low-slump, see concrete, low-slump

■ M

maturity meter 17, 119
mesh reinforcement 9, 45
misting, see initial cure, misting
mixing concrete, see concrete, mixing
mixture
design 17, 21, 33, 35, 51, 54, 59, 61, 66, 68, 79, 81, 95, 97, 101-104, 112-113, 118, 120-121, 125, 127-132, 137
properties 34, 93
moisture content 6, 29, 31-33, 84, 124-125

■ N

night paving 13, 72, 76-77
NRMCA 25, 37

■ O

opening strength, see strength requirements, opening

137
OSHA 26, 100

■ **P**

pavement
durability 72, 85
paving
equipment 10-12, 31, 35, 41, 48, 54, 59, 65-68, 112
fixed form 9-10, 28, 43-45, 52-56, 64, 86
operations 1, 12-13, 21, 24, 27-28, 37, 41-42, 44, 49, 51, 59, 64-65, 69, 70-71, 75, 77, 91, 97, 113
slipform 11-12, 40, 43-45, 50, 54-55, 56-61, 63-69, 75, 82, 87, 111, 113
petrographic examination 76, 129
placement rate 41-42
placing 1, 8-9, 15, 21, 27, 41, 43, 45-47, 49, 51, 53, 55, 57, 59, 61, 63, 65, 67, 69, 71, 73, 75, 77, 84, 97-98, 109, 121, 128
plastic sheeting, see final cure, plastic sheet

■ **Q**

quality assurance (QA) 19-21, 26-27, 123, 126-127
quality control (QC) 1, 3-5, 8, 19-29, 37, 123, 125, 127
testing programs 4, 26
tests 3, 8, 21-24, 26, 28

■ **R**

rainy conditions, see weather conditions, rainy
rain-damaged pavement 76
raveling, see sawcut, raveling
ready-mixed concrete, see concrete, ready-mixed
ready-mix truck, see hauling vehicles, ready-mix truck
reinforcing steel 9, 45, 112-113
repair 1, 25, 75-76, 84, 120, 123, 127, 129, 131
retarder, see initial cure, evaporation retarder

■ **S**
sawcut 9, 11, 15-16, 91-92, 97-98, 101, 103
raveling 15, 92-94, 116
depth 91, 101
speed 101
sawing equipment 57, 93-94, 98, 101
scratch test 94-95
screeds 52, 54, 63
sealant, see joint, sealant
sealed joint, see joint, sealed
severe weather, see weather conditions, severe
shrinkage 18, 23, 51, 72, 79, 85-87, 92, 102, 120
side-dump truck, see hauling vehicles, side-dump truck
skid resistance 74, 76, 79-80
slipform paver 43-45, 54-55, 57-62, 64-65
slipform paving, see paving, slipform
sloughing 68
slump 8, 12, 22, 24, 27-28, 32, 37, 39, 42-43, 47, 56, 67-69, 72, 124-126
spalling, see joint, spalling
spreading 43, 55
spring-back 46-47, 70
spud vibrator, see vibrator, spud
stationary mixed concrete 6, 7, 36-38
steel 9, 15-16, 45-47, 64, 73-75, 109, 112-113, 131
stockpile 6, 31-33, 127
straightedge 53, 56, 66, 68
strength requirements 17, 115-117
compressive 24, 26, 91, 117-118, 124, 126
flexural 116-118, 124-126
opening 17, 115, 118-120
subbase 9, 11, 44-45, 48-49, 51, 59, 64-65, 71-72, 89, 92, 96, 101-103, 110, 113, 128
subgrade 9, 11, 44, 64, 71-72, 98, 113
surface chatter 43, 67-68

surface texture
  burlap drag 80, 83
  broom, 79, 82
  diamond grinding 68, 75-76, 84, 130
  drag 13, 79-81, 83-84
  longitudinal tining 82
  tining 14, 67, 79-82
  transverse tining 67, 81
  turf drag 79-80, 83-84

temperature-controlled heating 71
terminal joint 112-113
testing 3-4, 17, 19, 21-28, 56, 88, 93-94, 96, 117-118, 121, 123-125, 127, 131-133, 138-139
texture, see surface texture
thickness 5, 9, 11, 17, 19, 28, 42-43, 45, 52, 56, 65, 76, 116-117
tiebar 9, 12, 43, 45, 50-51, 69, 75, 109-110, 112
tining, see surface texture, tining
transverse joint, see joint, transverse
transverse tining, see surface texture, transverse tining
truck-mixed concrete, see concrete, truck-mixed
turf drag, see surface texture, turf drag

vibrator
  monitoring systems 63
  spud 10, 52, 55

weather content 124, 126
weather conditions
  cold 4, 14, 19, 27, 70, 118, 120
  hot 4, 12, 19, 27, 70-72, 76, 96, 103, 107
    sunshades 72
    windbreaks 72
  rainy 72
  severe 27
  wet weather friction 81-83

unit weight, see density
unsealed joint, see joint, unsealed
utility blockout 10-11