Concrete Pavement Field Reference

Pre-Paving

A practical guide to understanding and troubleshooting:

- Joint layout
- Subgrades
- Subbases
- Pre-paving setup
- Concrete mixture analysis & approval

American Concrete Pavement Association
Concrete Pavement Field Reference
Pre-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.pavement.com/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 technical staff member.
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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, placing a quality concrete pavement requires planning before paving to address not only material and constructability factors, but also to address the sub-grade or subbase placed below the concrete pavement. After all, if a pavement is built upon a poorly controlled support system, even the most well constructed pavement likely will fail prematurely. 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.

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 pre-paving considerations. Rather, it is a common-sense guide to pre-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 joint layout; subgrade/subbase design and preparation; stringline, forms, and embedded steel arrangement and placement; and concrete mixture analysis and approval.

This is a document which serves to educate, guide, and inform all parties involved in any pre-construction considerations for concrete paving, 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 pre-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.pavement.com/fieldreference.

### Joint Layout

**Joint Types (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>Ensure that all parties involved in joint design and construction understand each joint type.</td>
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<tr>
<td>2.</td>
<td>Check that the location of special joint types (i.e., isolation, tied contraction, etc.) are clearly indicated on project plans.</td>
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</table>

**Special Considerations for Intersections (Section 1.2)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
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<tbody>
<tr>
<td>1.</td>
<td>Check plans and attempt to eliminate all joints that intersect another joint or the pavement edge at an acute angle. Where it is not possible for joints to intersect at 90 degrees, ensure that the angle at the intersection is at least 60 degrees.</td>
<td></td>
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</tbody>
</table>

**Rules for Joint Layout (Section 1.3)**

<table>
<thead>
<tr>
<th>No.</th>
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<tbody>
<tr>
<td>1.</td>
<td>If paving immediately adjacent to existing pavement, as an overlay, or on a jointed lean concrete subbase ensure that the locations of existing joints or cracks are matched with new joints.</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Make certain that joints intersect any in-pavement structures, or else isolate those structures properly.</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Ensure that isolation joints are placed only where needed.</td>
<td></td>
</tr>
</tbody>
</table>
The following is the 10-step method for intersection joint design for concrete pavements:

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>Draw all pavement edge and back-of-curb lines in the plan view. If integral curbs and gutters are to be used, draw only the back-of-curb lines.</td>
<td>☐</td>
</tr>
<tr>
<td>2.</td>
<td>Lightly draw the circumference-return, the taper-return, and the crossroad return lines as offsets of 1.5 to 3.0 ft (0.5 to 1.0 m).</td>
<td>☐</td>
</tr>
<tr>
<td>3.</td>
<td>Draw all lines that define lanes on the mainline and crossroad. Do not extend these lines past the circumference-return, taper-return, or crossroad-return lines.</td>
<td>☐</td>
</tr>
<tr>
<td>4.</td>
<td>Define the mainline lanes for paving. Find all locations where the crossroad intersects the mainline paving edges and, at these locations only, extend the mainline paving edge lines past the circumference-return or taper-return line(s). Block-outs &amp; doglegs will occur in the gutter at these locations.</td>
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<tr>
<td>No.</td>
<td>Task</td>
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</tr>
<tr>
<td>5.</td>
<td>Add transverse joints at all locations where a width change occurs in the pavement (begin and end of tapers, tangents, curves, curb returns, etc.) and extend these joints through the curb and gutter and/or concrete barrier walls that are not isolated from the adjacent pavement. On the cross road(s), the joint at the tangent point farthest from the mainline becomes an isolation joint.</td>
<td>〇</td>
</tr>
<tr>
<td>6.</td>
<td>Add transverse joint(s) between and beyond the joints defined in the last step, but do not add joints to the center of the intersection. Attempt to keep the distance between joints the same, and less than the maximum desirable length (approximately 15 ft [4.5 m]).</td>
<td>〇</td>
</tr>
<tr>
<td>7.</td>
<td>Extend the edge of pavement lines for the mainline and cross-road to define the intersection box. (Note: For skewed intersections, do not extend the lines for the turning lanes. Instead, place a transverse joint normal to the crossroad centerline starting from the corner of the intersection box that is nearest to the acute angle of the intersection.)</td>
<td>〇</td>
</tr>
<tr>
<td>8.</td>
<td>Check the distances between the intersection box and the surrounding joints. If the distance is more than the maximum desirable joint spacing, add transverse joint(s) at an equal spacing. Do not extend these joints past the circumference-return or cross-road return lines.</td>
<td>〇</td>
</tr>
<tr>
<td>9.</td>
<td>Lightly extend lines from the center of the curb return radii to the points defined by the intersection box, any intermediate joints surrounding the intersection box, and point(s) along any islands. Add joints along these radius lines. Also, make slight adjustments to eliminate doglegs in mainline edges.</td>
<td>〇</td>
</tr>
<tr>
<td>10.</td>
<td>Make any additional adjustments for in-pavement objects.</td>
<td>〇</td>
</tr>
</tbody>
</table>
Alternate Skewed Intersection Layout (Section 1.5)

No. Task Complete
1. Add additional longitudinal joints in any slabs that would otherwise be more than 15 ft (4.5 m) wide, beginning and ending this new joint at transverse joints. □
2. To avoid sympathy cracking when ending a longitudinal joint at a transverse joint, either core or form holes through the entire depth of the pavement to arrest the cracking or, alternatively, include reinforcing bars transverse to the joint in the uncut slab to prevent cracks from propagating. □

Handling Wide Medians and Dual-Left Turn Lanes (Section 1.6)

No. Task Complete
1. Before planning the joint layout for dual-left turn lanes, consider all construction staging possibilities. □
2. If possible, use a skew joint through the intersection box instead of moving the isolation joints closer to the intersection; isolation joints usually require more maintenance than typical joints. □

Roundabouts (Section 1.7)
The following is a 6-step guide to successful joint layout of concrete roundabouts:

No. Task Complete
1. Draw all pavement edge and back-of-curb lines in the plan view. Draw locations of all manholes, drainage inlets, and valve covers so that joints can intersect these. □
2. Draw all lane lines on the legs and in the circular portion. If isolating the roundabout circle from the legs, do not extend these through the circle. If using the “pave-through” method, determine which roadway will be paved through. Make sure no distance is greater than the maximum recommended width. □
### Cul-de-sacs (Section 1.8)

<table>
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<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
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<tbody>
<tr>
<td>3.</td>
<td>In the circle, add “transverse” joints radiating out from the center of the circle. Make sure that the largest dimension of a pie-shaped slab is smaller than the maximum recommended slab width. Extend these joints through the back of the curb &amp; gutter.</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>On the legs, add transverse joints at all locations where a width change occurs (at bullnose of median islands, beginning and end of curves, tapers, tangents, curb returns, etc.). Extend these joints through the back of the curb and gutter.</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Add transverse joints beyond and between those added in Step 4. Space joints out evenly between other joints, making sure not to violate the maximum joint spacing.</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Make adjustments for in-pavement objects, fixtures, and to eliminate L shapes, small triangular slabs, etc.</td>
<td></td>
</tr>
</tbody>
</table>

### Adjusting Joints for Utilities and Boxing out Fixtures (Section 1.9)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
</tr>
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<tbody>
<tr>
<td>1.</td>
<td>After all other steps of a joint layout process are completed, adjust joints that fall within 5 ft (1.5 m) of a fixture to intersect the fixture.</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>If a joint must be moved to intersect a fixture, and the resultant slab exceeds the maximum slab width, adjust several joints immediately adjacent to the moved joint so that no joint spacing is greater than the maximum.</td>
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### Subgrade

**Problematic Soils (Section 2.1)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
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<tbody>
<tr>
<td>1.</td>
<td>With adequate time before paving begins, examine existing soils and identify potential problems, such as swelling and heaving.</td>
</tr>
<tr>
<td>2.</td>
<td>If expansive soils are found, address the problem by providing proper grading and/or relocation and mixing, moisture-density control during compaction, a non-expansive cover of compacted aggregate subbase, or chemical modification, such as cement treatment or lime stabilization.</td>
</tr>
<tr>
<td>3.</td>
<td>If frost susceptible soils are found, address the problem by providing proper grading and/or relocation and mixing, high grade lines and low ditches, moisture-density control during compaction, drain tiles to lower the water table, or a non-frost susceptible aggregate subbase layer to protect the subgrade.</td>
</tr>
</tbody>
</table>

**Uniformity and Stability (Section 2.2)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
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<tbody>
<tr>
<td>1.</td>
<td>Proof roll the area with a loaded 10-wheel dump truck to check the uniformity of support and to detect soft spots that require correction. Ensure that the entire field crew understands that the degree of rutting is indicative of both uniformity and stability.</td>
</tr>
<tr>
<td>2.</td>
<td>If subgrade remediation techniques are not necessary (i.e., no actions were taken to correct problematic soils), address any uniformity and stability issues by cross hauling and mixing of soils.</td>
</tr>
<tr>
<td>3.</td>
<td>Stabilize any nonuniform or instable areas of the soil, or the entire area if necessary, with portland cement, blended cement, fly ash, or lime.</td>
</tr>
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</table>
### Construction (Section 2.3)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
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<tbody>
<tr>
<td>1.</td>
<td>If necessary, bring the subgrade material to the optimum moisture content before compaction by adding water.</td>
<td>☐</td>
</tr>
<tr>
<td>2.</td>
<td>Adequately compact the subgrade by achieving a minimum of 95 percent of the standard proctor density (AASHTO T99/ASTM D698); check local specifications as density requirements may vary.</td>
<td>☐</td>
</tr>
<tr>
<td>3.</td>
<td>Repeat proof rolling after compaction to detect areas that may require additional corrective action.</td>
<td>☐</td>
</tr>
<tr>
<td>4.</td>
<td>Within a week of completing the compaction, trim the grade to the correct elevation and cross-slope. When using a slip-form paver, reference the same stringline to be used for subbase construction operations and pavement placement if site conditions allow.</td>
<td>☐</td>
</tr>
</tbody>
</table>
Subbase Design (Section 3.1)

1. If possible, extend the subbase far enough beyond the pavement edges to provide a stable track line for the formwork or slipform paver (approximately 3 ft [1 m] on each side of the pavement).

2. Ensure that unstabilized subbases, if used, have a maximum aggregate size of no more than one third the subbase thickness, a plasticity index (PI) of less than 6.0 and contain a maximum of 15 percent fines.

3. If used, ensure that unstabilized (granular) subbases are compacted to no less than 95 percent of the standard proctor ASTM T99/ASTM D698 density.

4. Ensure that stabilized subbases, if used, have a plasticity index (PI) of less than 10.0; contain a maximum of 35 percent fines; and the maximum aggregate size is limited to 1 in. (25 mm), or more preferably $\frac{3}{4}$ in. (19 mm).

5. Ensure that subbase thicknesses are at least 4 in. (100 mm) for unstabilized subbases, 4 in. (100 mm) for cement-stabilized subbases (i.e., cement-treated subbases and lean concrete subbases), and 2 in. (50 mm) for asphalt-stabilized subbases.
### Subbase Construction (Section 3.2)

<table>
<thead>
<tr>
<th>No.</th>
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<tbody>
<tr>
<td>1.</td>
<td>Ensure that the proportions of the subbase mixture conform to the approved job mix formula (JMF) or mixture design and that there is consistency within and between batches.</td>
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<tr>
<td>2.</td>
<td>Check that the permeability of the free-draining subbase materials, if used, comply to project specifications.</td>
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</tr>
<tr>
<td>3.</td>
<td>Check for damage caused by trucks and/or laydown equipment to the subgrade/subbase surface. Ensure that subbase material is placed without segregating or mixing into the subgrade.</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>During placement of stabilized subbases, check the adequacy of the volume of cement paste or asphalt binder for coating the aggregate particles and ensure that the material is spread evenly across the paving width.</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Check for stability (firm and unyielding), surface texture (uniform, with no crushing of aggregate), and depth (using probes, string lines and tape/ruler) after each roller pass.</td>
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</tr>
<tr>
<td>6.</td>
<td>Test surface and grade tolerances (typically ±½ in. (12 mm)). Regrade and recompact areas that are out of tolerance.</td>
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<tr>
<td>1.</td>
<td>Ensure that paving hubs, or construction stakes, are installed at appropriate intervals (typically 25 ft (7.5 m) or less) outside the pad line, along with grade/pie stakes (flats) showing the difference in elevation between the top of the slab and the hub. Decrease the interval through sharp horizontal or vertical curves.</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Check that a stringline support stake is securely placed just outside each hub, so that the stringline will be directly over the hub.</td>
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<tr>
<td>3.</td>
<td>Check that the appropriate stringline height is calculated relative to the hub elevations, the offset distance (either level or projected) between the hub and a pavement reference point, and the desired grade.</td>
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</tr>
<tr>
<td>4.</td>
<td>Install stringline winches at about 1,000 ft (300 m) intervals.</td>
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<tr>
<td>5.</td>
<td>Verify that the stringline is installed between stakes, adjusted to the desired height, and then made taut using hand winches. (Apply tension carefully; a line break may cause injuries.)</td>
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<tr>
<td>6.</td>
<td>Install stringlines on both sides of the proposed pavement for maximum control.</td>
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<tr>
<td>7.</td>
<td>Warn all workers to be cautious around the set stringline to avoid tripping over, nudging, or otherwise touching it.</td>
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### Setting Forms (Section 4.2)

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<tr>
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<tbody>
<tr>
<td>1.</td>
<td>Examine all forms with a straightedge or stringline before use. Discard, repair, or replace forms that are bent by more than 0.125 in. (3 mm) along the top or 0.25 in. (6 mm) along the inside edge.</td>
<td>☐</td>
</tr>
<tr>
<td>2.</td>
<td>Before placement, ensure the quality of support beneath the forms is assessed so no settlement will occur.</td>
<td>☐</td>
</tr>
<tr>
<td>3.</td>
<td>Ensure that fixed-forms have the proper alignment and elevation to provide the best possible smoothness.</td>
<td>☐</td>
</tr>
<tr>
<td>4.</td>
<td>Check that no forms are shimmed up more than ¼ in. (6 mm).</td>
<td>☐</td>
</tr>
<tr>
<td>5.</td>
<td>Make certain that all forms receive a light application of a form-release agent before casting the pavement.</td>
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<tr>
<td>6.</td>
<td>If wooden forms are used, ensure that they in good condition and have not been used too frequently.</td>
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### Placing Dowels (Section 4.3)

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<th>No.</th>
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<tbody>
<tr>
<td>1.</td>
<td>Check dowels for an approved, factory-applied debonding coat or plan and prepare to coat each bar with form release oil after baskets are placed. (Dowels for insertion must have factory-applied coating.)</td>
<td>☐</td>
</tr>
<tr>
<td>2.</td>
<td>After inspection of the subbase, and if you are placing dowel bar assemblies (baskets) manually, ensure that all baskets are aligned perpendicular to, and at the correct distance from, the pavement edge.</td>
<td>☐</td>
</tr>
<tr>
<td>3.</td>
<td>Check that all baskets are correctly aligned and adequately secured with stakes, pins, nails, and/or clips. View down the grade to ensure that all dowels are parallel to the centerline and across the basket to ensure all dowels are level and centered.</td>
<td>☐</td>
</tr>
<tr>
<td>4.</td>
<td>In intersection approaches and other areas where adjustments are likely to the joint locations, ensure that the dowel baskets are placed and marked correctly to the plan.</td>
<td>☐</td>
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</tbody>
</table>
**Placing Reinforcement (Section 4.4)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
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<tbody>
<tr>
<td>1.</td>
<td>If paving two lanes or more, check machine settings or chairs to ensure that all tiebars will be placed at the proper spacing and perpendicular to the longitudinal contraction joint(s).</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>When mechanically placing tiebars along a longitudinal construction joint, ensure that tiebars are being placed at the proper spacing by using a timing device. Check specifications of the owner/agency for the maximum allowable grade and bend for bent tiebars.</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Ensure that no tiebar is placed within 15 in. (380 mm) of a transverse joint.</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>For odd shaped slabs or areas requiring mesh reinforcement, ensure that welded wire fabric is set into place prior to paving. Once paved, lift this reinforcement to the proper depth. Alternatively, place the reinforcement on chairs before placing the fresh concrete.</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>For a continuously reinforced concrete pavement, ensure that the longitudinal reinforcement is placed at the proper depth in the slab per the project plans.</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Mark the location of every dowel basket on both sides of the roadbed by pens, colored nail heads, or paint marks to identify the location of a necessary sawcut at the center of the dowel basket. Be mindful and careful that the location tolerance for the joint cut is just 1.5 in. (38 mm) or less to either side of the actual center of the dowel, depending on its length.</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>For dowel bar insertors, check the carriage spacing and depth control settings to ensure proper dowel placement will be achieved.</td>
<td></td>
</tr>
</tbody>
</table>
## Paving Equipment Setup (Section 4.5)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Setup the slipform mold according to the manufacturer’s recommendations. In general, this will require an initial leveling of the paving machine’s frame, followed by a leveling of the slipform mold from front to back and side to side. Then, the slipform pan is typically adjusted for cross slope and edge slump.</td>
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<tr>
<td>2.</td>
<td>Setup the vibrators according to the manufacturer’s recommendations. Typically, this requires setting one vibrator between 6 and 8 in. (150 and 200 mm) from each edge of the slipform mold and uniformly spacing additional vibrators at an interval of approximately 12 to 24 in. (305 to 610 mm). Ensure that the vibrators are set up at the proper spacing and frequency so that the zone of influence of neighboring vibrators overlaps.</td>
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<tr>
<td>3.</td>
<td>Ensure that the slipform paving machine (i.e., the slipform paving machine’s frame and tracklines) is perfectly parallel to the stringline(s) by measuring the distance between the slipform paving frame at both the front and back of the machine and confirming that the two distances are equal. Consult your paving machine’s setup manual for more details.</td>
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<tr>
<td>4.</td>
<td>Check that neither the elevation nor the alignment sensing wand deflects the stringline by more than ( \frac{1}{8} ) in. (3 mm) and, if either wand does, adjust the wand tension appropriately. Consult your paving machine’s setup manual for more details.</td>
<td></td>
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<tr>
<td>5.</td>
<td>Confirm that the slipform paving machine is, in fact, perfectly parallel to the stringline(s) and that the elevation and alignment sensing wands are properly functioning by moving the slipform paving machine forward 20 to 30 ft (6 to 9 m) and repeating the previous two steps. Consult your paving machine’s setup manual for more details.</td>
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<tr>
<td>6.</td>
<td>Check the final grade and cross slope of the slipform mold. This may be done by arranging two rows of three stakes so that the top of each stake is exactly 1 in. (25 mm) below the finished grade, one stake is 2 ft (610 mm) from each edge, one stake is at the centerline, and the lines of stakes are offset by approximately 3 ft (915 mm). Once the stakes are setup, the slipform paving machine is driven on top of the stakes, the grade checked, and final grade and cross slope adjustments are made.</td>
<td></td>
</tr>
</tbody>
</table>
Concrete Mixture Analysis and Approval

Cement (Section 5.1)

1. Ensure that the water-cementitious materials ratio does not exceed the maximum of 0.50 for hand pours and 0.45 for slip-form paving, except in special circumstances.

Cementitious Materials Content (Section 5.2)

1. Ensure that the cementitious materials content of the mixture is optimized for the same reasons as noted in Number 1 of the Section 5.1 checklist.
2. Check that the dosage of supplementary cementitious materials is within the allowable range of the owner/agency (typically, fly ash and slag cement dosages do not exceed 25% to 50%, by weight, respectively, although special circumstances might allow for even higher addition rates).

Water-Cementitious Materials Ratio (Section 5.3)

1. Ensure that the water-cementitious materials ratio does not exceed the maximum of 0.50 for hand pours and 0.45 for slip-form paving, except in special circumstances.
## Aggregates (Section 5.4)

<table>
<thead>
<tr>
<th>No.</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Check that the coarse and fine aggregates, combined, make up 60% to 75% of the total concrete volume.</td>
</tr>
<tr>
<td>2.</td>
<td>Check that the proportion (by weight) of coarse-to-fine aggregates is around 60/40 (roughly 55% to 65% coarse and 35% to 45% fine).</td>
</tr>
<tr>
<td>3.</td>
<td>Ensure that aggregates, both coarse and fine, pass any applicable tests for freeze-thaw durability, alkali-silica reactivity, alkali-carbonate reactivity and “D” cracking susceptibility.</td>
</tr>
<tr>
<td>4.</td>
<td>Ensure that the combined aggregate gradation is properly analyzed and passes all specifications. In doing so, the result should be a well-graded mixture that will provide a workable, strong, and durable concrete.</td>
</tr>
<tr>
<td>5.</td>
<td>Ensure that the fineness modulus of the fine aggregate is analyzed. (A FM of 3.0 to 3.5 or higher works best for concrete paving mixtures and a minimum of 2.7 is recommended.)</td>
</tr>
<tr>
<td>6.</td>
<td>Check that aggregates are clean and free of contaminants such as clayballs. Dirty (dusty) aggregates cause paving consistency and quality problems. Wash dirty aggregate before stockpiling for use or make arrangements with aggregate suppliers to improve materials. Ensure the cleanliness of the aggregates when batching concrete.</td>
</tr>
<tr>
<td>7.</td>
<td>Maintain aggregate stockpiles at a surface moisture condition of saturated surface dry (SSD) or greater.</td>
</tr>
</tbody>
</table>
Testing (Section 5.5)

No. Task

1. Prior to using a new concrete mixture in the field, ensure that a sufficient number of tests have been conducted in a laboratory to fully characterize its properties and understand possible strengths and weaknesses. Evaluate the mixture at different temperatures to understand potential constructability affects when paving in the field.

2. Ensure uniformity, quality, and conformance to specifications (ASTM C94 or project specific specifications) at the jobsite by testing the concrete for temperature (ASTM C1064), slump (ASTM C143/AASHTO T119), density (ASTM C138 / AASHTO T121), and air content (ASTM C231 / AASHTO T152; ASTM C457). Also conduct compressive (ASTM C39/AASHTO T22) and/or flexural (ASTM C78/AASHTO T97) strength testing and/or maturity method testing (ASTM C1074/AASHTO T325) to ensure conformance with strength requirements.

3. Ensure that all testing and field crews understand that concrete should not be qualified on slump; slump is only appropriate for comparing batch-to-batch consistency and for process control.

4. Ensure that all testing and field crews are educated not only on the testing procedures, but also on how to interpret results. Early detection of problems, such as sudden drops in unit-weight, will allow real-time process control and reduce mixture-related paving/durability problems.

Complete
CHAPTER 1
Joint Layout

Key Points:

- **Joint layout is critical for prevention of uncontrolled cracks, especially for complex geometries and intersections.**
- A systematic approach to joint layout, along with some simple rules, will ease joint layout for almost any project.
- Adjustments to joint layout can be made in the field, as long as all possible outcomes are taken into consideration.

Ideally, the joint layout for a concrete pavement is determined while developing the project plans. If so, the designer will produce views that illustrate the bird’s eye view of the joint layout for the entire project. However, even with such plans, it can still be difficult to visualize the entire project layout during construction. Some of the most difficult areas to visualize are intersections, because they require such specialized construction staging practices.

In most cases, an engineer or designer develops the joint layout plan without knowledge of the specific contractor, equipment, or process that will be used to construct the pavement. For this reason, some agencies do not provide a pre-developed jointing plan, but instead require the contractor to submit a proposed joint layout plan prior to the initiation of paving. This allows the contractor full flexibility of the joint layout, with the ability to customize the construction process, phasing, and equipment used.

Appropriate field adjustments often also are necessary for complex projects. Elements such as islands, medians, ramps, and turning lanes complicate joint layout. Thus, some forethought is required before construction, but tweaking of the joint layout is typically acceptable in the field as long as the contractor is aware of any possible consequences. An approximate proposed jointing plan, however, does aid contractors in more accurately bidding a project.
During construction, it is likely that location changes will be necessary for some joints. The primary reason is to ensure that joints pass through embedded fixtures, such as manholes or drainage inlets. It is common for the actual location of manholes or drainage inlets to vary from the location shown on the plans. As a result, it is desirable for the construction crew to adjust the location of the necessary joints to coincide with the actual location of any in-pavement object. The designer should consider placing a note on the plan to give the field engineer and contractor the latitude to make appropriate adjustments in the field.

The transverse and longitudinal contraction joints in concrete pavement primarily are necessary to control cracking. The desirable transverse joint spacing depends on the slab thickness and subgrade/subbase support, but is usually about 15 ft (4.5 m). On typical roadway pavements, longitudinal joints divide lanes of traffic and, in most cases, are no more than about 12 ft (4 m) apart (Figure 1.1).

Figure 1.1. A newly constructed, typical roadway with transverse joint spacing of approximately 15 ft (4.5 m) and lane widths of approximately 12 ft (4 m). Note that the longitudinal saw cuts (part of planned tied contraction joints) will help delineate the roadway into a passing lane, a truck lane, and a shoulder.

### 1.1 Joint Types

There are three basic joint types for concrete pavements: contraction, construction and isolation. Specific design requirements for each type depend upon orientation to the direction of the roadway (transverse or longitudinal). Figure 1.2 provides cross-sections detailing each type.
Figure 1.2. Cross sections of different joint types.
**Transverse Contraction Joints (Type A-1 or A-2)** – Joints that run transverse to the pavement centerline and are essential to control cracking from stresses caused by shrinkage, thermal contraction, and moisture or thermal gradients. Typically these joints are at a right angle to the pavement centerline and edges.

The need for dowels (smooth round bars) in transverse contraction joints depends upon the roadway or street classification. Undoweled contraction joints (Type A-1) are usually sufficient for light residential, residential, or collector pavements. Industrial and arterial streets that will carry heavy truck traffic for long periods require doweled contraction joints (Type A-2).

**Transverse Construction Joints (Type B-1 or C-1)** – Joints that are necessary at the end of a paving segment, or at a placement interruption for a driveway or cross road. A doweled butt joint (Type B-1) is preferable, and should be used whenever the construction joint will correspond to the location of a contraction joint or construction joint in an adjacent lane. Sometimes it is not feasible to match the location of a transverse joint in the adjacent lane, which necessitates use of a tied construction joint (Type C-1). The deformed tiebars in a Type C-1 joint prevent the joint from opening and causing sympathy cracking in adjacent lane(s).

**Longitudinal Contraction Joints (Type A-3 or A-4)** – Joints that are necessary to control cracking from stresses caused by concrete volume changes and moisture or thermal gradients. These joints run parallel to the pavement centerline and usually correspond to the edge of a driving lane. On two-lane and multilane pavements, a spacing of 10 to 13 ft (3.0 to 4.0 m) serves the dual purpose of crack control and lane delineation.

The need to tie longitudinal contraction joints will depend upon the degree of lateral restraint available to prevent the joints from opening permanently. Most longitudinal contraction joints on roadway tangent sections contain No. 4 or No. 5 (#13M or #16M) deformed reinforcing bars. The deformed bars are usually about 24 – 30 in. (600 – 750 mm) long and are spaced at 30 – 40 in. (750 – 1000 mm) intervals. Where there are curbs on both sides of the pavement, it may not be necessary to tie the joints unless local experience indicates otherwise.

**Longitudinal Construction Joints (Type B-2 or C-2)** – Joints that join pavement lanes that are paved at different times. Concrete intersections require these joints because of the numerous pours necessary to place pavement around islands and medians, and between the curves connecting the two roadways.

The optional keyway for a tied longitudinal construction joint can be difficult to construct correctly in thin pavements. Therefore, some agencies avoid placing keyways in slabs less than 10 in. (250 mm) thick. Keyway shear failures can occur in thin slabs when keyways are too large or too close to the slab surface. Some
contractors report that half-round keyways are easier to construct and less prone to problems than trapezoidal keyways.

**Isolation Joints (Type D-1, D-2, D-3 or D-4)** – Joints that are essential at asymmetrical and T-intersections to isolate the side road from the through street. Isolation joints also are needed where the pavement abuts certain manholes, drainage fixtures, sidewalks, aprons, structures, etc. Certain agencies and contractors also prefer to use isolation joints at crossroad intersections. Where used, the isolation joint will allow independent movement of the pavement and the structure, without any connection that could cause damage.

At asymmetrical or T-intersections, undoweled, thickened edge or sleeper-slab isolation joints (Type D-1 or D-3) are preferable to doweled isolation joints, because they each permit independent lateral movement of the through-street concrete slabs. The sleeper slab and thickened edge designs each provide improved support to compensate for the absence of dowel bars. For a thickened edge joint, the abutting edges of the concrete slabs should be 20% thicker at the joint and taper back to the nominal thickness over at least 4.5 ft (1.5 m).

### 1.2 Special Considerations for Intersections

Because the transverse and longitudinal joint spacings usually are not identical, it is difficult to maintain an even spacing on either roadway in an intersection.

The 10-step method described in this publication (Section 1.4) provides solid joint layout fundamentals, especially for confusing areas such as intersections. Examples show both right angle and skewed intersections. The detailed diagrams show preferable alternates, but there may be certain intersections with unique geometries that the methodology can not adequately address.

A primary goal of this method is to minimize or eliminate joints that intersect another joint or the pavement edge at an acute angle. Experience shows that cracks often occur near acute angles, especially angles less than 60°. For most intersections, it is possible to eliminate all angles less than 90° from the roadway slabs, but some acute angles in the curb and gutter may still exist. For skewed intersections, it is likely that some joints will intersect at angles less than 90°. However, even for skewed intersections, it is preferable to avoid angles less than 60°.

The 10-step method works equally well for separate and integral curbs and gutters. The sample diagrams here show how to place joints through curbs and gutters, and along curves between the intersecting roadways. The 10-step method also helps the designer produce a plan that is easier to construct because it avoids width changes along the edge of the mainline or primary paving lane(s).
Joint Layout Terminology:

Isolation Joint: A pavement joint that allows relative movement in three directions, avoids formation of cracks elsewhere in the concrete, and through which distributed reinforcement is interrupted. Allows large closure movement to prevent development of lateral compression between adjacent concrete slabs; usually used to isolate bridges, manhole blockouts, drainage inlets, and other in-pavement structures. Sometimes referred to as an expansion joint.

Doglegs: Construction block-outs at points where the pavement changes width.

Circumference-Return Line: A lightly drawn line 1.5 to 3.0 ft (0.5 to 1.0 m) from the face of the gutter along the curve between the edges of the intersecting roads. Any joint that meets the circumference-return line is brought along the curve’s radius to the back of the curb and gutter. Older publications use the term “off-set points” to refer to the points where the joints return to the back of curb along a radius.

Taper-Return Line: A lightly drawn line 1.5 ft (0.5 m) from the face of the gutter at the start of a turn lane taper. Any longitudinal joint that meets a taper-return line defines a location for a dogleg in the gutter.

Crossroad-Return Line: A lightly drawn line 1.5 ft (0.5 m) from the edge of the mainline roadway at a skewed intersection. Any crossroad longitudinal joint will meet a transverse joint from the mainline roadway at the crossroad return line.

Intersection Box: The box formed by the edge of the mainline and intersecting paving lanes (including turning lanes).

1.3 Rules for Joint Layout

Things to Do:
- Match existing joints or cracks.
- Place joints to meet in-pavement structures.
- Remember maximum joint spacing.
- Place isolation joints where needed.
- Understand that adjustments to joint locations can be made in the field.
- Be practical.

Things to Avoid:
- Slabs < 2 ft (0.6 m) wide.
- Slabs > 15 ft (4.5 m) wide*.

*ML = smallest of:
15 ft for streets, roadways, and highways
D x 24 for slabs on unstabilized (granular) subbases
D x 21 on stabilized subbases
Where:
ML = maximum slab length or width
D = slab thickness
- Angles < 60° (~90° is best); do this by dog-legging joints through curve radius points.
- Creating interior corners.
- Odd shapes (keep slabs near-square or pie-shaped).

### 1.4 The 10-Step Method for Intersections

**Step 1:** Draw all pavement edge and back-of-curb lines in the plan view. If integral curbs and gutters are to be used, draw only the back-of-curb lines.

**Step 2:** Lightly draw the circumference-return, the taper-return, and the crossroad-return lines as offsets of 1.5 to 3.0 ft (0.5 to 1.0 m).
**Step 3:** Draw all lines that define lanes on the mainline and crossroad. Do not extend these lines past the circumference-return, taper-return, or crossroad-return lines.

**Step 4:** Define the mainline lanes for paving. Find all locations where the crossroad intersects the mainline paving edges and, at these locations only, extend the mainline paving edge lines past the circumference-return or taper-return line(s). Blockouts & doglegs will occur in the gutter at these locations.
Step 5: Add transverse joints at all locations where a width change occurs in the pavement (begin and end of tapers, tangents, curves, curb returns, etc.) and extend these joints through the curb and gutter and/or concrete barrier walls that are not isolated from the adjacent pavement. On the cross road(s), the joint at the tangent point farthest from the mainline becomes an isolation joint.

Step 6: Add transverse joint(s) between and beyond the joints defined in Step 5, but do not add joints to the center of the intersection. Attempt to keep the distance between joints the same, and less than the maximum desirable length (approximately 15 ft [4.5 m]).
Step 7: Extend the edge of pavement lines for the mainline and crossroad to define the intersection box. (Note: For skewed intersections, do not extend the lines for the turning lanes. Instead, place a transverse joint normal to the crossroad centerline starting from the corner of the intersection box that is nearest to the acute angle of the intersection. See Section 1.5 for a skewed intersection example.)

![Diagram of concrete pavement with transverse joints and intersection lines]

Step 8: Check the distances between the intersection box and the surrounding joints. If the distance is more than the maximum desirable joint spacing, add transverse joint(s) at an equal spacing. Do not extend these joints past the circumference-return or cross-road return lines.

![Diagram of concrete pavement showing transverse joints and spacing]

**Step 9:** Lightly extend lines from the center of the curb return radii to the points defined by the intersection box, any intermediate joints surrounding the intersection box, and any point(s) along an island. Add joints along these radius lines. Also, make slight adjustments to eliminate doglegs in mainline edges. (See Details A, B, and C on page 30.)

**Step 10:** Make any additional adjustments for in-pavement objects and ensure that all of the “rules” are followed.
**Avoiding Acute Angles**
The following figures provide recommended jointing details at curb and gutter sections in order to avoid acute angles and the associated unwanted cracking.

**Detail A:**
Width change and dogleg in gutter near point of curvature.

**Detail B:**
Width change and dogleg in gutter near start of taper.

**Detail C:**
Width change and dogleg in paving slab for hand-pour areas.
1.5 Alternate Skewed Intersection Layout

For a skewed intersection with offset or compound radius curves or simple curve radii greater than 100 ft (30 m), a layout similar to Figure 1.3 can simplify field construction when the contractor builds the curve area in a single pour (indicated by the shaded area).

It is necessary to add an additional longitudinal joint near the center of the slabs that exceed the maximum width of 15 ft (4.5 m). This additional joint should prevent the occurrence of a longitudinal crack in these slabs. It is desirable to begin and end the additional longitudinal joint at transverse joints, as shown in Figure 1.3. To prevent sympathy cracking, some agencies core a small 2 in. (50 mm) hole at the ends of this longitudinal joint, while others cast the hole in the slab with the use of plastic pipe (Figure 1.4). The hole can be filled with sand, rigid foam, or other filler, and then topped off with joint sealant material.

Figure 1.3. Skewed intersection joint layout with shaded area indicating a single placement. Note the optional core hole to prevent the continuation of the longitudinal joint (sympathy cracking).
Figure 1.4. Series of photographs showing formed hole, which is intended to eliminate sympathy cracking into adjacent panels.

a. Plastic pipe half attached to form to create a "hole."

b. Plastic pipe half attached and ready for concrete placement.

c. Plastic pipe half attached to formwork just prior to the concrete pour.

d. After paving, the plastic pipe halves are removed.

Figure 1.4. Series of photographs showing formed hole, which is intended to eliminate sympathy cracking into adjacent panels.
Another alternative is to expect that the joint will continue into the adjacent panel, and then reinforce the area to keep the crack tight or prevent it from becoming a maintenance problem. In this case, some contractors place three #5 bars (16 mm) parallel to the transverse joint to arrest any potential sympathy cracks (Figure 1.5).

**1.6 Handling Wide Medians and Dual-Left Turn Lanes**

Large urban and suburban intersections that contain dual-left turn lanes can create joint alignment challenges. The medians in these large intersections are often up to 30 ft (9.2 m) wide. Figure 1.6 shows how to skew joints through the intersection box in order to maintain the joints along the lane lines for dual-left turn lanes. The ability to use this method will depend on construction staging; it is just one option to apply for complex intersections. An alternative method is to move the isolation joints closer into the intersection. This is, however, less desirable because isolation joints usually require more maintenance.
1.7 Roundabouts

Roundabouts are an increasingly popular intersection type due to their traffic flow and safety characteristics. Concrete is well suited to withstand the turning motion of vehicles at roundabouts, but the joint layout requires forethought. Adhering to the rules for joint layout (see Section 1.3), along with the following six steps, will ensure a successful joint layout:

Figure 1.6. Offset, opposing dual-left turn lanes require skewing some joints to match up.
**Step 1:** Draw all pavement edge and back-of-curb lines in the plan view. Draw locations of all manholes, drainage inlets, and valve covers so that joints can intersect these.

**Step 2:** Draw all lane lines on the legs and in the circular portion. If isolating the roundabout circle from the legs, do not extend these through the circle. If using the “pave-through” method, determine which roadway will be paved through. Make sure no distance is greater than the maximum recommended width (15 ft [4.5 m] is the typical maximum width).
Step 3: In the circle, add “transverse” joints radiating out from the center of the circle. Make sure that the largest dimension of a pie-shaped slab is smaller than the maximum recommended slab width. Extend these joints through the back of the curb & gutter.

Step 4: On the legs, add transverse joints at all locations where a width change occurs (at bullnose of median islands, beginning and end of curves, tapers, tangents, curb returns, etc.). Extend these joints through the back of the curb and gutter.

Step 5: Add transverse joints beyond and between those added in Step 4. Space joints out evenly between other joints, making sure not to violate the maximum joint spacing.
**Step 6:** Make adjustments for in-pavement objects, fixtures, and to eliminate L shapes, small triangular slabs, etc. Ensure isolation joints are used surrounding all islands.

*Figure 1.7. A completed isolated circle roundabout.*
### 1.8 Cul-de-sacs

Joint layout for cul-de-sacs also can be accomplished by following the rules for joint layout (see Section 1.3) and the 10-step method (see Section 1.4). Figure 1.8 provides two examples of cul-de-sac joint layouts. It is important to note that these examples show only specific instances of typical joint layout practice. If the street width, cul-de-sac radius, or geometric design is substantially different than what the figures depict, then a different joint layout will be necessary.

**Figure 1.8a. Example of a joint layout for cul-de-sac with separate curb and gutter.**

**Figure 1.8b. Example of a joint layout for cul-de-sac with integral curb and gutter.**
1.9 Adjusting Joints for Utilities and Boxing out Fixtures

When a joint is within 5 ft (1.5 m) of a fixture, it is desirable to adjust the joint so that it will pass through the fixture or the boxout surrounding the fixture.

After developing the jointing plan, plot any catch basins, manholes, or other fixtures that are within the intersection. Non-telescoping manholes will require a boxout to allow for vertical and horizontal slab movement. Consider using rounded boxouts or placing fillets on the corners of square boxouts to avoid corners that may induce cracking. Also, for square boxouts, using wire-mesh or small-diameter reinforcing bars in the concrete around any interior corners will hold cracks tightly, should they develop. Telescoping manholes can be cast integrally within the concrete and do not necessarily require a boxout. The two-piece casting does not inhibit vertical movement and is less likely to create cracks within the pavement.

Future expansion and contraction of the concrete surrounding embedded fixtures must be considered. Figure 1.9 shows options for isolating manholes, valve covers, drainage inlets, and other utility vaults.

![Figure 1.9. Boxout options for manholes and drainage inlets.](image-url)
CHAPTER 2
Subgrade

Key Points:

- Concrete pavements distribute applied loads so efficiently that little pressure is exerted on the subgrade.
- Uniform support is the primary concern; strength of support layer is secondary.
- If the subgrade can support construction equipment during construction, then it is strong enough to support a concrete pavement.
- Expansive soils should be addressed by proper mixing and grading and/or chemical stabilization.
- Frost heave, if of concern, can usually be addressed in grading operations. The pavement roadbed should extend to at least the depth of frost penetration wherever possible.

The subgrade is the natural ground, graded and compacted, which supports any subbases and the pavement. A reasonably uniform subgrade, with no abrupt changes in support, is ideal for any concrete pavement. The actions required to attain uniformity may vary considerably, depending on the subgrade soil type, environmental conditions, desired performance, and expected amount of heavy truck or bus traffic. In any case, the objective is to obtain a condition of uniform support for the pavement that will prevail throughout its service life. The major causes of non-uniformity are expansive soils and frost heave.

Where subgrade conditions are not reasonably uniform, correction is most economically and effectively achieved by proper subgrade preparation techniques such as selective grading, cross hauling, mixing at abrupt transitions, stabilization, and moisture-density control of subgrade compaction. Correction also may be achieved by using non-frost susceptible materials below the subbase layers down to the average depth of frost penetration.

For light traffic pavements – such as residential streets, secondary roads, and parking lots – the use of a subbase is not required if both an adequate construction
platform and pavement support can be obtained through proper subgrade preparation techniques such as compaction and/or stabilization.

## 2.1 Problematic Soils

Regardless of project type, the first step is to examine existing soils and determine potential problems such as swelling (expansive soils) and heaving (frost action).

### 2.1.1 Expansive Soils

The key to dealing with expansive soils is to first identify their expansive characteristics and then to determine the most appropriate treatment. Most soils that are sufficiently expansive to cause pavement distortion are classified in the AASHTO A-6 or A-7 groups. By the Unified Soil Classification System, soils classified as CH, MH, and OH are considered expansive. Experience has shown that soils with plasticity index (PI) values greater than 25 are very expansive and present a significant concern when used as a roadbed for pavements.

Expansive soils can be addressed by:

1. **Proper Grading** – Remove highly expansive soils. Put marginally expansive soils in the bottom of fills. Surcharge loads greatly reduce the potential for expansion. Marginal soils can also be mixed and blended with better quality materials.

2. **Moisture-Density Control** – Compact expansive soils slightly wet of optimum moisture content.

3. **Non-Expansive Cover** – Install a layer of non-expansive cover such as a 4- to 6-in. (100-150 mm) compacted unstabilized (granular) subbase.

4. **Chemical Modification** – Use cement, cement kiln dust, fly ash, lime, or other chemical agents to stabilize the soil and reduce swelling potential.

### 2.1.2 Frost Susceptible Soils

Subgrades that are particularly susceptible to frost action and subsequent heaving are low-plasticity, fine-grained soils with a high percentage of silt-size particles. These soils have pore sizes small enough to promote capillary action, yet large enough to permit migration of water to the frozen zone. Coarser soils could accommodate higher rates of flow, but do not have the capillary potential to lift enough moisture for heaving. Soils that are more cohesive have high capillary potential, but low permeability, thus water moves too slowly for thick ice lenses to grow.

Frost heave is most often found at the following locations:

- Transitions from cut to fill.
• Where ditches are inadequate or non-existent.
• Over culvert pipes.
• Adjacent to driveways that dam roadside ditches and/or collect water.
• Where there is an abrupt change in subgrade material.

Control of frost heave is accomplished by:

1. Grade and Water Table – Set grade lines high and ditches low, so that the grade remains 4 to 5 feet (1.2 to 1.5 m) above the bottom of the ditch.

2. Mixing and Grading – Place frost-susceptible soils in the bottom of fill sections, and cross-haul and mix marginal soils with better subgrades on the project. Transition and blend soils where the roadway cross-section changes from cut to fill (and vice-versa).

3. Removing Silt Pockets – Excavate and backfill these areas with soil similar to the surrounding subgrade.


5. Drainage – If high grades are impractical, install underdrains/subdrains to lower the water table.

6. Frost-Free Layer – Aggregate subbase layers will help reduce frost heave, although subbase thicknesses greater than 8 inches (200 mm) are generally not recommended.

2.2 Uniformity and Stability

The second step in subgrade preparation is to ensure that the subgrade soils are relatively uniform and compacted to the proper density. Uniformity is usually achieved during remediation of expansive and frost-susceptible soils. However, if subgrade remediation techniques are not necessary, some cross hauling or mixing of soils still may be needed to achieve consistent properties across the length of the project.

Proof rolling is a useful technique to check for uniformity of support. Proof rolling is typically accomplished using a loaded 10-wheel dump truck, or similar pneumatic-tire vehicle, driven slowly over the subgrade. The degree to which the tires rut and push the grade indicates uniformity, with deeper ruts indicating softer spots. Testing using a cone penetrometer is also a useful check of uniformity of the subgrade (Figure 2.1).
Chemical modification is a treatment used when localized pockets of undesirable material cannot be removed and replaced with the dominant soil type or with select backfill. Where chemical modification is specified, additional steps are necessary so the foundation will provide uniform support to the rest of the pavement structure (Figures 2.2, 2.3).
Typical stabilizing additives include the following:

- **Portland or blended cement**: Hydrates with moisture in the soil and hardens. Cement performs best with well-graded, sandy, and gravelly materials having 10 to 35 percent fines. More cement is usually needed for soils with few or no fines, as well as with clayey soils.

- **Fly ash**: When mixed with soil and water, it acts as a binder. Self-cementing Class C fly ash is useful for treating subgrades; Class F fly ash may also be used but it must be used in conjunction with an activator (such as lime) because it is not self-cementing.

- **Lime**: Either pebble quicklime or hydrated lime, either high calcium or dolomitic. Through chemical reactions with soil, lime reduces soil plasticity and increases compressive strength. Lime is sometimes used to stabilize wet soils.

### 2.3 Construction

The site is first graded to cut high points and fill low areas to the desired roadway profile elevations. Generally, cut material is used as embankment fill. However, peat, organic silt, or soil with high organic content should not be used; select borrow material should be used instead.

Before compacting, subgrade material may have to be brought to (or slightly above) the optimum moisture content. The subgrade must be thoroughly compacted to provide a strong platform for construction activities. For clayey soils, a sheepsfoot roller is typically used (Figure 2.4). Adequate compaction of the subgrade surface typically requires a compactor heavy enough to achieve a minimum of 95 percent
AASHTO T99 (alternatively, ASTM D698) density, although local specifications may vary. For confined areas, smaller equipment may require more time or passes to achieve density.

![A sheepsfoot (or pad foot) roller is excellent for compacting subgrade soils.](image)

The soil moisture content should be reasonably uniform during compaction; excessively wet or dry spots typically require correction to produce uniformity. For most soils, the best results occur when compaction is at moisture contents at or slightly (1% to 2%) above optimum.

Pay particular attention to sections of the subgrade overlying any utility installations, such as culverts, sewers, drainage structures, water mains, telecommunication lines, and power conduits. Careless compaction of fill materials in these trenches often causes weak layers and excessive settlement in the subgrade. Controlled low-strength material (flowable fill) is an economical alternative for backfill in these areas.

Proof rolling after backfill compaction is helpful to locate soft areas that may require additional corrective action. Non-destructive testing methods, such as the cone penetrometer (Figure 2.1), also are useful to verify uniform compaction/support.

After achieving acceptable uniformity and compaction, the grade must be trimmed to the profile grade in the plans. Typical specifications may require a subgrade surface that does not vary from the design elevation by more than 0.5 in. (13 mm). An electronically controlled trimming machine provides excellent results and accuracy. The trimmer may run off a stringline for both elevation and alignment control or it may be GPS controlled. Trimming should occur within a week of proof rolling.

The primary steps for the proper subgrade preparation and construction are summarized in Figure 2.5.
Chapter Two – Subgrade

Steps/Description

Unstabilized Subgrades

Initial Grading, Compaction, and Finish Grading

Grade the subgrade soil to the line and grade required by the roadway plans. Cross haul materials to avoid abrupt changes in subgrade character. Compact the subgrade soil, adding water, as needed to achieve the optimum moisture content for compaction (density).

Identify excessively soft spots and then, either undercut and replace the soils, or pre-treat with a stabilizing agent. Compact the subgrade again in areas where soft pockets are replaced with improved fill.

Protect the subgrade from rain by “tight blading” and finishing with a smooth drum roller.

Fine grade the subgrade to the shape of the typical section and to plan elevation within grade tolerance. Finish grading operations, which may take place anytime after final compaction occurs.

Chemically Stabilized Subgrades

Initial Grading and Compaction

Trim the subgrade. Finish the grade below the final grade elevation to allow for the increased volume from addition of the subgrade modifying material. Consider the density of the untreated subgrade and the volume of stabilizing material when estimating how far below finish grade to be after the initial shaping. Failure to leave the grade low after initial shaping will result in a modified subgrade layer that is thinner than designed, because it will need to be trimmed more during finish grading operations to meet grade elevation tolerances.

Spreading and Mixing Modifying/Stabilizing Materials and Compacting

Spread stabilizing agent as evenly as possible. Uniform spreading is vital to uniformly controlling the volume change of expansive soils and to achieving uniform support for the subbase and pavement layers. As dosage rates decrease, uniform spreading becomes even more critical with respect to constructing a consistent and uniform subgrade.

For Soil Modification with Cement:

• Mix, add water, and compact the stabilized soil mixture in a continuous operation to assure that final compaction is achieved in 2 hours or less.
• Target a moisture content within 2 percent optimum.
• When prepared properly, a minimum of 60% of the modified soil mixture should pass a #4 (4.75 mm) sieve. Most modern equipment is capable of achieving this gradation requirement in one pass. If pre-mixing is required, it should be done without the addition of water. The 2 hour working period begins when substantial water is added to the modified soil mixture during the final mixing operation.
• Matching of multiple longitudinal passes should be done carefully to avoid excessive overlap between passes. Areas that are mixed twice are subject to breaking the soil particle bonds and to addition of water twice, which can lead to non-uniform results.
• Attempts to further compact soils after the 2 hour time frame can be detrimental to the strength (capacity to control volume change) of the modified soil mixture. Strict adherence to the 2 hour working period should take precedence over strict adherence to density requirements.

For Soil Modification with Lime:

• Use either pebble quicklime spread in a dry state or hydrated lime, slaked and spread as a slurry. Regardless of which form is used, metering the application from the equipment is preferable.
• Mix and add water simultaneously to ensure complete hydration of the lime before final mixing occurs. Target a moisture content from optimum to optimum plus 5 percent.
• Lightly compact the modified soil and grade to drain excess water.
• Let the stabilized soil sit idle for a 24 to 72 hour mellowing period.
• Re-mix the grade, adding water as necessary and recompacting. Target a moisture content of optimum plus 3 percent.
• When prepared properly, a minimum of 60% of the modified soil mixture should pass a #4 (4.75 mm) sieve.

Finish Grading

The final thickness of the modified subgrade layer which impacts uniform support of the subbase and pavement is dependent upon the accuracy of initial shaping of the subgrade and the finish grading operations. Maintain moisture in the modified subgrade before, during and after (until subbase/pavement is placed up to 7 days) finish grading operations.

Curing

In lieu of continuous sprinkling, a bituminous prime coat may be placed to as a curing coat to maintain the moisture in the modified subgrade until succeeding layers are constructed.

Figure 2.5. Construction processes for subgrades, with special considerations for lime and cement modified soils.
CHAPTER 3
Subbase

Key Points:

• A subbase is a select or engineered layer of planned thickness placed between the subgrade and a concrete pavement. It serves one or more functions such as preventing pumping, distributing loads, providing drainage, minimizing frost action, or facilitating pavement construction.

• Thick subbases (greater than 6 in. [150 mm]) are typically not beneficial, and therefore are not recommended.

• A minimum of 95% AASHTO T99 (alternatively, ASTM D698) density is generally adequate for subbases.

• Stabilized (treated) subbases offer excellent support, but require careful attention to bonding issues, shorter joint spacing, and deeper joint sawcuts.

• The width of the subbase should accommodate the paving equipment by extending approximately 3 ft (1 m) beyond the width of the pavement on each side. This will provide a stable, all-weather working platform for the paving equipment.

3.1 Subbase Design

A subbase is a select or engineered layer, consisting of an unstabilized (granular) material, or a stabilized material (asphalt-treated (ATB), cement-treated (CTB), or lean concrete), placed atop the prepared subgrade. Subbases serve two primary purposes – providing uniform support to the pavement for the life of the pavement and providing a stable platform for construction equipment. Subbases also help prevent pumping of fine-grained subgrade soils at transverse pavement joints in roads subject to a large volume of unidirectional truck traffic. Parking lots, low-volume roadways, and even some streets that may carry a few heavy vehicles a day usually do not require a subbase, but one may be included to ensure uniformity and to provide the contractor a quality working platform during construction.
Recommended minimum subbase thicknesses are 4 in. (100 mm) for unstabilized (granular) subbases, 4 in. (100 mm) for cement-stabilized subbases (i.e., CTB and lean concrete subbases), and 2 in. (50 mm) for ATB. However, subbase thicknesses generally should not exceed 4 to 6 in. (100 to 150 mm); a thicker subbase is not necessary or economical under most conditions. Recycled materials (i.e., recycled aggregate, recycled concrete, etc.) can be used in any subbase type and fly ash is commonly included in cement-stabilized subbases.

One of the most significant design considerations is the use of a smooth, stable track line (or pad line) by the specifier. The track lines are the paths that a slipform paving machine’s tracks will follow. These tracks are usually about 3 ft (1 m) to either edge of the width of paving (Figure 3.1). To ensure a smooth pavement, provide the prepared subgrade and subbase layer beyond the edge of the pavement lane and across the track line. Some agencies pay for the track line because they understand its profound influence on smoothness and quality. Extending the prepared subgrade and subbase layers also contributes to edge support, which prevents settlement of shoulders or curb and gutter sections.

3.1.1 Unstabilized (Granular) Subbases
The gradation of the aggregates in an unstabilized (granular) subbase is critical. Ideal materials are very stable, but also free-draining (i.e., target permeability of about 150 ft/day (45 m/day), but no more than 350 ft/day (107 m/day), in laboratory tests). Unstabilized subbases should be compacted to no less than 95% of AASHTO T99 (alternatively, ASTM D698) density, particularly for subbases that use a stone
gradation with a significant amount of voids. A typical aggregate subbase gradation is shown in Table 3.1.

If a free-draining subbase material is too open-graded, the desired density cannot be achieved without crushing the subbase material during compaction, especially for softer aggregates. If this occurs, the subbase gradation is altered in place. In this case, the contractor cannot be held responsible for changes in gradation of the material.

To pass density tests, the contractor may need to increase the subbase water content well over the optimum to attain a measurement comparable to the desired density level. The open-graded nature of the material allows the voids to be easily filled with the added water, thus increasing measured density. This additional water

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Percent passing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spec</td>
</tr>
<tr>
<td>1 in.</td>
<td>25 mm</td>
</tr>
<tr>
<td>½ in.</td>
<td>12.5 mm</td>
</tr>
<tr>
<td>#4</td>
<td>4.75 mm</td>
</tr>
<tr>
<td>#30</td>
<td>600 μm</td>
</tr>
<tr>
<td>#200</td>
<td>75 μm</td>
</tr>
</tbody>
</table>

*Note: These gradations are not necessarily recommended.

is not, however, a suitable substitute for the mid-sized particles (i.e., coarse sandy material) that should fill the voids.

Good dense-graded, granular subbase materials have a plasticity index (PI) of 6.0 or less, and contain a maximum of 15 percent fine particles (pass the No. 200 (75 μm) sieve).

### 3.1.2 Stabilized (Treated) Subbases

Stabilized or treated subbases include asphalt-treated, cement-treated, and lean concrete subbases. The benefits of these stabilized subbases include:

1. Provide a stable working platform to expedite all construction operations and permit large daily production of concrete pavement with minimum downtime for inclement weather.
2. Produce firm support for slipform pavers or side forms.
3. Help construct smooth pavements due to stable track lines for slipform pavers.
4. Prevent subbase consolidation under traffic.
5. Reduce pavement deflections from vehicle loadings.
6. Provide improved load transfer at pavement joints.
7. Minimize intrusion of hard granular particles into the bottom of pavement joints.
8. Provide a more erosion-resistant subbase surface.

Granular materials in AASHTO Soil Classification Groups A-1a, A-2-4, A-2-5, and A-3 are used for treated subbases. They contain not more than 35 percent passing the No. 200 (75-μm) sieve, have a plasticity index (PI) of 10 or less, and may be either pit-run or manufactured. Treated subbases have been built with A-4 and A-5 soils in some non-frost areas successfully; however, such soils are not generally recommended for subbases in areas affected by frost or where large volumes of heavy truck traffic are expected. The use of A-6 and A-7 soils is not recommended for stabilized subbases under any circumstance. To facilitate accuracy during the subbase grading operation, the maximum aggregate size in the material usually is limited to 1 in. (25 mm), and more preferably to ¾ in. (19 mm).

Lean concrete (econocrete) subbases are typically designed for a specific application and environment. In general, they use aggregates that do not necessarily meet quality standards for conventional concrete. Lean concrete mixtures use a single aggregate rather than using both coarse and fine aggregates. The cement content is selected based on a target strength and it is less than that for normal concrete.

3.1.3 Permeable (Drainable) Subbases

Permeable subbases, also known as “drainable subbases” or “open-graded subbases,” became a very popular design element for concrete highway pavements in the 1990s. These subbases are generally characterized as a crushed aggregate (often stabilized with cement or asphalt) with a reduced amount of fines to increase the permeability of the subbase to levels from 500 to 20,000 ft/day (152 to 6,100 m/day) in laboratory tests. Despite the intuitive advantage of an ability of the permeable subbase to remove excess water from the pavement rapidly, permeable subbases have had a problematic history due to:

- Instability as a construction platform during construction.
- Inherent instability and associated destructive deflection of concrete slabs under repeated loads.
- Early mid-panel pavement cracking on properly sized slabs.
- Early erratic pavement cracking due to high friction between the subbase and the pavement.
• Early faulting from non-uniform support caused through consolidation of unsta-
bilized (granular) permeable layers.
• Intrusion of concrete into the voids in the permeable subbase, altering the struc-
tural section and the required jointing pattern.
• Infiltration of fines from underlying layers into the permeable subbase voids, 
clogging the system, and trapping water within the subbase.
• Settling, crushing, and plugging of retrofitted edge drain pipes during and after 
installation.
• Deferred or no planned maintenance to the drain pipe system, causing water to be trapped within the pavement structure.
• An initial cost of up to 25 percent more than other conventional subbases.

Permeable subbases – permeability greater than about 350 ft/day (107 m/day) in 
laboratory tests – are no longer considered a cost effective design element for 
concrete pavement. Without contributing appreciably to the performance of concrete 
pavement, there is no way to justify the high-cost of these rapid-draining systems.

3.1.4 Using Recycled Concrete in Subbases

A common source of aggregate for any subbase type is crushed, recycled concrete. 
Existing concrete pavements can be taken up, crushed, and re-used in subbase 
courses, either as unstabilized aggregate subbases or stabilized subbases. There 
are many benefits to using recycled concrete, including:

• The angularity of recycled subbases, coupled with potential residual cementa-
tion, provides a strong and durable platform for construction and improves load 
carrying capacity over the life of the pavement.
• Any desired gradation can be obtained by modifying the crushing and sizing 
operations.
• Savings are realized in the cost of transporting new aggregates, and in the cost 
of hauling and disposing of the old pavement.
• Reusing existing material is helpful where quality aggregate supplies are scarce.

3.2 Subbase Construction

Uniform stability of the subbase is the primary goal of subbase construction, with 
drainage secondary. Do not sacrifice the stability of the subbase material for the 
sake of drainability.

For stability, unstabilized (granular) subbases require compaction to no less than 
95% of AASHTO T99 (alternatively, ASTM D698) density. Thus, most agencies that 
use the standard proctor density test for subbase compaction require 95% of stan-
dard proctor density. Agencies that specify a modified proctor (AASHTO T180 or
ASTM D1557) also typically require 95% compaction. The primary steps for proper unstabilized (granular) subbase construction are summarized in Figure 3.2.

Asphalt-treated subbases (ATB) are usually placed with conventional asphalt paving equipment. Dense-graded asphalt mixtures will require additional compaction using steel drum or pneumatic-tired rollers.

Cement-treated subbases can be placed using either road-mixed or pre-mixed methods. For road-mixing, the material is processed on the grade. The proper amount of cement is placed with a cement spreader and the mixing is usually accomplished with a pulverizer or reclaimer. Once thoroughly mixed, the road-mixed material is then compacted with rollers. For pre-mixed subbases, the material can be mixed in either a pugmill or a central-mix concrete plant. The material is batched into dump trucks and typically placed using an asphalt paving machine. In some cases, the machine will achieve the proper density, but additional compaction

### Mixing

The key to proper unstabilized subbase construction is placing a uniformly moist material that is homogenously blended. The water and aggregate may be mixed using many different methods, including using a standard mixer or a pugmill mixer. The unstabilized subbase could alternatively be mixed on the roadway using motorgraders.

### Placing and Compacting

Once mixed, the unstabilized material may be placed to elevation with a paving machine; placed and trimmed with a hopper-converted auto-trimmer; or placed from trucks, spread with a motorgrader, and then cut to grade and cross-slope with an auto-trimmer. No matter which method is used, the material should be compacted to the required density (typically 95 percent of AASHTO T99 (alternatively, ASTM D698) or 98 percent of AASHTO T180 (alternatively, ASTM D1557)) and with minimal compaction effort to avoid segregation.

### Grading

The unstabilized subbase should be trimmed to the shape of the typical cross section and to plan elevation within grade tolerance. The moisture in the unstabilized subbase must be monitored and kept near optimum before, during and after finish grading operations. Obtaining the optimum moisture content immediately before paving is extremely important (especially if recycled concrete aggregates are used) to prevent early-age cracking.

Figure 3.2. Construction processes for unstabilized subbases.
Lean concrete (econocrete) subbases are constructed in essentially the same manner, and with the same equipment, as normal concrete pavements: they are mixed using a central-mixed concrete plant and placed using a slipform paver. The only difference is the lack of jointing operations and surface treatments in econocrete. Installation of joints in the lean concrete subbase and curing of the surface often are not considered necessary as long as a debonding treatment is applied to the surface.
### Mixing
Because lean concrete is of a comparable consistency as conventional concrete, lean concrete subbases are typically mixed in a central-plant mixer.

### Placing and Finishing
Again, because of the similarities in properties between lean concrete and conventional concrete, it is typically placed in the same manner as conventional concrete: usually by slipformed paving. Due to its consistency, it is relatively easy to keep the surface finish within the typical specified tolerance of 0.25 in. (6 mm) by a 10 ft (3 m) straightedge. There is no need for additional finishing work as with conventional concrete because the surface is not a riding surface; the surface of the lean concrete subbase also should not be textured: this helps prevent it from developing a mechanical bond with the concrete pavement.

### Curing and Jointing
Typical curing procedures for lean concrete subbases include the application of two heavy coats of wax based curing compound. This procedure prevents evaporation of water from the subbase surface to promote thorough hydration of the mixture and mitigates uncontrolled cracking in the subbase layer. The curing compound also serves as a bond breaker between the subbase and the concrete pavement.

![Figure 3.4. Construction processes for lean concrete subbases.](image)

...of the subbase before placing the pavement. The primary steps for proper lean concrete (econcrete) subbase construction are summarized in Figure 3.4.

There is a high potential for bonding of the concrete pavement to a stabilized subbase, particularly if a bond-breaking medium is not applied (use the Federal Highway Administration's (FHWA's) HIPERPAV software (www.hiperpav.com) to evaluate the risk of cracking at early ages for various subbase types, bond conditions, etc.). Current practice in the U.S. includes two heavy coats of wax-based curing compound on the surface of smooth subbases, such as cement-treated or lean concrete subbases. Table 3.3 provides some alternative materials that may be used to reduce friction and prevent bonding of pavement concrete to subbase layers.
Table 3.3. Alternatives for Reducing Friction or Bond Between Concrete Pavement and Stabilized Subbase Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curing compound</td>
<td>Two coats of white pigmented wax-based compound works well.</td>
</tr>
<tr>
<td>Sand</td>
<td>Dusting about 12 lb/yd² (5.5 kg/m²) works well.</td>
</tr>
<tr>
<td>Bladed fines</td>
<td>Recycled jobsite material works well as thin layer.</td>
</tr>
<tr>
<td>Asphalt emulsion</td>
<td>Works well on smoother subbase surfaces. Must be even coating.</td>
</tr>
<tr>
<td>Non-woven geotextile</td>
<td>Works well for CTB and LCB. Must be 0.2 in. (5 mm) thick, fastened to surface.</td>
</tr>
<tr>
<td>Polyethylene sheets*</td>
<td>Works well but difficult to use when windy; could pose traffic hazard in urban areas.</td>
</tr>
<tr>
<td>Tar paper</td>
<td>Works well as debonding medium directly over shrinkage cracks in subbase. Not recommended for application on entire subbase area.</td>
</tr>
<tr>
<td>Choker stone</td>
<td>For stabilized open-graded materials only — chip-size material to fill near-surface voids and minimize penetration of concrete into subbase.</td>
</tr>
</tbody>
</table>

*Note: Polyethylene sheets are recommended for small areas only. Large sheets can be difficult to work with and have been known to contribute to: (1) tearing (a form of cracking) along the edges of pavement during slipform construction; (2) slowing production to re-fasten dislodged sheets; and (3) vehicle accidents, if blown onto adjacent lanes with active traffic.

The method for trimming or shaping the grade varies by project and typically depends upon the project’s size. Typical specifications may require:

1. An unstabilized (granular) or cement-treated subbase surface with deviations that do not exceed ±0.5 in. (±12 mm), longitudinal or transverse, by a 10 ft (3 m) straightedge.
2. An asphalt-treated or lean concrete subbase surface with deviations that do not exceed ±0.25 in. (±6 mm), longitudinal or transverse, by a 10 ft (3 m) straightedge.
On large projects, contractors may use automatic trimming equipment to shape the subbase, and then deposit any excess material outside the paving area. For fixed-form paving, the automatic trimming machine rides on the forms after they are fastened in place. For slipform paving, the trimming machine references the same stringline(s) used for the slipform paving machine.

On small projects, and in confined work zones, it may not be practical to use automatic trimming equipment. In these cases, the contractor will typically trim the grade with a motor grader or small loader. Because final trimming disturbs the subbase surface slightly, additional compaction or rolling is usually necessary.
CHAPTER 4
Pre-Paving Setup

A stringline, supported by stakes alongside the paving lane, guides the slipform paving equipment horizontally and vertically. Some newer models of paving equipment use wireless technology to guide the paver. In a few circumstances, it is acceptable to use an average ski that references the prepared subbase or previous placement to control the elevation of the formed pavement surface.

The pad line, or track line (see Figure 3.1), is the space on which the paving machine’s tracks travel (usually a space at least 3 ft (1 m) wide between each stringline and the edge of a new pavement); it must have a stable, smooth surface and also provide adequate clearance for the paver’s tracks to maneuver along any straightaways and around any curves. A stringline is set outside the track line – parallel to the proposed pavement – to guide the trimmer, slipform paver, and any other paving equipment. Properly locating the stringline, with consideration of the stringline offset and projected distance, is an important pre-paving consideration.

An accurately set, taut stringline is critical to constructing a pavement of uniform thickness and with the desired profile. Meticulous setting of the stringline cannot be overemphasized. Before paving begins, the stringline must be carefully inspected for accuracy.

Once the stringline is set, be careful not to bump it out of alignment or knock the wands loose. Do not operate trucks or other equipment close to the pad line; this could pump the ground around the stakes and disturb the stringline alignment. Do not tie ribbons on the stringline for any reason (i.e., to reference the location of dowel baskets) because doing so might result in an unsmooth stringline. Any of these situations could cause the paver to deviate from the correct elevation, creating a dip or a bump (roughness) in the pavement surface. During paving operations, the stringline must be checked continuously to make sure it is not disturbed or misaligned.

4.1 Setting and Maintaining the Stringline

Before the grade is prepared for paving operations, surveyors set the grade for the stringline(s) and the stringline foremen install the stringline(s). The stringline is the
primary guidance system for a slipform paver. The paver's elevation sensing wand rides beneath the string and the alignment sensing wand rides against the inside of the string (Figure 4.1). Neither of these wands should deflect the line more than $\frac{1}{8}$ in. (3 mm) and, if they do, the stringline and/or wand tension should be appropriately adjusted (see Section 4.5.3).

![Figure 4.1. Close-up of a paver's elevation sensing wand, alignment sensing wand, and stringline, used for guidance of trimming and paving equipment.](image)

The use of averaging skis or lock-to-grade methods of grade control are contingent on the paving platform's grade tolerances, but are generally not recommended where the agency uses a tight smoothness specification, although such paver control methods might be necessary in certain scenarios such as paving next to traffic. (If an averaging ski is used, select a sufficient ski length [40 ft (12 m) minimum recommended].) Except for thin overlays on smooth existing pavements, or paving on closely controlled stabilized (treated) subbases, the use of two stringlines will usually result in a smoother surface than can be achieved using the averaging ski or lock-to-grade methods. Two stringlines also are beneficial for wide sections. If only one stringline is used at wider widths combined with cross slope control, small deviations in the stringline can result in large variations in the surface elevation on the opposite side of the paving machine.
4.1.1 Stringline Considerations

The stringline may be wire, cable, woven nylon, polyethylene rope, or another similar material. Regardless of material, tautness of the stringline must be checked continuously because air temperature and relative humidity variations during the day affect the length of the line, potentially causing sags between the stakes. Increasing the tension will result in less sag, even with substantial changes in weather conditions. Aircraft cable has been found to be an outstanding material for stringline, primarily because it is extremely durable, flexible, and strong; these features allow it to be placed under great tension with negligible risk of breakage.

Splices in the stringline need to be clean and tight. Loose ends can cause the sensors to go astray, creating a defect in the pavement surface. Wherever two separate lines meet to form a continuous run, the end treatment of each line requires particular care to prevent the sensors on the slipform machine from following the incorrect line (Figure 4.2).

![Two stringlines end at one location, but proper end treatment allows for a continuous run.](image)

Stakes that secure the stringline should be long enough to be firm when driven into the subgrade, while also having adequate stake length exposed above grade to allow adjustment of the stringline to the desired height above the reference hub, typically 1.5 to 2.5 ft (450 to 750 mm). A maximum spacing between stakes of no more than 25 ft (7.5 m) on tangent sections will produce the best results.
Decreasing this interval in horizontal and vertical curves may be necessary to produce the smoothest possible transitions. A tighter interval is necessary on vertical curves than on horizontal curves. This interval should be determined based upon the rate of change of curvature. The following equation calculates the rate of change of a vertical curve:

\[ VC = 100 \times \frac{(G_2 - G_1)}{L} \text{ (English)} \]
\[ VC = 30.48 \times \frac{(G_2 - G_1)}{L} \text{ (Metric)} \]

where:
- \( VC \) = Vertical curve change rate
- \( G_1 \) = Grade entering the vertical curve (in percent).
- \( G_2 \) = Grade leaving the vertical curve (in percent).
- \( L \) = Length of curve (in feet [meters]).

If the VC exceeds 0.6, a staking interval of 12.5 ft (3.75 m) will produce better results than a staking interval of 25 ft (7.6 m). Inputs for the above equation are easily found on the plan and profile sheets for the project.

The staking system normally involves placing hand winches at intervals not greater than about 1,000 ft (300 m). The winches allow the line to be tightened to avoid stringline sagging between stakes. (Operators are cautioned to apply stringline tension carefully because a line break may cause injuries.)

Reducing the number of times a stringline must be set up during the project can lead to better smoothness control. Where possible, it is advantageous to set up one stringline on each side of the paving area to serve all operations, including sub-grade preparation, subgrade stabilization, subbase construction, and pavement placement. For multi-operational usage, the stakes and strings must be offset farther from the pavement area to keep them clear of the equipment and operations. However, some equipment modifications, such as the attachment of a truss or cantilever arm to the paver, also may be necessary so that the sensor wands can reach the stringline(s). Figure 4.3 shows various stringline set-up positions.
4.1.2 Setting Reference Hubs

Hubs are placed with the use of a total station, Electron Distance Measuring (EDM) equipment or transit and have a tack or punch hole in the top to provide a line exactly referenced to centerline and normal (at a right angle) thereto. The tops of the hubs are shot for elevation that relates to plan profiles. (If an agency uses as widened pavement, special consideration is warranted when setting reference hubs.)

The contractor will determine the offsets of the hubs for the particular equipment and operations (i.e., 3 ft (1 m) of prepared subbase might be provided as a trackline on either side of the pavement, so the reference hubs might then have to be placed a distance of 4 to 6 ft (1.2 to 1.8 m) from either side of the pavement to provide adequate clearance for all paving equipment). These offset distances may not be equal on each side of the slab. At times the location normally selected for hubs must be adjusted to accommodate specific project staging and phasing.
Grade information is written on a grade stake or flag located adjacent to the hub and facing the centerline. These grade stakes may be a pie shape, a one meter wooden lath (Figure 4.4), or a marking flag. The information written on the grade stake or flag generally includes the following:

- Centerline stationing
- Curve information
- Offset distance from edge of slab
- Cut (C) or Fill (F) to 0.12 in. (3 mm)

Generally this grade information is referenced to the top edge of the slab. On tangent sections of alignment where both edges of slab are the same elevation, offset and projected grade information will be identical.

Proper communication during the setting of these hubs and the recording of the information on the grade stakes is absolutely essential. All parties must communicate to reach agreement for this activity to avoid confusion between the surveying crew, the trimming crew, and the paving crew.


4.1.3 Setting the Stringline

Projected grades are extensions of an imaginary line connecting the top of the proposed edges of the pavement slab. They are located in line with the offset reference hubs. Rotation of this imaginary line about a point on the slab centerline results in one edge being lowered, accompanied by a corresponding rise on the opposite edge. This is the fundamental concept in establishing grades and utilization of elevated stringlines for grade control of automated trimming of grade, laying of subbases, and placing of the concrete pavement.

The survey party will calculate the top of both edges of the concrete slab from the plan profiles and cross sections. The previously discussed imaginary line will be connected through the edges of the concrete slab and extended to a point over the tack in the reference hub. The elevation of this imaginary line at the hub location can be determined, which enables the calculation of the elevation of the stringline directly above the tack. This is the exact location where the stringline support stake should securely hold the stringline (Figure 4.5).

The primary steps involved in properly setting the stringline are as follows:

1. Per section 4.1.2, reference hubs or construction stakes are installed at appropriate intervals (typically 25 ft (7.5 m) or less) outside the pad line, along with grade or pie stakes (flats) showing the difference in elevation between the top of the slab and the hub. A stringline support stake is securely placed just outside each hub so that the stringline will be directly over the hub. (The string-
line stake arms and adjusting bolt sets should be checked at the time of installation to ensure that thread wear or mistreading does not allow arm movement. Use a small triangular file to remove all nicks or projections in the stringline slots to prevent tearing of the stringline.)

2. The appropriate stringline height is calculated relative to the hub elevation, the offset distance (either level or projected) between the hub and a pavement reference point, and the desired grade.

3. Finally, the stringline is installed between stringline stakes, adjusted to the desired height, and then made taut (alternatively, the stringline may be made taut before setting the stringline in its final location at each stringline support stake).

4. Hand winches are generally installed at about 1,000 ft (300 m) intervals (Figure 4.6). The winches allow the line to be tightened to prevent sagging between stakes. (Apply stringline tension carefully; a line break may cause injuries.) To ensure even tension in the string, pull it out of the rod holders before applying force to tighten the line.

5. For maximum control, stringlines are placed on both sides of the proposed pavement. Alternatively, one stringline can be used on one side and the paver set to pave a specific cross-slope.

Figure 4.6. Close-up of a hand winch.

The completed stringline installation should be checked by eye following its installation. Mistakes in setting the stringline and any survey staking errors will likely be detected by this check. Communicate with surveyors and ask them to resurvey the area in question before making changes. Although eyeballing might be a great way
to identify mistakes in the stringline alignment, misaligned stringlines should not be corrected by eyeballing; corrections of stringline misalignment must be performed using the proper surveying equipment. Again, meticulous setting of the stringline cannot be overemphasized. This is the time to resolve all questions, prior to any pavement being placed.

The paving crown (rooftop or uniform), superelevated transitions, and superelevated sections will be accommodated by the paving equipment (Figure 4.7). The various shapes typically are created by adjustments in the paving equipment and slipform paving frame, and not by adjusting the relative height or location of the stringline.

Figure 4.7. Stringline setup for a uniform superelevated slope and a rooftop slope.
In circular curves, spiral curves, and transition sections, the rotation (in a single roadway) is normally around the centerline. For example, the transition from a normal rooftop crown to a full, uniform superelevation in a circular curve to the right may be accomplished in a series of incremental steps with a rotation about the centerline of the slab (Figure 4.8). From the rooftop crown (Step 1), the cross-slope is reduced on both sides of the paving frame and the paving frame is rotated, creating a nearly level plane left of the centerline (Step 2). Next, both cross-slopes

Figure 4.8. The transition from a rooftop slope to a uniform slope in a superelevated right curve is made by adjusting the slipform pan through a series of incremental steps at a uniform rate, with the relative height of the stringlines at the offset and projected distances kept constant on each side of the pavement.
are removed as the paving frame continues to rotate, creating a uniform and superelevated cross-slope (Step 3). Lastly, the paving frame is rotated one more increment, resulting in the final superelevation (Step 4). All of these steps are accomplished at a uniform rate.

Rotation about the edge of a slab can also be used and often is used on dual roadways. Some dual roadways do not use a crown section, which simplifies the transition process.

Communication about proper interpretation of the information shown on the grade stakes is absolutely critical. Miscommunication about how the grades were established can result in the improper superelevation being constructed (Figure 4.9), possibly requiring replacement of the freshly placed concrete to meet grade specifications.

![Diagram of grade stakes and paving process](image)

**Figure 4.9.** Improper consideration of the reference hub offset distance may result in an erroneous pavement grade.

### 4.1.4 Maintaining the Stringline

All personnel working near the stringline must be careful to avoid tripping over, nudging, or otherwise touching the stringline. Some contractors increase the visibility of the stringline by tying on brightly colored ribbons. Despite these precautions, equipment or personnel may bump the line occasionally. After these instances, the crew should check and reposition the line immediately to avoid bumps in the pavement. Any stringline that has been broken should be replaced rather than tying knots in the line.

In many instances, the haul road is located alongside the stringline. This arrangement necessitates regular inspection of the stringline by eye to determine if any heaving or settling of the grade disturbed the reference hubs and/or stringline
support stakes (Figure 4.10). It takes considerable experience to properly “eyeball” corrections to a stringline due to a deviation in the grade. When noticed, the survey or stringline crew should reposition misaligned stakes immediately.

To cross the stringline with hauling units or other equipment, remove the line for about 100 ft (30 m), place it securely on the ground, and cover it with some form of protection before allowing hauling units or other equipment to cross over it. Check for any damage before retensioning the stringline and using it for paving operations.

It is sometimes advantageous to check a stringline at night using light from vehicle headlights. This night-smoothing technique reduces visibility of background objects and eases the ability to focus solely on the stringline because it becomes illuminated by the headlights.

Prior to beginning paving check, check, and check the stringline again and again! Air temperature and relative humidity variations during the day affect the length, and thus the tension, of the stringline. Check line tension often and tighten the winches as necessary.
4.2 Setting Forms

Fixed-form concrete paving is often used for streets, local roads, parking lots, short paving segments, and irregularly shaped slabs. Forms must be accurately set to line and grade and be supported uniformly by a firm foundation. The proper alignment and elevation of the forms determines the best possible surface smoothness a contractor may achieve. The best placement and finishing operations cannot overcome inadequate grading and form setting.

Because the majority of subgrades and subbases are now being trimmed full width with stringline controlled equipment, the form lines have been compacted and are at plan grade. Some contractors still use form line graders that operate with a stringline to trim the form grade lines. A firm and level foundation under all forms is required. The forms must not rest on pedestals of dirt or rock; a uniform subbase is required for support.

10 ft (3 m) steel forms (Figure 4.11) are most common, particularly for straight sections, but wooden forms also can be used on small jobs, if they are not reused too frequently. Plywood forms can also be used for short-radius turns, where they can be bent to the radius of the curve.

First, examine forms with a straightedge or stringline before using the forms on a project. Straight form sections that deviate by more than 0.125 in. (3 mm) along the top, or 0.25 in. (6 mm) along the inside edge should be repaired or replaced. Forms should also be clean and in acceptable condition.

Next, the quality of the support beneath the forms should be assessed. Settlement of the forms under paving equipment can also be a source of built-in roughness.

Figure 4.11. Inside (top) and outside (bottom) views of a typical steel form, with a detailed view of a typical key lock.
The base of the form should bear against the subbase or subgrade surface completely and not lie on any clumps of dirt or rocks.

For form setting, the stringline is set for the face of the form at the top elevation of the form (pavement). The stringline is installed on form pins located with the outside edge of the pins on the proposed edge of slab alignment as measured from the reference hub. Set a stringline pin opposite each reference hub. Using a carpenter's level, the desired finish grade is established by means of a pencil mark on the form pin. The stringline is then put up, fastened securely on each pin, and drawn as taut as is necessary to prevent stringline sags between pins.

Generally, the opposite reference hubs are not tacked for exact alignment control and are used for elevation reference only. Therefore, the alignment for the opposite side of slab stringline is obtained by measuring across the proposed width of slab (Figure 4.12).

![Figure 4.12. When opposite reference hubs do not include a tack, the required elevation of the top of the form may be found by measuring across the proposed width of slab.](image)

The forms should not be shimmed up more than $\frac{1}{4}$ in. (6 mm), to reduce the deflection of the form due to the paving equipment. Once the form is set to the proper elevation, the form lock checked and the support beneath the form checked once more, the form is fastened with at least 3 iron pins or stakes for a standard 10 ft (3 m) long form (Figure 4.13).

Keylocks (see Figure 4.11) are used for minor horizontal alignment changes. One wedge will adjust forms and the other will lock the pin in place. By driving the outside wedge in further than the inside wedge, the form can be moved inwards; the oppo-
site is true when the inside wedge is driven in further. The cross-sectional area of the wedge affects the distance between face of form (edge of pavement) and iron pin.

After ensuring that the forms are in their proper location, the inside and outside wedge of each key lock should be driven tight, and the horizontal and vertical alignment of the interconnected forms checked either by eye or with a straightedge. The forms should be given a light application of form-release agent to permit easy removal after the concrete has hardened.

Lastly, the subbase or subgrade should undergo any final preparation (grading and compacting) necessary to ensure uniform support before the concrete is placed.

### 4.3 Placing Dowels

In pavements designed to carry heavy traffic, dowels are often specified to transfer loads across transverse joints (from one slab to the next). This helps prevent faulting at the joint, which can lead to pavement damage. Dowels must be positioned and aligned within proper tolerances so that, as joints open in the winter (slab contraction) and close in the summer (slab expansion), the slabs on either side of the joints can move in a straight line along the smooth dowels. If a dowel bar is not aligned properly across the joint, the pavement cannot expand and contract freely, generating significant stresses within the concrete pavement. If the stresses become too high, the pavement can crack.
Dowels can be placed and aligned either prior to concrete placement using dowel bar assemblies (dowel baskets) as shown in Figure 4.14, or during concrete placement using a dowel bar inserter (DBI) as shown in Figure 4.15. Both of these methods provide satisfactory results, but, because a properly functioning DBI essentially takes all of the guess work out of placing dowels, the remainder of this section focuses solely on placing dowel baskets.

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 must all be parallel to the pavement centerline AND surface (this will inherently make all dowels parallel to each other) in order to avoid “locking up” the joint. They should be located at 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.

Figure 4.14. 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.
When the baskets are correctly aligned, they must be adequately secured with stakes, pins, nails, and/or clips. Practices vary from state to state, but 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 4.16).

The location of the dowel centers is then marked on both sides of the roadbed, either by setting pins or by painting marks (see Figure 4.14). The markers indicate where joints should be sawed, ensuring that they will be sawed across the center of the dowel assembly.

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 allowing the dowels to remain properly aligned.

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.
4.4 Placing Reinforcement

4.4.1 Tiebars

When paving two lanes or more in width, tiebars may be mechanically inserted or pre-placed along the planned longitudinal contraction joint location(s). The tiebars should be properly spaced and either implanted or fastened to chairs that place the bars at the correct depth in the slab. 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. In either case, a timing device such as a wheel measuring the distance between the bars is used to ensure the correct spacing and, to prevent transverse joints from locking up, no tie bar should be placed within 15 in. (380 mm) of a transverse joint. Check specifications of the owner/agency for the maximum allowable grade and bend for bent tiebars.

Figure 4.16. (a) Staking/pinning or (b) nailing (with clips) dowel baskets to grade.
4.4.2 Continuous Reinforcement

Continuously reinforced concrete pavements (CRCP) typically use epoxy-coated steel reinforcing bars that are placed longitudinally throughout the entire length of the pavement. Placement of the steel for this type of pavement is typically accomplished by placing the longitudinal bars on properly spaced transverse bars that rest on chairs, ensuring that the longitudinal bars are at the proper depth in the slab (Figure 4.17).

![Figure 4.17. Paving continuously reinforced concrete pavement over pre-placed bars.](image)

4.4.3 Other Reinforcement

For odd-shaped slabs or other areas requiring light reinforcing, welded wire fabric is often used. It is either placed on chairs prior to paving or set in place and lifted to the proper depth in the slab during concrete placement.

It is important not to allow the mesh to cross planned joint locations.

4.5 Paving Equipment Setup

Although specific design and operation details vary between slipform paving machines, the principle steps of slipforming a concrete pavement are (Figure 4.18):

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.

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.

Prior to beginning paving there are some critical elements in the slipform process that require extra attention and understanding. These include, but are not limited to, slipform mold (pan), vibrator and paver setup. Refer to your paving machine’s operation and maintenance manual for manufacturer recommended instructions on these and other important paving equipment setup details.

4.5.1 Slipform Mold (Pan) Setup

The setup of the slipform mold (pan) typically requires a preliminary leveling of the slipform paving machine’s frame. Once both sides of the paving machine frame are level from front to rear, all of the sections of the slipform mold are adjusted so that they are also level from front to rear.

Next, a straightedge is placed across each joint in the slipform mold to determine if the pan is straight and level at that point. If the straightedge can rock back and forth across the joint, the joint is too low and must be raised. If, alternatively, a gap is visible between the joint and the straightedge, the joint is too high and must be lowered. Independently adjust each joint until all joints are level and straight.
The plane that the slipform mold makes should now be perfectly flat, and level in the longitudinal direction.

At this point, adjust the center joint of the slipform mold to account for any necessary cross slope.

To confirm that everything is squared up, thread a stringline between the edges and the bottom of the slipform mold just in front of the mold exit point. Place equal sized spacers between the bottom of the slipform mold and the stringline and pull the string taut. Using a third spacer, check the gap between the bottom of the slipform mold and the stringline across the entire width of the slipform mold for a uniform section or measure the distance between the spacer and the crown to confirm the crown offset for a crowned section.

To adjust the edges of the slipform mold to account for edge slump, place a straight-edge near each edge of the slipform mold and adjust the height of each edge to the appropriate offset (Figure 4.19). The amount of over-build adjustment will depend upon the concrete mixture characteristics and the slab thickness. Well-graded mixtures tend to have less edge slump than gap-grade mixtures. Thus, well-graded mixtures require less over-build and typically hold edges better than gap-graded mixtures.

Because each slipform paving machine may have setup requirements that are specific to its slipform mold, please consult your paving machine’s operation and maintenance manual for the specific manufacturer’s recommendations.

![Horizontal Slipform Mold](image1.png)  
**Figure 4.19.** Adjust the edges of the slipform mold to prevent edge slump in the finished concrete pavement.
4.5.2 Vibrator Setup

Slipform paving machines typically utilize vibrators to aid in consolidating the fresh concrete as it is fed into the slipform mold (pan). Thus, the uniformity of the finished concrete pavement is influenced by the placement of the vibrators and the frequency to which they are set.

A typical vibrator setup might require a vibrator to be placed 6 to 8 in. (150 to 200 mm) from each edge of the inside of the slipform mold, with additional vibrators placed at approximately 12 to 24 in. (305 to 610 mm) intervals along the entire width of the slipform mold. The exact vibrator spacing to be used should be provided by the vibrator manufacturer and it should be such that the zone of influence (i.e., the area surrounding each vibrator in which the concrete is fluidized) at the operating frequency slightly overlaps between vibrators (Figure 4.20). Many modern paving machines include vibration monitoring systems that independently control the vibration rate (measured in vibrations per minute (VPM)) of each vibrator to ensure an overlap in the zone of influence of neighboring vibrators, a key factor in obtaining a uniformly consolidated concrete pavement.

Figure 4.20. Typical vibrator spacing and an explanation of the zone of influence.
A transverse vibrator mounting bar running the entire width of the slipform mold would interfere with slipforming operations if it were not placed above the concrete head in front of the tamper (see Figure 4.18). To overcome this potential problem, the bar to which the vibrators are mounted is placed at an elevation higher than the top of the slipform mold. Then, the vibrators are suspended from it, with the tip of each vibrator high enough to allow sufficient clearance over any embedded steel and/or dowel basket assemblies.

Because each vibrator model may have specific setup requirements, please consult the manufacturer’s recommendations for on vibrator spacing and operating frequency.

### 4.5.3 Slipform Paver Setup

The slipform paving machine must be perfectly parallel to the stringline(s). Although this is always a critical step, it is not as critical with two track paving machines as it is with four track paving machines because the horizontal alignment of two track paving machines can be changed relatively easily while paving. If the paving machine is not set parallel to the stringline(s), the slipform paving machine will be skewed in forward motion even though the tracks appear to be in line, causing the slipform mold to be skewed (Figure 4.21.a). A straightforward approach to setting the paving machine parallel to the stringline is to measure the distance between the stringline and the slipform paving frame at both the front and the rear of the machine and then confirming that these two distances are equal (Figure 4.21.b).

Once the slipform paver is set in the proper position, the machine may be lowered so that the slipform mold will extrude the concrete pavement at the required thickness.

Next, set both the elevation and alignment sensing wands on the stringline and adjust the sensor spring tension to hold each wand firmly against the stringline. Pull the elevation and alignment sensing wands away from the stringline, one at a time, while noting the stringline deflection. If the stringline deflects more than $\frac{1}{8}$ in. (3 mm) due to the pressure of the wand then the wand tension must be decreased.

Move the slipform paving machine forward 20 to 30 ft (6 to 9 m) and stop. Check the height of the slipform mold and distance between the slipform paver and stringline(s) to ensure that the slipform paving frame is square and slipform paver is perfectly parallel to the stringline(s).

Because each slipform paving machine may have paver-specific setup requirements, please consult your paving machine’s operation and maintenance manual for the manufacturer’s recommendations.
4.5.4 Checking the Final Grade and Cross Slope

To check the final grade and cross slope, set two lines of stakes across the grade. The stakes should be arranged so that one stake is 2 ft (610 mm) from each edge, one stake is at the centerline, and the lines of stakes are offset by approximately 3 ft (915 mm). All of the stakes should be driven into the grade until the head of each stake is exactly 1 in. (25 mm) below the finished grade (Figure 4.22.a).

Figure 4.21.a. The slipform paving machine can be skewed even though the tracks appear to be straight and parallel to the edge of the pavement.

Figure 4.21.b. The straightness of the slipform paving machine can be verified by measuring the distance between the slipform paving frame and the stringline at the front and rear of the machine and confirming that the two distances are equal.

4.5.4 Checking the Final Grade and Cross Slope

To check the final grade and cross slope, set two lines of stakes across the grade. The stakes should be arranged so that one stake is 2 ft (610 mm) from each edge, one stake is at the centerline, and the lines of stakes are offset by approximately 3 ft (915 mm). All of the stakes should be driven into the grade until the head of each stake is exactly 1 in. (25 mm) below the finished grade (Figure 4.22.a).
Drive the paving machine over the stakes until one line of stakes is immediately in front of the rear of the slipform mold and the other line of stakes is near the front of the slipform mold. Adjust the grade sensors on each side of the paving machine until there is exactly 1 in. (25 mm) of clearance above the stakes (Figure 4.22.b).

If all measurements are within the manufacture’s recommended tolerances, commence paving.

Again, because each slipform paving machine may have paver-specific requirements, please consult your paving machine’s operation and maintenance manual for the manufacturer’s recommendations.
Mixtures for pavement-quality concrete should be designed, proportioned, and pre-tested for the intended use, placement method, environmental and exposure conditions, desired durability, expected loads, etc. In most cases, developing a new concrete mixture involves making a series of trial batches in the laboratory, using job-specific materials. The contractor must run a sufficient number of trial batches so that adjustments for workability and air content can be made confidently during construction. Most concrete mixture designs are slightly altered variations of known or existing mixtures. ACI 211 and PCA EB001 both give guidance on designing and proportioning concrete mixtures.

Regardless of the method used to generate a concrete mixture design and to select material proportions, it is helpful to check a few key variables in order to ascertain

<table>
<thead>
<tr>
<th>Key Points:</th>
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<tbody>
<tr>
<td>• Lower cementitious materials content → lower water content at the same water-cementitious materials ratio → lower potential for drying shrinkage → lower risk of cracking.</td>
</tr>
<tr>
<td>• The maximum water-cementitious materials ratio for slipform paving should be 0.45, except in special circumstances.</td>
</tr>
<tr>
<td>• Proportion (by weight) of coarse-to-fine aggregates is typically 55/45 to 65/35.</td>
</tr>
<tr>
<td>• A very useful tool for analyzing the “pave-ability” of a concrete is to look at the combined aggregate gradation.</td>
</tr>
<tr>
<td>• Slump is not a mixture quality indicator; its primary purpose is for comparing batch-to-batch consistency.</td>
</tr>
<tr>
<td>• Freeze-thaw durability of the concrete is highly dependent on a good air-void system, not just total air content.</td>
</tr>
<tr>
<td>• The maturity method is a useful means of reasonably estimating in-place concrete strength.</td>
</tr>
</tbody>
</table>
whether the proposed concrete will work for a particular situation or project. Table 5.1 lists the recommended tests to conduct during the mixture design/proportioning and pre-construction mixture verification periods for various roadway classifications.

The following sections provide criteria, simple rules of thumb, and recommendations for selection and application of a proposed concrete mixture. The emphasis in these recommendations is placed on constructability and performance. Contractors are encouraged to analyze job mixtures before and during use to better evaluate their benefits and risks. Virtually any concrete mixture can be used to construct a concrete pavement. However, the recommendations in this manual can help ensure a workable, cost-effective, and long-lasting concrete mixture for paving.

Table 5.1. Recommended test requirements during the mixture design/proportioning and pre-construction mixture verification periods according to roadway classification.*

<table>
<thead>
<tr>
<th>TEST</th>
<th>PROCEDURE(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WORKABILITY</strong></td>
<td></td>
</tr>
<tr>
<td>Combined Grading – Coarseness and Workability Factors, 0.45 Power Curve, and Percent Retained Individual Sieves</td>
<td>ASTM C136/AASHTO T27</td>
</tr>
<tr>
<td>Aggregate Moisture Content</td>
<td>ASTM C566/AASHTO T255</td>
</tr>
<tr>
<td>Slump and Loss of Workability</td>
<td>ASTM C143/AASHTO T119</td>
</tr>
<tr>
<td>Mortar Flow</td>
<td>ASTM C1437, Testing Guide*</td>
</tr>
<tr>
<td>Cementitious Heat Generation (Coffee Cup Test)</td>
<td>Testing Guide*</td>
</tr>
<tr>
<td><strong>STRENGTH DEVELOPMENT</strong></td>
<td></td>
</tr>
<tr>
<td>Microwave Water Content</td>
<td>AASHTO T318</td>
</tr>
<tr>
<td>Heat Signature (Calorimetry)</td>
<td>Testing Guide*</td>
</tr>
<tr>
<td>Set Time</td>
<td>ASTM C403</td>
</tr>
<tr>
<td>Concrete Strength (3 and 7 Days)</td>
<td>ASTM C39/AASHTO T22, ASTM C78/AASHTO T97, ASTM C293/AASHTO T177</td>
</tr>
</tbody>
</table>

*Continued on next page
5.1 Cement

The cementitious binder is the “glue” that holds concrete together. Generally, as the cement content in a mixture increases, so does the compressive strength. While increased strength is typically beneficial, using a lot of cement to boost concrete strength may cause unintended side effects, including:

- The need for more air entraining admixture to maintain the desired air content.
- The need for more water to maintain workability and the same water-cementitious materials ratio, resulting in more drying shrinkage.
- The introduction of more paste and less aggregate in one cubic yard (meter) of material, possibly resulting in segregation or settlement of aggregates toward the bottom of the slab.
- The potential for more bleed water, resulting in more bleed water channels. This will increase the permeability and reduce the durability of the surface.

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* 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.
• Higher early strengths, requiring earlier saw cutting to ensure proper joint formation.
• Higher stiffness, resulting in a less forgiving concrete pavement (less strain absorbent, thus more brittle and less fatigue capacity).

### 5.2 Cementitious Materials Content

A minimum cementitious materials content is often specified by project owners or agencies. Generally, the cementitious materials content is directly related to concrete strength.* However, a good rule of thumb is to specify the least amount of cementitious material necessary to meet the strength and workability requirements. Low cementitious materials contents are possible when well-graded combined aggregates are used (See Section 5.4). As mentioned, a lower cementitious materials content may have significant benefits to the concrete pavement’s overall performance, including lower drying shrinkage, lower risk of cracking, lower air requirements, greater dimensional stability, and last but not least, lower cost. Experience tells us that a minimum cementitious materials content of about 500 lb/yd³ (300 kg/m³) is adequate for a slipform paving mixture utilizing well-graded aggregates.

The dosage of supplementary cementitious materials (SCMs) in a specific concrete mixture is usually reported as a percent by weight of total cementitious materials. Table 5.2 shows typical limits for the amount of SCMs in concrete pavements. Higher percent additions of SCMs (greater than 50% total addition) are possible for optimized mixtures in special circumstances.

The rate of strength gain at early ages may be retarded when SCMs are used, particularly when SCMs approach 35-50% of the total cementitious materials content. Thus, special attention to the timing of joint sawing and opening to construction loading is required for such mixtures.

#### Table 5.2. Typical Limits on SCM Dosages in Concrete Pavements

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum Dosage (% by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash</td>
<td>25%</td>
</tr>
<tr>
<td>Slag cement</td>
<td>40%</td>
</tr>
<tr>
<td>Total of fly ash and slag cement</td>
<td>50%</td>
</tr>
</tbody>
</table>

*Concrete strength is not a valid indicator of concrete durability. Durability is a complex issue affected by many factors.
5.3 Water-Cementitious Materials Ratio

The water-cementitious materials ratio (w/cm, by weight) also affects the strength of the concrete, with lower w/cm ratios generally yielding higher strength mixtures. Experience tells us that the w/cm ratio should be no greater than about 0.50 for fixed-form paving and hand-pour areas, and no greater than about 0.45 for slipform paving. However, a typical w/cm value for fixed-form and hand work is 0.45, and 0.40 for slipform. It should be noted that w/cm ratios less than about 0.40 can be subject to autogenous shrinkage. Autogenous shrinkage occurs when the cement does not have sufficient free water for hydration, causing the concrete to start to dry out internally. As the pore water is consumed, a net volume reduction or shrinkage occurs. For concrete mixtures with a very low w/cm ratio (i.e., less than about 0.35), autogenous shrinkage can be as much as 200 to 400 millionths, about half as much as the anticipated magnitude of drying shrinkage.

If both minimum cement contents and recommended w/cm ratios are followed, the resulting concrete should have sufficient strength at the 28-day mark to meet most design and specification requirements.

5.4 Aggregates

Aggregates are usually the hardest, strongest, and most durable constituent of concrete. Thus, they rightfully make up the bulk of a concrete mixture's volume, typically 60% to 75%. A typical proportion (by weight) of coarse aggregate to fine aggregate is 60/40. In other words, when considering just the aggregates in the concrete, the coarse aggregate typically makes up around 60% of the weight of all aggregates, and the fine aggregate makes up around 40%.

Aggregate selection is critical to concrete, both in terms of constructability and long-term performance. All aggregates should be tested or prequalified for durability. Freeze-thaw resistance, alkali-silica reactivity, alkali-carbonate reactivity and “D” cracking susceptibility all are influenced greatly by the aggregate used in the concrete. The coarse aggregate is a primary factor in the coefficient of thermal expansion (CTE) of the concrete, influencing how much a concrete expands and contracts with changes in temperature.

In general, siliceous aggregates have a higher thermal coefficient than limestones. In fact, some sandstones have a thermal coefficient twice that of certain limestones. What this means in practice is that concrete pavements constructed with such high CTE aggregates will expand and contract at twice the magnitude of the limestone concrete. Thus, joints will open twice as wide, slabs will curl up twice as much due to temperature differentials, and the average crack spacing for CRCP pavements will be much smaller. This has significant long-term pavement performance implications, as suggested by the Mechanistic-Empirical Pavement Design Guide (NCHRP...
A concrete mixture’s CTE can be measured using the AASHTO provisional standard TP-60.

Aggregate hardness also influences the selection of saw blades for cutting joints, and the ease and cost of joint sawing. Aggregate sources are normally prequalified by state highway agencies for freeze-thaw durability, resistance to “D” cracking, and alkali-silica reactivity.

Two final concerns for aggregates to be used in concrete pavement are cleanliness and surface moisture. Dirty (dusty) aggregates cause paving consistency and quality problems. Thus, dirty aggregates must be washed before stockpiling. Aggregate in the stockpile should be maintained at a moisture condition of saturated surface dry (SSD) or greater.

**5.4.1 Gradation**

The controlling factor of concrete mixture workability is the combined gradation of the fine and coarse aggregates. Individual gradations and the percent blend of each aggregate determine the combined gradation of the entire aggregate blend (Table 5.3). A well-graded combined aggregate includes particles of all sieve sizes, in suffi-

<table>
<thead>
<tr>
<th>% Blend</th>
<th>Coarse 60%</th>
<th>Fine 40%</th>
<th>Combined 100%</th>
<th>Percent Retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve Size</td>
<td>Percent Passing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 mm</td>
<td>2 in.</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>37.5 mm</td>
<td>1½ in.</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>25 mm</td>
<td>1 in.</td>
<td>95.0</td>
<td>100.0</td>
<td>97.0</td>
</tr>
<tr>
<td>19 mm</td>
<td>¾ in.</td>
<td>75.0</td>
<td>100.0</td>
<td>85.0</td>
</tr>
<tr>
<td>12.5 mm</td>
<td>½ in.</td>
<td>45.0</td>
<td>100.0</td>
<td>67.0</td>
</tr>
<tr>
<td>9.5 mm</td>
<td>¾ in.</td>
<td>35.0</td>
<td>100.0</td>
<td>61.0</td>
</tr>
<tr>
<td>4.75 mm</td>
<td>#4</td>
<td>5.0</td>
<td>96.0</td>
<td>41.4</td>
</tr>
<tr>
<td>2.36 mm</td>
<td>#8</td>
<td>2.5</td>
<td>85.0</td>
<td>35.5</td>
</tr>
<tr>
<td>1.18 mm</td>
<td>#16</td>
<td>0.0</td>
<td>70.0</td>
<td>28.0</td>
</tr>
<tr>
<td>600 μm</td>
<td>#30</td>
<td>0.0</td>
<td>40.0</td>
<td>16.0</td>
</tr>
<tr>
<td>300 μm</td>
<td>#50</td>
<td>0.0</td>
<td>12.0</td>
<td>4.8</td>
</tr>
<tr>
<td>150 μm</td>
<td>#100</td>
<td>0.0</td>
<td>3.0</td>
<td>1.2</td>
</tr>
<tr>
<td>75 μm</td>
<td>#200</td>
<td>0.0</td>
<td>1.0</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Combined Percent Passing =
Percent Passing for Coarse*% Blend for Coarse + Percent Passing for Fine*% Blend for Fine

Percent Retained =
Combined at the previous Sieve Size – Combined at the current Sieve Size
cient quantity to pack tightly and fill as much volume as possible. This maximizes aggregate particle density and fills voids between aggregates, typically occupied by less dense cement paste. Increased particle density typically results in:

- Reduced water demand.
- Lower drying shrinkage potential.
- Better workability.
- Improved early and long-term strength development.

### 5.4.2 Percent Retained

One way to achieve a well-graded aggregate mixture is by trying to obtain a relatively uniform distribution of material on each sieve size. Figure 5.1 plots the percent retained of the example aggregate gradation in Table 5.3. Note that the gradation roughly fits in the band having 8% to 18% of the combined aggregate retained on each sieve size.

![Combined gradation from Table 5.3.](image)

Figure 5.1. Example combined gradation plotted as percent retained on each sieve.
Of the aggregates typically available for concrete paving, many fine aggregate gradations are finer than desired and many coarse aggregate gradations are coarser than desired, thereby creating a wider gap in the combined gradation. Due to the nature of locally available fine aggregate, combined aggregate gradings are often found to have a deficiency in particles retained from the 3/8 in. (9.5 mm) to the #30 (600 μm) sieves and an abundance of particles retained on the #50 and #100 (300 and 150 μm) sieves. When there is a deficiency in two adjacent sieve sizes, the sizes on either side tend to balance them. However, three adjacent deficient sizes indicate a gap-gradation, an undesirable aggregate gradation.

5.4.3 Percent Passing

Another way to analyze a gradation is to plot the percent passing (100% – Percent Retained) each sieve along with recommended upper and lower limits. Figure 5.2 plots the percent passing on each sieve of the combined aggregate gradation in Table 5.3. Note that the gradation does not fall completely between the recommended boundaries, but it comes close. Gradations that fall within the limits have a much better chance of success, but that does not mean that gradations outside the limits will be inherently problematic.

![Combined gradation from Table 5.3](image)

Figure 5.2. Example combined gradation plotted as percent passing each sieve.
5.4.4 Workability and Coarseness

One method of determining the “pave-ability” of a particular gradation is to analyze it using a workability chart.* To implement such a chart, two factors must be calculated based on the combined aggregate gradation. These are the workability factor and the coarseness factor. Both factors are directly related to the quantity of aggregates passing or retained on two sieve sizes: the 3/8 in. (9.5 mm) sieve and the #8 (2.36 mm) sieve.

Workability Factor (WF) = percent passing the #8 (2.36 mm) sieve + [2.5 x (lb/yd³ of cementitious material – 564) / 94]

Coarseness Factor (CF) = \[
\frac{\% \text{ retained above the } \frac{3}{8} \text{ (9.5 mm) sieve}}{\% \text{ retained above the #8 (2.36 mm) sieve}} \times 100
\]

For the combined gradation in Table 5.3, the workability factor = 35.5 (for a mixture having 564 lb/yd³ of cementitious material) and the coarseness factor = [(3.0 + 12.0 + 18.0 + 6.0) / (3.0 + 12.0 + 18.0 + 6.0 + 19.6 + 5.9) x 100] = 60.5.

The next step is to plot the data point represented by these two numbers on a workability chart, such as Figure 5.3. If this mixture has a 1 in. (25 mm) maximum size aggregate, then it is considered well-graded based on the chart.

*The workability chart is a concept developed by Jim Shilstone, Sr., and published by him in "Concrete Mixture Optimization," Concrete International, American Concrete Institute, Farmington Hills, Michigan, June 1990, pages 33 to 39. It is a valuable tool and has been proven over many years of application.
Descriptions of the zones on Figure 5.3:

**SANDY** – Concrete made with a combined aggregate in the sandy zone (usually WF > 40) tends to demand more water and result in higher drying shrinkage than mixtures in the well-graded zone(s). These mixtures may have excessive build-up of surface laitance.

**ROCKY** – Concrete made with a combined aggregate in the rocky zone (below the control line) tends to be harsh, difficult to finish, and subject to poor consolidation and surface voids.

**COARSE GAP-GRADED** – Concrete made with a combined aggregate in the coarse gap graded zone (75 < CF < 90) experiences variable results, including segregation, uncontrolled voids, and excessive laitance. Some projects using such a gradation can still result in defect-free pavement, but the risk of defects is higher than if a well-graded mixture is used.

**WELL-GRADED** – Concrete made with a combined aggregate in the well-graded zones (29 < WF < 43 and CF < 75) places easily and is typically not prone to early distress. These concrete mixtures tend to slip and finish well, and conventionally have the least risk of uncontrolled cracking and/or other defects/problems.

Figure 5.3 is not a sure predictor of performance or quality. Other variables must be considered, including the variability of the natural concrete aggregate materials, the construction process, and other factors. Coarseness factors can vary as much as 15 points for one mixture and one project, making it understandable that a contractor would experience variability in placing and finishing. Sometimes this is an indication of poor stockpile management, or simply the result of the inherent variability in the aggregate gradations.

### 5.4.5 The 0.45 Power Chart

Yet another method of analyzing a combined aggregate gradation is to plot the percent passing each sieve size versus the sieve size (in. [mm]) raised to the 0.45 power. The 0.45 power chart should be used only as a guide and should not be incorporated into specifications. Experience has shown that good gradations plot roughly parallel to and within a few percent of the maximum density line on the 0.45 power chart (a line from the origin extending to the nominal maximum aggregate size). Trial batching and the behavior of the mixture will indicate whether the selected combined aggregate is satisfactory.

Figure 5.4 plots the combined gradation from Table 5.3 versus the maximum density line for mixtures with a 1 in. (25 mm) maximum size aggregate. Gradations that meander across the maximum density line indicate gap grading, whereas those that roughly follow the line are well optimized and indicate a good density of aggregates in the concrete. Figure 5.4 shows that the combined gradation from Table 5.3 is indicative of a well optimized aggregate combination.
5.4.6 Fineness Modulus

The fineness of the sand (fine aggregate) can be evaluated by calculating the fineness modulus (FM), which is a measure of the fineness or coarseness of an aggregate sample. The FM is determined by adding the cumulative percent retained on each of a specified series of sieves, and dividing the sum by 100. Thus, for fine aggregate, these sieve sizes are 3/8 in., #4, #8, #16, #30, #50, and #100. For the fine aggregate shown in Table 5.3, the fineness modulus is \[
\frac{(0.0 + 4.0 + 15 + 30 + 60 + 88 + 97)}{100} = 2.94.
\]

Sand gradations that adhere to the lower limit of ASTM C33 will be coarser and have a fineness modulus of over 3.4, while sands that approach the upper limit of ASTM C33 will be finer and have a fineness modulus of less than 2.2. Coarser gradations of fine aggregate are generally very good for concrete paving, but they may not meet ASTM C33 requirements (a fineness modulus between 2.3 and 3.1). Sands that approach or surpass the upper limit of ASTM C33 may be unsuitable for slipform paving or for concrete used in other paving applications due to the resulting increased susceptibility to uncontrolled cracking.

As an example, Figure 5.5 plots the gradation of the fine aggregate from Table 5.3 as well as the upper and lower limits of ASTM C33 for the same sieve sizes. This sample gradation follows the lower limit more closely, as it has a fineness modulus of almost 3.0. Thus, it is probably a sand that is well suited for concrete paving.
In general, fine aggregate for concrete paving mixtures should have a fineness modulus of 2.7 or greater, with the best results coming from sands with a FM between 3.0 and 3.5. Very coarse sands, with a FM from 3.5 to 3.8, also may work well for concrete used in paving applications, but the contractor is encouraged to verify this with records of past usage, or with test batching.

5.5 Testing

Concrete used for pavements is routinely tested on the job site for uniformity, quality, strength, and general conformance to specifications. Although Table 5.1 provides the complete suite of recommended tests for a specific roadway classification, typical tests included in agency specifications are: temperature, slump, unit weight, air content, strength, and maturity; the remainder of this section discusses these typical tests. All tests should be performed in accordance with applicable ASTM or AASHTO specifications. It is also highly recommended to have ACI Grade I Certified Field Technicians perform these tests.

5.5.1 Temperature

Temperature (ASTM C1064) is probably the easiest test to conduct among the suite of standard concrete pavement quality control tests. It involves placing a concrete thermometer into the fresh concrete to establish its temperature. The result may be used to verify conformance to a specified requirement for temperature of concrete at any given time. This may be especially important for fast track mixtures, or where outside ambient temperatures are either higher than ordinary (> 90°F or 32°C) or lower than ordinary (< 34°F or 1°C).
5.5.2 Slump

The slump test (ASTM C143 / AASHTO T119) is the most widely used method of measuring the consistency of concrete. Although it can be used as a crude indicator of a paving mixture's workability, slump does not fully characterize how the mixture will behave through a slipform paving machine nor how easy or difficult it will be to finish. Slump is useful to check batch-to-batch consistency in the field and for process control at the batch plant. However, it is not a test to be used as a quality indicator of a concrete mixture. Generally, slump values for slipformed concrete fall in the range of 0.5 to 1.5 in. (13 to 38 mm). For fixed form paving, slump values are generally between 3 and 4 in. (75 and 100 mm), to aid placement.

Slump is not only dependent on the amount of water, admixtures, and other concrete constituents used, but it is also dependent on the amount of time that passes between batching and slump measurement. Consistency in the time and manner of testing is necessary for any indication of batch-to-batch comparison. Slump test results at the batch plant, immediately after batching, will generally be higher than results from tests taken in front of the paver, after time elapses for hauling and placing. Figure 5.6 provides an example of the slump loss of three different mixtures.

![Slump Test Graph](image-url)  
*Figure 5.6. Slump loss at 73°F (23°C) in concrete mixtures containing conventional water reducers (ASTM C494 and AASHTO M194 Type D) compared with a control mixture. [PCA RD107T]*
5.5.3 Density (Unit Weight)

In simple terms, the density test (ASTM C138 / AASHTO T121) involves measuring the weight of a known volume of plastic (fresh) concrete that has been consolidated in a prescribed manner (Figure 5.7). It allows contractors to compare the unit weight of the batched concrete to the mixture’s theoretical density in only a few minutes.

The test method involves placing fresh concrete in a measure of known volume (usually a pressure meter bucket) in three consolidated layers of equal volume, and then determining its mass to the nearest 0.1 lb. (0.05 kg). With the possible exception of a balance (or scale), the quality technician’s toolkit should already include the equipment necessary to perform the test. The only additional step beyond the typically required pressure meter test is to weigh the pressure meter bucket (unit weight measure) immediately after filling. Typical density values for concrete used in pavement applications fall in the range of 130 to 150 lb/ft$^3$ (2,082 to 2,403 kg/m$^3$).

ASTM C138 also provides formulas for calculating the yield and air content of the concrete. A contractor can use the density test to estimate the air content of concrete, provided the specific gravities of the constituents are known. Therefore, density results are an indicator of the variability and overall quality of freshly mixed concrete. In fact, uniformity requirements of ASTM C94 specify density results among the suite of tests needed in order to establish within-batch uniformity of concrete. A change in a concrete’s density typically indicates a change in one or more of the other concrete performance requirements.

Excessive variability, batch-to-batch and even within-batch, can compromise overall concrete quality. A reduction in density may indicate a higher air content, a higher water content, a lower cement content, a change in the proportions of ingredients, or that the cement or aggregate has a lower specific gravity than expected. Conversely, a rise in density would indicate the opposite of the aforementioned characteristics. Clearly, a change in density not only has the potential to affect durability and strength, but it can also influence workability, placement energy requirements, finishability, and early age cracking potential.

Use of the density test at a prescribed interval during production allows contractor personnel to have a good handle on batch-to-batch concrete uniformity. It also allows faster responses to concrete variability. Such simple real-time process control can help reduce the frequency of mixture-related paving problems.
5.5.4 Air Content

Entrained air allows a concrete pavement to be durable under severe conditions of deicer application and freezing and thawing. For many pavements, air content is specified at 6%, by volume, with a variation of +2% and –1%, although the recommended air content varies with the maximum size of the coarse aggregate (Table 5.4).

<table>
<thead>
<tr>
<th>Nominal Maximum Size Aggregate in.</th>
<th>Target Air Content %</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8</td>
<td>7 1/2</td>
</tr>
<tr>
<td>1/2</td>
<td>7</td>
</tr>
<tr>
<td>3/4</td>
<td>6</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>1 1/2</td>
<td>5 1/2</td>
</tr>
</tbody>
</table>

The most common means of determining the air content of fresh concrete is via the pressure method, ASTM C231/AASHTO T152 (Figure 5.8). This method not only measures entrained air (the small, particularly beneficial air bubbles that ensure the durability of the paste) but it also measures entrapped air (larger air pockets in areas of the concrete that are not fully consolidated).

Figure 5.8. Air content is being measured by the pressure method in the foreground and a slump test is being performed in the background.
Most air content tests are performed at the batch plant and/or in front of the paving equipment, at the point of discharge onto the grade. Unfortunately, neither of these “locations” in the construction process are representative of the air content in the actual concrete pavement after consolidation by the paving process. As the concrete moves through the paving equipment, it can lose upwards of 2% air content, primarily due to the vibration forces used for consolidating the concrete. This loss of air from the batch plant to placement must be well understood by all parties involved so that the final in-place concrete pavement can have an adequate air content.

The quality of the air-void system is as critical to long-term pavement durability as the quantity of air bubbles. A pavement can have what seems to be an adequate volume (percentage) of air, but the resulting concrete may not be durable because the size and spacing of the air bubbles is not adequate for long-term durability.

For fresh concrete testing, the air void analyzer is capable of measuring the entrained air properties of a fresh mortar sample and providing feedback regarding the air void structure of the pavement within one hour of sampling. Even though this testing equipment is relatively new, some states in critical freeze-thaw climates have already adopted its use for monitoring entrained air properties during construction.

The air void system in hardened concrete can be assessed by a petrographer (ASTM C457). However, this method cannot be used to obtain any useful real-time quality control/quality assurance information. Instead, a given field-produced mixture design should be tested for hardened air properties and correlated to air content measured by the pressure method (ASTM C231/AASHTO T152). This practice will generally work as long as the batching methods, construction processes, equipment, materials, and mixture proportions remain the same. If any of these factors change, the procedure will have to be repeated.

The air content in the field is affected by the following:

- **Cement** – Increasing the alkali content will increase the air content. Increasing the finesses of the cement and/or increasing the cement content will decrease the air content.

- **Supplementary cementitious materials (SCMs)** – Increasing the carbon content (i.e., loss on ignition or LOI) will decrease the air content. Small variations in the composition of a fly ash may result in large swings in the air content, making production of uniform concrete difficult. The use of GGBF slag may require the use of additional air-entraining admixture to achieve the desired air content.
• **Chemical admixtures** – Increasing the dosage of lignin-based water reducers and/or retarders will increase the air content.

• **Gradation of the aggregates** – Increasing the coarse aggregate maximum size decreases the air content requirements. Increasing the fine aggregate content will increase the air content. Increasing the amount of material retained on the #30 to #50 (600 to 300 μm) sieves will result in increased air entrainment.

• **Water/cementitious materials ratio** – Increasing the water to cementitious materials ratio increases the air content.

• **Temperature** – An increase in temperature will require an increase in the amount of air-entraining admixture necessary to maintain the target air content.

• **Delays** – Increasing delays and/or delivery time will decrease the air content.

• **Placement/consolidation** – Placement and consolidation (vibrating) will decrease the air content, the magnitude of which is not quantifiable until petrographic analysis can be conducted after the concrete has set.

This extensive list of variables is a testament to the difficulty of producing concrete with a consistent air content. Therefore, sufficient trial batches should be conducted prior to construction to help characterize air content and determine which factors have the greatest impact on the mixture’s properties (i.e., placability, slipformability, finishability, etc.).

### 5.5.5 Compressive/Flexural Strength

Concrete strength is generally verified using either concrete cylinders (ASTM C39/AASHTO T22) or beams (ASTM C78/AASHTO T97) cast from concrete delivered to the site. Specimens are typically tested at an age of 28 days for acceptance. Strength requirements vary significantly between agencies, but typical compressive and flexural strength requirements are presented in Table 5.5.

**Table 5.5. Typical compressive and flexural strength requirements at 28 days.**

<table>
<thead>
<tr>
<th></th>
<th>Compressive Strength</th>
<th>Flexural Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>psi</td>
<td>MPa</td>
</tr>
<tr>
<td>Low</td>
<td>3000</td>
<td>20.7</td>
</tr>
<tr>
<td>Average</td>
<td>3500</td>
<td>24.1</td>
</tr>
<tr>
<td>High</td>
<td>4000</td>
<td>27.6</td>
</tr>
</tbody>
</table>
For early opening to traffic and fast-track applications, strength requirements are often set at earlier ages. In such situations, field-cured specimens may be necessary. Since in-place concrete curing conditions are difficult to replicate, even with field-cured specimens, non-destructive strength tests may be more appropriate and convenient. One such nondestructive strength measure that is gaining use with numerous highway agencies is the maturity method for estimating strength (see Section 5.5.6).

5.5.6 Maturity Method for Estimating Strength

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 method is a two-step process (Figure 5.9):

1. **Step 1** – A group of specimens is prepared (beams or cylinders) and their thermal history is recorded continuously from casting using temperature probes, thermocouples, or maturity sensors embedded in them (Figures 5.10 and 5.11). Sets of specimens undergo strength testing at prescribed intervals, at which time the thermal history is used to compute a time-temperature factor (TTF). After a sufficient number of tests are completed, a complete maturity curve (strength versus TTF) can be developed. The development of the maturity-strength curve must be completed prior to construction, using the same materials that will be used during construction. 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.

2. **Step 2** – In the field, a temperature probe, thermocouple, or maturity sensor similar to that used in the laboratory is embedded in a critical location in the fresh concrete pavement. Using the thermal history, as sampled by this sensor, a TTF can be calculated at any time and a strength can then be estimated using the laboratory developed maturity curve.
As an example of the maturity method, Figure 5.12 plots the hypothetical thermal history of a concrete specimen in the laboratory. Each bar is 1 hour wide and the height is the average measured temperature during that time interval. A time-
temperature increment can be calculated for each time interval by multiplying the time interval by the average surface temperature less any datum temperature. The TTF is the sum of these time-temperature increments up to the point in time of interest and it should be calculated at the time of strength testing of any set of specimens. Using the TTF calculated from Figure 5.12 and laboratory strength data, a maturity curve (Figure 5.13) can be constructed and a best-fit line plotted through the data.

![Figure 5.12. Example thermal history of a laboratory specimen, used to calculate the time-temperature factor (TTF).](image-url)
To implement the maturity curve for this concrete mixture, a temperature sampling device is installed in the freshly placed concrete and the temperature is measured periodically (Figure 5.14). 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 the 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 (Figure 5.15).

Using any of the aforementioned methods to gather the thermal history of the pavement at any time of interest, the strength of the pavement can be estimated at any time by calculating the TTF in a method complementary to that discussed for Figure 5.12 and reading the strength from a laboratory constructed maturity plot (Figure 5.13).
Figure 5.14. Maturity sensors (thermocouples) embedded in the freshly placed slab with a datalogging device connected.

Figure 5.15. Example of an embedded maturity sensor/datalogger and a handheld reader.
References

Chapter 1. Joint Layout
ACPA References

IS006P, “Intersection Joint Layout.”


IS045P, “Concrete Pavements with Undoweled Joints for Light Traffic Facilities.”

R&T Update #6.03, “Concrete Roundabouts – Rigid Pavement Well-Suited for Increasingly Popular Intersection Type.”


TB017P, “Airfield Joints, Jointing Arrangements and Steel.”


Chapter 2. Subgrade
ACPA References

EB204P, “Subgrades and Subbases for Concrete Pavements.”

IS184P, “Design of Concrete Pavement for Streets and Roads.”

IS041P, “Concrete Pavements without Subbases for Light Traffic Facilities.”

R&T Update #6.02, “Making the Grade – Grade Preparation is Important in Achieving Pavement Performance.”

Other References

AASHTO T99, “Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop.”

ASTM D698, “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft³ (600 kN-m/m³)).”
Chapter 3. Subbase

ACPA References

- EB204P, “Subgrades and Subbases for Concrete Pavements.”
- IS184P, “Design of Concrete Pavement for Streets and Roads.”
- IS404P, “Cement-Treated Permeable Base for Heavy-Traffic Concrete Pavements.”
- IS414P, “Concrete Pavements without Subbases for Light Traffic Facilities.”
- R&T Update #3.06, “Stabilized Subbases and Airfield Concrete Pavement Cracking.”

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