Accelerated Techniques for Concrete Paving

Reported by ACI Committee 325

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This report covers the state of the art of accelerated-concrete paving techniques, often referred to as “fast-track” concrete paving. Accelerated-concrete paving techniques are appropriate for roadways, airfield, and other paved surfaces where quick access is required. Considerations include planning, concrete materials and properties, jointing and joint sealing, curing and temperature control, concrete strength testing, and opening-to-traffic criteria. Applications and uses of accelerated-concrete paving are discussed.

Keywords: accelerated paving; airports; admixtures; aggregates; cement; construction; concrete pavement; curing; fast-track paving; gradation; highways; intersections; joint sealing compound; jointing; nondestructive strength testing; specifications; streets; temperature; opening-to-traffic.

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CHAPTER 1—INTRODUCTION

1.1—General

Airport authorities and road agencies face major challenges from increasing traffic volumes on existing airports, roadways, and urban streets. Owners must repair or replace deteriorated pavements while maintaining traffic on these structures. Traditional pavement construction, repair, or replacement solutions may no longer be universally acceptable due to increasing public impatience with traffic interruption. Traditional solutions are especially inappropriate in urban areas where congestion is severe. Accelerated construction techniques for portland cement concrete pavement resolve these problems by providing quick public access to a high-quality, long-lasting pavement. Accelerated construction techniques are suitable for new construction, reconstruction, or resurfacing projects. Accelerated construction for concrete paving is often referred to as “fast-track” concrete paving. Accelerated paving encompasses two classes of activities: technological methods to accelerate the rate of strength gain and contractual methods to minimize the construction time.

Many methods exist to accelerate pavement construction. Two traditional acceleration methods are time incentives and penalties for project completion. Agencies have been using these time-of-completion incentives for many years, and often contractors will meet these requirements by lengthening the work day or increasing the size of construction crews. Using accelerated paving techniques, a contractor often can complete a project without increasing crew size or changing normal labor schedules.

1.2—Changes to construction specifications and processes

To build an accelerated paving project, both the contractor and the agency must make some changes to traditional construction specifications and processes. Often, these involve high-early-strength concrete, but they also can include revising opening-to-traffic criteria, construction staging, joint construction, and worker responsibilities. Table 1.2 suggests changes to project components that can decrease construction time.

Table 1.2—Changes to project components useful to shorten concrete pavement construction time

<table>
<thead>
<tr>
<th>Project Component</th>
<th>Possible changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning</td>
<td></td>
</tr>
<tr>
<td>Concrete materials</td>
<td></td>
</tr>
<tr>
<td>Jointing and sealing</td>
<td></td>
</tr>
<tr>
<td>Concrete curing and temperature</td>
<td></td>
</tr>
<tr>
<td>Strength testing</td>
<td></td>
</tr>
<tr>
<td>Traffic opening criterion</td>
<td></td>
</tr>
</tbody>
</table>

CHAPTER 2—PROJECT APPLICATIONS

2.1—General

Accelerated techniques for concrete paving allow transportation officials to consider concrete for projects that...
might not otherwise be feasible because of lengthy concrete curing intervals. Some specifications require cure intervals from 5 to 14 days for conventional concrete mixtures. With accelerated paving techniques, concrete can meet opening strengths in less than 12 hours.

2.2—Highways and tollways
Many highway agencies use accelerated techniques for concrete paving techniques to expedite construction and ease work-zone congestion. Major projects in Chicago and Denver have shown how accelerated-concrete paving can decrease construction time for urban and suburban roadways.

Tollway authorities lose revenue as a result of lane closures because traffic delays cause many drivers to find alternative routes. Accelerated-concrete pavement minimizes revenue loss by allowing earlier access at high-congestion areas like toll booths and interchanges.

The need for accelerated techniques on rural highway or road construction is more limited. A contractor may use accelerated techniques to speed construction on portions of a project to allow construction equipment on the pavement sooner than usual. The contractor also may use accelerated-concrete paving for the last portion of a project to speed final opening to public vehicles. The Federal Highway Administration (FHWA) is encouraging all highway agencies to use accelerated techniques for concrete paving to meet special construction needs.

2.3—Streets
Accelerated paving technology also provides solutions for public access on residential and urban streets. Residents along suburban streets can usually gain access to their driveways within 24 hours.

2.4—Intersections
Intersections pose major construction staging and traffic interruption challenges because they affect two or more streets. A unique project by the Iowa Department of Transportation involved the replacement of nine intersections using accelerated paving. Using two concrete mixtures and night construction, the contractor finished each intersection without disrupting daily rush-hour traffic.

Reconstructing intersections one quadrant at a time allows traffic to continue to use the roadways. With accelerated construction techniques and quadrant construction, a contractor can pave the intersection in less than one week. Where it is feasible to close the entire intersection for a short time, a contractor can use accelerated paving techniques to complete reconstruction over a weekend.

2.5—Airports
On airport aprons, runways, and taxiways, accelerated-concrete paving speeds sequential paving placements. Such pavement gains strength quickly and allows contractors to operate slipform equipment sooner on completed adjacent paving lanes. The construction schedule is reduced by shortening the wait before paving interior lanes. Accelerated paving techniques also can speed reconstruction of cross-runway intersections, runway extensions, and runway keel sections. This may be necessary to maintain traffic at commercial airports or for the national defense at military air bases. Accelerated-concrete paving reduces the time that passenger loading gates are out of service at commercial airports for apron reconstruction.

Table 3.1—Important considerations for planning accelerated-concrete paving projects

<table>
<thead>
<tr>
<th>Important planning considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access for local traffic</td>
</tr>
<tr>
<td>Local business disruption</td>
</tr>
<tr>
<td>Utility work</td>
</tr>
<tr>
<td>Construction equipment access and operation</td>
</tr>
<tr>
<td>Availability of suitable materials</td>
</tr>
<tr>
<td>Work-zone safety</td>
</tr>
<tr>
<td>Pavement edge drop-off requirements</td>
</tr>
<tr>
<td>Crossovers that disrupt both directions of traffic</td>
</tr>
<tr>
<td>Detour routes that can suffer damage and congestion from prolonged construction zone detours</td>
</tr>
<tr>
<td>Using fast-track concrete near the end of one day’s paving can facilitate next-day startup</td>
</tr>
</tbody>
</table>

CHAPTER 3—PLANNING

3.1—Planning considerations
Developing a traffic-control plan before construction is essential for projects with high traffic volumes. The goal is to reduce the construction period and minimize traffic disruption. An agency will benefit because meeting this goal will reduce public complaints, business impacts, user-delay costs, and traffic-control costs. The contractor will benefit by reducing workers’ exposure to accidents and reducing the time for which equipment is committed to a project.

Planners should include accelerated paving techniques when assessing project feasibility or when developing construction staging plans. Table 3.1 lists other issues that should be considered when planning an accelerated project.

One common method specifiers use to ensure project completion by a certain date is through a time-of-completion contract that offers monetary incentives and penalties to the contractor. The agency specifies the completion date and the daily incentive or penalty value. The contractor earns the incentive for completing the project before the deadline or pays the penalty for finishing late. These arrangements are easily understood and usually ensure timely construction. Certain new lane-rental contracting techniques may be more useful for accelerated-concrete pavement construction, because they encourage more contractor flexibility and innovation than a completion-time contract.

3.2—Lane rental
Lane rental is an innovative contracting practice that encourages contractors to lessen the construction impact on road users. There are three basic lane rental methods: cost-plus-time bidding; continuous site rental; and lane-by-lane rental. For each method, the agency must determine a rental charge for use of all or part of the roadway by the contractor. The rental charge usually coincides with the user cost estimate for delays during project construction. The user costs vary for each project and, consequently, so should rental charges. Computer programs are available to determine work zone user costs.
Table 3.2—Sample hourly lane-by-lane rental charges

<table>
<thead>
<tr>
<th>Closure or obstruction</th>
<th>Peak time periods 6 to 9 a.m. 3 to 6 p.m.</th>
<th>All other hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>One lane</td>
<td>$X$</td>
<td>0.25 $X$</td>
</tr>
<tr>
<td>One shoulder</td>
<td>0.25 $X$</td>
<td>0.0625 $X$</td>
</tr>
<tr>
<td>One lane and shoulder</td>
<td>1.25 $X$</td>
<td>0.3125 $X$</td>
</tr>
<tr>
<td>Two lanes</td>
<td>2.25 $X$</td>
<td>0.625 $X$</td>
</tr>
<tr>
<td>Two lanes and shoulder</td>
<td>2.50 $X$</td>
<td>0.6875 $X$</td>
</tr>
</tbody>
</table>

*Proportional to a base amount $X$ for one lane during peak hours, for a given project length.*

Not all projects warrant lane-rental assessments. A lane-rental contract requires special contracting terms and is most suitable for large projects where construction congestion management is critical. To reduce congestion on smaller projects, an agency can modify concrete materials and construction specifications to decrease road or lane closure time. Contract management and record keeping on lane-rental projects can be difficult. Accounting for partial completion of portions of a project can be confusing. Therefore, it is important for contract language to cover these situations.

Cost-plus-time bidding (also called “A+B bidding”) divides each contractor’s bid into two parts: the construction cost and the time cost. Along with construction costs, the contractor must include an estimate of the number of days necessary to complete the project in the bid. The agency multiplies the time estimate by a daily time-value charge to determine a time cost, and then adds the time cost to the construction cost to determine each contractor’s total bid value. The contractor with the lowest combined cost receives the contract for construction. To encourage maximum production, cost-plus-time bidding should also include a completion-time incentive and disincentive.

With lane-by-lane rental, the contractor pays for the lanes or combination of lanes occupied by the crew during construction. The agency can vary the lane rental rates depending on the lane in use (outside, inside, shoulder) or upon the time of day or week (Table 3.2). This encourages the contractor to occupy lanes in off-peak hours and to plan construction thoughtfully. This contracting arrangement may not be suitable for certain reconstruction projects with limited staging options.

3.3—Partnering

For rapid-completion projects, the agency’s goal is usually clear—perform the work with minimal traffic disruption. Many agencies and contractors are now using partnering arrangements to focus on project goals and to maintain open communication. The result is timely decision making that keeps construction moving, saves money, and reduces the chance that a problem will become a dispute.

3.4—Specifications

Small specification changes that expand the contractor’s construction and equipment choices often result in significant time and cost savings while maintaining the quality of construction. Allowing the use of minimum clearance, slipform paving machines, dowel bar inserters, and early-age saws (See Section 3.5) are examples. Permitting more than one concrete mixture also will allow a contractor to meet different construction needs within a project.

End-result specifications provide the most freedom to the contractor. With end-result specifications, the contractor must provide a pavement meeting strength, slab thickness, and smoothness criteria. The agency does not closely control proportioning of the concrete mixture or the method of paving. Accelerated-concrete pavement construction automatically becomes a contractor option with end-result specifications.

Providing a choice of concrete mixtures is a simple way of expanding contractor flexibility. Project specifications for accelerated-concrete paving might include a mixture for normal, moderate, and high-early-strength concrete. The contractor can choose from the different concrete mixtures to suit different construction situations and environmental conditions. For the majority of a large project, the choice would probably be the normal mixture. The contractor might decide to use high-early-strength concrete for the final batches each work day to ensure that sawing can be done before nightfall. The high-early-strength mixture also will ensure that the concrete at the construction joint (header) is strong enough for startup the following day. A mixture with a moderate rate of strength gain would be useful for areas where construction traffic enters and leaves the new slabs.

3.5—Innovative equipment

Recent improvements in paving equipment enhance their versatility in accelerated-concrete paving. Minimum-clearance slipform paving machines allow placement of concrete pavement adjacent to traffic lanes or other appurtenances. This allows single-lane reconstruction or resurfacing next to traffic on adjacent lanes or shoulders.

Baskets to support dowel bars at contraction joints are not needed when dowel bar inserters are used. The dowel inser- tion equipment mounts to a slipform paving machine and frees the construction lanes for concrete haul trucks and other construction vehicles. Tests of the modern dowel bar inserters show that their placement accuracy is as good as or better than that with traditional dowel baskets.

Advancements in large-diameter (up to 1270 mm [50 in.]) coring equipment may reduce urban construction time. The new equipment can cut concrete around existing or planned manholes and eliminate the need to place utility boxes before paving new streets. The coring equipment is also useful to cut around a manhole so it can be raised for an overlay.

CHAPTER 4—CONCRETE MATERIALS

4.1—Concrete mixture proportioning

One of the primary ways to decrease facility closure time is to use a concrete mixture that develops strength rapidly. Rapid strength gain is not limited to the use of special blended cements or sophisticated construction methods. It is usually possible to proportion such a mixture using locally available cements, admixtures, and aggregates.
When proportioning concrete mixtures for accelerated paving, concrete technologists also should be aware of the additional influences of heat of hydration, aggregate size distribution, entrained air, concrete temperature, curing provisions, and ambient and subbase temperature. These factors may influence early and long-term concrete strength. Many different combinations of materials will result in rapid strength gain. Table 4.1 shows acceptable materials and proportions to achieve rapid early strength gain. A complete list and discussion of admixtures is provided in ASTM C 494.

A thorough laboratory investigation is important before specifying an accelerated paving mixture. The lab work should determine plastic and hardened concrete properties using project materials and should verify the compatibility of all chemically active ingredients in the mixture. Table 4.2 shows some factors that influence mixture properties and may aid mixture proportioning.

Generally, accelerated-concrete pavement will provide good durability. Most accelerated paving mixtures have entrained air and a relatively low water content that improves strength and decreases chloride permeability.³ Freeze-thaw deterioration can occur if water freezes and expands within a concrete binder with a poor air-void distribution or if the concrete contains poor-quality aggregates. Properly cured concrete with an adequate air-void distribution resists water penetration and relieves pressures that develop in the binder.³ Air-entrained concrete pavement is resistant to freeze-thaw deterioration even in the presence of deicing chemicals.

### 4.2—Cement

ASTM C 150 Types I, II, or III portland cement can produce successful accelerated paving mixtures.¹⁷ Certain ASTM C 595 portland/pozzolan cements and several proprietary cements that develop high early strengths may also be useful for accelerated paving applications.⁴ Not every portland cement will gain strength rapidly, however, and testing is necessary to confirm the applicability of each cement.¹⁸,¹⁹

The speed of strength development is a result of the hydration and heat-generation characteristics of a particular combination of cement, pozzolan, and admixtures. Cements play a major role in both strength and heat development, and these properties depend on the interaction of the individual compounds that constitute the cement. High levels of tricalcium silicate (C₃S) and finely ground cement particles will usually result in rapid strength gain.¹⁸ Tricalcium aluminate (C₃A) also can be a catalyst to enhance the rate of hydration of C₃S by releasing heat early during cement hydration. C₃A does not contribute much to long-term strength, and in general, C₃S is the major chemical contributor to both early and long-term strengths (Fig. 4.1).¹⁸,¹⁹

Finely ground cement increases surface area and allows more cement contact with mixing water and, consequently, the cement hydrates faster. Type III cement, which is much finer than other types of portland cement, usually develops strength quickly. Blaine fineness values for Type III cement

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**Table 4.1—Example concrete mixture components for accelerated pavements**¹⁵

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>ASTM C 150 Type I</td>
<td>415 to 475 kg/m³ (700 to 800 lb/yd³)</td>
</tr>
<tr>
<td></td>
<td>ASTM C 150 Type III</td>
<td>415 to 475 kg/m³ (700 to 800 lb/yd³)</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>ASTM C 618</td>
<td>10 to 20% of cement by weight</td>
</tr>
<tr>
<td>Water-cementitious materials ratio</td>
<td>0.37 to 0.43</td>
<td></td>
</tr>
<tr>
<td>Air-entraining admixture</td>
<td>ASTM C 260</td>
<td>As necessary</td>
</tr>
<tr>
<td>Accelerating admixture</td>
<td>ASTM C 494</td>
<td>As necessary</td>
</tr>
<tr>
<td>Water-reducing admixture</td>
<td>ASTM C 494</td>
<td>As necessary</td>
</tr>
</tbody>
</table>

**Table 4.2—Some factors that influence fresh and hardened mixture properties**³,¹⁶

<table>
<thead>
<tr>
<th>Fresh or hardened mixture property</th>
<th>Mixture proportioning or placement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term strength</td>
<td>- Low water-cementitious materials ratio</td>
</tr>
<tr>
<td></td>
<td>- Cement (composition and fineness)</td>
</tr>
<tr>
<td>Early strength gain rate</td>
<td>- Water-cementitious materials ratio</td>
</tr>
<tr>
<td></td>
<td>- Concrete temperature</td>
</tr>
<tr>
<td>Freeze-thaw durability</td>
<td>- Presence and type of admixtures</td>
</tr>
<tr>
<td>Workability</td>
<td>- Curing method</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>- Aggregate hardness</td>
</tr>
<tr>
<td></td>
<td>- Compressive strength</td>
</tr>
<tr>
<td></td>
<td>- Curing method and duration</td>
</tr>
</tbody>
</table>

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*Fig. 4.1—Contribution of cement compounds to strength development.*¹⁸
range from about 500 to 600 m$^2$/kg. Blaine fineness values for Type I cement usually do not exceed 300 to 400 m$^2$/kg.$^{3,18}$ Although the greater fineness of Type III cement provides a much greater surface area for the hydration reaction, it also may require more water to coat the particles. Because Type III cement is ground finer than other cements, however, there is more potential for problems that may result from overheating the cement during the grinding phase of manufacture, including false set. False set is a rapid stiffening of the concrete shortly after mixing. This is not a major problem, and it is possible to restore workability without damaging the normal set of the concrete through further mixing in a transit mixer.$^{19}$ The materials engineer and contractor should be aware of these phenomena when testing mixtures and trial batches. Tests should be conducted using the same cement that the contractor will use in construction.

A low water-cementitious material ratio ($w/cm$) contributes to low permeability and good durability.$^{18}$ A $w/cm$ between 0.40 and 0.50 provides moderate chloride permeability for concrete made from conventional materials. A $w/cm$ below 0.40 typically provides low chloride permeability.$^{20}$ Some accelerated-paving mixtures have a ratio less than 0.43 and, consequently, provide moderate to low permeability.

It is important to remember that durability is not a function of early strength but is a function of long-term strength, $w/cm$ permeability, a proper air void system, and aggregate quality. Mixtures using these materials may appear to meet the quick strength development necessary for accelerated-concrete paving but may not provide adequate durability. Because of this inconsistency, a mixture should be evaluated at various ages to ensure it meets both early strength and long-term durability requirements.

Type III cement has been primarily used for the manufacture of precast concrete products. Before using a specific cement supplier or local precast concrete manufacturers that are experienced with the cement. At least one state uses a minimum specimen strength for mortar cubes (ASTM C 189). In concrete, ground granulated blast-furnace slag can increase long-term strength and improve finishability.$^{3}$

Evaluating accelerated-concrete pavement mixtures containing fly ash is important. The total weight of the fly ash and cement is used to determine the $w/cm$ for mixture proportioning.$^{21}$ Strength tests should be made through a range of probable mixture temperatures to indicate how temperature influences rate of hydration. Knowledge of this temperature sensitivity will be useful to the inspector and contractor during construction under field conditions, particularly in the spring and fall. Accelerating admixtures will probably be necessary should the laboratory study show unacceptable strength gain with fly ash.

4.3.3 **Ground granulated blast-furnace slag**—Ground granulated blast-furnace slag is another cementitious material that might be acceptable in accelerated-concrete paving (ASTM C 989). In concrete, ground granulated blast-furnace slag can increase long-term strength and improve finishability.$^{3}$ Because its effects are temperature sensitive, however, laboratory studies are necessary to determine the optimal dosage rate and the effects of temperature on strength development. Strength development should be similar to normal concrete at temperatures around 21°C (70°F).$^{2}$ For cooler temperatures, it may be necessary to extend the curing and insulating period, or impose temperature and seasonal limitations.

4.4—Air-entraining admixtures

Air-entraining admixtures meeting ASTM C 260 requirements are used to entrain microscopic air bubbles in concrete. Entrained air improves concrete durability by reducing the adverse effects of freezing and thawing.$^{3,18,19}$ The volume of entrained air necessary for good durability varies according to the severity of the environment and the concrete’s maximum aggregate size. Mixtures with larger coarse aggregates usually have less mortar and require less air than those with smaller maximum aggregate sizes. Typically, concrete mixtures have 4.5 to 7.5% total air content.

Air entrainment is as necessary for accelerated-concrete mixtures as for normal-setting mixtures in freeze-thaw environments. During field mixing, it is important to use the appropriate air-entraining admixture dosage rate so that the air content is adequate after placement. Higher percentages of entrained air can reduce the early and long-term strength of the mixture, while lower percentages may reduce the concrete durability. Therefore, close control of air content is necessary for successful projects.
Table 4.3—Water-reducing admixtures specified in ASTM C 494

<table>
<thead>
<tr>
<th>Type and classification</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water reducer (Type A)</td>
<td>Reduces water demand by at least 5% increases early- and later-age strength</td>
</tr>
<tr>
<td>Water reducer and retarder (Type D)</td>
<td>Reduces water demand by at least 5% retard set reduces early-age (12 h) strength increases later-age strength</td>
</tr>
<tr>
<td>Water reducer and accelerator (Type E)</td>
<td>Reduces water demand by at least 5% accelerates set increases early- and later-age strengths</td>
</tr>
<tr>
<td>High-range water reducer (Type F)</td>
<td>Reduces water demand by at least 12% increases early- and later-age strengths</td>
</tr>
<tr>
<td>High-range water reducer and retarder (Type G)</td>
<td>Reduces water demand by at least 12% retard set reduces early-age (12 h) strength increases later-age strength</td>
</tr>
</tbody>
</table>

4.5—Water-reducing admixtures

Water-reducing admixtures reduce the quantity of water necessary in a concrete mixture or improve workability at a given water content. Water-reducing admixtures increase early strength in accelerated-concrete paving mixtures by lowering the quantity of water required for appropriate concrete placement and finishing techniques. Water reducers disperse the cement, reducing the number of cement agglomerations. More efficient and effective cement hydration occurs, thus increasing strength at all ages. Water reducers can be used to increase early concrete strength with any cement but are especially useful when using Type I cement in an accelerated-concrete paving mixture.

Table 4.3 lists five water-reducing admixtures covered by ASTM C 494. Water-reducing admixtures (Types A, E, and F) generally provide the necessary properties for accelerated-concrete paving. ASTM C 1017 also classifies certain high-range water-reducing admixtures as superplasticizers. Many available high-range water-reducing admixtures meet both ASTM C 494 and ASTM C 1017 requirements. While most water-reducing admixtures will work well with different portland cements, laboratory testing is essential to determine if a concrete containing the admixture will develop the desired properties. Excessive dosage of high-range water-reducing admixtures may lead to retardation of setting.

ASTM C 494 Type A admixtures are common in accelerated-concrete paving. Generally, a concrete containing a Type A water-reducing admixture will require from 5 to 10% less water than a similar mixture without the admixture. A Type D water-reducing, set-retarding admixture may be desirable when very high mixture temperatures induce an early set that preempts placing and finishing operations. Type D water reducers slightly retard the initial set to extend the period of good workability for placing and finishing. This retardation can also affect early strength gain, particularly during the first 12 hours. After 12 hours, the strength gain is similar to concrete containing a Type A water reducer. Concrete made with Type E, F, or G admixtures requires thorough laboratory evaluation to determine if the concrete properties are acceptable for anticipated environmental conditions and placement methods. Types F and G admixtures may be more appropriate for high-slump mixtures or when a lower w/cm is desired.

4.6—Accelerating admixtures

Accelerating admixtures aid strength development and reduce initial setting times by increasing the reaction rate of C3A. Accelerating admixtures generally consist of soluble inorganic salts or soluble organic compounds and should meet requirements of ASTM C 494, Type C or Type E.

A common accelerator is calcium chloride (CaCl2). Many agencies use CaCl2 for full-depth and partial-depth concrete pavement patching when quick curing and opening to traffic is needed. The optimum dose is about 2% by weight of cement. This dose will approximately double the one-day strength of normal concrete. It is very important to test both fresh and hardened concrete properties before specifying a mixture containing an accelerating admixture. With some aggregates, concrete will be susceptible to early freeze-thaw damage and scaling in the presence of CaCl2. Another drawback of CaCl2 is its corrosive effects on reinforcing steel. If the pavement requires any steel, it is advisable to select a nonchloride accelerator or an alternative method of achieving early strength.

4.7—Aggregate

Aggregates that comply with ASTM C 33 specifications are acceptable for use in accelerated-concrete pavements. Existing accelerated-paving projects made with concrete containing these aggregates have met their early-strength requirements and are providing good service. Further consideration of grading and aggregate particle shape may optimize early and long-term concrete strength. These factors also can have a significant influence on the plastic and hardened mixture properties and may warrant consideration for accelerated-concrete pavements.

Typical procedures consider the proportions of coarse and fine aggregates without specifying the combined or total grading. Consequently, concrete producers draw aggregate from two stockpiles at the plant site, one for coarse and one for fine material. To improve aggregate grading, additional intermediate sizes of material (blend sizes) at the plant site during project construction may be required.

4.7.1 Grading—Grading data indicate the relative composition of aggregate by particle size. Sieve analyses of source stockpiles are necessary to characterize the materials. The best use of such data is to calculate the individual proportions of each aggregate stockpile in the mixture to obtain the designed combined-aggregate grading. Well-graded mixtures generally have a uniform distribution of aggregates on each sieve. Gap-graded mixtures have a deficiency of aggregates retained on the 2.36 mm through 600 µm (No. 8 through 30) sieves.

An optimum combined-aggregate grading efficiently uses locally available materials to fill the major voids in the concrete to reduce the need for mortar. Particle shape and texture are important to the response of the concrete to vibration, especially in the intermediate sizes. A well-consolidated concrete mix-
ture with an optimum aggregate grading will produce dense and durable concrete without edge slump.

One approach to evaluate the combined-aggregate grading is to assess the percentage of aggregates retained on each sieve. A grading that approaches the shape of a bell curve on a standard grading chart indicates an optimal distribution (Fig. 4.2). Blends that leave a deficiency in the 2.36 mm through 600 µm (No. 8 through No. 30) sieves are partially gap graded.

There is a definite relationship between aggregate grading and concrete strength, workability, and long-term durability. Intermediate-size aggregates fill voids typically occupied by less dense cement paste and thereby optimize concrete density (Fig. 4.3). Increasing concrete density in this manner will result in:

- Reduced mixing water demand and improved strength because less mortar is necessary to fill space between aggregates;
- Increased durability through reduced avenues for water penetration in the hardened concrete;
- Better workability and mobility because large aggregate particles do not bind in contact with other large particles under the dynamics of finishing and vibration; and
- Less edge slump because of increased particle-to-particle contact.

Well-graded aggregates also influence workability and ease the placing, consolidating, and finishing of concrete. While engineers traditionally look at the slump test as a measure of workability, it does not necessarily reflect that characteristic of concrete. Slump evaluates only the fluidity of a single concrete batch and provides a relative measure of fluidity between separate concrete batches of the same mixture proportions.

Concrete with a well-graded aggregate often will be much more workable at a low slump than a gap-graded mixture at a higher slump. A well-graded aggregate may change concrete slump by 90 mm (3-1/2 in.) over a similar gap-graded mixture. This is because approximately 320 to 385 kg/m³ (540 to 650 lb/yd³) less water is necessary to maintain mixture consistency than is necessary with gap grading.

4.7.2 Particle shape and texture—The shape and texture of aggregate particles impact concrete properties. Sharp and rough particles generally produce less-workable mixtures than rounded and smooth particles at the same w/cm. The bond strength between aggregate and cement mortar improves as aggregate texture becomes rougher. The improved bond will improve concrete flexural strength.

Natural coarse aggregates and natural sands are very mobile under vibration. Cube-shaped crushed aggregate is also
more mobile under vibration than flat or elongated aggregate. The good mobility allows concrete to flow easily around the baskets, chairs, and reinforcing bars, and is ideal for pavements.

Flat or elongated intermediate and large aggregates can cause mixture problems. These shapes generally require more mixing water or fine aggregate for workability and, consequently, result in a lower concrete flexural strength (unless more cementitious materials are added). Allowing no more than 15% flat or elongated aggregate by weight of the total aggregate is advisable. Use ASTM D 4791 to determine the quantity of flat or elongated particles.

4.8—Water

The sooner the temperature of a mixture rises, the faster the mixture will develop strength. One way to raise the temperature of plastic concrete is to heat the mixing water; however, this is more practical for small projects that do not require a large quantity of concrete, such as intersection reconstruction.

Several factors influence the water temperature needed to produce a desirable mixture temperature at placement. The critical factors are ambient air temperature, aggregate temperatures, and aggregate free moisture content. When necessary, ready-mixed concrete producers heat water to 60 to 66 °C (140 to 150 °F) to elevate mixture temperature sufficiently for cool-weather construction. In such conditions, the use of blanket insulation is advised. To avoid a flash set of the cement, the hot water and aggregates should be combined before adding the cement when mixing batches. See ACI 306R for additional guidance on controlling the initial concrete temperature.

Hot water only facilitates early hydration, and its benefits are generally short-lived. Several hours of heat containment through insulation may be necessary for rapid strength gain to continue, particularly when cool conditions prevail.

CHAPTER 5—CONSTRUCTION

5.1—General

No special equipment is necessary for a contractor to place accelerated-concrete pavement. Because the time for placement can be shorter than with conventional paving, however, accelerated paving requires well-planned construction sequencing. Contractors and specifying agencies should be aware that operation adjustments will be necessary while the paving crew becomes accustomed to mixture characteristics. It will take time for workers to become comfortable with accelerating their duties. Constructing test slabs will familiarize an inexperienced crew with the plastic properties of the accelerated-concrete before starting full-scale operations.

Contractors have built successful accelerated-concrete pavements using both slipform and fixed-form construction techniques. There are no reports indicating unusual problems with mixing, placing, and finishing accelerated-concrete paving. The contractor and agency should carefully consider concrete haul distances on large projects.

The adjustments that accompany construction start-up on accelerated projects for concrete pavement normally will not interfere with the ride quality. Contractors have built accelerated-paving projects to meet conventional ride specifications, and agencies should not modify their smoothness specifications for accelerated-concrete pavements.

5.2—Curing and temperature management

5.2.1 Importance of curing—Curing provisions are necessary to maintain a satisfactory moisture and temperature condition in concrete for a sufficient time to ensure proper hydration. Internal concrete temperature and moisture directly influence both early and ultimate concrete properties. Therefore, applying curing provisions immediately after placing and finishing activities is important. Even more so than with standard concrete, curing is necessary to retain the moisture and heat necessary for hydration during the early strength gain of accelerated-concrete pavement. Accelerated pavements require especially thorough curing protection in environmental conditions of high temperature, low humidity, high winds, or combinations of these.

Air temperature, wind, relative humidity, and sunlight influence concrete hydration and shrinkage. These factors may heat or cool concrete or draw moisture from exposed concrete surfaces. The subbase can be a heat sink that draws energy from the concrete in cold weather or a heat source that adds heat to the bottom of the slab during hot, sunny weather.

Monitoring heat development in the concrete enables the contractor to adjust curing measures to influence the rate of strength development, the window for sawing (see Section 5.3.1), and the potential for uncontrolled cracking. Monitoring temperature when environmental or curing conditions are unusual or weather changes are imminent is particularly important. Maturity testing allows field measurement of concrete temperature and correlation to concrete strength. Chapter 6 describes maturity testing in more detail.

5.2.2 Curing compounds—Liquid membrane-forming curing compounds should meet ASTM C 309 material requirements. Typically, white-pigmented compound (Type 2, Class A) is applied to the surface and exposed edges of the concrete pavement. The materials create a seal that limits evaporation of mixing water and contributes to thorough cement hydration. The white color also reflects solar radiation during bright days to prevent excessive heat build up in the concrete surface. Class A liquid curing compounds are sufficient for accelerated-concrete paving under normal placement conditions when the application rate is sufficient.

Agencies that build concrete pavements in mountainous and arid climates often specify a slightly heavier dosage rate of resin-based curing compound meeting ASTM C 309, Type 2, Class B requirements. The harsher climate causes dramatic daily temperature changes, often at low humidity levels. As a result, the concrete is often more susceptible to plastic-shrinkage cracking and has a shorter window for joint sawing.

Most conventional paving specifications require an application rate around 5.0 m²/L (200 ft²/gal.). Accelerated-concrete pavement mixtures rapidly use mixing water during early hydration and this may lead to a larger potential for plastic shrinkage at the surface. Therefore, increasing the application of curing compound for accelerated paving
projects to about 3.75 m²/L (150 ft²/gal.) is advisable. Because deep tining increases surface area, the higher application rate also is important where surface texture tine depth exceeds about 3 mm (1/8 in.). Bonded overlays less than 150 mm (6 in.) thick require an application rate of 2.5 m²/L (100 ft²/gal.). The thin overlay slabs have a large ratio of surface area to concrete volume so evaporation consumes proportionately more mixing water than with typical slabs.25

The first few hours, while the concrete is still semiplastic, are the most critical for good curing. Therefore, the contractor should apply the curing compound as soon as possible after final finishing. Construction and public vehicle tires may wear some of the compound off of the surface after opening, but this does not pose a problem because the concrete should have reasonable strength and durability by that time. Curing compound should be applied in two passes at 90 degrees to each other. This will ensure complete coverage and offset wind effects, especially for tined surfaces.

5.2.3 Blanket insulation—Insulating blankets provide a uniform temperature environment for the concrete. Insulating blankets reduce heat loss and dampen the effect of both air temperature and solar radiation on the pavement, but do not negate the need for a curing compound.5 The purpose of blanket insulation is to aid early strength gain in cool ambient temperatures. Table 5.1 indicates when insulation is recommended.24

Care should be taken not to place blankets too soon after applying a curing compound. In warm conditions, waiting several hours and placing the blankets as the joint sawing progresses may be acceptable. In any case, it is inadvisable to wait until after finishing all joint sawing to start placing insulating blankets. Figure 5.1 shows how effective insulating blankets are in maintaining the temperature of concrete compared to an exposed surface of the same mixture.

Experience indicates that an insulating blanket with a minimum thermal resistance (R) rating of 0.035 m²·K/W (0.5 h·ft²·F/Btu) is adequate for most conditions.5,21,24-27 The blanket should consist of a layer of closed-cell polystyrene foam with another protective layer of plastic film. Additional blankets may be necessary for temperatures below about 4 C (40 F).

5.2.4 Plastic shrinkage—The temperatures of accelerated-paving mixtures often exceed air temperature and require special attention to avoid plastic-shrinkage cracking. Plastic-shrinkage cracks can form during and after concrete placement when certain prevailing environmental conditions exist. The principal cause of plastic-shrinkage cracking is rapid evaporation of water from the slab surface.3 When this occurs while concrete is in a plastic or semiplastic state, it will result in shrinkage at the surface. Air temperature, relative humidity, wind velocity, and concrete temperature influence the rate of evaporation. The tendency for rapid evaporation increases when concrete temperature exceeds air temperature.24 Additional guidance on controlling plastic-shrinkage cracking is given in ACI 305R.
Among the ways to moderate the environment and cool concrete components to slow evaporation are:

- Pave during the evening or nighttime;
- Water-mist aggregate stockpiles and subbases before paving; and
- Use an evaporative retardant (monomolecular compound) on the surface.

Figure 5.2 shows the effect of environmental factors on evaporation of surface moisture. When the evaporation rate exceeds 1.0 kg/m²/h (0.2 lb/ft²/h), plastic-shrinkage cracking is likely. As a precaution, closely monitor and adjust the field-curing practice if the evaporation rate exceeds 0.5 kg/m²/h (0.1 lb/ft²/h). Fog misting immediately after placement may be needed to prevent plastic-shrinkage cracking.

5.3—Jointing and sealing

After paving and curing the concrete, the final step is jointing the pavement. While there are several methods to form the joints in the plastic concrete, sawing the concrete is by far the most common method. Tooling the joints may be a viable jointing method and should be given some consideration for smaller projects.

The typical time sequence for joint sawing and sealing is not compatible with rapid strength gain and early opening to traffic. Rapid strength gain reduces the time available for sawing. The contractor must keep in mind that it is necessary to saw much sooner after paving than with normal concrete. To meet public traffic opening requirements, earlier joint sealing and special consideration of sealant materials may also be necessary.

5.3.1 Sawing—The sawing window is a short period of time after placement when the concrete can be cut successfully before it cracks. The window opens when concrete strength is acceptable for joint cutting without excessive raveling along the cut. The window closes when significant concrete shrinkage occurs and induces uncontrolled cracking, unless sawing is done in time.

Uncontrolled cracking has not been a problem on accelerated-concrete pavements because the concrete gains strength rapidly enough that sawing can usually be done before the temperature starts to drop and the concrete starts to shrink. Contractors and inspectors should be aware of the factors that influence the sawing window, and in particular, differential shrinkage and thermal shock that may bring about random uncontrolled cracking.

Internal concrete temperature and moisture also influence the time available for joint sawing. Concrete temperature directly relates to the strength of concrete, which controls the ability to commence sawing. Under warm, sunny, summer conditions, the maximum concrete temperature will vary depending on when the concrete is placed during the day. Concrete placed in early morning often will reach higher maximum temperatures than concrete placed in the late morning or afternoon, because it receives more radiant heat throughout the day (Fig. 5.3). As a result, concrete placed early in the morning will generally have a shorter sawing window.

Sawing must be completed before the concrete shrinks and significant restraint stresses develop. Drying shrinkage occurs partly from moisture consumption through hydration and moisture loss to the environment. Thermal contraction and curling-restraint stresses occur as the concrete temperature begins to fall and the top of the slab cools more rapidly than the bottom. For accelerated-concrete paving, it is preferable to complete sawing before the concrete surface temperature begins to drop after the initial set.

After the concrete sets, uncontrolled cracking might occur when conditions induce differential concrete shrinkage and contraction. Differential shrinkage is a result of temperature differences throughout the pavement depth. Normally, the concrete surface temperature drops before the temperature at middepth or bottom (Fig. 5.4). The temperature at middepth usually remains warm for the longest period. The temperature differential may be enough to cause cracking.
Research indicates that a drop in surface temperature of more than 9.5 C (15 F) can result in excessive surface shrinkage and induce cracking if sawing has not been completed. This is critical in most regions during the spring and fall because air temperature often drops significantly from day to night. Differential shrinkage also occurs from rain showers falling because air temperature often drops significantly from day to night. Differential shrinkage also occurs from rain showers that cool the slab surface. Therefore, the contractor should monitor the weather and saw joints as soon as possible when conditions change from placement conditions.

Thermal shock also may occur within a few hours after removing curing blankets from a new slab. Removing only the blankets needed to allow joint sawing may be necessary. To minimize uncontrolled cracking from thermal shock, blankets should not be completely removed until after completion of all sawing.

To decide when to begin sawing any concrete pavement requires some experience and judgment. The quality of saw cut will vary with concrete strength. Excessive spalling and raveling along the joint face will result if the sawing is too soon. Slight raveling is acceptable if a second saw cut will be made to form a sealant reservoir.

Some design factors also influence the optimal time to begin sawing. Subbase or subgrade friction will restrain shrinkage as the concrete cools after final set. The high-friction surface of asphalt or cement-stabilized subbases decreases the time allowable before sawing is necessary. In some extreme cases, bond between the surface and subbase has induced cracking before sawing was possible without unacceptable raveling. A double application of a wax-based curing compound can be used to reduce friction between the concrete pavement slab and a lean concrete subbase, a bituminous subbase, or a cement-treated subbase, thus extending the time for sawing. Fill-in lanes for airport pavements and parking areas also tend to have a shorter time for joint sawing due to edge restraint. Granular subbases and subgrade soils provide the least frictional restraint and the longest sawing time.

Mixtures with softer limestone aggregates require less strength for sawing than do mixtures with harder coarse aggregates. Table 5.1 shows cylinder compressive strengths necessary to begin sawing different mixtures for acceptable and excellent results.

Contractors have successfully cut joints using wet-sawing, dry-sawing, and early-age sawing equipment. It is usually possible to dry-saw the concrete slightly earlier than it is to wet-saw it. Dry-sawing also does not require a water flushing for slurry removal and may shorten the drying time necessary before sealing.

A contractor should choose a saw blade depending on the hardness of the aggregate in the concrete. Silicon carbide or carborundum (dry-sawing) blades are only effective for softer aggregates like limestone. Wet-saw diamond blades are acceptable for all types of aggregates and are most advantageous for concrete containing hard aggregates. A contractor also may saw through most aggregates without water using certain diamond blades mounted on saws powered by less than 26 kW (35 hp) engines.

Early-age saws allow cutting very early during the initial concrete set stage. Cutting is feasible after compressive strengths reach about 1.0 MPa (150 psi), usually an hour or two after paving. All cutting should be done before the final set of the concrete. Most currently available early-age saws provide only a shallow initial cut of about 18 to 33 mm deep (3/4 to 1-1/4 in.) and require a second cut using a standard saw for a sealant reservoir or to meet typical specifications of saw cut depths of 1/3 or 1/4 of the slab thickness (D/3 or D/4). Using early-age sawing equipment can allow cutting before curing blanket placement and can be effective for accelerated-concrete paving projects.
Table 6.1—Nondestructive test methods for concrete

<table>
<thead>
<tr>
<th>Test method</th>
<th>Standard</th>
<th>Basic description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse velocity</td>
<td>ASTM C 597</td>
<td>Velocity of sound wave from transducer to receiver through concrete relates to concrete strength</td>
</tr>
<tr>
<td>Penetration resistance</td>
<td>ASTM C 803</td>
<td>Penetration depth of gun-fired probe correlates to surface hardness and compressive strength</td>
</tr>
<tr>
<td>Schmitt rebound number</td>
<td>ASTM C 805</td>
<td>Rebound number correlates to compressive strength</td>
</tr>
<tr>
<td>Pullout</td>
<td>ASTM C 900</td>
<td>Force to remove cast-in-metal probe correlates to surface compressive strength</td>
</tr>
<tr>
<td>Maturity</td>
<td>ASTM C 1074</td>
<td>Internal temperature of concrete relates directly to concrete strength</td>
</tr>
<tr>
<td>Break-off</td>
<td>ASTM C 1150</td>
<td>Force necessary to break a circular core cast or cut partially into slab correlates to flexural strength</td>
</tr>
</tbody>
</table>

*Cap and pullout (CAPO) variation of pullout test not approved by ASTM.

Step cut blades also are available to allow cutting the joint seal reservoir and depth-cut at the same time, eliminating the time necessary for a second cut to form the joint seal reservoir.

5.3.2 Sealing—Joint sealing should begin as soon as practicable after sawing is complete. Normally, liquid sealant manufacturers recommend delaying installation for a considerable moisture-free period. Most sealant manufacturers also provide cleaning recommendations for use of their product in accelerated-pavement construction. The rapid strength gain and low w/cm of accelerated-paving concrete reduce excess moisture on the side walls of the joint reservoirs. This allows sealing earlier than with standard concrete. Therefore, always consult the sealant manufacturer’s particular product recommendations.

Cleaning is the most important aspect of joint sealing. Every liquid sealant manufacturer requires essentially the same cleaning procedures, which include sandblasting. Likewise, the performance claims of any liquid sealant product is predicated on those cleaning procedures. Cleaning is not as critical for compression seals, because they do not require bond to the concrete.

Cleaning operations will vary depending on the saw blade type. Reservoir faces require a thorough cleaning to be sure of good sealant adhesion and long-term performance. Proper cleaning after wet sawing requires mechanical brushing and flushing with pure water to remove contaminants. Dry sawing requires only a filtered air-blowing operation to remove particulate residue from the joint reservoir. This can produce considerable dust and may be inadvisable in urban areas.

Preformed seals are not sensitive to dirt or moisture on side walls and may allow sealing earlier than a liquid sealant. On one project, a low-modulus rubber sealant sufficiently adhered to the reservoir faces as early as eight hours after paving. Silicone sealants also have been used for accelerated projects. Manufacturer’s recommendations regarding joint dryness and time before opening to traffic should be followed. Reference 30 and ACI 228.1R provide more information on joint sealants and sealing procedures.

CHAPTER 6—NONDESTRUCTIVE TESTING

6.1—Appropriate methods

Increasingly, agencies, consultants, and contractors are using nondestructive testing to adequately determine strength at early ages. Table 6.1 describes six nondestructive test methods for concrete. Maturity and pulse velocity testing are appropriate and common for predicting strengths on accelerated-concrete pavement projects.

6.2—Maturity

Maturity testing provides strength evaluation through monitoring of internal concrete temperature in the field. The temperature history is used to calculate a maturity index that accounts for the combined effects of time and temperature. The basis of maturity testing is that each concrete mixture has a unique relationship of strength to maturity index. Therefore, a mixture will have the same strength at a given maturity no matter what time and temperature conditions have prevailed up to that point.

There are two methods for computing maturity (ASTM C 1074). The first method uses the Nurse-Saul maturity function to calculate the time-temperature factor using the following equation. This approximation holds provided that sufficient water is available for hydration.

\[ M(t) = \Sigma(T_a - T_o)\Delta t \]

where

\( M(t) = \) temperature-time factor, degree-days or degree-hours;

\( \Delta t = \) time interval, days or hours;

\( T_a = \) average concrete temperature during time interval, \( ^\circ C \); and

\( T_o = \) datum temperature, \( ^\circ C \) (typically –10 \( ^\circ C \) [14 \( ^\circ F \)]).

The second method uses the Arrhenius maturity equation and is less common for concrete pavement work in the United States. More information is available in ASTM C 1074 and References 24 and 32.

Thorough laboratory testing is necessary before a technologist can confidently apply concrete maturity testing in the field. Laboratory testing requires preparation of trial batches using the actual field-mixture materials. Technologists must monitor the concrete temperature during curing and test cylinders at different ages to develop a relationship between compressive strength and the maturity index, such as the time-temperature factor (Fig. 6.1). This relationship becomes the calibration curve for estimating the in-place concrete strength based on the measured in-place maturity index.

Field maturity evaluation begins with the embedment of thermocouples or temperature probes in the concrete when practicable after finishing and curing. Positioning the temperature probes along the project requires forethought to ensure they are in areas of critical importance for joint sawing and opening to traffic. The probes must connect to either commercial or commercially available maturity meters or temperature recorders with an accuracy to 1 \( ^\circ C \) (2 \( ^\circ F \)). Technologists take readings at regular intervals and then estimate strength using the temperature-time relationship from the laboratory study.
6.3—Pulse velocity

Pulse velocity is another available nondestructive test for determining concrete strength at early ages. A true nondestructive test, it measures the time required for an ultrasonic wave to pass through the concrete from one transducer to another. The distance between the transducers is divided by the travel time to obtain the pulse velocity. The velocity of the wave correlates to concrete strength. Further information is available in ACI 228.1R and Reference 33.

Like maturity testing, pulse-velocity testing requires laboratory calibration for reliable in-place strength estimates. The distance between the transducers has to be accurately determined. Trial batches must contain the same mixture materials at similar proportions as the project mixture. In the laboratory, technologists take pulse-velocity measurements through a representative number of cast concrete specimens, test the specimens for strength, and plot the results against the pulse-velocity readings to create a calibration curve (Fig. 6.2).

Field measurement of pulse velocity is relatively simple. Technologists hold the sending and receiving transducers flush to the pavement surface. Sometimes it may be necessary to grind a rough surface, but usually a layer of grease or gel will sufficiently fill surface voids and provide full transducer contact. Optimal readings occur with the transducers held axially for direct measurement, but this arrangement usually requires a cast-in boxout in the slab. An acceptable alternative is to hold the transducers in a perpendicular arrangement providing a semidirect measurement. Figure 6.3 shows typical arrangements.

Comparing field pulse-velocity readings to the calibration curve provides an early-age estimate of concrete strength. Studying the manufacturer’s equipment instructions for specific recommendations and to make reading corrections necessary for concrete temperature and moisture content is necessary. To avoid inaccurate measurements, take readings away from any embedded steel that will affect travel of the ultrasonic pulses.

CHAPTER 7—TRAFFIC OPENING

7.1—Strength criteria

The chief issue in accelerated pavement construction is determining when traffic can begin to use the new pavement. The basis for this decision should be made on the concrete strength and not arbitrarily on the time from placement. Strength directly relates to load-carrying capacity and provides certainty that the pavement is ready to accept loads by construction or public traffic.

For concrete pavement applications, flexural strength is the most direct indicator of load capacity. Flexural-strength values indicate the tensile strength at the bottom of the slab where wheel loads induce tensile stresses. For that reason, this document lists opening criteria in terms of flexural strengths of test beams under third-point loading. Flexural strength tests from ASTM C 78 are very sensitive to the beam fabricating and testing procedures. Many agencies realize this shortcoming and use compressive strength tests (ASTM C 39) to evaluate concrete for acceptance and opening.
To use the flexural strength opening criteria in this publication with compressive strength data, a correlation should be developed between compressive strength and flexural strength in the laboratory for each specific mixture. The strength necessary to allow vehicles onto a new pavement will depend on the following factors:

- Type, weight, and number of anticipated loads during early-age period;
- Location of loads on slab;
- Concrete modulus of elasticity;
- Pavement design (new construction, unbonded overlay, bonded overlay, or overlay on asphalt);
- Slab thickness;
- Foundation support (modulus of subgrade reaction, \( k \)); and
- Edge support condition (widened lane, or tied curb and gutter, or tied concrete shoulder).

As slab support or pavement thickness increase, stress in the concrete will decrease for a given load. This relationship allows different opening strength criteria for different pavement designs and early traffic loads. An opening strength as low as 1.0 MPa (150 psi) in third-point loading is acceptable if the pavement will carry only automobiles. If the pavement will carry trucks, a strength of up to 4.5 MPa (650 psi) may be necessary for thin slabs.

Wheel-load location also influences the magnitude of stress. Critical flexural stresses occur from wheels that ride directly on the pavement edge away from a slab corner. Wheel loads that ride near the center of the slab induce considerably lower stress than edge loads. These flexural stresses lead to pavement fatigue cracking. Often, however, stresses less than 50% of the flexural strength of the pavement do not induce fatigue damage.

Two traffic categories exist for early opening assessment: construction and public traffic. In most cases, the construction contractor’s vehicles use the pavement before any public traffic; however, this may not be typical for accelerated paving projects. It is important to keep public traffic off the pavement until after joint sawing to avoid overstressing the concrete.

### 7.2—Construction traffic

Typical construction vehicles include slipform pavers, span saws, haul trucks, and water trucks. Except for slabs less than 175 mm (7.0 in.) thick, span saws do not induce concrete fatigue even during very early ages. The 80 kN (18,000 lb) single axles and 151 kN (34,000 lb) tandem axles on construction trucks induce much higher stresses. Fortunately, operators tend to drive these vehicles within the center of new slabs to avoid drop-offs that exist before shoulder placement or final grading. Table 7.1 provides opening criteria for span saw and truck loads and assumes that these loads will occur at least 0.6 m (2.0 ft) from the edge of the slab.

#### Table 7.1—Flexural strength requirements for opening concrete pavements to use by construction traffic

<table>
<thead>
<tr>
<th>Slab thickness, mm (in.)</th>
<th>Subgrade modulus ( k ), MPa/m (psi/in.)</th>
<th>To support span-saw loads, MPa (psi)</th>
<th>To support 151 kN (34,000 lb) tandem axle loads, MPa (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 (6.0)</td>
<td>27.2 (100)</td>
<td>1.5 (210)</td>
<td>2.8 (410)</td>
</tr>
<tr>
<td></td>
<td>54.3 (200)</td>
<td>1.3 (190)</td>
<td>2.5 (360)</td>
</tr>
<tr>
<td></td>
<td>135 (500)</td>
<td>0.8 (100)</td>
<td>2.1 (300)</td>
</tr>
<tr>
<td>165 (6.5)</td>
<td>27.2 (100)</td>
<td>1.3 (190)</td>
<td>2.5 (360)</td>
</tr>
<tr>
<td></td>
<td>54.3 (200)</td>
<td>1.1 (160)</td>
<td>2.1 (310)</td>
</tr>
<tr>
<td></td>
<td>135 (500)</td>
<td>1.0 (150)</td>
<td>2.1 (300)</td>
</tr>
<tr>
<td>175 (7.0)</td>
<td>27.2 (100)</td>
<td>1.0 (150)</td>
<td>2.1 (300)</td>
</tr>
<tr>
<td></td>
<td>54.3 (200)</td>
<td>1.0 (150)</td>
<td>2.1 (300)</td>
</tr>
<tr>
<td></td>
<td>135 (500)</td>
<td>1.0 (150)</td>
<td>2.1 (300)</td>
</tr>
</tbody>
</table>

*For concrete pavements more than 175 mm (7.0 in.) thick, span saws cause no fatigue when the modulus of rupture exceeds 1.0 MPa (150 psi), the practical minimum for sawing operations. Note: Span-saw criterion allows 0.5% fatigue consumption. Truck-axle criterion allows 1.0% fatigue consumption. Assumes that the loads occur at least 0.6 m (2.0 ft) from the slab edge.*

### 7.3—Public traffic

Public traffic includes many different vehicles. To determine the acceptable opening strength for public traffic requires an estimate of the number of loads before the concrete reaches design strength.

The public traffic opening criterion for municipal and highway pavements is found in Appendix A, Table A.1. The use of Table A.1 requires estimates of traffic volume, slab thickness, and foundation support. Table A.1 assumes a 0.6 m (2.0 ft) offset of traffic from the lane edge. Wide truck lanes, tied concrete shoulders, and curbs and gutters all serve to reduce load stresses to levels equivalent to a 0.6 m (2.0 ft) traffic offset. If the pavement design does not include these features, the contractor can place barricades to prevent edge loads. Normally, after the concrete flexural strength reaches 3.0 MPa (450 psi), the contractor may remove the barricades. It may be necessary to wait for concrete to gain full design strength on thin municipal pavements that require more than 4.5 MPa (650 psi) flexural strength for opening.
7.4—Aircraft traffic

No studies have been made to determine early-age opening criteria for aircraft traffic. The Federal Aviation Administration’s current specifications allow opening to traffic at 3.8 MPa (550 psi) flexural strength with no time limitation.35

CHAPTER 8—REFERENCES

8.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Society for Testing and Materials (ASTM)

ASTM C 33 Standard Specification for Concrete Aggregate

ASTM C 39 Test Method for Compressive Strength of Cylindrical Concrete Specimens

ASTM C 78 Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)

ASTM C 109 Text Method for Compressive Strength of Hydraulic Cement Mortar

ASTM C 150 Standard Specification for Portland Cement

ASTM C 260 Standard Specification for Air Entraining Admixtures for Concrete

ASTM C 309 Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete

ASTM C 494 Standard Specification for Chemical Admixtures for Concrete

ASTM C 597 Test Method for Pulse Velocity through Concrete

ASTM C 595 Standard Specification for Blended Hydraulic Cements

ASTM C 618 Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete

ASTM C 803 Test Method for Penetration Resistance of Hardened Concrete

ASTM C 805 Test Method for Rebound Number of Hardened Concrete

ASTM C 900 Test Method for Pullout Strength of Hardened Concrete

ASTM C 989 Specification for Ground Granulated Blast-furnace Slag for Use in Concrete and Mortars

ASTM C 1017 Standard Specification for Chemical Admixtures for Producing Flowing Concrete

ASTM C 1074 Practice for Estimating Concrete Strength by the Maturity Number

ASTM C 1150 Test Method for the Break-Off Number of Hardened Concrete

ASTM D 4791 Test for Flat or Elongated Particles in Coarse Aggregates

American Concrete Institute (ACI)

228.1R In-Place Methods to Estimate Concrete Strength

305R Hot Weather Concreting

306R Cold Weather Concreting

The above publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, Mich. 48333-9094

American Society for Testing and Materials
100 Barr Harbor Drive
West Conshohocken, Pa. 19428-2959

8.2—Cited references


5. Grove, J., 1989, “Blanket Curing to Promote Early Strength Concrete,” Research Project MLR-87-7, Iowa Department of Transportation.


8.3—Other references

APPENDIX A—OPENING TO PUBLIC TRAFFIC
A.1—Flexural strength requirements
Table A.1 can be used to determine the flexural strength required to open concrete pavement to public traffic.

A.2—Example
For example, consider a 200 mm (8.0 in.) municipal pavement designed to carry 3 million equivalent single-axle loads (ESALs) one way in the design lane for a 20-year period using the AASHTO procedure for concrete pavement design. The pavement is plain-doweled with curb and gutter and resting on a foundation with an equivalent subgrade modulus of 27.2 MPa/m (100 psi/in.). The design thickness is based on an average third-point flexural strength of 4.8 MPa (700 psi).

In laboratory conditions, the concrete achieved 4.8 MPa (700 psi) flexural strength in 24 hours. The pavement is being built in the fall, so the concrete may take longer to reach 4.8 MPa (700 psi) in field conditions. For illustrative purposes, assume 48 hours from the time the concrete is placed until the design strength of 4.8 MPa (700 psi) is achieved in the field.

\[
\frac{3,000,000 \text{ ESALs} \div 20 \text{ yr} \div 365 \text{ day/yr}}{411 \text{ ESAL/day}} = 728 \text{ days}
\]

\[
411 \text{ ESAL/day} \times 2 \text{ days} = 822 \text{ ESALs to specified design strength}
\]

From Table A.1, the required opening flexural strength is 2.3 MPa (340 psi).
Table A.1—Flexural strength requirements for opening concrete pavements to use by public traffic\(^1,34\)

<table>
<thead>
<tr>
<th>Slab thickness, mm (in.)</th>
<th>Foundation support (k), MPa/m (psi/in.)</th>
<th>Modulus of rupture for opening, MPa (psi), to support estimated ESALs repetitions to specified strength*</th>
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<tbody>
<tr>
<td></td>
<td>100 ESALs(^*)</td>
<td>500 ESALs(^*)</td>
</tr>
<tr>
<td>150 (6.0)</td>
<td>27.2 (100)</td>
<td>3.4 (490)</td>
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<tr>
<td></td>
<td>54.3 (200)</td>
<td>2.8 (410)</td>
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<tr>
<td></td>
<td>135 (500)</td>
<td>2.3 (340)</td>
</tr>
<tr>
<td>165 (6.5)</td>
<td>27.2 (100)</td>
<td>3.0 (430)</td>
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<tr>
<td></td>
<td>54.3 (200)</td>
<td>2.4 (350)</td>
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<td></td>
<td>135 (500)</td>
<td>2.1 (300)</td>
</tr>
<tr>
<td>Municipal</td>
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<td>2.1 (310)</td>
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<td>2.1 (300)</td>
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<td>190 (7.5)</td>
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<td>135 (500)</td>
<td>2.1 (300)</td>
</tr>
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</table>

*Traffic is estimate of the total one-way ESALs\(^*\) that will use the pavement truck lane between time of opening and time concrete reaches design strength (usually 28-day strength.)

†Slabs greater than 265 mm (10.5 in.) thick can be opened to traffic at a flexural strength of 2.1 MPa (300 psi) or greater with barricade protection of free edges. Reduce opening strengths by 30% (2.1 MPa [300 psi] minimum) if no barricades protect free edges, but the pavement includes a 4.2 m (14 ft) wide or greater truck lane and/or tied concrete shoulders.