

ADVANCING CONCRETE PAVEMENT TECHNOLOGY SOLUTIONS

Optimizing Concrete Pavement Opening to Traffic

National Concrete Pavement
Technology Center



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Executive Summary

This technical summary reviews the science and strategy behind current practices related to the decision to open new pavement surfaces to traffic and how opening to traffic can be accelerated when necessary. Strategies that enable the pavement to be opened to traffic earlier can shorten construction duration, improve safety by reducing the need for detours, and save costs for both agencies and contractors.

The topics covered in this technical summary include planning and contracting considerations, pavement strength development, traffic loading, pavement stresses, early-age concrete pavement fatigue damage, and materials and construction considerations for early opening of concrete pavements. Nondestructive testing applications for determining when concrete pavements can be opened to traffic are also discussed. Additionally, case studies from Iowa, Georgia, Ohio, California, Virginia, and Indiana are presented.

The current strength requirements set by some state transportation agencies for opening concrete pavements to traffic may be overly conservative. Excessive strength requirements lead to concrete mixtures that may achieve the required strength quickly but may not be durable in the long term. Instances of significant pavement fatigue damage due to early opening were not reported in the case studies or the literature. For opening to traffic, the Strategic Highway Research Program (SHRP) recommends a minimum flexural strength of 300 psi with third-point bending and/or a minimum compressive strength of 2,000 psi.

Alternatively, a damage-based online tool has been published that uses early opening damage analysis to determine cracking risks for a given pavement system loaded at a given strength (Khazanovich 2021).

Introduction

This technical summary discusses the factors affecting the decision of when a concrete pavement can be opened to traffic. Research and state practices regarding opening criteria are reviewed, including strength assessment using tools such as strength testing, the maturity method, ultrasonic pulse velocity (UPV), and other nondestructive sensors.

When considering whether early opening to traffic is appropriate, the term “early” should be defined precisely for each case under consideration. Overnight or weekend closures of busy roadways will require opening to regular traffic within a few hours, or at most two days. For conventional construction sites, “early” may mean allowing construction traffic onto the roadway after a few days, even if regular traffic is not expected until much later.

Factors to be considered regarding early opening include the type of expected traffic and its potential to contribute to fatigue damage, the strength development of the mixture and how it can be accelerated, the side effects of acceleration, and the costs and environmental impacts of acceleration.

State-of-the-industry technical expertise and strategies that enable pavements to be opened to traffic at the optimum point may shorten construction duration, improve safety, reduce congestion, and save costs for both agencies and contractors. Additionally, if construction traffic can be allowed onto the pavement earlier rather than later, the reduction in the amount of time that traffic must be diverted or delayed can improve the sustainability benefits of a new pavement or overlay project.

Background

The parameter most commonly used to assess whether a pavement is ready to carry traffic is strength. The use of this parameter is based on a concern that insufficient strength to carry a load will lead to damage, which may progressively increase with continued cycling (fatigue). It therefore seems logical to seek to impose high minimum strength requirements at the age when the pavement will be trafficked.

For concrete construction, it is often thought that requiring higher strength is a conservative approach for determining when to open a pavement to traffic. However, the experience of early cracking and durability problems with some high early-strength (HES) concrete pavements suggests that this approach may not be conservative for paving applications (Antico et al. 2015b). Current practices regarding opening to traffic are largely based on rules of thumb rather than data (Antico et al. 2015a, Freeseaman et al. 2016a, Freeseaman et al. 2016b, Khazanovich et al. 2021).

In a series of studies, Graveen (2001), Barde et al. (2006), and Antico et al. (2015a, 2015b) found that when requirements for opening to traffic rely on high strengths, they result in mixtures that optimize performance during the first few days rather than in the long term. In turn,

these mixtures result in higher pavement costs due to increased cement content and reduce the potential for using materials with a lower CO₂ footprint that normally hydrate at slower rates. In addition, high early-age strength requirements can lead to materials that exhibit higher heats of hydration, which may result in increased curling and cracking at later ages.

It may, therefore, be better to determine whether pavements and repairs can be loaded at lower strengths without compromising their fatigue capacity (Antico et al. 2015b).

Another factor that should be considered in determining opening time is that the required strength of a mixture is often achieved far earlier than specified, largely because of factors of safety built into the proportioning, batching, and delivery processes.

In cases where it is necessary to allow traffic at early ages, agencies have developed specific concrete paving mixtures designed for early opening to traffic (EOT) and have carried out research on early opening of conventional paving mixtures, as discussed in the case studies in this technical summary.

Planning and Contracting Considerations

The time needed for a concrete pavement to develop sufficient opening strength is only part of the construction time window, and other factors may be more important in determining the schedule for a paving project. Other factors to consider when scheduling a project include the traffic control required, the use of overnight lane rentals, the use of weekend and/or nighttime construction, and the time needed for post-paving work such as constructing shoulders and striping.

The full construction window should be considered when deciding whether to use an EOT mixture designed to be opened in 6 to 8 hours for an overnight closure or an EOT mixture designed to be opened in 20 to 24 hours for a weekend closure, or even whether EOT concrete should be used at all. The decision whether to use EOT concrete for all or part of a project should also be considered during planning.

Strength

Strength Development

The strength development of a concrete mixture is a function of the water-to-cementitious materials (w/cm) ratio, the type of cementitious system, and the temperature of the mixture. Typically, strength development occurs rapidly after setting and gradually slows. Data have shown that stiffness (and hence stress) develops faster than compressive strength over the first 24 hours (Taylor et al. 2006). Flexural strength is also reported to develop faster than compressive strength for high early-strength mixtures. Therefore, opening criteria can be conservatively based on compressive strength alone (ACI Committee 325 2019).

An implication of the strength development characteristics of concrete is that the amount of damage incurred by a single loading cycle will also decrease rapidly in the first 24 hours and then continue to decrease over time, as discussed in the next section.

Opening Strength

Different approaches can be used to determine when pavements can be opened to traffic. Flexural strength can be tied to the structural design of the pavement. However, not every agency specifies or measures flexural strength because of logistical challenges, such as the size of the sample required, and the challenges of delivering reliable results. An alternative is to use compressive strength as a surrogate. While the property is not a direct measure of the critical failure mechanism, it can be correlated with flexural strength for a given mixture. The advantages of this approach are that samples are smaller, reducing the risk of injury to staff, and the test is more easily repeatable. Another alternative is to use nondestructive approaches, such as the maturity method, to assess the strength of the in situ concrete. A third alternative is to specify a given period of time after mixing based on the assumption that the mixture will achieve the needed performance in that time. While easy to measure, this approach must necessarily be conservative to ensure that factors such as cold weather do not lead to premature loading.

The findings of a survey of practices at 16 state highway agencies in 2000 (Van Dam et al. 2005) and another survey in 2020 (Cavalline et al. 2020) are summarized in Table 1.

The rationale behind specifying lower numbers for early-loading mixtures is that such mixtures will continue to gain strength over time.

Researchers have reported minimum opening strengths needed to prevent damage:

- 1,600 psi compressive strength (Tia and Kumara 2005, Elfino et al. 2013)
- 300 psi flexural strength (Freeseaman et al. 2016a, 2016b)

Temperature Considerations

For a given concrete mixture, strength develops more rapidly at higher ambient temperatures. For this reason, an opening time specification for EOT concrete may not be conservative at low temperatures but may be overly conservative at higher temperatures. Some transportation agencies therefore place a lower limit on ambient temperatures for patching. For example, the Virginia Department of Transportation (VDOT) does not allow existing pavement to be removed for patching if the removal would result in the patching concrete being placed at temperatures below 40°F (Elfino et al. 2013).

Research for VDOT by Elfino et al. (2013) suggests using HIPERPAV software (Ruiz et al. 2005, The Transtec Group 2021) as a tool to predict the early-age behavior and long-term performance of pavements or full-depth patches. In particular, the rate of strength gain and the risk of early-age cracking can be determined for a given concrete mixture under a given set of pavement design parameters and environmental conditions. However, HIPERPAV 3.2 does not explicitly include an option for patches, which may have different restraint conditions than new pavements. Restrained shrinkage research on patches and tied sections has shown that the potential for cracking increases due to an increase in the degree of restraint (Shah et al. 1998). Patches may be modeled in HIPERPAV as new pavement slabs of the appropriate length, but patches may have additional restraints that may not be captured by the analysis results (Elfino et al. 2013).

Table 1. Results of 2000 and 2020 surveys on opening strength

Survey Year	Opening Time (Hours)	Traffic	Compressive (psi)		Flexural (psi)		Time (Hours)	
2000	6–8	—	1,200	3,500	260	400	4	12
	20–24	—	2,500	3,500	300	600	—	—
2020	—	Construction	2,200	3,500	500	650	—	—
	—	Regular	3,000	4,500	500	650	—	—

Sources: Van Dam et al. 2005, Cavalline et al. 2020

Traffic Loading

Highway traffic presents the worst early-loading case in terms of both the number and weight of vehicles. Light-duty traffic, such as passenger vehicles, is much less likely than highway traffic to impose damage in most cases. While construction vehicles may be heavy, there will be fewer of them.

However, damage is always possible if any errant vehicles drive onto the pavement shortly after placement. Light vehicles that drive onto the pavement before final set would probably only cause easily repaired surface damage. If heavy vehicles drive onto the pavement after final set but before adequate strength gain, damage may result.

Khazanovich et al. (2021) tested a pavement with vehicles shortly after placement and found that the vehicles in the study caused surface damage but no long-term damage. Based on the data collected, the authors developed a model to predict cracking risks for a given pavement system loaded at a given strength.

Construction Vehicles

Construction traffic may include haul trucks, water trucks, slipform pavers, and span saws. While haul trucks produce the highest pavement stresses, there is usually a relatively small number of them, and operators are encouraged to stay away from the pavement edges (ACI Committee 325 2019). Stresses are much higher if vehicles drive near or across the pavement edges. If heavy construction vehicles must drive onto the pavement from the side, steel plates can be used to protect the pavement edges from damage.

For 7 in. or thicker pavements, a flexural strength of 300 psi is considered sufficient for opening, assuming that traffic loads are kept at least 2 ft from the pavement edges. For 6 in. pavements with less stiff support, the suggested opening flexural strength is 460 psi (ACI Committee 325 2019).

Appendix A shows some typical agency specifications for opening to construction traffic, many of which are more conservative than the recommendations in ACI 325-11R-19 (ACI Committee 325 2019). The Minnesota Department of Transportation (MnDOT)

allows an opening flexural strength as low as 350 psi based on pavement thickness. The lowest compressive strength found for opening to traffic is 2,200 psi from the Florida Department of Transportation (FDOT) (Cavalline et al. 2020).

Appendix B provides recommendations from the American Association of State Highway and Transportation Officials (AASHTO) for opening to construction traffic based on pavement thickness and k-value (FHWA 1994).

Light-Duty Traffic

No literature specifically addressing the effects of light-duty traffic was found. Once the pavement has achieved sufficient strength for sawcutting, it can also support light-duty traffic.

Flexural strength can be as low as 150 psi to support light saws (Appendix B). This is consistent with the results of field testing by Khazanovich et al. (2021), which found little damage in panels that were loaded when they had achieved a strength of 73 psi.

Highway Traffic

In addition to presenting typical agency specifications for opening to construction traffic, Appendix A also shows some typical agency specifications for opening to highway traffic. The lowest flexural strength found is 500 psi from the West Virginia Department of Transportation (WVDOT), and multiple states specify an opening compressive strength of 3,000 psi (Cavalline et al. 2020). In contrast, the AASHTO recommendations in Appendix B suggest an opening flexural strength as low as 300 psi in some cases.

The following criteria have been suggested for opening to public (highway) traffic (Van Dam et al. 2005, Yu et al. 2006, Croveti and Khazanovich 2005, Collier et al. 2018):

- For mixtures that allow opening in 8 hours or less: compressive strength of 2,000 psi
- For mixtures that require 12 hours or more for opening: compressive strength of 3,000 psi

Early Opening to Traffic Concrete

For the purposes of this section, EOT mixtures may be divided into two categories: (1) mixtures designed to be opened in 6 to 8 hours for an overnight closure and (2) mixtures designed to be opened in 20 to 24 hours for a weekend closure (Van Dam et al. 2005). In some cases, special mixtures may not be necessary, especially if the desired time to opening is two or three days, because conventional paving concretes can often achieve sufficient strength in that time.

EOT concrete mixtures often use high cement contents and multiple admixtures to attain the required opening strength. As a consequence, these mixtures can be prone to high shrinkage, an altered microstructure, and unexpected interactions among the mixture constituents (Van Dam et al. 2005).

It has been observed that pavements whose construction schedules required opening to traffic at very early ages developed more than 90% of their ultimate tensile

strength by 18 to 24 hours. Such rapid strength development results in pavements that may be especially susceptible to cracking. For example, several mixtures of this type observed near the Indianapolis, Indiana, area tended to exhibit cracks propagating through the aggregate after 18 hours (Barde et al. 2006).

Another observed problem with EOT mixtures has been poorly formed air void systems due to interactions between certain mixture constituents, particularly large amounts of Type III cement combined with Type F high-range water reducer (HRWR). Van Dam et al. (2005) notes that “there is a higher level of risk associated with using a 6- to 8-hour EOT concrete than a 20- to 24-hour EOT concrete that must be considered when selecting a specific mixture to reduce lane closure time.”

Other durability issues reported for EOT mixtures include freeze-thaw deterioration, deicer scaling/deterioration, and calcium oxchloride damage (Weiss et al. 2018).

Stresses in Pavement Slabs

The strength required for a pavement to survive fatigue cycling is related to the stresses imposed on the pavement. Therefore, it is appropriate to consider the factors that influence stresses in full-depth pavements, overlays, and full-depth and partial-depth patches.

Full-Depth Pavements and Overlays

For new pavements, the traffic-related stresses of concern to designers are flexural stresses and dowel bearing stresses.

Pavement flexural stresses depend on the magnitude and location of the traffic load applied, the pavement thickness, the slab support system, and the pavement geometry. As pavement thickness increases, the stresses for a given load decrease in proportion to the square of the pavement thickness (Delatte 2014). Stresses are also higher at slab edges and corners due to the lower amount of support from the surrounding region. Increased slab support in the form of a stiffer base reduces pavement flexural stresses for a given load, allowing for lower opening strengths (Rheinheimer et al. 2010). Dowel bearing stresses are a function of the dowel diameter, where larger diameter dowels reduce bearing stresses.

Other imposed stresses include environmental effects, such as thermal changes and shrinkage due to loss of moisture and chemical processes. The environmental effects are generally dealt with through careful selection of joint spacing and configuration. HIPERPAV software (Ruiz et al. 2005, The Transtec Group 2021) may be used to evaluate the risk of early-age cracking due to thermal effects for the weather at the time of placement.

Full-Depth Repairs

The stresses that develop in full-depth repairs are similar to those that develop in newly constructed pavements. The length of the full-depth repair may affect the stresses experienced by the concrete, with greater environmental stresses observed in longer patches.

VDOT classifies full-depth patches into three categories: jointed concrete pavement (JCP) patches less than 15 ft long, longer JCP patches, and patches of continuously reinforced concrete pavement (CRCP) (Elfino et al. 2013).

For repairs up to 12 ft in length, a flexural strength of 300 psi or a compressive strength of 2,000 psi appear to be reasonable opening criteria under most conditions. For sections 6 ft in length or less, the dowel bearing stress is the critical factor (Whiting et al. 1997).

Partial-Depth Repairs

Partial-depth repairs are placed within concrete slabs, and as such these repairs are subjected to low stresses from tire loadings; stresses are largely due to shear incurred at the joint face.

Many proprietary repair materials are formulated for very early time to opening, as little as ½ to 3 hours (Barde et al. 2006, Delatte et al. 2016). However, experience is showing that high strength is less important than a low elastic modulus for preventing stress concentrations (Ram et al. 2019).

Other Design Factors

A key consideration in limiting fatigue damage is the need to channel traffic loads away from the slab edges when slabs are loaded early in order to reduce imposed stresses (ACI Committee 325 2019).

An additional consideration is dowel bearing stress. Delatte (2014) explains the importance of this factor:

Proper minimum dowel size is based on having a sufficient diameter to resist shear and bending forces transmitted from one slab to another and to reduce the bearing stress of the steel dowel against the concrete to an acceptable value. Generally, the concrete bearing stress is the critical design parameter. If it is too high, the dowel will wear away the concrete and become loose.

Lower compressive strengths may be used for opening to traffic when larger diameter dowels, which reduce concrete bearing stress, are used. For 1.25 in. diameter dowels, Crovetti and Khazanovich (2005) recommend an opening compressive strength of 3,000 psi, which could be reduced to a range of 2,300 to 2,750 psi for pavements with 1.5 in. diameter dowels.

Fatigue Damage

The strength required for opening a pavement to traffic is based on minimizing fatigue damage to the pavement. Fatigue damage is the increasing damage incurred in a system due to cyclic loading, observed as the development and growth of microcracks. Fatigue damage increases as the stress ratio (SR) increases, where SR is the stress in the pavement divided by the pavement flexural strength:

$$SR = (\sigma/MOR) \quad (1)$$

where

σ = stress

MOR = flexural strength

When the SR = 1, the stress is equal to the MOR and the concrete cracks with one load application. At a sufficiently low SR of approximately 0.4 to 0.45, the stress from the resultant applied load does not incur perceptible damage and is considered to be below the endurance limit for the material. For intermediate values of SR, Delatte (2014) presents relationships that have been developed to determine how many loads may be applied before failure. These relationships are highly nonlinear—as SR decreases, the allowable number of load repetitions increases substantially.

For mixed traffic, a cumulative damage function (CDF) may be used to estimate the pavement life:

$$CDF = \sum_i \frac{n_i}{N_i} \quad (2)$$

where

i = the number of load groups or configurations

n_i = the actual or projected number of load repetitions for load group i

N_i = allowable number of load repetitions for load group i

When the CDF = 1.0, the pavement is predicted to fail through fatigue. Therefore, the concern with opening the pavement to traffic early, i.e., at a reduced strength, is that early fatigue consumption will reduce the remaining life of the pavement. As concrete gains strength, the SR decreases and the allowable number of load repetitions increases rapidly, even for the same amount of traffic stress. Regardless of the strength specified for the concrete, the rate of strength gain at early ages is high.

Therefore, the SR drops rapidly initially and damage accumulation slows over time. Note, also, that there is considerable scatter, and therefore different curves have been developed for different desired values of reliability.

Whatever fraction of the CDF is consumed at early ages will, in theory, reduce the life of the pavement. For example, assume a pavement edge stress of 343 psi. If the pavement has attained a flexural strength of 500 psi at the time of opening, the stress ratio is $343/500 = 0.69$. At a reliability of 80%, this ratio corresponds to 10,000 load repetitions. If there are 1,000 actual load repetitions, then the fatigue consumption is 10%. Once the pavement strength increases to 600 psi, the stress ratio drops to $343/600 = 0.57$, which now corresponds to 1,000,000 allowable repetitions. Therefore, with a pavement that attains a flexural strength of 500 psi at the time of opening, approximately 10% of the fatigue life would be consumed in the first day, and fatigue damage would be negligible thereafter.

Edge stress, however, represents the most severe loading scenario. If traffic is kept away from the edge of the pavement, the interior stress would be more applicable for determining fatigue damage. For the same pavement and loading conditions as above, the interior stress would be 183 psi. Therefore, the corresponding allowable opening strength to keep fatigue consumption on the first day to 10% would be $183/0.69 = 265$ psi. This value is lower than the recommended opening strength of 310 psi from FHWA (1994).

Antico et al. (2015b) developed a mechanistic method to assess the damage from early loading on a specific pavement. The pavement modeled was located in Minneapolis, Minnesota, and had a 6 in. slab thickness, a 15 ft joint spacing, and tied portland cement concrete (PCC) shoulders. The modeling was based on a mixture with a strength of 340 psi on day 2 and 590 psi on day 28. Traffic was applied on day 2 with the full spectrum of *Mechanistic-Empirical Pavement Design Guide* (MEPDG) default loads, which caused damage equivalent to about half of the first year's traffic (Freeseaman et al. 2016a, 2016b). The model was also used to examine the impact of limiting early-age truck traffic on the pavement. Axle weights were limited to 14 kips for single-axle vehicles and 20 kips for tandem-axle vehicles for the first 28 days. The subsequent fatigue damage was negligible (Freeseaman et al. 2016a, 2016b).

Khazanovich et al. (2021) continued the research by Antico et al. (2015b). Six test cells were constructed at the MnROAD facility in 2017 and load tested. Despite loading as early as 2 to 10 hours after paving, no damage was observed. The test cells were investigated using strain gauge and MIRA nondestructive testing (NDT) data, roughness measurements, falling weight deflectometer (FWD) testing to determine whether any loss of load transfer occurred at doweled joints, and petrographic

examination of cores. The researchers concluded that the current criteria for opening to traffic are overly conservative and that modern concrete pavements can safely open to traffic earlier than currently allowed, especially when the traffic consists of lightweight/passenger vehicles. The experiment showed that no damage occurred at an estimated flexural strength of 73 psi (Khazanovich et al. 2021).

Materials Considerations

Desirable Concrete Characteristics

Material requirements may differ among new construction, full-depth patching, and partial-depth patching projects because of the different quantities of material required and the different constraints imposed by lane rental and labor costs.

The higher cost of EOT hydraulic cement concrete may be justified for overnight or weekend closures when the costs of failing to reopen the pavement to traffic on time are considered. For projects where labor costs are a large proportion of the project cost, such as partial-depth patching projects, EOT and pre-packaged mixtures can also be justified. For new construction, higher-cost EOT materials may only be necessary at the end of a section.

Table 1.1.1 in ACI 325-11R-19 (ACI Committee 325 2019) suggests the following concrete materials for consideration:

- Different cement types (such as Type III cement)
- Accelerating and water-reducing admixtures
- Well-graded aggregate systems
- Materials that yield a low w/cm ratio below 0.45
- Prewetted lightweight fine aggregate to achieve internal curing

Patching materials may include modified hydraulic cements, polymer-based materials (epoxy concrete, methyl methacrylate concrete, or polyester-styrene concrete), and magnesium phosphate concrete (Ram et al. 2019).

For EOT applications, desirable concrete characteristics include the following:

- Sufficient strength for opening to traffic
- Low heat
- Low shrinkage
- Good bonding characteristics (for patches)

For certain applications, selecting materials whose durability is consistent with the expected remaining life of the pavement should be a consideration. For example, it does not make sense to use a patch with a 30-year life on a pavement with an expected 10 years of useful life remaining. Rapidly hydrating portland cement systems are generally more permeable and exhibit high heat generation and high shrinkage (Taylor et al. 2019).

Another consideration in selecting materials is the coefficient of thermal expansion (CTE) of the concrete, which is largely dependent on the CTE of the aggregates. High-CTE concrete will have higher thermal strains with temperature changes and thus a higher risk of cracking at lower temperatures. High-CTE concrete combined with high temperatures at final set, due to high cement contents, leads to higher thermal contraction stresses (Van Dam et al. 2005).

Cements and Cementitious Materials

EOT mixtures are generally made with Type I or Type III portland cement, often with very high cement contents (Elfino et al. 2013). As Buch et al. (2008) explain, “When specified, the minimum cement content varies from state to state, ranging from 440 to 550 kg/m³ (740 to 925 lb/yd³) for Type I cement and 390 to 490 kg/m³ (660 to 825 lb/yd³) for Type III cement.”

Cements with high alkali content, high C3S and C3A contents, low C4AF content, and high fineness have high strength gain but have been found to have higher cracking tendencies (Burrows 1998, Jeunger and Jennings 2002, Babaei and Purvis 1995a, Chariton and Weiss 2002, TRB 2006).

Proprietary rapid-setting cements that contain calcium sulfoaluminate compounds may also be used, as they offer rapid strength development with fewer negative side effects such as high permeability (Van Dam et al. 2005).

Accelerators

Chloride-based accelerators are a cost-effective and reliable means of accelerating the setting and early strength gain of a mixture. However, they significantly increase the risk of corrosion of embedded steel, such as dowel bars (Taylor et al. 2019). Therefore, some state agencies do not allow chloride accelerators (Gholami et al. 2019). Non-chloride accelerators are available and can be used in accordance with the manufacturers’ guidelines.

Patching Materials

While proprietary patching materials are generally more expensive than conventional concrete, they may be suitable for partial-depth patches, in part because these patches typically only require a small quantity of material. Some considerations for selecting partial-depth patching materials are listed in Table 2.

Table 2. Decision matrix for partial-depth repair material selection

Factor	Categories	Recommendation	Example Materials
Traffic interruption	Low traffic, long closure possible	Conventional cement-based, lower-cost repair material	Conventional concrete
	High traffic, short daytime closure	Lower-cost repair material or high-performance (HP) repair material, allow bonding agent, open to traffic in 2 hours	Polymer-modified or polyurethane elastomeric concrete
	Very high traffic, short nighttime closure only	HP repair material not requiring bonding agent, rated for traffic opening in 1 hour	Magnesium phosphate, polymer-modified, or polymer concrete
Durability requirement	Short-term solution, facility replacement within 5 years	—	Rapid-hardening or polymer-modified concrete
	Long-term solution, 10 to 15 years	—	Magnesium phosphate or polyurethane elastomeric concrete
Temperature during installation	Low (near or below freezing)	Low-temperature rated material	Magnesium phosphate or polymer concrete
	Moderate (40°F to 70°F)	Conventional or HP	Rapid-hardening, polymer-modified, or polyurethane elastomeric concrete
	High (80°F and higher)	Conventional, HP only if high-temperature rated or with retarder	Rapid-hardening or polymer-modified concrete
Patch size	Smaller than about 2 by 2 ft by 3 in. deep	Use small batches, do not extend material with pea gravel	Rapid-hardening, polymer-modified, or polyurethane elastomeric concrete
	Larger than about 2 by 2 ft by 3 in. deep	Use a portable higher capacity mixer, extend with pea gravel	Magnesium phosphate or polymer-modified concrete w/pea gravel

Source: Modified from Delatte et al. 2016

Concrete Mixture Examples

Van Dam et al. (2005) published some example mixture designs, shown in Table 3, that reportedly provided good performance. The 6- to 8-hour mixtures (Mixtures 1 through 3) used 716 to 885 lb/yd³ of Type I cement and either chloride or non-chloride accelerators. The 20- to 24-hour mixtures (Mixtures 4 through 6) used 678 lb/yd³ of Type I cement with accelerators or 805 lb/yd³ of Type I

cement without accelerators. All mixtures were made using a vinsol resin air-entraining agent.

The early mixtures achieved at least 2,380 psi compressive strength and 350 psi flexural strength at 8 hours, and the later mixtures achieved at least 2,580 psi compressive strength and 490 psi flexural strength at 20 hours.

Table 3. Example EOT mixtures

Constituent/Property	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5	Mixture 6
Type I Cement	885 lb/yd ³	885 lb/yd ³	716 lb/yd ³	678 lb/yd ³	678 lb/yd ³	805 lb/yd ³
w/c Ratio	0.40	0.36	0.40	0.43	0.40	0.43
Accelerator Type	Non-chloride	Non-chloride	Calcium chloride	Calcium chloride	Non-chloride	None
Water Reducer	None	None	None	None	None	None
Coarse Aggregate (Crushed Limestone)	1,736 lb/yd ³	1,736 lb/yd ³	1,736 lb/yd ³	1,736 lb/yd ³	1,736 lb/yd ³	1,736 lb/yd ³
Fine Aggregate (Natural Sand)	720 lb/yd ³	812 lb/yd ³	716 lb/yd ³	1,060 lb/yd ³	1,010 lb/yd ³	1,110 lb/yd ³
Average Slump	5.5 in.	2.75 in.	2.5 in.	3.35 in.	2 in.	6 in.
Average Air Content	5.0%	5.0%	5.6%	6.6%	5.7%	5.9%
8-Hour Compressive Strength	2,375 psi	3,000 psi	2,465 psi	—	—	—
20-Hour Compressive Strength	—	—	—	3,550 psi	2,890 psi	2,580 psi
28-Day Compressive Strength	6,400 psi	8,150 psi	7,800 psi	6,670 psi	5,890 psi	5,700 psi
8-Hour Flexural Strength	350 psi	435 psi	350 psi	—	—	—
20-Hour Flexural Strength	—	—	—	490 psi	550 psi	520 psi

Source: Delatte 2014, modified from Van Dam et al. 2005

Construction

Equipment

Construction of conventional concrete pavements that will be opened early to construction traffic does not require any special equipment or mixtures except the following:

- Systems must be in place to keep construction vehicles away from or protect the edges of the slabs, including locations where vehicles will drive onto or leave the pavement.
- Monitoring systems such as the maturity method must be in place to ensure that damage is not incurred during early loading.

Accelerated concrete pavements do not generally require special equipment (ACI Committee 325 2019). An exception is that proprietary repair materials may need to be prepared on site in volumetric mixers. The chief consideration is that some rapid-setting mixtures may have a working time insufficient to haul from a batch plant to the site.

When constructing test slabs, it is advisable for the contractor and the agency to observe the behavior of the concrete and preempt problems during construction.

Removal of Existing Material for Patching

For full-depth and partial-depth patching, sufficient time is needed to remove the existing distressed concrete. If the subbase is disturbed during the process, that may need to be repaired as well. It is important during removal to go beyond the distressed concrete and into sound concrete—otherwise, the distress is likely to reappear next to the patch.

In some cases, temporary precast panels have been used after removing the existing concrete to allow traffic for the short interval between removal of the old concrete and placement of the new patches.

Load Transfer and Reinforcement

It may be necessary to establish load transfer for full-depth patches. Delatte (2014) explains this process as follows:

Dowels may be drilled into the adjacent concrete and grouted in place to provide load transfer between the full-depth patch and the existing pavement. Automated dowel drill rigs can make this process more rapid and accurate. Next, the drill holes are cleaned, and then dowels are installed with grout and grout retention disks. Deformed reinforcing bars are used to restore longitudinal joints. A bond breaking board may be installed along the edge of the full-depth patch.

Placement

Conventional placement techniques can be used with EOT concrete, although allowance must be made for the shorter working time.

Texturing

The final concrete surface should be smooth but with adequate texture for friction. In some cases, it is faster to place and cure patches and then diamond grind the patches for a smooth transition to the existing concrete.

Sawcutting

Table 1.1.1 in ACI 325-11R-19 (ACI Committee 325 2019) suggests the following jointing and sealing considerations:

- Allow early-entry sawing.
- Use dry-sawing blades.
- Use step-cut blades for single-pass joint sawing.
- Use a sealant that is unaffected by moisture or reservoir cleanliness.

Early-entry saws allow joints to be cut before the mixture is ready for conventional saws. EOT concrete mixtures have earlier and shorter sawing windows than conventional paving mixtures. Early-entry sawcutting may begin once the concrete has reached a flexural strength of approximately 150 psi and should be completed before final set of the concrete.

Curing

Table 1.1.1 in ACI 325-11R-19 (ACI Committee 325 2019) suggests the following concrete curing and temperature considerations:

- Use blanket curing to aid strength gain when beneficial, such as in low temperatures.
- Monitor the concrete temperature and understand the effect of the relationships among ambient, subgrade, and mixture temperatures on strength gain.
- Improve the characteristics of the concrete through internal curing by using prewetted lightweight aggregate sand.

While curing is important for all concrete pavements, it is particularly important for portland cement-based EOT concrete mixtures with low w/cm ratios. The rate of application of curing compound should be increased at least by a third relative to conventional mixtures (ACI Committee 325 2019). For patches, wet burlap and white polyethylene may also be used for curing (Elfino et al. 2013).

In order to prevent moisture loss, the curing compound should be applied shortly after placement but after bleeding has slowed (if bleeding occurs). Inclusion of some saturated lightweight fine aggregate in the mixture will assist in enhancing hydration and reduce moisture differentials through the thickness of the slab (Daghighi et al. 2021).

Curing blankets can insulate freshly placed concrete pavement against heat loss and accelerate strength gain, particularly in cold weather. The blankets may be placed over the curing compound once the concrete has hardened enough to not be damaged. Care should be taken to avoid thermal shock when the blankets are removed (ACI Committee 325 2019).

Nondestructive Test Methods

A number of NDT technologies have been developed for concrete. These are described extensively in various publications, such as *ACI 228.1R-19: Report on Methods for Estimating In-Place Concrete Strength* (ACI Committee 228 2019), *ACI 228.2R-13: Report on Nondestructive Test Methods for Evaluation of Concrete in Structures* (ACI Committee 228 2013), and Malhotra and Carino (2004). For opening concrete pavements to traffic, verification of the actual in-place pavement strength is important, and the maturity and stress-wave methods are often considered for this purpose.

Table 1.1.1 in ACI 325-11R-19 (ACI Committee 325 2019) suggests the following strength testing approaches:

- Use nondestructive methods to replace or supplement the use of cylinders and beams for strength testing.
- Use concrete maturity or pulse velocity testing to predict strength.

In order to find alternative approaches for determining concrete strength, Freese et al. (2016b) evaluated a wide range of NDT technologies to supplement the maturity method for early opening of pavements to traffic. The authors considered ground-penetrating radar (GPR), electromechanical impedance methods, sounding methods (e.g., chain dragging), impact echo, spectral analysis of surface waves, UPV, ultrasonic pulse-echo, ultrasonic wave reflection, and ultrasonic tomography. Khazanovich et al. (2021) investigated maturity, pulse velocity, and ultrasonic tomography methodologies. Key NDT methods are discussed below.

Maturity

Background

ASTM C1074-19 defines the maturity method as “a technique for estimating concrete strength that is based on the assumption that samples of a given concrete mixture attain equal strengths if they attain equal values of the maturity index” (ASTM C1074-19). Laboratory testing is used to determine a strength-maturity relationship for a given concrete mixture. However, every set of mixture proportions has a unique relationship to maturity.

The basis of maturity is that concrete gains strength more rapidly at higher temperatures than at lower temperatures, and thus curing time alone does not accurately predict strength development. The maturity method is standardized as ASTM C1074-19, Standard Practice for Estimating Concrete Strength by the Maturity Method. Details on the theory and applications of this method are provided by Malhotra and Carino (2004) and ACI Committee 228 (2013, 2019).

ASTM C1074-19 cites three major limitations to the maturity method:

- The concrete must be maintained in a condition that permits cement hydration.
- The method does not consider the effects of early-age concrete temperature on long-term strength.
- The method needs to be supplemented by other indications of the potential strength of the field concrete.

Two different functions may be used to compute the maturity index. One is the temperature-time factor, and the other is the equivalent age.

The temperature-time factor is given by the following (ASTM C1074-19):

$$M(t) = \sum (T_a - T_o) \Delta t \quad (3)$$

where

$M(t)$ = temperature-time factor at age t , degree-days or degree-hours

Δt = time interval, days or hours

T_a = average concrete temperature during time interval Δt

T_o = datum temperature, °C

The datum temperature is considered to be the temperature at which the concrete no longer gains strength. This may be an input or a default of the testing equipment. A typical value is 14°F (−10°C) (Malhotra and Carino 2004).

The equivalent age is given by the following (ASTM C1074-19):

$$t_e = \sum e^{-Q\left(\frac{1}{T_a} - \frac{1}{T_s}\right)\Delta t} \quad (4)$$

where

t_e = equivalent age at a specified temperature, T_s , days or hours

Q = activation energy divided by the gas constant, K

T_s = specified temperature, K

T_a and Δt are defined above, except that all temperatures must be in Kelvin, K

The activation energy Q may be an input or a default of the testing equipment. Malhotra and Carino (2004) provide a detailed discussion and some sample values. The appendix to ASTM C1074-19 provides a method for calculating the activation energy for a given concrete mixture using mortar specimens (ASTM C1074-19).

To implement the full procedure, ASTM C1074-19 suggests preparing at least 15 cylindrical specimens. The specimens are moist cured and tested at ages of 1, 3, 7, 14, and 28 days. Flexural strength specimens may be used instead. Strength-maturity relationships may then be developed that plot strength versus the temperature-time factor or equivalent age (ASTM C1074-19).

The strength-maturity relationship is developed for a particular concrete mixture, so if the mixture is changed a new relationship must be developed.

However, if the method is to be used to determine the correct maturity value for opening a pavement to traffic, performing the full method is not necessary. For a pavement that is to be opened to traffic at one day, the maturity corresponding to 28 days is not of interest. Instead, it is more important to bracket the desired strength and maturity values, preferably with two points less than and two points greater than the desired strength.

Even so, the laboratory work required to develop a strength-maturity relationship may be difficult to justify for small projects.

A study for MnDOT by Rohne and Izevbekhai (2009) developed strength-maturity relationships for several commonly used mixtures. It was found that “maturity curves are sensitive to small changes of 10 lb/yd³ of cementitious material. It was also found that a maturity datum temperature of 0°C was too high. Strength continued to increase even when the concrete fell below this temperature” (Rohne and Izevbekhai 2009).

Bassim and Issa (2020a) investigated the strength-maturity relationships for Illinois paving and patching mixtures. The authors noted that “[t]he maturity method as per ASTM C1074-19 is less accurate for estimating low figures of f_c' or f_r typically falling within 1 day of concrete age for PCC pavement and patch mixtures” (Bassim and Issa 2020a). They suggested that future research focus on developing strength-maturity relationships within the first 24 hours. Small errors between laboratory and field specimens are likely to occur when maturity values begin to be collected, depending on when the sensors are installed and when data collection begins. While this error is not significant if the concrete is several days old, it may be important within the first 24 hours.

Weiss et al. (2019) showed that while the use of HES concrete for patching enables the repaired pavement to be opened to traffic within hours of placing the concrete, there are challenges in using HES materials due to the influence of temperature on sulfate balance, which may stifle strength development. In addition, HES materials may also self-desiccate, which limits flexural strength development and the ability to predict strength using the maturity method (Wilson and Weiss 2020).

Instruments and Equipment

Maturity measurement in the field requires some method of temperature measurement plus some type of datalogger. Instruments are available from a number of manufacturers. The simplest and oldest equipment uses inexpensive thermocouple wires embedded in the concrete that are plugged into a datalogger box. After testing, the wires are cut and left behind in the pavement. Since the dataloggers are generally left connected to the wires during field measurements, they are subject to damage and theft on the project site. This is less of a concern during short-term closures when project personnel are on the site.

Other systems use embedded sensors that combine the temperature measurement and datalogging functions. They use either a wired or wireless reader to download the data. For these systems, the individual sensors are more expensive than thermocouple wires but are still relatively economical.

A more direct way to implement the maturity method is through temperature-matched curing. This is discussed in more detail in the Virginia and Washington case studies below.

Ultrasonic and Stress-Wave Propagation Methods

Several nondestructive testing methods for concrete measure the velocity of acoustic waves through the material. While not all of these methods have been standardized by ASTM International, the UPV method (ASTM C597-16) and impact-echo method (ASTM C1383-15) have been, and several manufacturers sell test equipment compatible with these standards. UPV and impact-echo instruments may both be used to measure compression wave (P-wave) velocity, though in slightly different ways. Both methods use light, portable, battery-operated equipment.

The UPV and impact-echo methods make use of the velocity of a compression wave through an elastic material, in this case concrete. The compression wave velocity is, in essence, the “speed of sound” through a material. It is a mechanical property based on the dynamic modulus of elasticity, the dynamic Poisson’s ratio, and the density of a material (ASTM C597-16):

$$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad (5)$$

where

V = pulse velocity or compression wave velocity

E = dynamic modulus of elasticity

μ = dynamic Poisson’s ratio

ρ = density

The equation may also be written as follows:

$$V = \sqrt{\frac{KE}{\rho}} \quad (6)$$

where $K = (1 - \mu)/(1 + \mu)(1 - 2\mu)$.

For a given concrete mixture, the Poisson’s ratio and density remain relatively constant. The Poisson’s ratio is often taken as 0.2. Therefore, the compression wave velocity V will depend only on E . The dynamic modulus of elasticity E is typically greater than the static modulus of elasticity E_c , which is typically used in structural and pavement calculations since it represents the initial steeper slope of a nonlinear concrete stress-strain curve.

The dynamic modulus of elasticity may be related to strength for a given concrete. Thus, as concrete ages, the strength, E , and compression wave velocity all increase. Therefore, in the same way that it is possible to determine a minimum value of maturity associated with the opening strength of a paving concrete mixture, it is possible to determine a minimum value of compression wave velocity.

Ultrasonic Pulse Velocity

The UPV method uses two 2 in. ultrasonic transducers connected to an instrument. One transducer sends the signal and the other receives it, and the instrument measures the time between sending and receiving. The pulse velocity is calculated as follows (ASTM C597-16):

$$V = L/t \quad (7)$$

where

L = distance between the centers of the transducer faces, feet or meters

t = transit time in seconds (ASTM C597-16 uses T for time instead of t , but that could be confused with thickness T in [equation \(8\)](#).)

There are three different modes of UPV transmission. The direct mode sends a signal from one side of the structure or specimen to the other, such as through a column or wall. Concrete cylinders and beams may be tested using the direct mode. In the indirect mode, both transducers are placed on the same side of the structure or specimen. The semidirect mode is used at a corner. The direct mode is considered the most accurate, and the indirect mode is considered the least accurate because the signal is weakest (Malhotra and Carino 2004). For pavements, however, only the indirect mode is practical.

Wang et al. (2016) found that the UPV method can be used to determine initial set in concrete in order to predict sawcutting times. The authors suggested that sawing should begin about 220 minutes after initial set for early-entry saws and about 310 to 390 minutes after initial set for conventional saws. Because commercially available UPV equipment is light and portable and because testing is rapid and easy to interpret, it would be logical to use UPV on a project to both monitor initial set and time of opening.

Tran and Roesler (2021) described a noncontact ultrasonic testing system that can be used to determine the final set time of concrete over a 3/8 in. air gap. The equipment is not yet commercially available.

Impact-Echo

While impact-echo equipment is often used to measure the thickness of concrete elements or to identify flaws inside of concrete, it can also be used to measure compression wave velocity. The impact-echo method uses a small steel ball or hammer and a small accelerometer. The impact of the ball or hammer echoes back and forth within the concrete at a frequency determined by the wave velocity and concrete thickness.

The basic impact-echo equation is as follows (ASTM C1383-15):

$$T = \frac{C_{p,plate}}{2f} \quad (8)$$

where

T = thickness of the plate, feet or meters

$C_{p,plate}$ = apparent P-wave speed in the plate, fps or m/s, which may be assumed to be 0.96 V

f = frequency of the P-wave thickness mode of the plate obtained from the amplitude spectrum, Hz

Equation (8) is used to determine the thickness of a concrete element or to determine the depth to a horizontal crack or delamination. If the thickness of the pavement is known, equation (8) may be rewritten as follows:

$$C_{p,plate} = 2Tf \quad (9)$$

Some instruments are supplied with a P-wave measurement bar that is intended to be used to determine the wave velocity before carrying out thickness measurements. The bar has two transducers 12 in. apart, which measure the wave speed when an impact is made 6 in. from one of the transducers.

Tia and Kumara (2005) used the impact-echo method to monitor early-age strength and stiffness development and to detect early cracking for full-depth patches loaded with a heavy vehicle simulator (HVS). The researchers found that “[c]ompressive strength development with respect to dynamic modulus followed a distinct growth rate irrespective of w/c ratio, binder content, curing regime, and synthetic fiber dosage” (Bassim and Issa 2020b). While flexural strength also correlated well with dynamic modulus, compressive and flexural strength had different growth rates relative to dynamic modulus. For EOT concrete mixtures, strength predictions based on dynamic modulus were within 10% of actual values.

Field Application Issues

An issue for field applications with both the UPV and impact-echo methods is the need to couple sensors to the pavement. Coupling allows the acoustic wave to pass from the transducer into the pavement and vice versa. Both tining and other texturing of concrete pavements and curing compounds interfere with coupling.

UPV transducers typically require a coupling agent, such as grease, petroleum jelly, or liquid dish soap, between the transducer face and the concrete (ASTM C597-16). For UPV transducers, two flat spots on the pavement at least 2 in. in diameter can be troweled in for later testing, and, if necessary, curing compound may be removed just before the test.

Impact-echo accelerometers are smaller, so the flat area may be smaller as well. Some impact-echo accelerometers are magnetic, and metal washers may be glued to the pavement to provide coupling.

Combining Maturity and UPV or Impact-Echo

ASTM C1074-19 recommends using other test methods in addition to the maturity method to verify that strength has been attained before performing critical operations (ASTM C1074-19). One suggested method is to cast field companion specimens, monitor their maturity, and break them for verification.

Another method is to test specimens for compression wave velocity (using either the UPV or impact-echo method) while developing the strength-maturity relationship. Then, in the field, the maturity values may be monitored and the compression wave speed measured for verification before opening the pavement to traffic.

Graveen (2001) investigated the use of in situ, nondestructive test methods to determine early property development in concrete pavement. Impact-echo, compression wave (P-wave) velocity, and maturity testing were conducted to assess flexural strength and

slab thickness. Strength–P-wave velocity relationships were developed to estimate flexural strength and were found to more precisely estimate strength when limited to early-age information. The use of either a strength–P-wave velocity relationship or an early-age test result in combination with the maturity method improved the estimate of the 28-day flexural strength over the use of the maturity method alone.

An example of combining the maturity method and the use of UPV or impact-echo devices is discussed in the Washington case study below. As described in that case study, the original calibration curve predicted a compressive strength of 2,500 psi at 191°C-hours. However, in the second week of the project a set of cylinders was cast for verification, and these only attained a compressive strength of about 2,000 psi at 191°C-hours and did not attain the target strength until 318°C-hours (Anderson et al. 2009). It is possible that a compression wave measurement taken at 191°C-hours would have caught the lower strength.

Case Studies

Following is a discussion of six case studies reported in the literature.

Case Study: Iowa Bonded Concrete Overlay

The project discussed in this case study is a 7.5 mile long concrete overlay placed in 1986 on US 71 in Buena Vista County, Iowa. The principal goal of the research in this project was to evaluate the materials, equipment, and procedures used to construct a concrete overlay under traffic and to allow opening to traffic loads in less than one day.

Other goals included the following:

- Reduce traffic disruption on a single lane to less than 5 hours
- Reduce traffic disruption on a given section of two-lane roadway to less than 2 days
- Follow an economically viable procedure that is competitive with existing alternatives
- Achieve a 20-year minimum design life for the rehabilitated pavement

The motivation behind this work was that while overlays were proving to be effective for extending the life of existing pavements, detouring traffic during construction for up to 10 days was unacceptable to the traveling public. At the same time, contractor concerns associated with working with very rapid setting concrete had to be addressed.

Background

The existing concrete pavement constructed in 1937 was 20 ft wide, and the plan for the 1986 project was to widen it to 24 ft and strengthen it with a 4 in. bonded concrete overlay. Other work included installation of a longitudinal drain on one side. The sequence for this project was to overlay and widen one-half of the roadway, place the shoulder material adjacent to the newly constructed side on the following day, and open it to contractor and local traffic while the other side of the roadway was being prepared for overlay and widening.

Materials

To achieve early strength, calcium chloride was added to the mixture in small amounts at driveways and intersections with county roads to allow opening to traffic the following day. In addition, a selected Type III cement was used to assist with reaching a compressive strength of 1,300 psi in 12 hours. This was necessary because of a wide variation found in the strength of concrete made from cements that met the regular Type III requirements. A thermal blanket was also used to raise hydration temperatures and accelerate strength gain.

Other innovative features included placing epoxy-coated reinforcing steel across longitudinal random cracks in the existing pavement to control reflective cracking. Additionally, 4 in. wide adhesive tape was placed over random cracks, and a control joint was sawed within the limits of the tape. The intent was to simplify maintenance of the sawcuts rather than fully repair the random cracks.

Two sections were constructed without a bonding grout. This approach was based on the theory that sufficient grout was available in the matrix of the concrete to do the bonding.

Construction

The mixture parameters included the following:

- 640 lb/yd³ of Type III cement
- 70 lb/yd³ of Type C fly ash
- Target air content of 6.5%
- Water reducing agent as needed
- 45% fine aggregate and 55% coarse aggregate
- Slump target of 1½ in.
- Water-cement ratio ranging from 0.43 to 0.45

The existing concrete pavement was prepared by first removing paint, oil drippings, rubber, and other contaminants from the surface. This was achieved by shotblasting using a 4 ft wide machine firing steel shot. Two or more passes were required to remove tightly adhered materials like centerline paint and asphalt materials.

Epoxy-coated #6 tie bars 18 in. in length were drilled and glued into the edges of the existing pavement to tie the widening unit to the main slab. The contractor designed a drill rig that drilled four holes at a time. The pull-out strength of these bars was measured to be about 15,000 lb after four hours.

Surface spalls were corrected by milling and placing partial-depth patches at the time that the 4 in. overlay was placed.

Ambient temperatures were about 90°F during the day and 60°F at night. The temperature under the thermal blanket was 115°F 36 hours after placement.

Testing

The strength development of the pavement is shown in Table 4. The bond strength measured by a direct shear test was slightly over 300 psi.

One-Year Review

The project was evaluated again in May 1987 using visual observations and compressive strength, bond strength, and profilometer tests. In general, the pavement condition appeared the same after one year as it did immediately after completion. No distress related to traffic usage or to the severe winter conditions was apparent.

Some transverse cracking was observed that appeared to be associated with reflective cracking at the mid-panels in the old pavement. About six months after construction of the overlay, a reservoir was cut over these reflective cracks and sealed. There was a tendency for minor debonding to occur at the mid-panel cracks, but this was not considered a threat to long-term performance. Ride quality was similar to that observed at the time of construction.

The compressive strength of the cores was measured to be greater than 6,000 psi at about 9 months.

Table 4. Strength development data

Age	Flexural Strength, psi	Compressive Strength, psi
8 Hours	390	1,900
12 Hours	490	2,500
24 Hours	600	3,500
7 Days	720	5,000
14 Days	820	5,300

Long-Term Performance

A review of a video log recorded in 2014 indicates that the joints seemed to exhibit staining and spalling, likely related to oxychloride-based joint deterioration. Although the pavement had significant distress, it was not resurfaced until 2018 with 6 in. of hot-mix asphalt.

Conclusions

The following conclusions were drawn regarding the performance of the overlay project:

- The bonded overlay provided 30 years of service life, as expected at the time of construction.
- It is possible to open roads to the public in 24 hours.

The Iowa Department of Transportation (Iowa DOT) has since moved away from the use of Type III cement due to problems encountered in other pavements. The department has also found that the use of maturity meters has enabled contractors to allow traffic onto pavements within 18 to 36 hours of construction using conventional mixtures in summer.

Case Study: Early Opening of Full-Depth Pavement Repairs

Yu et al. (2006) reported on the long-term performance of full-depth pavement repair test sections made with HES materials that had been placed as part of SHRP C-206, Optimization of Highway Concrete Technology (Whiting et al. 1994). The field testing program used maturity monitoring as well as temperature-matched curing and UPV (Whiting et al. 1994, 1997).

The test sections were placed in Georgia in July 1992 and in Ohio in September 1992 and included 11 different HES mixtures with opening times ranging from 2 to 24 hours. The mixtures used either Type I portland cement, Type III portland cement, or one of several proprietary blended cements. The length of each repair section was between 6 and 15 ft. After construction, the sections were evaluated once a year from fall 1994 through fall 1998 for cracking, faulting, and spalling.

Georgia Test Sections

The Georgia test sections were located on eastbound I-20 near Augusta, Georgia. The existing pavement was a 9 in. thick jointed plain concrete pavement (JPCP) pavement with a 30 ft joint spacing. Three mixtures were used for the full-depth patches, two designed for opening at 4 hours and one for opening after 12 to 24 hours. The sections were placed overnight between 10 p.m. and 2 a.m., with opening to traffic at 6 a.m. Each of the test sections consisted of 18 to 20 individual full-depth patches.

The concrete was delivered at relatively high temperatures ranging from 89°F to 96°F (Whiting et al. 1994). For each of the 58 patches, the age, compressive strength, and flexural strength at opening were recorded. Opening times were as early as 2.7 hours, although most were over 4 hours. The patches placed with the 12- to 24-hour mixture were opened between 6.8 and 8.8 hours after placement. The opening strengths were as low as 900 psi compressive and 155 psi flexural. Yu et al. (2006) estimated that due to early opening, up to 12.2% of the pavement's fatigue life was consumed with the lowest opening flexural strength. In most cases, the predicted fatigue damage was much lower.

Overall, performance after six years of service was excellent. There was almost no faulting despite the expectation of curling in the 15 ft patches.

Ohio Test Sections

The Ohio test sections were located on the eastbound and westbound lanes of State Route 2 near Vermilion, Ohio, to the west of Cleveland. The existing pavement was a 9 in. thick JRCP with a 40 ft joint spacing, and all repairs were 6 ft long. Eight different concrete mixtures were used for the full-depth patches, three designed for a 2- to 4-hour opening, three for a 4- to 6-hour opening, and two for a 12- to 24-hour opening. Type III portland cement or two different proprietary cements were used for the mixtures. Each of the eight test sections had 10 patches.

The concrete was delivered at moderate temperatures ranging from 77°F to 90°F (Whiting et al. 1994). In contrast to the Georgia test sites, the work in Ohio was performed during daylight hours, with work starting at 7 a.m., concrete placement typically starting at 10 a.m.,

and opening to traffic at 5:30 p.m. Opening times were as early as 1.8 hours, with compressive strengths as low as 1,000 psi and flexural strengths as low as 135 psi. Yu et al. (2006) estimated negligible fatigue consumption in many cases, but three patches opened at 2 to 2.3 hours were estimated to experience a fatigue consumption of 15%.

Within weeks after construction, the majority of the sections developed longitudinal cracking. Possible causes that were investigated included dowel restraint of the slabs' horizontal movement and excessive curling stress. All of the test sections, with the exception of two made with one of the proprietary blended cements, exhibited more than 50% longitudinal cracking by 1998.

In addition, the 2- to 4-hour mixture and the 4- to 6-hour mixture made with Type III cement developed map cracking consistent with delayed ettringite formation (DEF), which was confirmed using cores. Both of these mixtures had 900 lb/yd³ or more of cement and exceeded the 158°F temperature threshold for DEF.

Findings

The results of maturity and pulse velocity testing agreed with the strength values measured in cores extracted from the repair sections before opening to traffic (Yu et al. 2006). While HES full-depth patches can provide excellent service, performance can be compromised by large temperature differences shortly after placement—in particular, a difference of more than 50°F between the high curing temperature and the subsequent low temperature. Yu et al. (2006) suggested using the HIPERPAV computer program to estimate the risk of early-age cracking and noted that if curing temperatures exceed 158°F, the concrete may be damaged by DEF.

The fatigue damage due to early opening was minimal. Yu et al. (2006) noted that the “results of this evaluation showed that in terms of fatigue damage or faulting performance, the repairs could be opened to traffic at much lower strengths than those typically recommended.” However, given the risk of random failures caused by a single heavy load at an early age, Yu et al. (2006) recommended that the opening criteria outlined in the SHRP C-206 report be used (Whiting et al. 1994).

Case Study: California I-15 Reconstruction

One example of the reconstruction of a very heavily trafficked highway is I-15 in southern California. The concrete truck lanes were badly deteriorated, and a 2.8 mile section was rebuilt using only two nine-day closures. The project is discussed in detail by Lee et al. (2005).

Some of the key features of the project included the following:

- The pavement was rebuilt using nine-day closures as opposed to overnight closures because the longer closures had been found to yield much higher contractor productivity.
- Longer closures reduce the overall disruption to the traveling public, provide greater life expectancy for the pavement, improve safety, and significantly reduce construction costs.
- The existing pavement, which consisted of 8 in. of concrete over 4 in. of cement-treated base over 12 in. of aggregate base, was replaced with 11½ in. of concrete over 6 in. of asphalt over half of the reused aggregate base. The pavement grade was not changed. The outer truck lane was widened by 2 ft to reduce edge loading stresses.
- The California Department of Transportation (Caltrans) went to considerable effort to communicate to the public how the selected strategy would reduce the overall project duration and minimize disruption to the traveling public. An automated work zone information system gave the public travel time and detour information on changeable message signs.
- Rapid strength gain concrete with Type III cement allowed the pavement to be opened to traffic in 12 hours. About 50% of the project was able to use a more conventional concrete with Type II cement, as long as 24 hours of curing time was available in the schedule.
- Project completion time incentives and disincentives and late opening penalties were specified in the contract (Delatte 2014).

Case Study: Virginia Field Tests for Full-Depth Patching of CRCP

VDOT observed that full-depth patches in CRCP often experienced premature failures, with some patches lasting only one to five years. To investigate the causes of these failures, Sprinkel et al. (2019) monitored the installation and performance of full-depth patches in four pavement test sections. According to the VDOT recommended

practice for full-depth patches, the patches should be the full lane width of 12 ft and a minimum of 6 ft long. A minimum of 1 ft of sound concrete must be removed past the distressed concrete or an existing transverse crack. Additionally, patches must be at least 10 ft apart (Sprinkel et al. 2019).

The reinforcement in CRCP presents some difficulty in patching since the bars must be cut and spliced. Cutting the bars may release tensile forces and allow the adjacent pavement to contract. Therefore, Sprinkel et al. (2019) also investigated methods of splicing the new bars to the existing bars. Alternative splicing methods are illustrated in Sprinkel et al. (2019).

Sprinkel et al. (2019) identified eight possible causes of repair failure as hypotheses for further investigation:

1. Failure to remove deteriorated concrete adjacent to the area being patched
2. Damage to concrete adjacent to the patch during concrete removal (possibly because of the use of heavy equipment)
3. Cutting of steel and inadequate splicing of steel
4. Inadequate load transfer
5. Improper base preparation, including lack of provision for drainage when needed
6. Poor concreting practice
7. Use of high early-strength concrete mixtures that are opened to traffic in 5 to 6 hours, before the required compressive strength of 2,000 psi (13.8 MPa) is achieved
8. Failure to assess the overall pavement condition, which may warrant more substantial rehabilitation such as placing an overlay on the patched pavement to protect the pavement and reduce the level of stress caused by traffic and environmental changes

The four test sites were as follows:

- I-85S in Dinwiddie County, an 8 to 9 in. thick CRCP built in 1969
- SR 288N in Chesterfield County, an 8 in. thick CRCP built in 1988
- US 58W in South Hampton County, an 8 in. thick CRCP with a 4 in. overlay built in 2012 (presumably the year of the overlay)
- I-264E in Norfolk County, a 9 to 11 in. thick JCP built from 1967 through 1972

For each site, both temperature match-cured (TMC) and air-cured (AC) cylinders were prepared. TMC molds are insulated and can be heated to a specified temperature based on thermocouples embedded in the patch or new placement.

I-85S Test Site

For the I-85S test site, the investigation determined that the removal of deteriorated concrete was sufficient and that there was no sign of concrete damage during removal of the existing pavement. Therefore, the first two causes of repair failure were ruled out, as were problems with load transfer, base preparation, and drainage. It could not be determined whether there were problems with cutting or splicing the steel reinforcement. Some isolated areas of poor concrete consolidation were identified.

Two different concrete repair mixtures (an 8-hour mixture and a 5-hour mixture) were used, both with high cement contents exceeding 750 lb/yd³. The 8-hour mixture achieved a compressive strength of 2,000 psi at eight hours, but the 5-hour mixture was not able to achieve the same strength at five hours.

The final potential cause of failure was determined to be that the pavement overall was too structurally deficient for patching and probably should have been overlaid instead.

SR 288N Test Site

The patches for the SR 288N test site used the 5-hour concrete mixture from the I-85S test site with a cement content of 800 lb/yd³. The minimum strength requirement for opening the pavement to traffic was set as 1,750 psi, which was expected to be achieved at five hours. Some of the patches were 381 ft long.

The compressive strength of the concrete was monitored with both TMC and AC cylinders. The TMC cylinders had higher strengths than the AC cylinders and were assumed to better represent the actual patch strength. All but one set of TMC cylinders exceeded the required opening strength, while one set was only 5% below the opening strength requirement.

US 58W Test Site

The US 58W test site, like the SR 288N site, also used the 5-hour mixture and used both TMC and AC cylinders

to estimate strength. As with the SR 288N test site, the TMC cylinders had significantly higher strengths than the AC cylinders. All TMC cylinders except one met the specified opening strength at 6 hours.

Findings

Sprinkel et al. (2019) found that one of the most significant causes of premature patching failure was the use of high early-strength concrete mixtures with high cement content. These mixtures led to excessive concrete shrinkage cracking, and the transverse cracks led to spalls, punchouts, and other distresses in about one to five years. Therefore, a revised mixture was recommended that included less cement but included fly ash and slag as a replacement.

Sprinkel et al. (2019) also pointed out the importance of assessing the overall pavement condition before patching. If the pavement structure is not adequate for current traffic, patching should be supplemented with an overlay of the entire section.

Some other potential causes of localized failure for the CRCP patches were cutting of the reinforcement and the subsequent movement and stress redistribution within the pavement, difficulties in splicing short bars, damage to the concrete adjacent to the patch, poor consolidation of patches, and lack of concrete cover over the reinforcement.

Other findings included the following:

- No distress observations were related to opening the pavement to traffic before it reached its specified strength.
- TMC cylinders appear to be a good way to use maturity to estimate in-place concrete strength. One caveat is that most TMC systems require external electrical power, so if power is lost, the cylinders are no longer heated to the same temperature as the concrete. Another limitation is that a testing machine is needed on site to test the TMC cylinders' compressive strength.
- Opening the pavement to traffic at 5 hours with a compressive strength of 1,750 psi did not lead to damage.
- Mixtures with very high cement contents were vulnerable to shrinkage cracking.

Recommendations

Sprinkel et al. (2019) made two recommendations:

1. In the future, VDOT's Materials Division and Construction Division should require special provisions that concrete patching mixtures include much less cement (similar to regular paving concrete) and include fly ash or slag when longer lane closures can be specified. In a single project, multiple mixture designs with varying cementitious materials can be used to achieve the required strength.
2. Chapter 6 of the VDOT *Materials Division Manual of Instructions* should be revised to indicate that VDOT districts should require a preliminary engineering assessment prior to patching to consider the condition of the existing pavement, future traffic, and the need for patching and placement of an overlay to improve the structural capacity.

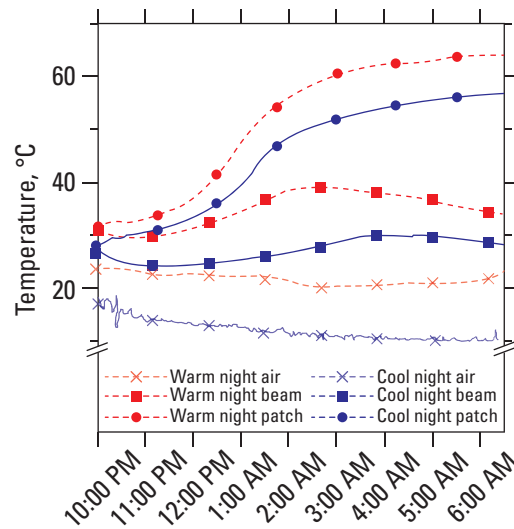
Case Study: Indiana Overnight Lane Closures

The Indiana Department of Transportation (INDOT) uses overnight lane closures for roadway construction to attempt to take advantage of the significant reductions in traffic volumes during nighttime hours (Wilson and Weiss 2020).

Field surveys were conducted as a part of an ongoing pavement rehabilitation project on US 30 in northwest Indiana (Todd 2015). A combination of short (less than 15 ft) and long (15 ft or more) full-depth HES concrete patches were examined. Four primary features were investigated:

1. Nondestructive testing (using the maturity method and the mini-Windsor Probe System)
2. Accelerated heating
3. Sulfate balance
4. Self-desiccation

Temperature profiles from two sites at the INDOT US 30 repair project are shown in Figure 1. The temperatures shown were measured on cool and warm nights in a repair patch in the pavement, in a field-cast concrete beam, and in the air near the samples. The chart shows that the temperature in the concrete patches was in excess of 50°C and 60°C for cool and warm nights, respectively. When these temperatures are compared to the air and beam temperatures, it is apparent that the concrete pavements are reaching a substantially higher temperature and a substantially higher equivalent age than the flexural beams used to determine opening to traffic after as little as 6 hours (in real time).



Recreated from Todd 2015

Figure 1. Temperature profiles at INDOT US 30 repair project on warm and cool nights for different concrete geometries

A testing plan was developed to investigate the influence of temperature on the rate of strength development and the resulting long-term strength utilizing a temperature-matched curing procedure. Temperature-matched curing was achieved using heating blankets layered around the concrete test specimens (Figure 2).



Weiss et al. 2019

Figure 2. Field images of (a) temperature-matched curing beams from a trial batch and (b) temperature-matched curing beams and air-cured beams during a site visit

The beams subjected to elevated temperatures typically had a large strength gain up to 4 to 6 hours followed by a lower rate of strength gain. Compared to the TMC beams, the AC beams experienced a more constant strength development at both early and late ages. The beams cured at higher temperatures had a lower long-term strength.

Case Study: Washington State Department of Transportation Use of the Maturity Method

In a study for the Washington State Department of Transportation (WSDOT), Anderson et al. (2009) investigated contractor and agency use of the maturity method on three major projects beginning in 2003. Two projects involved panel replacements (I-5 in Bellingham and I-205 in Vancouver), and the third project involved replacement of a short section of I-5 in downtown Seattle. For all three projects, the target opening compressive strength was 2,500 psi while the target opening time was 7 hours. The projects used Intellirocks maturity readers and dataloggers.

Anderson et al. (2009) summarized the findings from the projects in terms of five questions:

1. Were valid calibration curves developed for each mix design used on the project?
2. Were verification procedures used to make sure the mixture design used on the project matched the original mixture design used for calibration?
3. Were the times to the target maturity value consistent throughout the project, indicating that the concrete delivered to the job site was consistent?
4. Were target maturity values used to open the pavement to traffic?
5. Were the maturity data collected and reported in a clear and understandable format?

Only the first two projects used valid calibration curves for all mixture designs. In one case, all of the test points were higher than the target strength, so the value of maturity at the target strength was unknown.

As indicated by the second question, WSDOT also required a verification process to ensure that the concrete placed in the field had not deviated from the original mixture design that had been used to develop the maturity curve. To this end, sets of cylinders were cast from the field concrete with embedded dataloggers. At the target maturity reading, the strength was expected to be within 10% of the predicted value. No verification testing was performed for one of the projects, and for the other two projects the verification process did not show conclusively that the field concrete matched the laboratory concrete used to develop the strength-maturity curves.

To determine whether target maturity values were used to open the pavement to traffic, Anderson et al. (2009) examined whether the maturity records stopped once the target strength was achieved. That appeared to happen on one project, but it was not clear for the other two.

A common theme was that project personnel did not fully understand the maturity concept and that additional education and training was necessary. Adequate record keeping was not evident for any of the projects. For example, it was not clear whether the maturity probes had been placed at the beginning or at the end of the concrete placement.

Anderson et al. (2009) concluded the following:

Maturity is a very good tool for predicting the in-place strength of concrete. Proper understanding and use of the maturity method can allow contractors to increase their productivity on projects with accelerated schedules. In only one of the three [projects] was it clear that the contractor understood the maturity method and was able to use it to his advantage.

Summary

Evidence from research and case studies suggests that current opening strength requirements, such as those shown in Appendix A, are overly conservative. This has several negative consequences. In some cases, certain concrete mixtures may not be considered for a particular project because of the perception that they cannot be opened to traffic quickly enough. In other cases, excessive strength requirements lead to concrete mixtures that may achieve the required strength quickly but may not be durable in the long term.

In contrast, the SHRP C-206 testing documented by Yu et al. (2006) showed that even when full-depth patches were opened with strengths as low as 900 psi compressive and 155 psi flexural, the fatigue life of the pavement was not compromised. No difference in fatigue performance was evident between sections that were opened to traffic very early and those that were opened a little later. Despite the fact that field observations showed that opening strengths could be lower, Yu et al. (2006) recommended keeping the SHRP C-206 recommendation of a minimum flexural strength of 300 psi with third-point bending or a minimum compressive strength of 2,000 psi. Antico et al. (2015b) recommended an opening flexural strength of 275 psi for pavements 5 in. thick or thicker. These strengths are lower than any of the typical state transportation agency requirements listed in Appendix A.

A damage-based online tool has been published by Khazanovich et al. (2021) that uses early opening damage analysis to determine cracking risks.

Nondestructive technologies, particularly the maturity, UPV, and impact-echo methods, have proven effective at verifying strength for opening to traffic, whether the methods are used alone or in combination. Using the maturity method to predict strength is an effective strategy, along with the UPV or impact-echo method as a secondary test.

For concrete construction, it is often thought that requiring higher strength is a more conservative approach for determining when to open a pavement to traffic. However, the experience of early cracking and durability problems with some EOT concrete pavements, particularly mixtures designed for very short closures, suggests that this approach may not be conservative for paving. Rather, it may be better to reduce opening strength requirements and use more durable mixtures.

References

- ACI Committee 228. 2013. ACI 228.2R-13: *Report on Nondestructive Test Methods for Evaluation of Concrete in Structures*. American Concrete Institute, Farmington Hills, MI.
- ACI Committee 228. 2019. ACI 228.1R-19: *Report on Methods for Estimating In-Place Concrete Strength*. American Concrete Institute, Farmington Hills, MI.
- ACI Committee 325. 2019. ACI 325.11-19: *Accelerated Techniques for Concrete Paving*. American Concrete Institute, Farmington Hills, MI.
- Anderson, K. W., J. S. Uhlmeier, C. Kinne, L. M. Pierce, and S. Muench. 2009. *Use of the Maturity Method in Accelerated PCCP Construction*. Washington State Department of Transportation, Olympia, WA.
- Antico, F. C., H. S. Esmaeeli, I. De la Varga, W. Jones, T. Barrett, P. Zavattieri, and W. J. Weiss. 2015a. *Removing Obstacles for Pavement Cost Reduction by Examining Early Age Opening Requirements: Material Properties*. FHWA/IN/JTRP-2015/18. Joint Transportation Research Program, Purdue University, West Lafayette, IN.
- Antico, F. C., I. De la Varga, H. S. Esmaeeli, T. E. Nantung, P. D. Zavattieri, and W. J. Weiss. 2015b. Using Accelerated Pavement Testing to Examine Traffic Opening Criteria for Concrete Pavements. *Construction and Building Materials*, Vol. 96, pp. 86–95.
- Babaei, K., and R. L. Purvis. 1995. *Prevention of Cracks in Concrete Bridge Decks: Report on Laboratory Investigations of Concrete Shrinkage*. PA-FHWA-95-004+89-01. Pennsylvania Department of Transportation, Harrisburg, PA.
- Barde, A. D., S. Parameswaran, T. Chariton, W. J. Weiss, M. D. Cohen, and S. A. Newbolds. 2006. *Evaluation of Rapid Setting Cement-Based Materials for Patching and Repair*. FHWA/IN/JTRP-2006/11. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, IN.
- Bassim, R., and M. Issa. 2020a. Maturity-Based Estimates of Concrete Strength for Portland Concrete Cement Pavements and Patches at Early Age of Opening to Traffic. *ACI Materials Journal*, Vol. 117, No. 1, pp. 197–208.
- Bassim, R., and M. Issa. 2020b. Dynamic- and Static-Elastic Moduli and Strength Properties of Early-Age Portland Cement Concrete Pavement Mixtures. *ASCE Journal of Materials in Civil Engineering*, Vol. 32, No. 5.
- Buch, N., T. J. Van Dam, K. Peterson, and L. Sutter. 2008. Evaluation of High-Early Strength PCC Mixtures Used in Full-Depth Repairs. *Construction and Building Materials*, Vol. 22, No. 3, pp. 162–174.
- Burrows, R. W. 1998. *The Visible and Invisible Cracking of Concrete*. ACI Monograph No. 11. American Concrete Institute, Farmington Hills, MI.
- Cavalline, T. L., B. Q. Tempest, R. B. Biggers, A. J. Lukavsky, M. S. McEntyre, and R. A. Newsome. 2020. *Durable and Sustainable Concrete Through Performance Engineered Concrete Mixtures*. FHWA/NC/2018-14. University of North Carolina, Charlotte, NC.
- Chariton, T., and W. J. Weiss. 2002. *Using Acoustic Emission to Monitor Damage Development in Mortars Restrained from Volumetric Changes*. American Concrete Institute, Farmington Hills, MI.
- Collier, Z., A. Rahavendra, and T. Rupnow. 2018. *Reliable Early Opening Strength for Concrete Pavements and Patch Work*. Louisiana Transportation Research Center, Baton Rouge, LA.
- Crovetti, J., and L. Khazanovich. 2005. *Early Opening of Portland Cement Concrete (PCC) Pavements to Traffic*. Marquette University, Milwaukee, WI.
- Daghighi, A., P. Taylor, H. Ceylan, and Y. Zhang. 2021. *Impacts of Internally Cured Concrete Paving on Contraction Joint Spacing Phase II: Field Implementation of Internally Cured Concrete for Iowa Pavement Systems*. National Concrete Pavement Technology Center, Ames, IA.
- Delatte, N. J. 2014. *Concrete Pavement Design, Construction, and Performance*. Second Edition. CRC Press, Boca Raton, FL.
- Delatte, N., R. Miller, M. Asghar, A. Sommerville, A. Lesak, K. Amini, L. Susinskas, and J. Woods. 2016. *Evaluation of High Performance Pavement and Bridge Deck Wearing Surface Repair Materials*. Ohio Department of Transportation, Columbus, OH.
- Elfino, M., A. Habib, L. Lundy, and S. Haider. 2013. Concrete Pavement Patching Challenges in Virginia. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2347, No. 1, pp. 52–60.
- FHWA. 1994. *Accelerated Rigid Paving Techniques State-of-the-Art Report, Special Project 201*. FHWA SA-94-080. Federal Highway Administration, Washington, DC.

- Freeseaman, K., K. Hoegh, B. I. Izevbekhai, and L. Khazanovich. 2016a. Effect of Early Opening to Traffic on Fatigue Damage to Concrete Pavement. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2590, No. 1, pp. 94–103.
- Freeseaman, K., K. Hoegh, and L. Khazanovich. 2016b. *Concrete Strength Required to Open to Traffic*. University of Minnesota, Minneapolis, MN.
- Gholami, S., J. Hu, Y. Kim, and M. Mamirov. 2019. Performance of Portland Cement-Based Rapid-Patching Materials with Different Cement and Accelerator Types, and Cement Contents. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2673, No. 11, pp. 172–184.
- Graveen, C. 2001. Nondestructive Test Methods to Assess Pavement Quality for Use in a Performance-Related Specification. MS thesis. Purdue University, West Lafayette, IN.
- Juenger, M. C. G., and H. M. Jennings. 2002. Examining the Relationship between the Microstructure of Calcium Silicate Hydrate and Drying Shrinkage of Cement Pastes. *Cement and Concrete Research*, Vol. 32, No. 2, pp. 289–296.
- Khazanovich, L., K. Kosar, and H. Li. 2021. *Evaluation of Long-Term Impacts of Early Opening of Concrete Pavements*. University of Pittsburgh, Pittsburgh, PA.
- Lee, E., J. T. Harvey, K. Choi, and D. Thomas. 2005. Innovative Approach to Rapid Rehabilitation of Concrete Pavement on Urban Highway. *Proceedings of the 8th International Conference on Concrete Pavements*, Vol. 3, pp. 1066–1086. International Society for Concrete Pavements, Colorado Springs, CO.
- Malhotra, V. M., and N. J. Carino. 2004. *Handbook on Nondestructive Testing of Concrete*. Second Edition. CRC Press, Boca Raton, FL.
- Ram, P. V., K. D. Smith, A. Shah, J. Olek, T. Van Dam, and L. Sutter. 2019. *Non-Cementitious Repair Materials Study*. Wisconsin Department of Transportation, Madison, WI.
- Rheinheimer, V., M. A. Argenta, R. C. A. Pinto, H. L. La Rovere, and G. Triches. 2010. The Effect of Subbase Type on Opening Times for Fast-Track Concrete Pavements. *International Journal of Pavement Engineering*, Vol. 11, No. 3, pp. 215–222.
- Rohne, R. J. and B. I. Izevbekhai. 2009. *Demonstration of Concrete Maturity Test Process on the TH-694/TH-35E Interchange—Unweave the Weave*. Minnesota Department of Transportation, Maplewood, MN.
- Ruiz, J. M., R. O. Rasmussen, G. K. Chang, J. C. Dick, and P. K. Nelson. 2005. *Computer-Based Guidelines for Concrete Pavements, Volume II: Design and Construction Guidelines and HIPERPAV II User's Manual*. FHWA-HRT-04-122. Federal Highway Administration, McLean, VA.
- Shah, S. P., W. J. Weiss, and W. Yang. 1998. Shrinkage Cracking—Can it be Prevented? *Concrete International*, Vol. 20, No. 4, pp. 51–55.
- Sprinkel, M. M., M. S. Hossain, and C. Ozyildirim. 2019. *Premature Failure of Concrete Patching: Reasons and Resolutions*. Virginia Transportation Research Council, Charlottesville, VA.
- Taylor P. C., V. C. Johansen, L. A. Graf, R. L. Kozikowski, J. Z. Zemajtis, and C. F. Ferraris. 2006. *Identifying Incompatible Combinations of Concrete Materials, Volume I—Final Report*. FHWA-HRT-06-079. Federal Highway Administration, Washington, DC.
- Taylor, P., T. Van Dam, L. Sutter, and G. Fick. 2019. *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual*. National Concrete Pavement Technology Center, Ames, IA.
- The Transtec Group. 2021. HIPERPAV. <https://www.thetranstecgroup.com/hiperpav/>.
- Tia, M. and W. Kumara. 2005. *Evaluation of Early Strength Requirement of Concrete for Slab Replacement Using APT*. University of Florida, Gainesville, FL.
- Todd, N. T. 2015. Assessing Risk Reduction of High Early Strength Concrete Mixtures. MS thesis. Purdue University, West Lafayette, IN.
- Tran, Q. and J. Roesler. 2021. Contactless Ultrasonic Test System for Set Times of Mortar and Concrete. *ACI Materials Journal*, Vol. 118, No. 2.
- TRB. 2006. *Control of Cracking in Concrete: State of the Art*. Transportation Research Circular E-C107. Transportation Research Board, Washington, DC.

- Wang, X., P. Taylor, and X. Wang. 2016. Comparison of Setting Time Measured Using Ultrasonic Wave Propagation with Saw-Cutting Times on Pavements—A Case Study. *Proceedings of the 11th International Conference on Concrete Pavements*, San Antonio, TX. August 28–September 1.
- Weiss, W. J., J. Olek, N. M. Whiting, P. Panchmatia, C. Qiao, and P. Suraneni. 2018. *Synthesis: Accelerating Implementation of Research Findings to Reduce Potential Concrete Pavement Joint Deterioration*. FHWA/IN/JTRP-2018/24. Joint Transportation Research Program, Purdue University, West Lafayette, IN.
- Weiss, W. J., P. Zavattieri, J. Olek, C. Wilson, H. S. Esmaeeli, and N. Todd. 2019. *Concrete Patching Materials and Techniques and Guidelines for Hot Weather Concreting*. FHWA/IN/JTRP-2019/11. Joint Transportation Research Program, Purdue University, West Lafayette, IN.
- Whiting, D., M. Nagi, and P. Okamoto. 1994. Early Strength Gain of Rapid Highway Repair Concrete. *Concrete International*, Vol. 16, No. 8, pp. 28–35.
- Whiting, D., M. Nagi, P. Okamoto, T. Yu, D. Peshkin, K. Smith, M. Darter, J. Clifton, and L. Kaetzel. 1997. *Optimization of Highway Concrete Technology*. SHRP-C-373. Strategic Highway Research Program, Washington, DC.
- Wilson, C. and W. J. Weiss. 2020. Improving the Durability of High Early Strength (HES) Concrete Patching Materials for Concrete Pavements. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2674, No. 8, pp. 12–23.
- Van Dam, T. J., K. R. Peterson, L. L. Sutter, A. Panguluri, J. Sytsma, N. Buch, R. Kowli, and P. Desaraju. 2005. *Guidelines for Early-Opening-to-Traffic Portland Cement Concrete for Pavement Rehabilitation*. National Cooperative Highway Research Program, Washington, DC.
- Yu, H. T., J. Mallela, and M. I. Darter. 2006. *Highway Concrete Technology Pavement Development and Testing: Volume IV—Field Evaluation of Strategic Highway Research Program (SHRP) C-206 Test Sites (Early Opening of Full-Depth Pavement Repairs)*. FHWA-RD-02-085. Federal Highway Administration, McLean, VA.

Appendix A. Selected Agency Specifications on Early-Age Compressive and Flexural Strength

Table A-1. Selected agency specifications on early-age compressive and flexural strength

State Agency	Concrete Type	Construction Equipment Requirement (psi)		Age (days)	Regular Traffic (psi)		Age (days)
		Compressive	Flexural		Compressive	Flexural	
Florida DOT	Class A paving	2,200	—	14	3,000	550	28
Illinois DOT	PV paving	3,500	650	7 or 14	Min of 3,500 or 650 by 14 days prior to loading		
Iowa DOT	Class A paving	Depends on project	500	14	Specified by project, approved by engineer		
	HES Class M paving	Depends on project	500	48 hours	Specified by project, approved by engineer		
Louisiana DOTD	B and D paving	3,000	550	7	3,000	Only if engineer requires	14
	HES mod. A1 paving	3,000	—	4 hours	4,500	—	28
Minnesota DOT	Class A paving	3,000	500–350 (depends on slab thickness)	—	—	—	—
	HES grade F paving or structural	—	—	—	—	—	—
New York DOT	Class A, C paving	2,500	—	3, 7	4,000	600	28
	HES Class F paving or structural	2,500	—	—	4,000	—	28
Virginia DOT	A3 paving	Maturity method	600	14	3,000	600	28
West Virginia DOT	Class A paving	Maturity method or prove 28-day strength met		4, 6, 8	3,000	500	28

Source: Modified from Cavalline et al. 2020

Appendix B. Opening Strength Recommendations (FHWA 1994)

The tables presented in this appendix have been adapted from pages 18 through 22 of the Federal Highway Administration's (FHWA's) *Accelerated Rigid Pavement Techniques State-of-the-Art Report, Special Project 201* (FHWA 1994), primarily to add SI units to the tables.

Tables B-1 and B-2 address opening to construction traffic for span saws or construction vehicles. Tables B-3 and B-4 address municipal streets and highways, respectively. The main difference between Tables B-3 and B-4 is the pavement thickness range: 6 to 8 in. versus 8 to 10.5 in.

Table B-1. Opening to construction traffic – span saws using flexural strength ASTM C78/C78M-21

Thickness, in.	k-value, pci	Required flexural strength, psi
6	100	210
	200	190
	500	100
6.5	100	190
	200	160
	500	150
7 or greater	100	150
	200	150
	500	150

Source: Modified from FHWA 1994

Table B-2. Opening to construction traffic – construction vehicles using flexural strength ASTM C78/C78M-21

Thickness, in.	k-value, pci	Required flexural strength, psi
6	100	460
	200	390
	500	300
6.5	100	390
	200	350
	500	300
7	100	340
	200	300
	500	300
7.5 or greater	All	300

Source: Modified from FHWA 1994

Note: The table in the original reference has two columns that are unclear, so only the more conservative values are listed.

Table B-3. Opening to public traffic – municipal streets with barricades, without widened lanes or tied concrete shoulders, using flexural strength ASTM C78/C78M-21

Thickness, in.	k-value, pci	Required flexural strength, psi Estimated ESALs to specified strength, one direction, truck lane				
		100	500	1,000	2,000	5,000
6	100	490	540	570	590	630
	200	410	450	470	490	520
	200	340	370	390	400	430
6.5	100	430	470	490	520	550
	200	350	390	410	430	450
	200	300	320	330	350	370
7	100	370	410	430	450	480
	200	310	340	360	370	400
	200	300	300	300	300	320
7.5	100	330	370	380	400	430
	200	300	300	320	330	350
	200	300	300	300	300	300
8	100	300	330	340	360	380
	200	300	300	300	300	310
	200	300	300	300	300	300

Source: Modified from FHWA 1994

Table B-4. Opening to public traffic – highways with barricades, without widened lanes or tied concrete shoulders, using flexural strength ASTM C78/C78M-21

Thickness, in.	k-value, pci	Required flexural strength, psi Estimated ESALs to specified strength, one direction, truck lane				
		100	500	1,000	2,000	5,000
8	100	370	410	430	450	470
	200	310	340	350	370	390
	200	300	300	300	300	310
8.5	100	340	370	380	400	430
	200	300	300	320	330	350
	200	300	300	300	300	300
9	100	300	330	350	360	390
	200	300	300	300	300	320
	200	300	300	300	300	300
9.5	100	300	300	320	330	350
	200	300	300	300	300	300
	200	300	300	300	300	300
10	100	300	300	300	300	320
	200	300	300	300	300	300
	200	300	300	300	300	300
10.5	All	300	300	300	300	300

Source: Modified from FHWA 1994



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