"Moving Advancements into Practice"
MAP Brief Winter 2021–2022
Best practices and promising technologies that can be used now to enhance concrete paving

Optimizing Concrete Pavement Opening to Traffic

NATIONAL CONCRETE CONSORTIUM

www.cptechcenter.org/national-concrete-consortium

Winter 2021

PROJECT TITLE
Optimizing Concrete Pavement Opening to Traffic

AUTHORS
Norbert J. Delatte
M.R. Lohmann Professor and Head, School of Civil and Environmental Engineering, Oklahoma State University, Stillwater, Oklahoma

EDITOR
Sabrina Shields-Cook

SPONSORS
Technology Transfer Concrete Consortium TPF-5(437)

MORE INFORMATION
National Concrete Pavement Technology Center
515-294-8103
dfwagner@iastate.edu

Ells T. Cackler
Woodland Consulting, Inc.
tcackler.wci@prairieinet.net

Introduction

For concrete pavements, early opening may be desirable to provide access for local traffic, for construction traffic, or to put the pavement into service. For heavily trafficked pavements, particularly in urban areas, it may be necessary to limit closures to weekends or even overnight. Early opening to traffic needs to be balanced with potential negative impacts, such as early fatigue damage and poor curing.

While conventional paving concretes have been used for short closures, agencies often use special early-opening-to-traffic (EOT) mixtures. The EOT mixtures are subdivided into two categories—mixtures designed to be opened in 6–8 hours and mixtures designed to be opened in 20–24 hours (Van Dam et al. 2005).

In some cases, EOT mixtures may not be necessary. If, for example, the desired time of opening is two or three days, it is possible that conventional paving concrete may achieve sufficient strength in that time. For larger projects, it might also be desirable to consider more than one mixture, such as conventional paving concrete for the bulk of the project and EOT concrete for the final closure placements.

There are current specifications for opening concrete pavements to traffic that are very conservative and lead to unnecessary delays and user costs. Data often do not support such extended time to opening and required opening strengths (Antico et al. 2015a; Freeseman et al. 2016a, 2016b).

Furthermore, while increasing concrete strength may appear at first to be a conservative approach to early opening to traffic, some EOT mixtures have been found to crack early or show poor durability. Therefore, there appears to be considerable risk, as well as higher cost, to using mixtures with high cement contents (Antico et al. 2015b). When developing EOT mixtures for overnight closures, low heat, low shrinkage, and durability are more important than excessively high strength.

Agency Opening Strength Requirements

Many agencies have developed specific EOT concrete paving mixtures or opening specifications. Often, agencies have specified a minimum time to open to traffic (e.g., seven days). Depending on temperatures and mixture constituents, the concrete may attain sufficient strength much earlier.

"On the basis of results obtained from fatigue analyses, it appears that the strengths typically required for early opening to traffic–a flexural strength (MOR) of 300 psi (2.1 MPa) or a compressive strength of 2,000 psi (13.8 MPa)–are reasonable criteria under most conditions for repairs up to 12 feet (3.7 m) in length. The compressive strength is a more accurate indicator of early opening for very short sections 6 feet (1.8 m) or less–because dowel bearing stress is the critical factor in these cases" (Whiting et al. 1997, 181).

A survey of 16 state highway agencies (as of 2000) found opening strength requirements for compressive strength of overnight or 6–8 hour mixtures between 1,200 and 3,500 psi (8.3–24 MPa) and third-point flexural strength between 260–400 psi (1.8–2.8 MPa). Minimum opening times for early mixtures also varied by state, from as little as 4 hours (Kansas and Ohio) to 12 hours (Maryland and Minnesota). Strength requirements for 20–24 hour mixtures were generally higher—2,500 to 3,500 psi (17–24 MPa) compressive strength and 300–600 psi (2.1–4.2 MPa) flexural strength (Van Dam et al. 2005).

Some more recent results were obtained in 2020. Some agencies differentiate between construction traffic and regular traffic and/or between conventional paving concrete and EOT/high-early-strength (HES) concrete. Typical compressive opening strengths are between 2,200–3,500 psi (15.2–24.1 MPa) for construction traffic and between 3,000–4,500 psi (20.7–31.0 MPa) for regular traffic. Typical flexural opening strengths are between 500–650 psi (3.4–4.5 MPa) for construction traffic and are similar for regular traffic. Minnesota requires 350–500 psi (2.4–3.4 MPa), depending on slab thickness (Cavalline et al. 2020).

Concrete strength requirements for design, acceptance, and opening may be different. Since nearly all the concrete placed will be somewhat above the acceptance strength and the concrete will continue to gain strength after the time specified for acceptance, the design strength may realistically be higher. Conversely, due to strength gain, early opening strength may be somewhat lower.

Fatigue Damage

Required pavement opening strength is based on minimizing fatigue damage to the pavement. Fatigue damage increases as the stress ratio (SR) increases. The SR is the applied stress due to traffic divided by the pavement flexural strength (or modulus of rupture):

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

where σ is stress and MOR is modulus of rupture flexural strength as measured by testing a concrete beam specimen (e.g., ASTM C78, 2021).

At a sufficiently low SR of approximately 0.4–0.45, the stress does not do any damage and is below the endurance limit for the material. For intermediate values of SR, relationships have been developed to determine how many load applications may be applied before failure (Figure 1). The relationship is highly nonlinear—as SR decreases, the allowable number of load repetitions increases substantially.

For mixed traffic, the Cumulative Damage Function (CDF) may be used to estimate the pavement life:

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

where i is the number of load groups or configurations; n_i is the actual or projected number of load repetitions for load group i; and N_i is the allowable number of load repetitions for load group i, determined from Figure 1.

Once the CDF = 1.0, the pavement is predicted to fail through fatigue. Therefore, the concern with opening the pavement to traffic early 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 traffic stress.

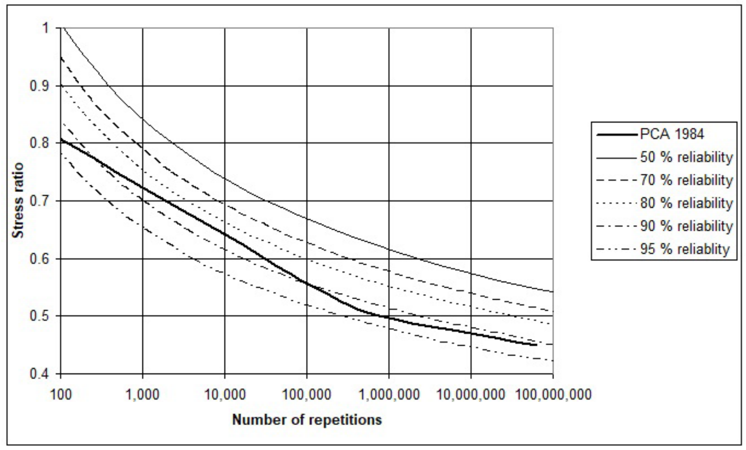


Figure 1. Comparison of PCA 1984 and StreetPave fatigue relationships (Delatte 2014, 113)

Under SHRP SP 201, percentages of lost fatigue life were calculated for some field test patches. Those patches with higher calculated fatigue damage did not show any reduced performance as compared to others (Yu et al. 2006). In these cases, it does not appear that early loading before design strength was reached reduced pavement life significantly.

Concerns with EOT Concrete

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

One observed problem has been poorly formed air-void systems, often due to interactions between mixture constituents, particularly large amounts of Type III cement combined with Type F high range water reducer (HRWR). While durable concrete repairs can be made with both 6–8 and 20–24 hour concrete, the 6–8 hour mixtures have been found more prone to durability-related problems (Van Dam et al. 2005, 19).

Rapidly hydrating systems are always more permeable. Potential durability issues include freeze-thaw deterioration, deicer scaling/deterioration, calcium oxychloride damage, external sulfate attack, and internal sulfate attack. This may become even more of an issue at ramps, intersections, and crossovers, where straight cement mixtures are used to replace mixtures with supplementary cementitious materials (Weiss et al. 2018).

Because of these concerns, it is recommended that EOT mixtures be designed to consider durability, not just rapid strength gain, and should normally include SCMs in order to gain the desired performance particularly under harsh winter maintenance practices.

Stresses in New Pavements and Full-Depth Repairs

Pavement flexural stresses depend on the magnitude and the location of the traffic load applied as well as the pavement thickness and other factors such as slab support and geometry. As pavement thickness increases, the stress for a given load drops rapidly in relation to the square of the pavement thickness (Delatte 2014, 129–131). Because the SR drops as well, the fatigue damage is also reduced. Thus, thinner pavements may require a higher opening flexural strength than thicker pavements.

Dowel bearing stresses are a function of dowel diameter. Thicker dowels reduce bearing stresses. Because thicker pavements require thicker dowels, this is another reason that thinner pavements may require a higher opening compressive strength.

Agencies may wish to consider thickening the pavement for EOT projects, which reduces traffic stresses. The cost of the additional concrete may be offset by either a lower opening strength and/or the use of a less expensive conventional concrete mixture.

As an example, using a calculation from Delatte (2014, 130), an 8-inch (200 mm) thick pavement supported by a subbase value k = 200 psi/in (54.2 MPa/m) loaded with a 9,000 pound (40 kN) single wheel load would have an edge stress of 343 psi (2.36 MPa). If the pavement thickness is increased to 10 inches (250 mm), the edge stress drops to 239 psi (1.65 MPa). With the 43% decrease in stress and stress ratio, the number of load repetitions to failure increases by several orders of magnitude.

Stresses in full-depth repairs are more or less the same as in new pavement construction. The length of the full-depth repair may also affect stresses, with higher environmental stresses in longer patches.

Partial-Depth Repairs

Partial-depth repairs are placed at the top of concrete slabs and generally are subjected only to very low compressive stresses directly from tire pressures. Strength is more of a consideration for patches used to repair joint damage, because those are impacted by traffic at the joints. Details on partial-depth patching planning, execution, and materials are provided in Smith et al. (2014, ch. 5).

Many proprietary repair materials are formulated for very early time to opening, as little as 0.5–3 hours (Barde et al. 2006; Delatte et al. 2016). Strength is not a consideration and, in fact, a low elastic modulus is important to prevent stress concentrations (Ram et al. 2019).

Traffic Loading

For highway pavements, full highway traffic represents the worst early loading case in terms of both numbers and weight of vehicles. Construction vehicles may also be heavy, but there will be fewer of them. Keeping traffic away from the pavement edges and restricting truck numbers both substantially reduce traffic stress, σ, and therefore also SR (ACI 325-11R-19). Light-duty traffic (i.e., passenger vehicles) is much less likely to do damage in most cases. Even for very low concrete strength, the SR is so low that there is no fatigue damage.

Materials Considerations

Material requirements may be different for new construction, full-depth patching, and partial-depth patching because of the quantities of material required as compared to labor costs. For new construction, all or most of the project can be built using conventional paving concrete, with perhaps higher cost EOT materials used at the end of a section.

In contrast, for full-depth patching, there is considerable labor cost with removing existing concrete and preparing for patching. The higher cost of 20–24 hour or even 6–8 hour EOT hydraulic cement concrete may be justified, particularly for overnight or weekend closures. For partial-depth patching, high-cost proprietary materials may be justified, due to the effort involved in preparation and the small quantities of materials used. Prepackaged products may also be convenient for field use.

In addition to conventional concrete, 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, 3–4).

For these applications, desirable concrete characteristics include the following:

- Sufficient but not excessive strength for opening to traffic
- Low heat
- Low shrinkage
- Durability consistent with expected remaining life of the pavement (e.g., it does not make sense to use patches with a 30-year life on a pavement with an expected 10 years of useful life remaining)

Many proprietary patching materials are more expensive, sometimes considerably more expensive, than conventional or EOT concrete. While they may be too expensive to use for new pavement or full-depth patching, they may be suitable for partial-depth patches because those typically only require a small quantity of material. One difficulty with proprietary materials is that new materials are frequently introduced and existing materials may be discontinued or modified, such that approved product lists may quickly become out of date. Some proprietary repair materials are rated for low temperatures, which is useful if cold weather patching is necessary (Delatte et al. 2016).

Construction Considerations

Some of the mixtures, such as the 6–8 hour opening or overnight mixtures, may provide much less working time than conventional concrete—there may be less time available for placement, finishing, and saw cutting. For unfamiliar materials, constructing test slabs provides an opportunity to the contractor and the agency to observe the behavior of the concrete and avoid problems during construction.

For full- and partial-depth patching, additional time is needed to remove existing concrete. If the subbase is disturbed during the process, that may need to be repaired as well. It is important for removal to go past distressed concrete into sound concrete; otherwise distress is likely to appear rapidly next to the patch. If it is necessary to establish load transfer for full-depth patches, this requires an additional step before concrete placement.

In cool or cold weather, simply insulating the pavement or patch can help with strength development. The insulation can allow the use of more forgiving mixtures with lower cement content even in low-temperature conditions.

Applications of Nondestructive Testing

A number of nondestructive testing (NDT) technologies have been developed for concrete strength prediction, and many are applicable to early opening of pavements to traffic. For this application, maturity and stress wave methods are often mentioned.

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. ASTM 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 2019, 1). Figure 2 shows an example of implementation of concrete maturity from the Minnesota Department of Transportation.

As of 2001, 32 states were applying or researching maturity concepts, and 13 states had adopted protocols or specifications for the use of maturity (Tepke and Tikalsky 2001). A quick Internet search shows specifications from Colorado, Florida, and Texas, in addition to Minnesota.

Several nondestructive testing methods for concrete measure the velocity of acoustic waves through the material. The ultrasonic pulse velocity (UPV) method (ASTM C597-16 2016) and the impact-echo method (ASTM C1383-15 2015) have been standardized by ASTM. Several manufacturers sell test equipment.

State transportation agency adoption of UPV appears less widespread than maturity. Wisconsin references UPV in chapter 13 of its Structure Inspection Manual (https://wisconsindot.gov/dtsdManuals/strct/inspection/insp-fm-pt5ch13.pdf). Many state transportation agencies have sponsored research but have not developed specifications.

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. Like UPV, while many state transportation agencies have researched the impact-echo method, it does not appear that any have developed specifications.

Lessons Learned from Case Studies

Delatte, Weiss, and Taylor (2021) review several case studies.

Washington State

The Washington State Department of Transportation (WSDOT) tested contractor and agency use of maturity on three major projects beginning in 2003. A common theme was that project personnel did not fully understand the maturity concept and that additional education and training were necessary. None of the case studies had adequate record keeping. 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).

Iowa

A 7.5 mile (12 km) long overlay was placed on US 71 in Buena Vista County, Iowa, in 1986. The existing 1937 concrete pavement was 20 feet (6.1 m) wide, and it was planned to widen it to 24 feet (7.3 m) and strengthen it with a 4-inch (100 mm) bonded overlay. Other work was to include installation of a longitudinal drain on one side. The plan for this project was to overlay and widen one-half of the roadway, place the shoulder material adjacent to it 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.

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

Minnesota Department of Transportation

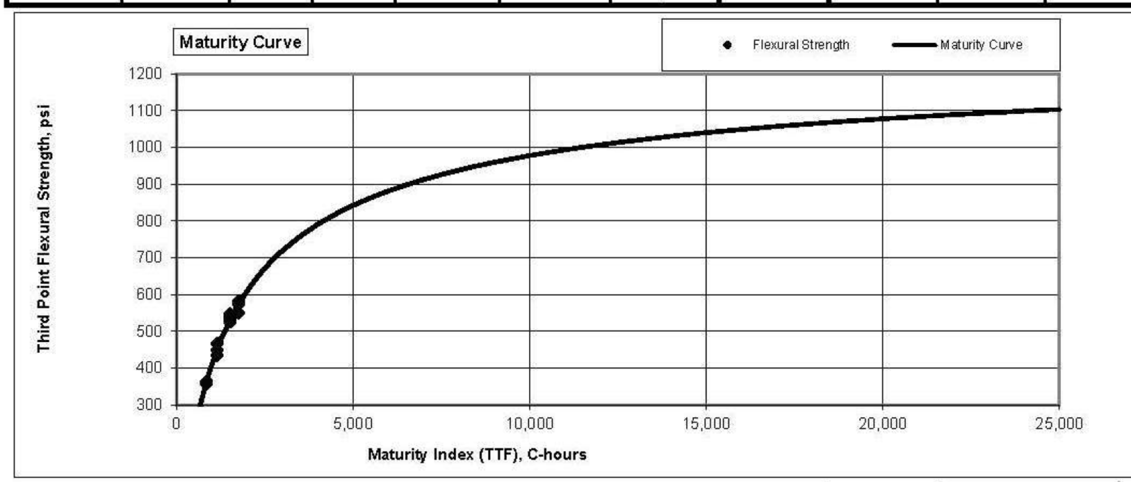
1/2017

Concrete Maturity - Flexural Beam Strength Development

Project No.:	8901-23	Tester:	C.Calloway	Report Date:	5/27/17
Location:	I-425	Contractor:	TUV Paving	Casting Date:	5/24/17
Curve #:	1	Engineer:	T.Sander	Casting Time:	14:15
				Slab Thickness:	7

Beam Breaker Type: Rainhart Beam Breaker

Beam No.	Age at Break (hours or days)	Ave. Width "B" (in)	Ave. Depth "D" (in)	Total Test Load, psi	Area Correction Factor	Broken in Center Third? (Y/N)	Modulus of Rupture (psi)	TTF Sensor 1 (C-Hours)	TTF Sensor 2 (C-Hours)	Ave. TTF (C-Hours)
1	16.5	6.00	5.94	242	1.01	y	244	525	534	530
2		6.06	6.00	248	0.98	y	243			
3		6.00	6.00	225	1	y	225			
4	28.5	6.03	6.00	361	0.99	y	357	852	864	860
5		6.06	6.00	371	0.98	y	364			
6		6.12	6.00	380	0.96	y	365			
7	39.5	6.12	6.00	453	0.96	y	435	1148	1160	1155
8		6.09	5.94	477	0.98	y	467			
9		6.06	6.00	458	0.98	y	449			
10	53.5	6.06	5.94	543	0.99	y	538	1508	1534	1520
11		6.12	5.88	536	0.98	y	525			
12		6.00	5.97	543	1.01	y	548			
13	64.5	6.09	6.00	567	0.97	y	550	1752	1781	1765
14		6.06	5.97	588	0.99	y	582			
15		6.00	6.00	575	1	y	575			



Curve Coefficients:

Su= 1295.35
t= 1263.14
a= 0.61256372

Solve Maturity Curve

Required Strength for Opening 500 psi
Required TTF for Opening **1370** C-hours

Comments:

Mix Information	
Mix No.	3A21-1
Truck No.	5200791
Air, %	8.7
Slump, in.	2.5
W/C Ratio	0.37

Certified Contractor Representative: Bill Batcher

Maturity Curve Reviewed by: Leo Bean

Figure 2. Development of Flexural Strength–Maturity Relationship (MnDOT 2021)

Ride quality was like that at the time of construction.

The following conclusions were drawn:

- 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 DOT has moved away from the use of Type III cement due to problems encountered in other pavements. They have also found that use of maturity meters has enabled contractors to put traffic onto pavements within 18–36 hours using conventional mixtures in summer.

Georgia and Ohio

Yu et al. (2006) report on the performance of full-depth pavement repair test sections made with high-early-strength (HES) materials as part of the SHRP project C-206, Optimization of Highway Concrete Technology. Test sections in Georgia and Ohio were used to evaluate 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 feet (1.8 and 4.6 m). After construction, the sections were evaluated once a year from fall 1994 through fall 1998 for cracking, faulting, and spalling.

For the Georgia test sections, performance after six years of service was excellent. There was almost no faulting. In fact, the early opening to traffic was judged to have a negligible effect on fatigue life, even for the longer patches. The greatest risk of cracking was associated with patches more than 12 feet (3.7 m) long.

Within weeks after construction, most of the Ohio sections developed longitudinal cracking. Possible causes investigated include dowel restraint of slab horizontal movement and excessive curling stress. All the test sections, with the exception of the two made with one of the proprietary blended cements, had more than 50% longitudinal cracking by 1998.

In addition, the 2–4 hour mixture and the 4–6 hour mixture made with Type III cement developed map cracking consistent with delayed ettringite formation (DEF), which was confirmed with cores. Both mixtures had 900 pounds per cubic yard (540 kg/m^3) or more of cement and exceeded the 158° F (70° C) temperature threshold for DEF.

The high and low temperatures at the two sites were compared to explain why the Ohio sections had extensive longitudinal cracking while the Georgia sections did not. At both sites, the average high temperature during curing was between 102.3 and 114.3° F (39 to 45.7° C) except for the Ohio FS sections that reached 133.5° F (45.3° C). The overnight lows, however, were 70° F (21° C) in Georgia but 50° F (10° C) in Ohio. If possible, this work should be avoided when these temperature extremes are predicted. If it is necessary to pave under these conditions, insulating blankets may be applied as temperatures drop to prevent thermal shock.

Virginia

The Virginia Department of Transportation (VDOT) observed that full-depth patches in continuously reinforced concrete pavement (CRCP) often had premature failures, in some cases lasting only one to seven years. To investigate the problems in more detail, four pavement test sections were built and monitored.

For each patching site, temperature-match cured (TMC) cylinders were prepared as well as air cured (AC) cylinders. TMC molds are insulated and may be heated to a specified temperature based on thermocouples embedded in an adjacent pavement or structure. TMC cylinders are essentially a direct application of the maturity method because they account for temperature as well as time.

The report found that one of the most significant causes of premature patching failures was the use of HES concrete mixtures with high cement content. These led to excessive concrete shrinkage cracking, and the transverse cracks led to spalls, punchouts, and other distress in about one to five years. Therefore, a revised mixture with less cement, including fly ash and slag as a replacement, was recommended.

Several conclusions were drawn from this study:

1. TMC cylinders are a good way to use maturity to estimate in-place concrete strength. One caveat is that most of these 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 cylinder's compressive strength. A need to arrange for electrical power or a generator as well as a testing machine is an obstacle to wider TMC implementation.
2. Opening the pavement to traffic at five hours with a 1,750 psi (12 MPa) compressive strength did not lead to damage.
3. Mixtures with very high cement content are vulnerable to shrinkage cracking.

Summary of lessons learned include the following:

- It is important to provide training to project personnel on the use of maturity.
- Use of maturity allows contractors to put traffic on the pavement within 18–36 hours.
- Use of Type III cement and abnormally high cement content should be avoided for EOT mixtures.
- Early opening to traffic does not appear to compromise performance.

Recommendations

For concrete construction, it is often thought that higher strength is more conservative. However, given the experience of early cracking and durability problems with some EOT concrete, particularly mixtures designed for very short closures, that approach may not be conservative for paving. Instead, it is probably better to reduce opening strength requirements and use more durable mixtures.

- When developing EOT mixtures for overnight closures, low heat, low shrinkage, and durability are more important than excessively high strength.
- Agencies should reduce opening strength requirements. Experience suggests that the opening strengths provided in the tables in the Appendix are reasonable.
- When possible, agencies should use conventional paving mixtures for early opening to traffic, particularly for weekend closures.
- Agencies should consider small increases in pavement thickness combined with lower strength requirements. As shown in Table A4 in the Appendix, for a heavily trafficked highway over a 200 psi/in (54 MPa/m) subbase, increasing the pavement thickness from 8 inches (200 mm) to 10 inches (250 mm) reduces the opening strength from 390 psi (2.7 MPa) to 300 psi (2.1 MPa).
- Agencies should consider maturity, UPV/impact-echo, and other NDT technologies rather than curing time for opening pavements to traffic.
- Agencies should routinely use maturity on concrete paving projects so that contractors and agency personnel become comfortable with the technology. Agencies should also use technologies such as impact-echo or UPV on these projects to foster familiarity with equipment and interpretation.
- While it is preferable to develop job-mixture-specific strength–maturity curves, agencies should determine typical strength–maturity curves for both conventional paving mixtures and typical EOT mixtures. Those curves could be used on projects with a small safety margin added.
- Maturity curves may also be used for project planning to select either conventional or EOT concrete based on the available time interval and anticipated temperature conditions. Planning may use HIPERPAV software or hand calculations to estimate maturity at the desired opening time.

Table 1. Applying EOT Mixtures to Projects

Application Type	Agency Considerations	Contractor Considerations
Patching • Full-depth (FD) 6–8-hour mixtures • FD 20–24-hour mixtures • Partial-depth (PD) mixtures	• Reduce opening strength requirement (see Appendix A) • Base opening time upon field monitoring of strength development • Avoid removing SCMs • Avoid high cement contents and Type III cement • Increase patch thickness to reduce strength needed • Allow proprietary materials for PD repairs	• Develop mixture for EOT requirements • Manage the curing temperatures in cool weather • Cure patches avoiding extreme temperature highs and lows • Field-monitor strength development • Plan operations to be effective for the time available
Projects with EOT needs • Where construction traffic needs early access • Where maintenance of thru traffic is required • Where overlays are being constructed • Where staged construction is utilized • Where construction during off-peak traffic is required • Where continued local access is required	• Allow contractor flexibility • Avoid removing SCMs • Reduce opening strength requirement (see Appendix A) • Base opening time upon field monitoring of strength development	• Use EOT or standard mixture as appropriate for project needs • Keep mixture temperature at or above 50 degrees in cool weather • Field-monitor strength development • Keep traffic away from pavement edges
Normal FD paving projects • Where construction traffic needs early access	• Allow contractor flexibility • Avoid removing SCMs • Reduce opening strength requirement (see Appendix A) • Base opening time upon field monitoring of strength development	• Use standard mixtures • Field-monitor strength development • Keep traffic away from pavement edges

References

ACI 325.11-19. 2019. "Accelerated Techniques for Concrete Paving." American Concrete Institute, Farmington Hills, Michigan.

Anderson, K.W., J.S. Uhlmeyer, C. Kinne, L.M. Pierce, and S. Muench. 2009. Use of the Maturity Method in Accelerated PCCP Construction, Report Number WA-RD 698.1, April 2009.

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." Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2015/18. West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316003.

Antico, F.C., I. De la Varga, H.S. Esmaeeli, T.E. Nantung, P.D. Zavattieri, W.J. Weiss. 2015b. "Using Accelerated Pavement Testing to Examine Traffic Opening Criteria for Concrete Pavements." *Construction and Building Materials*, 96 (2015): 86–95, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2015.07.177. (https://www.sciencedirect.com/science/article/piiS0950061815301999).

ASTM C78/C78M – 21. 2021. "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)." ASTM Inc., West Conshohocken, PA.

ASTM C597-16. 2016. "Standard Test Method for Pulse Velocity through Concrete," ASTM Inc., West Conshohocken, PA.

ASTM C1074-19. 2019. "Standard Practice for Estimating Concrete Strength by the Maturity Method." ASTM Inc., West Conshohocken, PA.

ASTM C1388-15. 2015. "Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method." ASTM Inc., West Conshohocken, 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." Publication FHWA/IN/JTRP-2006/11. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2006. https://doi.org/10.5703/1288284313392.

Cavalline, T.L., B. Tempest, R.B. Biggers, A.J. Lukavsky, M.S. McEntyre, and R.A. Newsome. 2020. "Durable and Sustainable Concrete through Performance Engineered Concrete Mixtures." NCDOT Project 2018-14, FHWA/NC/2018-14, July 2020.

Delatte, N.J. 2014. Concrete Pavement Design, Construction, and Performance, 2nd edition, CRC Press.

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." State Job Number 134816, Ohio Department of Transportation, August 2016. http://cdm16007.contentdm.oclc.org/cdm/ref/collection/p267401ccp2/id/14023.

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*, No. 2347, Transportation Research Board of the National Academies, Washington, DC, 2013, pp. 52–60.

Freeseman, 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*, No. 2590, Transportation Research Board, Washington, DC, 2016, pp. 94–103.

Freeseman, K., K. Hough, and L. Khazanovich. 2016b. "Concrete Strength Required to Open to Traffic." Final Report 2016-01, Minnesota Department of Transportation, January 2016.

MnDOT. 2021. "Maturity Method Procedure." http://www.dot.state.mn.us/materials/concretematurity.html accessed October 2, 2021.

Ram, P.V., K.D. Smith, A. Shah, J. Olek, T. Van Dam, and L. Sutter. 2019. "Non-Cementitious Repair Materials Study." Report No. 0092-18-02, Wisconsin Department of Transportation.

Smith, Kurt, D. Harrington, L. Pierce, P. Ram, and Kelly Smith. 2014. ***Concrete Pavement Preservation Guide***, 2nd Edition. Report No. FHWA-HIF-14-014, National Concrete Pavement Technology Center. https://intrans.iastate.edu/app/uploads/2018/08/preservation_guide_2nd_ed_508_final.pdf

Sprinkel, M., M. Hossain, M. Shabbir, C. Ozyildirim. 2019. "Premature Failure of Concrete Patching: Reasons and Resolutions, Final Report VTRC 19-R14." Virginia Transportation Research Council, March 2019.

Tepke, D., and P.J. Tikalsky. 2001. "Concrete Maturity Progress: Survey of Departments of Transportation." *Transportation Research Record: Journal of the Transportation Research Board,* No. 1775. Transportation Research Board, 2001, Washington, DC.

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, NCHRP Report 540, Transportation Research Board.

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." Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/24. West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316869.

Whiting, D., M. Nagi, and P. Okamoto. 1997. "SHRP-C-373 Optimization of Highway Concrete Technology." Construction Technologies Laboratories, Inc. Washington, DC: Strategic Highway Research Program, 1997.

Wilson, C. and J.W. 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*, No. 2674(8), Washington, DC, 2020, pp. 12–23.

Yu, H., J.M. Thomas, 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), Report No. FHWA-RD-02-085, August 2006.

Appendix: Opening Strength Recommendations (Accelerated 1994)

These tables have been adapted from pages 18 through 22 of the FHWA State-of-the-Art Report on Accelerated Rigid Pavement Techniques. Table A1 and Table A2 address opening to construction traffic for span saws or construction vehicles.

Table A3 and Table A4 address municipal streets and highways, respectively. The main difference between Tables 3 and 4 is the pavement thickness range: 6–8 inches (150–200 mm) versus 8–10.5 inches (200–265 mm).

Table A1. Opening to Construction Traffic—Span Saws Using Flexural Strength ASTM C78 (modified from Accelerated 1994, p. 18)*

Thickness in inches	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

Table A2. Opening to Construction Traffic—Construction Vehicles Using Flexural Strength ASTM C78 (modified from Accelerated 1994, p. 18)*

Thickness in inches	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

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

Table A3. Opening to Public Traffic—Municipal Streets with Barricades and without Adjacent Concrete Lane or Tied or Integral Curb and Gutter, using Flexural Strength ASTM C78 (modified from Accelerated 1994, p. 22)

Thickness in inches	k-value, pci	Required flexural strength, psi Estimated ESALs to specified strength (one direction, truck lane)				
		100	500	1000	2000	5000
6	100	490	540	570	590	630
	200	410	450	470	490	520
	500	340	370	390	400	430
6.5	100	430	470	490	520	550
	200	350	390	410	430	450
	500	300	320	330	350	370
7	100	370	410	430	450	480
	200	310	340	360	370	400
	500	300	300	300	300	320
7.5	100	330	370	380	400	430
	200	300	300	320	330	350
	500	300	300	300	300	300
8	100	300	330	340	360	380
	200	300	300	300	300	310
	500	300	300	300	300	300

Table A4. Opening to Public Traffic—Highways with Barricades and without Widened Lane or Tied Concrete Shoulders, using Flexural Strength ASTM C78 (modified from Accelerated 1994, p. 22)

Thickness in inches	k-value, pci	Required flexural strength, psi Estimated ESALs to specified strength (one direction, truck lane)				
		100	500	1000	2000	5000
8	100	370	410	430	450	470
	200	310	340	350	370	390
	500	300	300	300	300	310
8.5	100	340	370	380	400	430
	200	300	300	320	330	350
	500	300	300	300	300	300
9	100	300	330	350	360	390
	200	300	300	300	300	320
	500	300	300	300	300	300
9.5	100	300	300	320	330	350
	200	300	300	300	300	300
	500	300	300	300	300	300
10	100	300	300	300	300	320
	200	300	300	300	300	300
	500	300	300	300	300	300
10.5	All	300	300	300	300	300