CIVIL ENGINEERING STUDIES
Illinois Center for Transportation Series No. 23-003
UILU-ENG-2023-2003
ISSN: 0197-9191

State-of-the-Practice Review of Field-Curing Methods for Evaluating the Strength of Concrete Test Specimens

Prepared By
Pranshoo Solanki
Haiyan (Sally) Xie
John Awaitey
Tejaswi Reddy
Illinois State University

Research Report No. FHWA-ICT-23-002

The first of two reports of the findings of

ICT PROJECT R27-219
Influence of Field-Curing Conditions on Strength of Concrete Test Specimens

https://doi.org/10.36501/0197-9191/23-003

Illinois Center for Transportation

April 2023

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-ICT-23-002	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A
4. Title and Subtitle State-of-the-Practice Review of Field-Curing Methods for Evaluating the Strength of Concrete Test Specimens		**5. Report Date** April 2023 **6. Performing Organization Code** N/A
7. Authors Pranshoo Solanki (https://orcid.org/0000-0002-5372-178X), Haiyan (Sally) Xie (https://orcid.org/0000-0002-1571-110X), John Awaitey, Tejaswi Reddy		**8. Performing Organization Report No.** ICT-23-003 UILU-2023-2003
9. Performing Organization Name and Address Illinois Center for Transportation Department of Civil and Environmental Engineering University of Illinois Urbana-Champaign 205 North Mathews Avenue, MC-250 Urbana, IL 61801		**10. Work Unit No.** N/A **11. Contract or Grant No.** R27-219
12. Sponsoring Agency Name and Address Illinois Department of Transportation (SPR) Bureau of Research 126 East Ash Street Springfield, IL 62704		**13. Type of Report and Period Covered** Interim Report 8/16/20–4/30/23 **14. Sponsoring Agency Code**

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

https://doi.org/10.36501/0197-9191/23-003

16. Abstract

The American Association of State Highway and Transportation Officials (AASHTO) T 23 standard provides instructions for making and curing concrete test specimens in the field. However, further research is needed to compare the strength of the field-cured specimen with the strength of the actual in-place concrete item. The purpose of this research is to build an understanding of the current state of the practice for field-curing methods. Specifically, the research team conducted a literature review and questionnaire survey to identify the selection criteria and details of field-curing methods. The results of the literature data and survey outcomes indicate most transportation agencies use field-cured cylinders, followed by the maturity method, to decide when to open pavement to traffic or remove formwork or falsework. The most commonly used field method found among transportation agencies was curing the test specimens near (or on) the cast concrete in the same manner as the concrete item represented. The cylindrical specimens are mostly field cured in insulated boxes such as a cooler or under burlap/insulation near the concrete item. In contrast, beams are mostly field cured in a damp sandpit or under burlap/insulation near the concrete item. Other field-curing technologies used by agencies are match curing, SureCure™ cylinder-mold system, piezoelectric sensors, calorimetry, and penetration-resistance tests.

17. Key Words Pavement, Structures, Concrete, Field Curing, Match Curing, Maturity Method, Traffic, Formwork, Falsework, Cylinders, Beams	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 58 + appendices	**22. Price** N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS' NAMES

This publication is based on the results of **ICT-R27-219: Influence of Field-Curing Conditions on Strength of Concrete Test Specimens**. ICT-R27-219 was conducted in cooperation with the Illinois Center for Transportation, the Illinois Department of Transportation, and the U.S. Department of Transportation, Federal Highway Administration.

Members of the Technical Review Panel (TRP) were the following:

- Douglas Dirks, TRP Co-chair, Illinois Department of Transportation
- James Krstulovich,TRP Co-chair, Illinois Department of Transportation
- Michael Ayers, Illinois Chapter of the American Concrete Pavement Association
- Dennis Bachman, Federal Highway Administration
- Kevin Finn, Illinois Department of Transportation
- Stephen Jones, Illinois Department of Transportation
- Ally Kelley, Illinois Department of Transportation
- Chad Morse, Illinois Department of Transportation
- Jim Randolph, Illinois Ready Mixed Concrete Association
- Curtiss Robinson, Federal Highway Administration
- Mark Shaffer, Illinois Department of Transportation
- Megan Swanson, Illinois Department of Transportation
- Steve Worsfold, Illinois Department of Transportation

EXECUTIVE SUMMARY

The American Association of State Highway and Transportation Officials (AASHTO) T 23 standard provides instructions for making and curing concrete test specimens in the field and provides some direction for when field-cured test specimens are applicable (e.g., timing the opening to traffic, formwork or falsework removal). In 2014, Illinois Department of Transportation (IDOT) began allowing 100 × 200 mm (4 × 8 in.) cylindrical specimens to be used for testing strength. However, when cured in the field, the smaller 100 × 200 mm (4 × 8 in.) cylindrical specimens appear not to develop strength as quickly as do beams. This trait may result in the contractor reverting to using beams for the sake of opening or loading structures sooner. However, considering the differences between strength gain of cylinder and beam specimens in the field due to environmental factors, it is not clear how equivalent compressive strength can be established from the required flexural strength. Therefore, further research is needed to compare the strength of the field-cured specimen with the strength of the actual in-place concrete item.

This report is a compilation of information gathered from a review of pertinent literature and a nationwide survey about the current state of the practice for field-curing methods of concrete specimens. The literature included reports collected from the Transportation Research Information Service (TRIS) and standard specifications from web pages of various departments of transportation (DOTs). A total of 36 highway agencies (34 states in the United States and 2 provinces in Canadian) were reviewed by summarizing the literature. The survey was sent to highway agencies within the United States and Canada. A total of 29 states in the United States and 2 provinces in Canada participated in the survey.

The review found that most transportation agencies use field-cured cylinders, followed by the maturity method, to decide when to open pavement to traffic or remove formwork or falsework. Both 100 × 200 mm (4 × 8 in.) and 150 × 200 mm (6 × 12 in.) field-cured cylinders were sizes commonly used by transportation agencies. For beams, both the literature and survey results indicate the 150 × 150 × 500 mm (6 × 6 × 20 in.) beam to be the size most used for field curing. The most common field-curing method found among transportation agencies was placing the specimens near (or on) the cast concrete in the same manner as the concrete item represented. The cylindrical specimens were mostly field cured in an insulated box such as a cooler or under burlap/insulation near the concrete item. In contrast, beams were mostly field cured in a damp sandpit or under burlap/insulation near the concrete item. The curing period depended on the time of formwork or falsework removal determination or pavement opening to traffic, as well as the type of mix. Other field-curing technologies used by agencies were match curing, SureCure™ cylinder-mold system, piezoelectric sensors, calorimetry, and penetration-resistance tests.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

The American Association of State Highway and Transportation Officials (AASHTO) T 23 standard recommends using field-cured strength specimens to determine when to put a concrete structure into service or to remove formwork or falsework. However, according to the Illinois Department of Transportation (IDOT) Research Needs Statement dated August 2019, when cured in the field, smaller 100 × 200 mm (4 × 8 in.) cylindrical specimens tend to take a longer time to develop strength than do beams. This trait may result in the contractor's reverting to using beams for the sake of opening the pavement to traffic or loading structures on concrete surfaces sooner. Considering the differences in strength gain between field-cured cylinders and beam specimens, there is an urgent need to develop a field-curing method that can accurately represent the strength of an in-place concrete item. Therefore, the researchers conducted a literature review and a survey of state transportation agencies to identify the current state of the practice for field-curing methods. Furthermore, the researchers compared the survey data and outcomes from the literature review on prevailing standards and practices.

The report is organized as follows. Chapter 2 explains the research method design, including assumptions, data collection, and analysis methods, as well as the activities to gather data. Chapter 3 presents the results from the literature review. Chapter 4 is the analysis of the survey results. Chapter 5 concludes this report. There are four appendices in this report: the recruitment letter (Appendix A), the data-management policy (Appendix B), the questionnaire for the survey (Appendix C), and Illinois Tollway Special Provision (Appendix D).

CHAPTER 2: METHODS

ASSUMPTIONS

One of the assumptions of the current research project is that the respondents provided honest responses to the survey sponsored by this IDOT project. Another assumption is that the literature and reports the researchers collected and reviewed from TRIS and DOTs' web pages about concrete-curing practices are contemporary. Additionally, this research has a few limitations. First, the opinion survey was narrowed to engineers and practitioners affiliated with state-level DOTs in the United States and Canada. Second, the data collection and literature review focused on pavement and structural concrete field curing and excluded the curing practice of precast concrete, due to the proposed research scope. Third, for many variables in the dataset, data from individual agencies may either be missing or omitted for privacy. For example, the literature search of a particular state DOT may imply the AASHTO standards because the standards are either in the references or indicated in context. When this happens, necessary speculations should be made based on the references and contexts. Fourth, the sample criterion also presents limitations, as the surveyed data for analysis includes only participants' own experiences and observations. Finally, the use of secondary data poses another limitation; and future researchers might consider using a combination of primary and secondary data sources for a thorough understanding of the state of the practice.

DATA AND METHODS

The research design is an exploratory and quantitative study examining both the open literature and the opinion-survey data of engineers and practitioners, collected through online questionnaires sent to highway agencies within the United States and Canada. The design for the current study is exploratory and descriptive, providing an exploration of the variance in factors affecting the quality of concrete field curing, as well as a descriptive analysis of any observed trends and innovations. Because the primary survey data was obtained using an anonymous online instrument (see Chapter 4) and the secondary data was from published reports and standard specifications, the researchers' interference in the present study is minimal; and the study setting is non-contrived (Figure 1). Therefore, the data collection is unobtrusive, and measurement is conducted using operational definitions of the identified variables (listed in Chapter 4). The survey—which was conducted from November 19 to December 18, 2020—is transverse and includes 29 respondents sampled from the United States, as well as 2 respondents sampled from Manitoba and Ontario, Canada. IDOT also provided responses in March 2023.

In contrast, the literature review (see Chapter 3) is longitudinal, with the information covering 2003 to 2021. The purpose of the data analysis is to build a baseline for examining the features of concrete field-curing practices, so the review focused on the literature from the DOT of an individual state, the frequency of a specific curing practice, and the reasons for curing-practice selection on the quality control of field concrete construction.

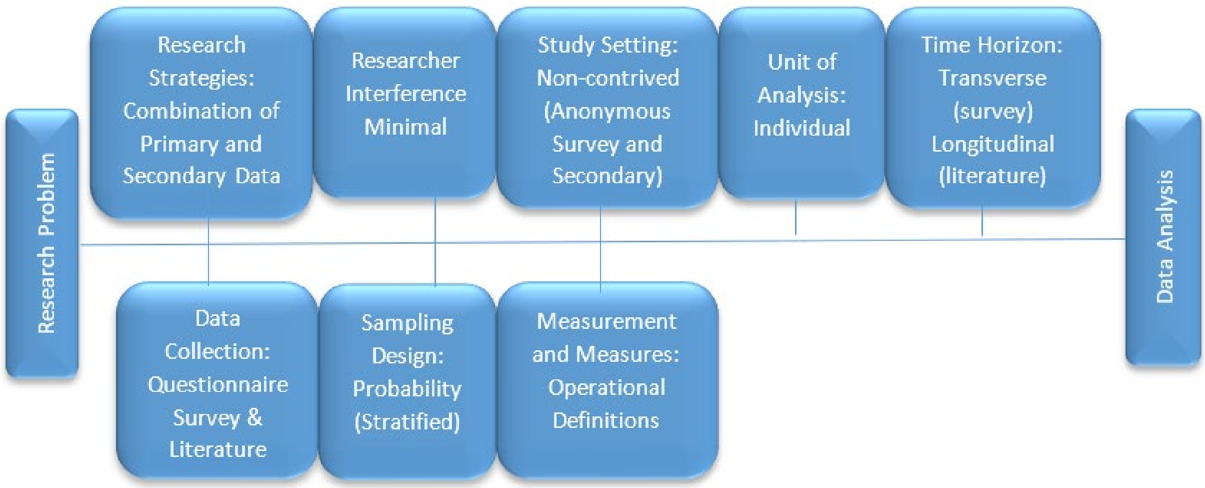


Figure 1. Flowchart. Research design.

POPULATION AND SAMPLING

This study used an estimated population size of 50 US states (corresponding to the number of state DOTs) plus Canadian agencies. The survey received replies from 32 respondents, representing 29 states in the US and 2 provinces in Canada. The sample details are explained in Chapter 4.

The researchers designed the research methodology, survey instrument, and data-collection system in September 2020. The recruitment methods (Appendix A), data-management method (Appendix B), and survey questionnaire (Appendix C) were reviewed and approved by the Institutional Review Board of Illinois State University in October 2020. Meanwhile, the researchers shared the survey instrument and the associated documents with the Technical Review Panel Chairs for review, suggestion, and approval. The data-collection instrument and method were approved by the Institutional Review Board in November 2020, and the Qualtrics system for online distribution and database management was completed two weeks after approval. Based on the number of questions in the survey, information for 28 dimensions was populated using the sample data collected through the instrument (Appendix C). The sampling selection used a total population sampling method. Immediately afterward, the designed instrument was delivered and shared as a secured website link and administered by IDOT.

The survey answers entered by the respondents were automatically collected and saved to a password-protected online database, and the research team had a designated member who downloaded and backed up the data on a daily basis. Participants who did not respond to the electronic survey received an email from IDOT in December 2020 to remind them about the survey. The research team verified the collected data to make sure there was only one respondent from a state DOT and removed duplicate answers if there were two or more respondents from the same DOT. After verification, there were 45 respondents in the dataset in December 2020, but 13 did not provide any answers to the survey. One respondent’s answers were considered duplication; therefore, these answers were removed from further analysis. One respondent’s answers were added to the analysis in March 2023.

CHAPTER 3: LITERATURE REVIEW

AGENCY LITERATURE REVIEW

To help guide and supplement the project, several sources of information were investigated. Specifically, the literature included reports collected from Transportation Research Information Service (TRIS) and standard specification from DOTs' web pages. Overall, 36 highway agencies, in 34 US states and 2 Canadian provinces, were reviewed by summarizing the literature. A summary of field-curing practices used by state DOTs (in alphabetical order) is presented in subsequent sections.

Alabama Department of Transportation

The Alabama Department of Transportation (AlDOT, 2012) requires a minimum of one set of two 28-day concrete cylinders that represent the pavement-testing unit. The compressive strength required for opening the pavement to traffic should be determined by tests of standard concrete cylinders cured under the same climatic and moisture conditions as the slab unless maturity meters are used. The concrete should be cured initially in accordance with AASHTO T 23. Specifically, field curing is done in a protective environment, consisting of at least one curing box with a capacity to hold at least 22 test cylinders that are of 150 × 300 mm (6 × 12 in.) in size. Each curing box shall be equipped with heating/cooling capabilities, automatic temperature control, and maximum/minimum temperature readout. The completed pavement can be opened for traffic when the strength of the concrete reaches 20 MPa (3,000 psi) but not earlier than 72 hours. The pavement may be opened to unrestricted traffic after 7 days if the 28-day compressive strength is achieved and the engineer has accepted the pavement without restriction. If the ambient temperature drops below 4°C (40°F), then the period of time that the temperature is below 4°C (40°F) should be added to the minimum time to opening. Alternatively, the contractor may utilize a maturity meter to determine concrete strength.

California Department of Transportation

The California Department of Transportation (Caltrans) describes Test Method No. 524 (Caltrans, 2013) for fabricating and testing beams at the jobsite where short construction windows require rapid curing (typically 3 to 24 hours) to meet traffic-opening criterion. The beam molds should be 150 × 150 mm (6 × 6 in.) in cross-section and at least 500 mm (20 in.) in length. Beams are fabricated in sets of three. After finishing of the beam, the same curing compound should be applied to it as to the pavement. As soon as the concrete slab sets, prepared beam specimens should be placed directly on the slab. The beam specimens are to be covered with an insulating blanket to hold the heat and moisture in the beams while they cure. The beams are transported to a laboratory for a 7-day or longer flexural strength test. During transport, wet towels are used to cover the beams to maintain moisture. Then, the beams are removed and placed in a limewater bath or moist-curing room or sandpit until the time of testing. The water bath is maintained at a temperature of 23°C ± 2°C (73°F ± 3°F).

Colorado Department of Transportation

The Colorado Department of Transportation (CDOT, 2019) tests field-cured cylinders made for determining form removal time or when a structure may be put into service; they are referred to as "information cylinders." Field-cured cylinders should be cured in the same manner as the structure and should not be exposed to direct sunlight or stored where they may be disturbed by the contractor. CDOT (2019) recommends keeping field-cured specimens in the molds until tested.

Connecticut Department of Transportation

Henault (2007), in a study conducted for the Connecticut Department of Transportation (ConnDOT), concluded that field-cured specimens do not adequately represent in-place concrete of the structure. For preparing field-cured specimens, ConnDOT uses the ASTM C31 procedure. Henault (2007) reported that the mass of concrete inside a 150 × 300 mm (6 × 12 in.) cylinder specimen differs significantly from the mass inside most structures. Therefore, it is incorrect to assume that field-cured cylinder results always represent in-place concrete of the structure, as proved by comparing field-cured specimens to in-place concrete temperatures and maturities. For many instances, their respective temperatures and maturities differed significantly. Further, the following conclusions were made in Henault's study. First, the accuracy of estimated concrete compressive strengths by the maturity method strongly depended on properly determining the maturity function for concrete mixtures actually used in the field. Second, the procedure for developing strength–maturity relationships was found to be cumbersome; and if the maturity method is used on projects, it is likely that the procedure will have to be done more than once due to concrete-mixture variations. Third, in-place concrete-strength estimations by the maturity method were particularly good when the strength–maturity relationship is developed from the actual batch used to pour the structure being monitored. Fourth, concrete-temperature profiling with maturity kits provided accurate data for monitoring the curing of in-place concrete, especially for concreting in hot/cold weather and for mass-concreting operations. Furthermore, this study recommended that field-cured specimens should be prepared for more important structures, with a companion instrumented field-cured specimen for monitoring the maturity of a field-cured specimen. This approach can provide engineers with more data, from which better decisions can be made.

Delaware Department of Transportation

The minimum requirement for form removal by the Delaware Department of Transportation (2016) is defined by the strength requirements. For example, concrete beams should have a minimum strength of 60% of the required design strength (f'c) before form removal. Cylinders cast for determining the time of form removal should be field cured in the same conditions as the concrete they represent. The contractor should also ensure that the 7- and 28-day cylinders are cured for the first 24 to 48 hours in a moisture- and temperature-controlled environment in accordance with AASHTO T 23. The contractor may supply the SureCure™ cylinder-mold system in lieu of match curing specimens. The cylinders are tested at the time the contractor wishes to remove forms.

For concrete patching, a minimum compressive strength of 13.8 MPa (2,000 psi) at 6 hours measured by the SureCure™ cylinder-mold system is needed. The engineer may also use the concrete-maturity meter in accordance with AASHTO T 325 to determine compressive strength.

Florida Department of Transportation

The Florida Department of Transportation (FDOT, 2021) recommends keeping the pavement closed to construction and vehicular traffic until (1) 14 days after placement of the concrete, (2) cylinders cured in the field in a manner identical to the represented pavement concrete indicate minimum compressive strength of 15 MPa (2,200 psi), or (3) the maturity method indicates that concrete has achieved 15 MPa (2,200 psi). Specifically, when cylinders are used for opening-to-traffic strength determination, fabricate three cylinders for that purpose and three for 28-day strength. When the maturity method is used for determining opening to traffic, fabricate three cylinders for maturity-curve correlation testing and three for 28-day strength.

The minimum time for form removal is 7 days, excluding days in which the temperature falls below 4°C (40°F) for slabs, curbs, sidewalks, and bridge decks. Forms can also be removed if concrete attains a specified minimum percent of 28-day compressive strength. For example, Class II bridge-deck concrete forms can be removed if 75% of the 28-day compressive strength is attained. If the percentage of required strength is used to determine readiness, cast and cure the cylinders as practical in the same manner as the concrete represented.

Georgia Department of Transportation

The Georgia Department of Transportation (GDOT, 2016) requires preparation of two 150 × 300 mm (6 × 12 in.) cylinders or three 100 × 200 mm (4 × 8 in.) cylinders for testing. GDOT recommends use of 100 × 200 mm (4 × 8 in.) cylinders only for nonstructural applications, as directed by the engineer. Specimens can be prepared in cardboard or plastic molds. After molding in cardboard, specimens should be covered with wet burlap, a plastic bag, or a glass or metal plate. The standard plastic mold should be covered with the standard sealing lid to avoid evaporation. After molding, specimens should be stored for the first 24 hours at 16°C to 27°C (60°F to 80°F) for cardboard molds and 21°C to 24°C (70°F to 76°F) for plastic molds. After 24 hours, test specimens should be removed from the cardboard mold; if a plastic mold is used, the specimens can be left inside it. According to GDOT (2016) guidelines, test specimens used to determine when a structure shall be put into service should be protected from the elements with the same materials as used for protecting the in-place structure they represent.

For beam specimens, the cross-section of the specimen should be 150 × 150 mm (6 × 6 in.), with a minimum length of 500 mm (20 in.). For determining when a structure or pavement may be put into service, cure beams for 24 hours as nearly as practicable in the same manner as the concrete in the structure or pavement slab. After 24 hours, take the specimens in the molds to a location, preferably near a field laboratory, where the specimens are removed from the molds and stored on the ground. The sides of the specimens are banked with damp earth or sand, leaving the top surface exposed to the curing treatment on damp sand. Another way to cure the specimens is by using a moist-curing tank at a temperature of 21 to 24°C (70 to 76°F).

Illinois Department of Transportation

According to Illinois, strength specimens should be field cured with the concrete item they represent when a contractor desires to open the pavement or structure prior to 14 days (IDOT, 2019). It is recommended to cure test specimens in the field in the same manner as the pavement or structure they represent, which may include protective measures such as insulation. The test specimens should be stored near the concrete item they represent and be removed from the mold when the formwork is removed from the concrete item. Further, IDOT's specifications (2016) for falsework and formwork removal (see Articles 503.05 and 503.06) allow that "a compressive strength established through field testing to be equivalent to the required flexural strength may be used if approved by the Engineer." It should be noted that IDOT uses portable, hand-pumped beam breakers when testing flexural strength in the field, and that all such testing, whether in the field or lab, is center-point tested according to AASHTO T 177. Additional notes collected from various IDOT districts through personal communication with James Krstulovich on February 1, 2021, are summarized below.

According to IDOT District 1, 100 × 200 mm (4 × 8 in.) cylinders are typically field cured under the blankets near the concrete item poured. No beams are used by IDOT District 1 for field curing; however, the district did note that some local agencies do specify beams or the larger size 150 × 300 mm (6 × 12 in.) cylinders only.

IDOT District 3 typically requires field curing for patches and early-strength concrete mixes for bridge decks only. Specifically, field-cured beams and cylinders are used for patch and early-strength concrete mixes, respectively. The test specimens are field cured on top of the poured concrete item, underneath a covering (e.g., blankets, cotton mats, plastic).

IDOT District 4 requires field curing when the weather conditions are cooler than 22°C (73°F) and there is a need to put an item in service quicker than allowed by specification. In contrast, when ambient conditions are warmer than 22°C (73°F) (summertime), lab-cured cylinders are used for early breaks. The test specimens, which are typically 100 × 200 mm (4 × 8 in.) cylinders and occasionally beams, are field cured in the same manner as the concrete item they represent. For example, field-cured cylinders or beams are placed close to (or on) the concrete item and underneath a covering (e.g., blankets, plastic). If the temperature is near or below freezing, cylinders are field cured in an insulated box (cooler) for 24 hours for initial set, then moved underneath the covering close to (or on) the concrete item they represent.

IDOT District 5 requires field curing for pavement patching, bridge deck patching, early opening of pavement or shoulder, temperature extremes, and latex bridge decks. The test specimens used for pavement, shoulder, latex bridges, and temperature extremes are 100 × 200 mm (4 × 8 in.) cylinders. For most patching jobs, 150 × 150 × 475 mm (6 × 6 × 19 in.) beams are used. Similar to IDOT District 4 practice, an insulated box is used for field curing during cold-weather conditions.

IDOT District 8 requires field curing for patching, where beams are field-cured for same-day opening strength, and 100 × 200 mm (4 × 8 in.) cylinders are field-cured for required strength in a specified time.

Furthermore, District 1 tried the maturity method, but adoption did not receive momentum, "probably a bit of a lack of preparation issue because most field curing is done in an 'emergency' fashion at the end of the season." District 4 tried placing cylinders in a mound of fresh mix for field curing during freezing temperatures, which helped but was not practical.

Illinois Tollway

The Illinois Tollway (2020) produces field-cured cylinders or beams in accordance with AASHTO T 23 (IDOT, 2019). Compressive specimens should be cylinders 150 × 300 mm (6 × 12 in.) or 100 × 200 mm (4 × 8 in.). Flexural-strength specimens should be rectangular beams with a cross-section of 150 × 150 mm (6 × 6 in.) and a minimum length of 500 mm (20 in.). Specifically, strength specimens should be field cured whenever (1) the contractor desires to open the pavement to traffic prior to 14 days, (2) pavement patching or bridge-deck patching is performed, or (3) sequential deck pour is involved. After finishing, specimens should be initially cured up to 48 hours in a temperature range from 16°C to 27°C (60°F to 80°F) in an environment preventing moisture loss from the specimens. For concrete with a specified strength of 40 MPa (6,000 psi) or greater, the initial curing temperature should be between 20°C and 26°C (68°F and 78°F). According to the AASHTO T 23 test method, a satisfactory moisture environment can be achieved by (1) immersing specimens with lids in water saturated with calcium hydroxide, (2) storing in wood boxes, (3) placing in damp sandpits, (4) covering with plastic lids, (5) placing in sealed plastic bags, or (6) covering with plastic sheets. A satisfactory temperature environment can be attained by use of ventilation, ice, a thermostatically controlled heating/cooling device, or a heating method such as stoves or light bulbs.

After initial curing, cylinders should be cured in the field in the same manner as the concrete item represented, which may include use of protective measures such as insulation. Cylinders should be placed on their sides underneath protection. If field-cured cylinders tested at 7 days exhibit less than 70% of 14-day design strength, corrective action should be implemented.

Recently, Illinois Tollway included some additional requirements for field curing via special provision, see Appendix D (Krstulovich, pers. comm.). Specifically, field curing is required whenever using cold-weather protection of a concrete item. The test-specimen size used for field curing is 150 × 300 mm (6 × 12 in.). Further, temperature monitoring (at quarter-hourly intervals) and protection of the concrete structure are required when temperature is expected to fall below 7°C (45°F). The contractor is required to implement corrective actions in case temperature-probe readings are below 10°C (50°F) or above 32°C (90°F) and/or field-cured cylinders tested at 7 days are less than 70% of 14-day design strength. Protection of a concrete structure required during cold weather includes Protection Method I (insulating material cover, e.g., fiberglass, Rockwool) and Protection Method II (concrete enclosed in adequate housing and air to keep temperature of at least 10°C (50°F) for 7 days). The Illinois Tollway also stated they are interested in moving toward using the maturity method for opening pavement to traffic in the future (Krstulovich, pers. comm.).

Indiana Department of Transportation

The Indiana Department of Transportation (InDOT, 2020) allows pavement to open to traffic after 14 days or when the flexural strength of a beam is 3.8 MPa (550 psi) or greater. For determining early strength, both field-cured beams and the maturity method in accordance with ITM 402 test method (2020) are allowed. For structural concrete, the removal of formwork is allowed when the flexural strength of the beam exceeds a certain required strength, which is determined using field-cured beams. For falsework, concrete is required to attain a flexural strength of 3.3 MPa (480 psi) before removal. The beams should be cured under the same conditions as the concrete they represent. Specifically, beams should be prepared and tested as simple beams with third-point loading. In a field study conducted by Newbolds and Olek (2001) for InDOT, both concrete beams and cylinders were prepared and cured in one of four curing conditions: lime bath, sandpit, air, or temperature match. Specimens cured in the sandpit most closely matched the maturity development in the concrete pavement. Currently, the sandpit method is used by InDOT for curing concrete test-beam specimens in the field, which is a fairly inexpensive method.

In a recent study sponsored by InDOT, Su et al. (2020) developed an in-situ testing method to determine the strength of concrete for traffic opening. Specifically, piezoelectric sensors installed during the construction of pavement were used to monitor changes in the properties of newly cast concrete. However, no cost comparisons were made between piezoelectric sensors and existing methods such as maturity and field-cured specimens.

Iowa Department of Transportation

In a study conducted for the Iowa Department of Transportation, Cable et al. (2003) investigated the effects of the materials and application technology of curing compounds on concrete properties. Specifically, five tests—maturity, sorptivity, conductivity, moisture content, and permeability—were performed on concrete. The maturity method showed a slight difference between wet curing, no curing, and curing with compounds. They concluded that when concrete is cast in the summer, maturity is a good indicator of strength gain but not for evaluating the curing effect. Overall, the conductivity test was found to be the best method to evaluate curing effects in the field.

Kansas Department of Transportation

According to the Kansas Department of Transportation test method KT-22 (KDOT, 2012), 150 × 300 mm (6 × 12 in.) or 100 × 150 mm (4 × 8 in.) cylinders may be used for determining time of removal of formwork. Specifically, when the maximum size of the coarse aggregate does not exceed 50 mm (2 in.), 150 × 300 mm (6 × 12 in.) cylinders should be used. When the nominal maximum size of the coarse aggregate does not exceed 25 mm (1 in.), the specimens may be 100 × 200 mm (4 × 8 in.) cylinders. After finishing, protect the outside surface of cardboard molds from wet burlap or other sources of water. Wet burlap may be used over nonabsorbent plates or impervious plastic to retard evaporation. The cylinders must be stored in or near the in-place structure they represent. All surfaces of the cylinders should be protected from the elements in as nearly as possible the same way as is the formed work. Provide the cylinders with the same temperature and moisture environment as the structural work. The test specimens should be removed from the molds at the time formwork is removed.

For pavement or slabs on grade, beams with a cross-section of 150 × 150 mm (6 × 6 in.) and a minimum length of 530 mm (21 in.) must be prepared. After 48 ± 4 hours, remove beams from the mold and store near the point in the structure they represent; place the beams on the ground as molded, with their top surfaces up. The sides of the beams should be banked with damp earth or sand, leaving the top surfaces exposed to the specified curing treatment. At the end of the curing period, leave the specimens in place, exposed to the weather in the same manner as the structure. The beam specimens should be removed from field storage and stored in limewater at 23°C ± 2°C (73°F ± 3°F) for 24 ± 4 hours immediately before testing, to ensure a uniform moisture condition from specimen to specimen.

Louisiana Department of Transportation

For determining when to put structures into service or to remove forms, the Louisiana Department of Transportation (2019) specifies the use of 100 × 200 mm (4 × 8 in.) or 150 × 300 mm (6 × 12 in.) concrete cylinders. For preparing beams, molds with an internal cross-section of 150 × 150 mm (6 × 6 in.) and a minimum length of 500 mm (20 in.) are recommended. The molded specimens should not be disturbed for the initial 20 hours of curing. The specimens should be cured near the in-place structure they represent, with the same temperature and moisture environment as that of the represented portion of the structure. On the same day as testing is to take place, transport the specimens in the mold to the laboratory.

Maine Department of Transportation

According to the Maine Department of Transportation (MeDOT, 2020), all concrete surfaces should be cured for at least 7 days after placing. Curing of concrete can be stopped or forms can be removed before 7 days when it is shown that the concrete has developed 80% of design strength. No load or traffic should be allowed on concrete superstructures until concrete cylinders cured with the slab attain design strength. Note that MeDOT (2020) describes a curing box, along with construction details for concrete cylinders; however, it was not clear if this box is used for field curing of cylinders.

Manitoba Infrastructure and Transportation

According to the Manitoba Infrastructure and Transportation (2011), concrete test results from field-cured specimens can be used for deciding early form removal. Specifically, one set of cylinders should be prepared for every 15 cu m (20 cu yd) of concrete, with a minimum of one set per pour. A set of cylinders should have at least five cylinders, one as field cured (referred to as job cured), one for 7-day break, one for 14-day break, and one for 28-day break. The field-cured cylinder should be broken at the conclusion of the heating operations or at the instruction of the resident engineer. All cylinders should be protected from freezing, as well as excessive heat. In cold conditions, the field-cured cylinder must be placed in a hoarding enclosure immediately after casting, where it is not subjected to direct heat or damage from the contractor's operation. Specifically, when the ambient temperature falls below 5°C (41°F) within 24 hours of placing the concrete, the contractor shall make provisions for hoarding and heating the concrete repair. More description of the hoarding enclosure and heating can be found in Manitoba DOT specification 1039 (2010).

Maryland Department of Transportation

In a research report by the Maryland Department of Transportation (Johnson and Hosten, 2011), the maturity method is a powerful tool that has the potential to allow for the nondestructive testing of concrete to determine in-place strength. This method is extremely sensitive to concrete-mixture proportions, uniformity, and sameness of individual mix constituents; and a strength–maturity relationship must be developed for every application. In this project the strength–maturity relationship developed in the lab was not representative of the concrete placed in the field. When comparing the two sets of cylinders poured in the field, one set of which was transported to the lab while the other was left in the field, their strength–maturity relationships were consistent. The fact that these two sets of cylinders had comparable strength–maturity relationships shows that the strength of concrete can indeed be estimated even when the test specimens and the item represented differ in temperature. Because the maturity method is highly mix-specific, the deviation from the expected results could have been caused by unexpected differences between the concrete mix initially used in the lab and that ultimately poured in the field. This method is more efficient than traditional methods. For the maturity-method concept associated with this study, engineers must select proper locations for temperature measurement and estimation of the critical strength of the in-place concrete. Sensors should be installed within the structure at locations that are critical in terms of exposure and structural requirements. Traditionally, the compressive strength of concrete is used as a measure of its suitability; however, flexural strength may also be of interest for concrete pavement applications.

Michigan Department of Transportation

According to a Michigan Department of Transportation (MDOT, 2016) special provision, the maturity method may be used to determine the in-place flexural strength for determining traffic-opening time. However, according to MDOT (2012) specifications Section 601.03 H, pavement and structures can be opened to construction or vehicular traffic or form removal once they reach the required strength. The concrete strength can be determined by (1) testing cylinders or beams cured in environmental conditions similar to those in which the pavement or structure represented will cure; or (2) nondestructive tests, namely, penetration resistance and rebound number conducted in accordance with ASTM C803 and ASTM C805 test methods, respectively.

Minnesota Department of Transportation

The Minnesota Department of Transportation (MnDOT, 2016) requires field-cured specimens (cylinders or beams), called control-strength specimens, for determining the in-place concrete strength. The control cylinders and beams are cured with and in the same manner as the poured concrete structure. Field-cured cylinders are tested at varying ages, depending upon the concrete operations. Three cylinders are required for field-cured specimens. The cylinder-specimen sizes allowed are 100 × 200 mm (4 × 8 in.) and 150 × 300 mm (6 × 12 in.), though for mixes containing maximum aggregate size greater than 30 mm (1.25 in.), the larger size cylinders are required.

For normal-strength concrete, MnDOT recommends storing field-cured cylinders in or on the structure as near as possible to the point of deposit of the concrete represented. It is critical to protect all surfaces of the cylinders; cylinder covers should also be used on control cylinders. MnDOT also requires the beams to cure right along with the concrete pavement and then break without any moist cure.

For high-early (HE)-strength concrete, MnDOT allows storage of HE field-cured cylinders in an insulated storage box, provided the contractor monitors both the temperature inside the insulated storage box and the internal temperature of the cast in-place concrete structure. The temperature inside the insulated box needs to be the same or less than for the corresponding in-place concrete structure. The rise of temperature in the insulated box by greater than ±15°C (5°F) invalidates the field-cured cylinders' compression-test results. Additional field-cured cylinders should be cast/cured with the cast-in-place concrete structure and tested when the insulated-box temperature exceeds the ±15°C (5°F) differential requirements.

In a study conducted by Freeseman et al. (2016) for MnDOT, extensive laboratory and field trials were conducted on pavement concrete. Specifically, ultrasound tomography shear wave–velocity measurements were collected throughout the curing process at early concrete ages in the field. Field testing showed that shear wave–velocity development with hydration of the concrete matched the strength-development curves observed in the laboratory.

Mississippi Department of Transportation

The Mississippi Department of Transportation (MsDOT, 2018) allows the use of field-cured cylinders to estimate the in-place compressive strength of concrete for the purpose of form removal and opening pavement to traffic. Additionally, the maturity method may be used in lieu of field-cured cylinders. MsDOT follows the requirements of AASHTO T 23 for field curing of cylinders. Specifically, the cylinders should be stored in or on the structure as near as possible to the point of deposit of the concrete represented. The cylinders should be protected from direct sunlight and provided with the same temperature and moisture environment as the structural work. If the formed work has a curing blanket on it, place one on the cylinders as well. In cool weather, when the in-place concrete is under a curing blanket, it may be necessary to place the cylinder in an empty ice chest. The type of coolers recommended to give the best results were the “5-day cooler” variety or better, which are advertised as keeping ice inside the cooler for 5 days when the outside temperature is 32°C (90°F). It was also reported that most of the Igloo brand MaxCold™, Quick & Cool™, and MARINE lines of coolers are the “5-day” type. Also, most of the Coleman brand Xtreme®, Ultimate® Xtreme®, and “Marine” lines of coolers are the “5-day” type. Specimens should be removed from their mold just before being tested to determine the strength of the in-place concrete item.

Missouri Department of Transportation

The Missouri Department of Transportation (MoDOT, 2020) requires field-cured cylinders in accordance with AASHTO T 23 (ASTM C31) for determining when to open concrete pavement to traffic. Specifically, cylinders used for determining when forms may be removed should be stored in or on the structure as near as practical to the represented concrete for field curing. All surfaces of the cylinders should be protected from the elements, and temperature as well as moisture environment like that of the formed work should be ensured. Further, field-cured specimens should be removed from the molds at the time of removal of formwork of the in-place concrete structure. The field-cured cylindrical specimens consist of one or more sets of either 150 × 300 mm (6 × 12 in.) or 100 × 200 mm (4 × 8 in.) cylinders. MoDOT does not utilize flexural strength of beams for determining when to open concrete pavement to traffic.

For specimens representing bridge decks, cylinders should be cured on the deck under wet mats until tested or wet curing is discontinued. If cylinders remain after wet curing has ended, they should be cured in plastic molds under field conditions until they are to be broken. Curing of bridge decks should include wet curing for 7 days and until the concrete has reached a minimum of 20 MPa (3,000 psi). For specimens representing heated concrete, cylinders should be left in the enclosure subject to the same protection as in-place concrete until tested. Cylinders should remain in the molds and covered with wet burlap for 48 hours. After the heating period has ended, cylinders should be cured in the plastic molds under field conditions until they are tested.

Montana Department of Transportation

The Montana Department of Transportation (MtDOT, 2013) requires field-cured specimens for determining whether a structure is capable of being put into service or for form/shoring removal time requirements. The engineer may also elect to use the department's "7-day" break-strength results for determining opening of traffic or form removal. The concrete cylinder specimens should be 150 × 300 mm (6 × 12 in.) for maximum aggregate size of 50 mm (2 in.) and 100 × 200 mm (4 × 8 in.) for maximum aggregate size of 25 mm (1 in.). After molding and finishing, cylindrical specimens should be cured for up to 48 hours between 16°C and 27°C (60°F and 80°F) and kept in a moist environment, preventing any loss of moisture from the specimens. For concrete strength of 40 MPa (6,000 psi) or greater, the initial curing temperature should be between 20°C and 26°C (68°F and 78°F). Specifically, cylinders should be cured initially in a temperature-controlled, chest-type curing box or by burying in the earth. Further, field-cured cylinders should be stored near the in-place concrete structure they represent. Specimens should be provided with the same temperature and moisture environment as the structural work. Specimens should be removed from the molds at the time of removal of formwork.

The standard flexural-strength beam required by MtDOT (2013) should be 150 × 150 mm (6 × 6 in.) in cross-section, and length should be 50 mm (2 in.) greater than three times the depth 508 mm (≥20 in.). Initially, beams should be cured the same as cylinders. At the end of 48 ± 4 hours after molding, the molded beams are removed from the molds and stored near the pavements or slabs they represent, by placing them on the ground. Bank the sides and ends of the beams with damp earth or sand. The top surface remains exposed for the curing treatment. At the end of the curing time, leave the specimens in place exposed to the weather, as is the represented structure. The beam specimens are removed from the field storage and placed in water saturated with calcium hydroxide at 23°C ± 2.0°C (73.5°F ± 3.5°F), for 24 ± 4 hours immediately before testing, to make sure the moisture condition is uniform in all specimens.

Nevada Department of Transportation

The Nevada Department of Transportation (2019) recommends preparation of field-cured cylindrical specimens for determining the earliest date a structure may be put into service in accordance with Nevada Test Number 428F Method B. The approved standard cylinder sizes are 100 × 200 mm (4 × 8 in.) and 150 × 300 mm (6 × 12 in.), though for maximum aggregate sizes greater than 25 mm (1 in.), the larger cylinder size is required. Specimens should be cured initially for 24 hours in the same location under the same conditions as the concrete they represent; then, maintain the temperature in the range of 16°C to 27°C (60°F to 80°F) and prevent loss of moisture from the specimens. It is recommended to store specimens in tightly constructed, insulated, firmly braced wooden boxes; damp sandpits; temporary buildings at construction sites; under wet burlap in favorable weather; or in heavyweight closed plastic bags, limiting specimen temperature and moisture loss. After the initial 24-hour storage period, the specimens shall be placed in or on the structure as near as possible to the point of sampling and should receive the same protection from the elements as is given the in-place concrete structure they represent for another 24 hours. The cylindrical specimens should be kept in the field as long as possible, preferably right up to a day or two before being tested.

New Hampshire Department of Transportation

The New Hampshire Department of Transportation (NHDOT, 2016) recommends not to remove the form until field-cured concrete test cylinders achieve 80% of the specified design compressive strength. If not controlled by field-cured test cylinders, load-bearing falsework can be removed after 14 days. The test cylinders should be made and tested in accordance with the AASHTO T 23 and AASHTO T 22 test methods, respectively. Note that NHDOT (2016) requires a curing box for concrete cylinders. Specifically, on projects with less than a total of 16 cu m (21 cu yd) of concrete, the curing box should be airtight, with provision for storing cylinders in damp sand or sawdust at temperatures between 16°C and 27°C (60°F and 80°F). On projects with more than 16 cu m (21 cu yd) of concrete, the curing box should have internal dimensions of approximately 760 mm long × 450 mm wide × 480 mm deep (30 in. long × 18 in. wide × 19 in. deep). Further, the box should have a rustproof interior, a moisture proof seal between the lid and the box, a drainpipe through the side of the box, and a minimum/maximum thermometer.

New Mexico Department of Transportation

The New Mexico Department of Transportation (2007) recommends one of the following methods for determining in-place concrete strength: (1) core testing; (2) the maturity method, ASTM C1074; (3) the Windsor Probe, ASTM C803; (4) the pull-out test, ASTM C900; (5) the match-cure method; (6) the cast-in-place cylinder method, ASTM C873, in which cylinder that is cast into the concrete is evaluated; and (7) field-curing of cylinders cast in accordance with AASHTO T 23 and cured in accordance with AASHTO T 23, Section 9.4.1. The contractor may strip forms or allow traffic on the pavement/structure if in-place compressive strength is at least equal to the strength required for the intended application.

New York Department of Transportation

According to the New York Department of Transportation standard specifications (NYDOT, 2021), a minimum of three-cylinder sets (six total) should be cast from each 300 m (1000 ft) of paving length. Cylinders should be marked and placed adjacent to the pavement under similar curing conditions. The pavement may be opened to construction and general traffic if the average compressive strength of all cylinder pairs exceeds 17 MPa (2,500 psi) and 20 MPa (3,000 psi), respectively. Additionally, the minimum average compressive strength of each cylinder should exceed 13 MPa (2,000 psi) and 17 MPa (2,500 psi) for construction and general traffic, respectively. According to NYDOT specifications, the maturity method may also be used to open the pavement to traffic.

North Carolina Department of Transportation

According to Section 420 of North Carolina Department of Transportation's specifications (2018), forms and falsework for the newly poured portions of the structures should not be removed until concrete attains the minimum compressive strength. The concrete strength is determined by approved nondestructive tests or by compressive-strength tests conducted in accordance with AASHTO T 22 and T 23 test methods. Specifically, the minimum compressive strengths recommended for bridge deck slabs and arch culverts are 20 MPa (3,000 psi) and 16 MPa (2,400 psi), respectively.

North Dakota Department of Transportation

According to ND T 23 testing procedure, the North Dakota Department of Transportation (2019) requires the preparation of 100 × 200 mm (4 × 8 in.) or 150 × 300 mm (6 × 12 in.) cylinders for field curing. Field specimens are initially cured for up to 48 hours by keeping test specimens moist and at a temperature between 16°C and 27°C (60°F and 80°F). Appropriate temperatures must be maintained by various acceptable methods. If the weather is hot, the specimens should be covered with wet burlap or wet sand. In cold weather, some means of heating may be required. Cylinders may be kept moist by covering them with plastic lids and placing them in wood boxes or structures. If the concrete is for a specified strength of 40 MPa (6,000 psi) or greater, the initial curing temperature should be between 20°C and 26°C (68°F and 78°F). At the end of the initial curing, remove the molds from the test specimens and store them as near as possible to the point of sampling for the remainder of their curing time, so the specimens receive the same protection from environmental elements as the portions of the structure they represent.

Cure beams for determining when a structure may be put into service in the same manner as the concrete in the structure. At the end of the initial 48 ± 4 hours cure time, take the beams, still in the molds, to a location near the field laboratory. Remove the test specimens from the molds and store by placing them on the ground with their top surface facing up. Bank the sides and ends with earth or sand and keep damp, leaving the top surface exposed to the specified curing treatment.

For 24 ± 4 hours immediately before testing, remove all beams from field storage and store in water saturated with calcium hydroxide at 23°C ± 2°C (73°F ± 3°F) to ensure a uniform moisture condition.

Ohio Department of Transportation

According to the Ohio Department of Transportation (ODOT, 2019), remove falsework only after the field-cured concrete cylinder has reached a compressive strength of 85% of specified design strength at 28 days or greater. For field-cured beams, a flexural strength of 4 MPa (650 psi) or greater is recommended for opening pavement to traffic. Specifically, field-cured beams are prepared and tested in accordance with ODOT Supplement 1023. The rectangular beam size of 150 × 150 × 1,010 mm (6 × 6 × 40 in.) should be prepared from the same concrete as is placed in the pavement. Beams should be cured as nearly as possible in the same manner as the concrete that it represents. Pavement beams are tested at 3, 5, and 7 days of age. However, beams made from high-early-strength concrete are tested at times from 4 hours to 3 days. The maturity-curve method may also be used for determining the strength in accordance with ODOT Supplement 1098 procedure. Field-cured compressive-strength test cylinders use the maturity method and should indicate a strength of 85% of the specified design strength at 28 days or greater. If the flexural beams are used, then they should have a center-point modulus of rupture of 4 MPa (650 psi) or greater before opening the pavement to traffic. The burlap is kept wet for 7 days by a continuous supply of water; and after 7 days, the forms are removed. To maintain the moisture, the burlap is covered with polyethylene sheeting or plastic-coated burlap blankets.

Ontario Ministry of Transportation

According to OPSS 904 Provincial Standard Specification for Concrete Structures (Ontario Ministry of Transportation, 2019), the contractor may elect to prepare sets of field-cured cylinders for early-strength determination. Curing of cylinders for early-strength determination should consist of storing the cylinders in or on the structure as near as possible to the component they represent. The cylinders should receive protection from the elements on all surfaces in a manner similar to that of the structure they represent. Prior to any early loading, field-cured cylinders should attain a minimum compressive strength of 20 MPa (2,900 psi).

Pennsylvania Department of Transportation

The Pennsylvania Department of Transportation (PennDOT, 2019) describes a procedure for making and curing concrete compression and flexural-test specimens in the field in test method number PTM 611. PTM 611 specifies the use of 150 × 300 mm (6 × 12 in.) cylinders when the nominal maximum size of the aggregate is greater than 25 mm (1 in.) but less than 50 mm (2 in.). The size of a cylindrical specimen of 100 × 200 mm (4 × 8 in.) may be permitted for compression testing if the nominal maximum aggregate size is less than 25 mm (1 in.). For flexural testing, the size of a rectangular beam must be 150 × 200 × 550 mm (6 × 8 × 22 in.). The specimens should be cured initially for 24 ± 2 hours between 16°C and 27°C (60°F and 80°F), and moisture loss should be prevented. Storage temperature and moisture may be regulated by means of firmly braced wooden boxes, damp sandpits, wet burlap covering in favorable weather, temporary buildings near at construction sites, or other suitable methods. It is also noted in the PennDOT (2019) manual that the temperature within damp sand and under wet burlap or similar materials will always be lower than the temperature in the surrounding atmosphere if evaporation takes place. Therefore, a temperature record of the specimens is recommended by means of high–low thermometers or other appropriate temperature-recording devices. Specimens prepared in cardboard molds should be covered with a layer of polyethylene sheeting, with wet burlap placed over them. After 24 ± 2 hours, the specimens should be stored in or on the structure as near as possible to the point of use and should receive the same protection from the elements as is given to the structure they represent. The specimens are stripped from the molds at the time the formwork is removed from the concrete structure represented.

South Dakota Department of Transportation

According to the South Dakota Department of Transportation SD 405 method (SDDOT, 2019), only 150 × 300 mm (6 × 12 in.) cylinders can be used unless an alternate system has been preapproved. The alternative cylinder size is 100 × 200 mm (4 × 8 in.), which is used only when 100% of the coarse aggregate used passes through a 25 mm (1 in.) sieve. Additional cylinders are recommended for field curing to determine form removal timing and allowing traffic on pavement/structure. The temperature and moisture of field-cured cylinders should be kept as close as possible to that of the in-place concrete represented. Further, the SD 405 method (SDDOT, 2019) recommends that specimens should be left in the mold until tested or forms or blankets are removed.

Tennessee Department of Transportation

According to the Tennessee Department of Transportation manual (2020), cylindrical specimens should be made and cured in accordance with the AASHTO T 23 test method. The cylindrical specimen size should be 100 × 200 mm (4 × 8 in.) or 150 × 300 mm (6 × 12 in.). After finishing, specimens are cured initially for up to 48 hours between 16°C and 27°C (60°F and 80°F). High-early-strength 41.3 MPa (> 6,000 psi) cylinders should be kept between 20°C and 26°C (68°F and 78°F). Field-cured cylinders should be cured in the same manner and method as the placed concrete they represent.

Utah Department of Transportation

The Utah Department of Transportation (UDOT, 2020) recommends opening pavement to traffic or construction equipment when concrete has attained a minimum compressive strength of 25 MPa (4,000 psi), as determined by the maturity method in accordance with AASTHTO T 325 or field-cured cylinders cured and protected the same way as the represented concrete. UDOT (2020) also provides a description of a cylinder storage device. The recommended storage device should be able to maintain cylinders at a range of 16°C and 27°C (60°F and 80°F) for the initial 16 hours of the curing period. It should also be equipped with an automatic 24-hour temperature record that continuously records on a time/temperature chart with an accuracy of ±0.5°C (±1°F). However, it was not clear if this storage device is used for curing of cylinders in the field.

Virginia Department of Transportation

According to a Virginia Department of Transportation (VDOT, 2019) report, cement concrete pavement may be opened to traffic if (1) the modulus of rupture tested in accordance with ASTM C78 (third-point loading) has reached a minimum of 4 MPa (600 psi) or (2) the pavement is at least 14 days old. The maturity-test method conducted in accordance with ASTM C1074 may be used to determine the opening-to-traffic strength. However, the acceptance test for cement concrete pavement is the compressive strength, in accordance with the ASTM C39 method.

Further, according to VDOT (2016) specifications, formwork may be removed once concrete has attained 60% of concrete design strength (f'_c). Concrete strength (f'_c) is the design minimum laboratory compressive strength at 28 days. Section 404.03 (j) states that if the time of removing formwork is determined using cylinder strength, the cylinders should be cured under conditions "that are not more favorable than the most unfavorable conditions for the portion of the concrete the cylinders represent." Section 404.03 (m) states that structures should not be opened to traffic before the concrete has attained the 28-day minimum design compressive strength. Field-cured cylinders used for determining when to open pavement to traffic should be cured in conditions "that are not more favorable than the most unfavorable conditions for the portions of concrete the cylinders represent." According to Section 404.03 (b), falsework should remain in place until concrete has attained the minimum 28-day compressive strength. Section 411.05 states that a set of field-cured cylinders is used to determine if the cement concrete has sufficient strength to remove the forms. A set of cylinders is defined as three 100 × 200 mm (4 × 8 in.) cylinders or two 150 × 300 mm (6 × 12 in.) cylinders.

Washington State Department of Transportation

The Washington State Department of Transportation (WsDOT, 2020) follows the AASHTO T 23 test method for field curing. A set of two cylindrical specimens are prepared and stored in or on the structure as near as possible to the point of deposit of the concrete represented. All surfaces of the cylinders should be protected from the elements in the same way as is the formed work. The cylinders must be provided with the same temperature and moisture environments as is the structural work. The specimens should be removed from the mold at the time of removal of the formwork.

The curing compound is applied to the top surface of the beams and covered with white reflective sheeting, and the beams remain undisturbed for an initial curing period of 24 ± 4 hours at ambient conditions. After the initial curing, specimens should be removed from the mold and cured either by burying the specimen in wet sand or wrapping the beam in a saturated towel and placing it in a sealed plastic bag. Beams should be left on the pavement in the vicinity where it was molded until time to test. Beam specimens should be soaked in limewater at 23°C ± 2.8°C (73.4°F ± 5°F) for 24 ± 4 hours immediately before testing, to ensure uniform moisture condition.

Note that WsDOT (2020) recommends two methods for initial curing. The first method cures cylinders in a temperature-controlled, chest-type curing box. The second method places cylinders on level sand or earth, or on a board; and piles sand or earth around the cylinder to within 50 mm (2 in.) of the top. The document states that the latter method may not be preferred for initial curing due to problems in maintaining the required temperature range.

West Virginia Department of Transportation

West Virginia Department of Transportation (WVDOT, 2020) specifications allow the use of either 150 × 300 mm (6 × 12 in.) or 100 × 200 mm (4 × 8 in.) cylinders for concrete testing. However, the diameter of the cylinder should be three times larger than the nominal maximum size of the coarse aggregate in the concrete. A set of three test cylinders is used for either compressive strength, acceptance, or determining when the forms could be removed. WVDOT (2020) requires cylinders to be cured initially for a period of 24 ± 8 hours between 16°C and 27°C (60°F and 80°F) after molding, in an environment that prevents moisture loss from the specimens. For concrete mixtures with a specified strength of 40 MPa (6,000 psi) or greater, the initial curing temperature shall be between 20°C and 26°C (68°F and 78°F). All specimens should be protected from direct sunlight and radiant heating devices. It is recommended to create a satisfactory temperature environment by use of ventilation or ice or a thermostatically controlled heating/cooling device or light bulbs. If cardboard molds are used, the outside surface of the molds should be protected from contact with wet burlap or other sources of water. A satisfactory moisture environment can be created during the initial curing by using one of the following methods: (1) immersing specimens with lids in water saturated with calcium hydroxide, (2) storing specimens in wood boxes, (3) placing specimens in damp sandpits, (4) covering specimens with plastic lids, (5) placing specimens in sealed plastic bags, or (6) covering specimens with plastic sheets and damp burlap. However, it was not clear from the manual if field-cured cylinders should be cured initially.

Further, to obtain similar temperatures and moisture conditions, field-cured cylinders are stored in or on the structure as close as possible to the location of the in-place concrete structure represented. The cylinders should be protected from the elements in the same way as is the represented concrete. For determining when a structure may be put into service, field-cured cylinders must be removed from the molds at the same time the formwork is removed from the represented concrete. During transport, the specimens should be protected with suitable cushioning material to prevent damage from jarring. When field-curing is used, specimens should not be transported to the lab unit just prior to testing. During cold weather, protect the specimens from freezing with suitable insulation material. Prevent moisture loss during transportation by wrapping the specimens in plastic, wet burlap, or by placing them in the wet sand where the transportation time shall not exceed more than 4 hours.

Wisconsin Department of Transportation

The Wisconsin Department of Transportation (2020) uses the maturity method for administering timing of job control functions such as ending the curing period or cold weather protection periods, opening to service, or removal of forms or falsework. The maturity sensor is placed for each 1,529 cubic meters (2,000 cu yd) of concrete pavement, and at least one sensor for each 16 cubic meters (21 cu yd) of concrete placed under non-pavement bid items. Additionally, the contractor should provide a set of three verification cylinders to the engineer for developing a strength-maturity field-calibration curve: specifically, two cylinders for compressive-strength testing, and one with a data-encrypted maturity sensor embedded in its center. These cylinders should be cast, cured on-site, and field cured. Further, cylinders should be delivered to the engineer promptly after attaining 50% of their opening maturity so the engineer can perform verification testing as close as possible to the opening maturity level.

NEW TECHNOLOGIES

The literature review and survey (as discussed in Chapter 4) revealed new technologies, namely the SureCure™ cylinder-mold system, piezoelectric sensors, calorimetry, and penetration-resistance tests. These new technologies are discussed in subsequent paragraphs.

According to the SureCure™ cylinder-mold system (SureCure, 2008), the system consists of two major components: (1) a one-piece mold for a standard 100 × 200 mm (4 × 8 in.) test cylinder and (2) a temperature-matching controller. Concrete in the mold follows the same time-temperature curve as the concrete in the form because molds have built-in heating and temperature-sensing capabilities.

Piezoelectric sensors convert electrical energy into a mechanical wave. Then, the sensor sends this mechanical wave into the concrete and measures its propagation and speed using a resonator. The concrete strength is determined by measuring the resistance of the wave's propagation through concrete; the stronger the concrete, the more resistance it offers to the wave propagation. Some advantages of using piezoelectric sensors is that they can monitor concrete strength in real time, are free from calibrations, and are not dependent on concrete composition (Lu and Su, 2020).

Calorimetry measures the heat generated from the hydration reactions of cementitious materials (FHWA, 2021). The heat outflow tracks the hydration reactions of cement, which gives visibility into the behavior of concrete or mortar in a way that a simple set time or compressive strength test could not. The timing and shape of the temperature curve obtained through calorimetry is an indicator of relative performance of cementitious mixes. According to Calmetrix (2021), the measurement of the reaction rate in a calorimeter is continuous and in real time, giving visibility into the behavior of cement paste, concrete, or mortar in a way that traditional testing such as set time or compressive strength tests could not.

A penetration-resistance test on hardened concrete is conducted on concrete structures using a Windsor Probe test machine (*The Constructor,* 2021). In this test method, a steel probe is fired on the concrete surface by a sudden explosion. The penetration is inversely proportional to the strength of the concrete. The result of the test is influenced by aggregate strength and nature of the formed surfaces of concrete. The purpose of the penetration-resistance test is to determine the uniformity of concrete, specify the poor-quality or deteriorated concrete zones, and evaluate the in-place strength of concrete. It is sometimes necessary to estimate the strength of concrete on-site for early form removal or to investigate the strength of concrete in place because of low cylinder test results (*The Constructor,* 2021). The penetration-resistance test on hardened concrete can be carried out in accordance with the ASTM C 803 test method.

SUMMARY OF LITERATURE REVIEW FINDINGS

The literature review of 36 US DOTs presented in aforementioned sections is summarized in Table 1 and Table 2 for cylinders and beams, respectively. The following conclusions can be made regarding the field-curing practices of concrete specimens:

- The literature review revealed that most transportation agencies use field-cured cylinders (28 out of 36, 78%), followed by the maturity method (16 out of 36, 44%), for deciding when to open pavement to traffic or remove formwork or falsework. Only 12 out of 36 (33%) agencies use beams for determining field-cure strength. It is also important to note that several agencies use more than one method for determining field-cure strength.

- Some of the other field-curing technologies used by agencies are match curing, conductivity, and penetration-resistance tests. The Illinois Tollway respondent reported that the agency plans to implement temperature monitoring and the maturity method for determining field-cure strength. InDOT is currently exploring the use of piezoelectric sensors installed in pavements for determining early strength of concrete.

- Both 100 × 200 mm (4 × 8 in.) and 150 × 300 mm (6 × 12 in.) were field-cured cylinder sizes commonly used by transportation agencies. For beams, 150 × 150 × 500 mm (6 × 6 × 20 in.) and 150 × 150 × 530 mm (6 × 6 × 21 in.) were found to be the most popular sizes among DOTs reviewed in this study.

- The length of the curing period of field-cured specimens was not clear from the literature review, as most of the literature lacked this information. However, in general, most of the DOTs were in favor of curing until the time of formwork or falsework removal determination and varied between 3 and 14 days. The structures utilizing early-strength concrete mixes preferred curing times varying from 4 hours to 3 days.

- In the literature review, specific cylinder- and beam-curing methods used in the field were not reported. However, in general, several agencies reported curing cylinders (23 out of 36, 63.9%) or beams (8 out of 36, 22.2%) near the cast concrete in the same manner as the concrete item is subjected to. Furthermore, several agencies reported curing cylinders under burlap or insulation near the concrete item (9 out of 36, 25%), followed by curing inside a thermostatically controlled or insulated curing box (6 out of 36, 16.7%). For beams, a damp sandpit near the concrete item (10 out of 36, 27.8%) was found to be the most popular curing method, followed by curing under a burlap or insulation near the concrete item (5 out of 36, 13.9%).

Table 1. Summary of Field-curing Methods of Cylinders Used by Various State Highway Agencies Based on Literature Review

State	Field-cured Strength Determination Method(s)	Cylinder Curing Method(s)	Specimen Size(s) (C#)
Alabama	Cylinder, Maturity Method	Thermostatically controlled curing box (power-operated) near the item/structure poured	C1
California	Beam	—	—
Colorado	Cylinder	Same as for concrete item	Not available*
Connecticut	Maturity Method	—	—
Delaware	Cylinder, Sure-Cure Method, Match-curing Method, Maturity Method	Same as for concrete item	Not available*
Florida	Cylinder, Maturity Method	Same as for concrete item	Not available*
Georgia	Cylinder, Beam	Same as for concrete item; under burlap or insulation near the item/structure poured	C1, C2
Illinois	Cylinder, Beam	Same as for concrete item	C1, C2
Illinois Tollway	Cylinder, Beam	Same as for concrete item; under burlap or insulation near the item/structure poured; damp sandpit near the item/structure poured	C1, C2
Indiana	Beam, Maturity Method	—	—
Iowa	Conductivity Test, Sorptivity, Maturity Method, Moisture Content, Permeability	—	—
Kansas	Cylinder, Beam	Same as for concrete item; under burlap or insulation near the item/structure poured	C1, C2
Louisiana	Cylinder, Beam	Same as for concrete item	C1, C2
Maine	Cylinder	Thermostatically controlled curing box (power-operated), but not clear if they use field-curing method	Not available*
Manitoba	Cylinder	In an insulated box with other specimens (gang-cured) near the item/structure poured	Not available*

State	Field-cured Strength Determination Method(s)	Cylinder Curing Method(s)	Specimen Size(s) (C#)
Maryland	Maturity Method	—	—
Michigan	Cylinder, Beam, Maturity Method, Penetration Resistance	Same as for concrete item	Not available*
Mississippi	Cylinder, Maturity Method	Same as for concrete item; under burlap or insulation near the item/structure poured	Not available*
Minnesota	Cylinder, Beam	Same as for concrete item; in an insulated box with other specimens (gang-cured) near the item/structure poured	C1 and C2
Missouri	Cylinder	Same as for concrete item; under burlap or insulation near the item/structure poured	C1 and C2
Montana	Cylinder, Beam	Same as for concrete item; thermostatically controlled curing box (power-operated) or damp sandpit near the item/structure poured	C1 and C2
Nevada	Cylinder	Same as for concrete item; under burlap or insulation near the item/structure poured; damp sandpit near the item/structure poured	C1 and C2
New Hampshire	Cylinder	Thermostatically controlled curing box (power-operated) near the item/structure poured; damp sandpit near the item/structure poured	Not available*
New Mexico	Cylinder, Core Testing, Windsor Probe, Match-curing Method, Maturity Method	Same as for concrete item	Not available*
New York	Cylinder, Maturity Method	Same as for concrete item	Not available*
North Carolina	Cylinder, Maturity Method	—	Not available*
North Dakota	Cylinder, Beam	Same as for concrete item; under burlap or insulation near the item/structure poured	C1 and C2
Ohio	Beam, Maturity Method	—	—
Ontario	Cylinder	Same as for concrete item	Not available*
Pennsylvania	Cylinder, Beam	Same as for concrete item; under burlap or insulation near the item/structure poured; damp sandpit near the item/structure poured	C1 and C2

State	Field-cured Strength Determination Method(s)	Cylinder Curing Method(s)	Specimen Size(s) (C#)
South Dakota	Cylinder	Same as for concrete item	C1 and C2
Tennessee	Cylinder	Same as for concrete item	C1 and C2
Utah	Cylinder, Maturity Method	Same as for concrete item; cylinder-storage device	Not available*
Virginia	Cylinder, Maturity Method	—	C1 and C2
Washington	Cylinder	Same as for concrete item; thermostatically controlled curing box (power-operated) near the item/structure poured	Not available*
West Virginia	Cylinder	Same as for concrete item; under burlap or insulation near the item/structure poured; damp sandpit near the item/structure poured	C1 and C2
Wisconsin	Maturity Method	—	—

Note: C1 = 150 × 300 mm (6 × 12 in.); C2 = 100 × 200 mm (4 × 8 in.); *Not available in open literature

Table 2. Summary of Field-curing Methods of Beams Used by Various State Highway Agencies Based on Literature Review

State	Field-cured Strength Determination Method(s)	Beam Curing Method(s)	Specimen Size(s) (B#)
Alabama	Cylinder, Maturity Method	—	—
California	Beam	Under burlap or insulation near the item/structure poured; damp sandpit near the item/structure poured	B1
Colorado	Cylinder	—	—
Connecticut	Maturity Method	—	—
Delaware	Cylinder, Sure-Cure Method, Match-curing Method, Maturity Method	—	—
Florida	Cylinder, Maturity Method	—	—
Georgia	Cylinder, Beam	Same as for concrete item; damp sandpit near the item/structure poured	B1
Illinois	Cylinder, Beam	Same as for concrete item	B1, B2, B3
Illinois Tollway	Cylinder, Beam	Under burlap or insulation near the item/structure poured; damp sandpit near the item/structure poured	B1
Indiana	Beam, Maturity Method	Damp sandpit near the item/structure poured	Not available*
Iowa	Conductivity Test, Sorptivity, Maturity Method, Moisture Content, Permeability	—	—
Kansas	Cylinder, Beam	Damp sandpit near the item/structure poured	B2
Louisiana	Cylinder, Beam	Same as for concrete item	B1
Maine	Cylinder	—	—
Manitoba	Cylinder	—	—
Maryland	Maturity Method	—	—
Michigan	Cylinder, Beam, Maturity Method, Penetration Resistance	Same as for concrete item	Not available*
Mississippi	Cylinder, Maturity Method	—	—
Minnesota	Cylinder, Beam	Same as for concrete item	Not available*
Missouri	Cylinder	—	—

State	Field-cured Strength Determination Method(s)	Beam Curing Method(s)	Specimen Size(s) (B#)
Montana	Cylinder, Beam	Same as for concrete item; damp sandpit near the item/structure poured	B1
Nevada	Cylinder	—	—
New Hampshire	Cylinder	—	—
New Mexico	Cylinder, Core Testing, Windsor Probe, Match-curing Method, Maturity Method	—	—
New York	Cylinder, Maturity Method	—	—
North Carolina	Cylinder, Maturity Method	—	—
North Dakota	Cylinder, Beam	Same as for concrete item; damp sandpit near the item/structure poured	Not available*
Ohio	Beam, Maturity Method	Same as for concrete item; under burlap or insulation near the item/structure poured; damp sandpit near the item/structure poured	B4
Ontario	Cylinder	—	—
Pennsylvania	Cylinder, Beam	Same as for concrete item; under burlap or insulation near the item/structure poured; damp sandpit near the item/structure poured	B2
South Dakota	Cylinder	—	—
Tennessee	Cylinder	—	—
Utah	Cylinder, Maturity Method	—	—
Virginia	Cylinder, Maturity Method	—	—
Washington	Cylinder	Ambient air on the site near the item/structure poured; under burlap or insulation near the item/structure poured; damp sandpit near the item/structure poured	—
West Virginia	Cylinder	—	—
Wisconsin	Maturity Method	—	—

Note: B1 = 150 × 150 × 500 mm (6 × 6 × 20 in.); B2 = 150 × 150 × 530 mm (6 × 6 × 21 in.); B3 = 150 × 150 × 750 mm (6 × 6 × 30 in.); B4 = 150 × 150 × 1,000 mm (6 × 6 × 40 in.);
*Not available in open literature

CHAPTER 4: SURVEY RESULTS AND ANALYSIS

DEMOGRAPHY

In the survey, 31 responses from various transportation agencies were collected, including 29 responses from individual US states and 2 responses from Canadian provinces. The survey aimed to understand the current practice and asked the respondents to answer the questions based on their experiences and observations. The following analysis keeps two records of the Delaware DOT because they show different answers to the questions. Moreover, the summary table of literature review (Table 2) includes the curing methods documented by IDOT and additional details from Illinois Tollway. The survey response was only provided by Illinois Tollway. Among the respondents, 23 had over 15 years of concrete-related experience, 3 had 11 to 15 years, 4 had 6 to 10 years, and 1 (from Virginia) had between 1 and 5 years. All respondents were familiar with at least one of the following types of concrete work: design, testing, manufacturing, and handing. Additionally, the Manitoba respondent was familiar with specification preparation, inspection, or research of concrete work.

ISSUES OF CONCRETE FIELD OPERATION

When asked whether the selection of specimen type (cylinders vs. beams) would affect the quality of field-cured concrete (and to what extent), the respondents were presented with the following options: strongly agree, agree, neutral, disagree, and strongly disagree. Out of the 31 respondents, 2 strongly agreed, 9 agreed, 13 were neutral, 5 disagreed, and 2 strongly disagreed (as shown in Table 3 and Figure 2).

Also, respondents were asked whether the selection of the specimen size, e.g., 100 × 200 mm or 150 × 300 mm cylinders vs. 500 or 760 mm beams (4 × 8 in. or 6 × 12 in. cylinders vs. 20 or 30 in. beams), could affect the quality of field-cured concrete (and to what extent). Out of the 30 valid responses received, 4 respondents strongly agreed with the statement, 8 agreed, 11 were neutral, 5 disagreed, and 2 strongly disagreed (Table 3 and Figure 2).

TYPES OF FIELD-CURE STRENGTH-DETERMINATION METHODS USED

Table 4 and Figure 3 show the responses to the question asking the type of field-cure strength-determination method used by agencies for the opening of pavement to traffic sooner. Thirty-one valid responses were received, of which 3 respondents used only the maturity method, 1 used only beams, 6 used only cylinders, 18 used at least two methods, and 3 used only other methods. Additionally, the survey asked the type of field-cure strength-determination method used by agencies for formwork or falsework removal. The results indicated that 2 respondents used only the maturity method, 13 used only cylinders, 2 used only beams, 9 used at least two methods, 1 used only other methods, and 1 did not use any method (Table 4 and Figure 4).

Table 3. Selection of Specimen Type and Size versus Quality of Field-cured Concrete

Extent of Agreement by Respondents Numbers Shown in Parenthesis)					
Statement	**Strongly agree**	**Agree**	**Neutral**	**Disagree**	**Strongly disagree**
Selection of specimen type affects the quality of field-cured concrete.	DE, KY	FL, IL Tollway, LA, NC, NM, RI, VA, WI, UT	AR, Canada (Manitoba and Ontario), DE (Dover), MD, ME, ND, NH, SC, TN, WV, OH	CO, IA, ID, NJ, SD	IN, MS
	6.7% (2)	30.0% (9)	40.0% (13)	16.6% (5)	6.7% (2)
Selection of specimen size affects the quality of field-cured concrete.	DE, DE (Dover), KY, WI	FL, IL Tollway, NC, ND, NM, RI, VA, WV	AR, Canada (Manitoba and Ontario), ID, LA, MA, MD, NH, OH, TN, UT	CO, IA, NJ, SC, SD	IN, MS
	13.3% (4)	26.7% (8)	40.0% (11)	16.6% (5)	6.7% (2)

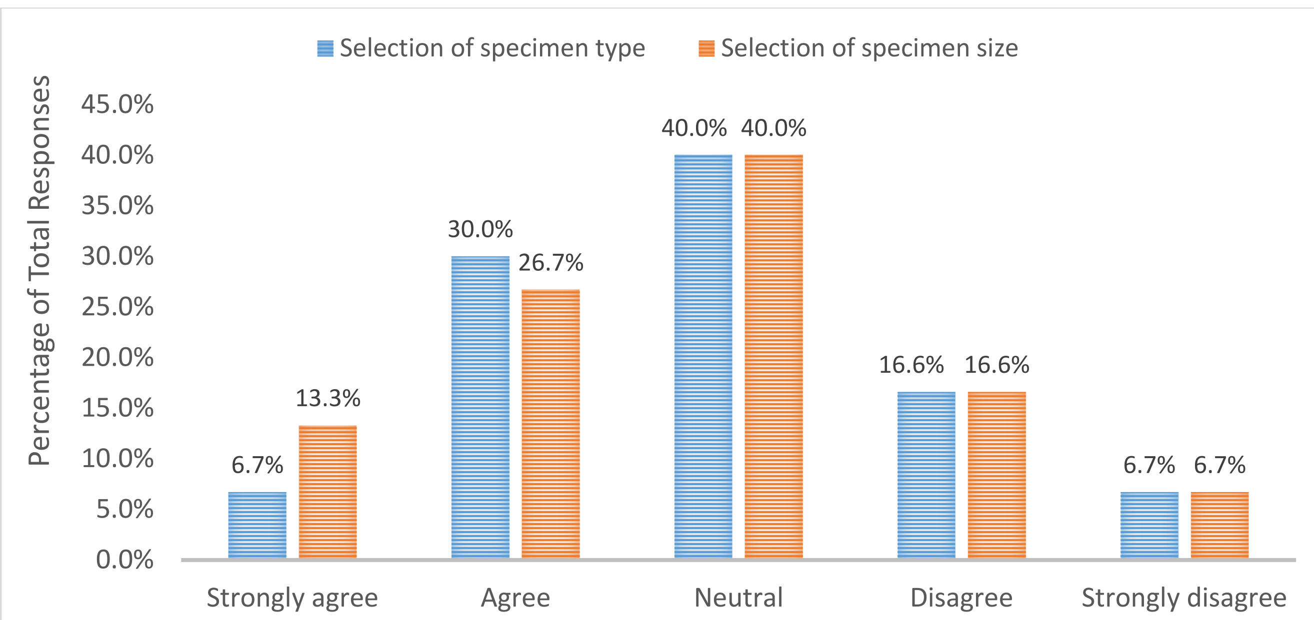


Figure 2. Clustered Column Chart. Selection of specimen type or size versus the quality of field-cured concrete (31 respondents).

Table 4. Types of Field-cured Strength Determination Methods Used by Agencies

	Maturity	Cylinder	Beams	Others	None
For opening of pavement to traffic sooner	CO, FL, IA, ID, IL*, IL Tollway, LA, Manitoba (Canada), MS, NC, NM, OH, UT, VA, WI, WV (count = 16)	AR, FL, ID, IL, IL Tollway, KY, LA, Manitoba (Canada), MD, MI, MS, NH, NJ, NM, RI, SC, SD, TN, UT, VA, WI, WV (count = 22)	IL, IN, LA, NJ, OH (count = 5)	AR, DE, DE (Dover), MD, NH, OH, Ontario (Canada) (count = 7)	—
For deciding when falsework or formwork can be removed	CO, FL, ID, MD, MS, ND, NJ, NM, OH, RI, WI, WV (count = 12)	AR, DE (Dover), FL, IL, IL Tollway, KY, LA, ME, MS, ND, NH, NM, OH, Ontario (Canada), RI, SC, SD, TN, UT, VA, WI, WV (count = 22)	IA, IL, IN, LA, NJ, ND, OH (count = 7)	DE, FL, NH, OH, Ontario (Canada) (count = 5)	NC (count = 1)

* IL DOT only allows maturity for opening pavement patches, not new pavement.

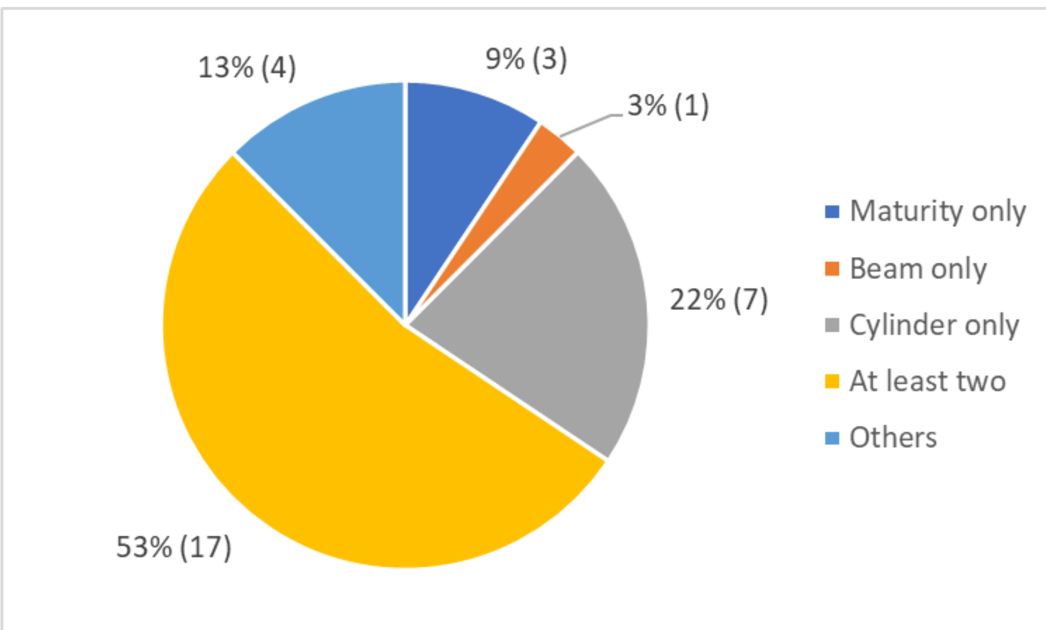


Figure 3. Pie Chart. Types of field-cure strength-determination methods used by agencies in opening pavement to traffic sooner (32 respondents).

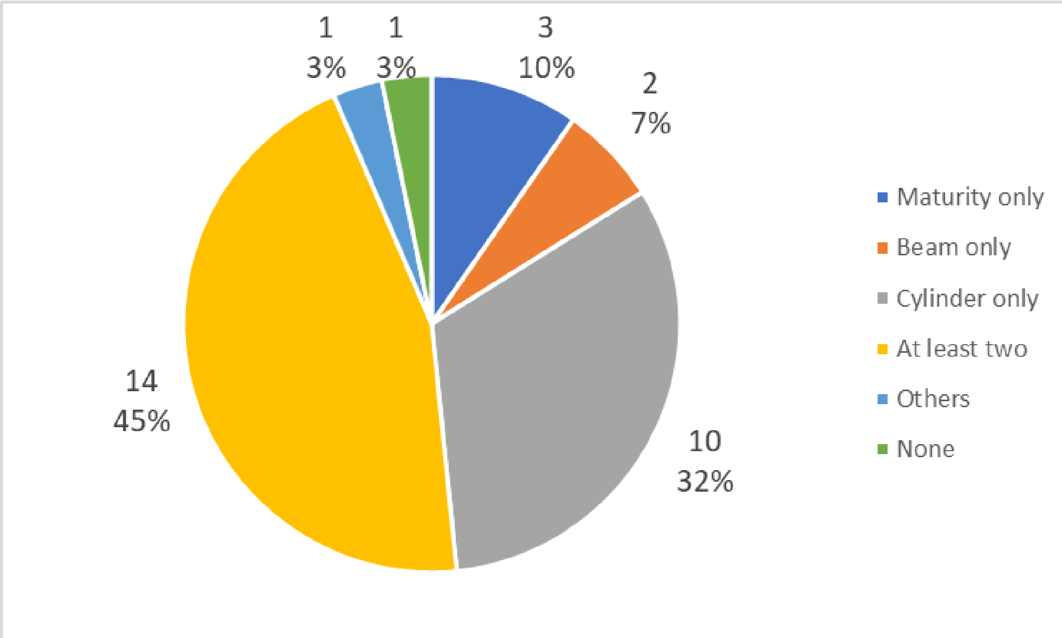


Figure 4. Pie Chart. Types of field-cure strength-determination methods used by agencies in formwork or falsework removal decisions (31 respondents).

Figures 5 and 6 show responses about pavement opening and formwork or falsework removal (as presented in Table 4), respectively, on a US map. The respondent from Ohio said, “For concrete pavements and pavement patching, the initial opening is handled by beam breaks. For patching, it is either 2.76 MPa (400 psi) flex in 24 hours or 400 flex in 4 hours. Our Rapid Repair Concrete Mix is 2.76 MPa (400 psi) in 4 to 6 hours and requires maturity. For new concrete pavement, a contractor can use beam break to decide or wait 5 days to allow construction traffic. Cores are required for new pavements to be tested between 28 and 90 days,” in response to the question of how to open pavement to traffic sooner. Also: “The contractor has the option of beams, cylinders, or maturity in Ohio. Beam-4.48 MPa (650 psi) flex (ASTM C293 center-point). Cylinder-85% f'c (design strength), where fRE'c= 31.03 MPa (4,500 psi) (superstructure) or 27.58 MPa (4,000 psi) (substructure). Maturity curves can be developed with the mix design prior to submittal for approval and maintain the curve throughout the life of the project and verify periodically” for deciding when falsework or formwork can be removed.

IDOT suggests both beam and cylinders (light purple in Figure 5 and Figure 6). Illinois Tollway, however, suggests all three methods—beams, cylinders, and maturity—as noted in the captions for Figure 5 and Figure 6.

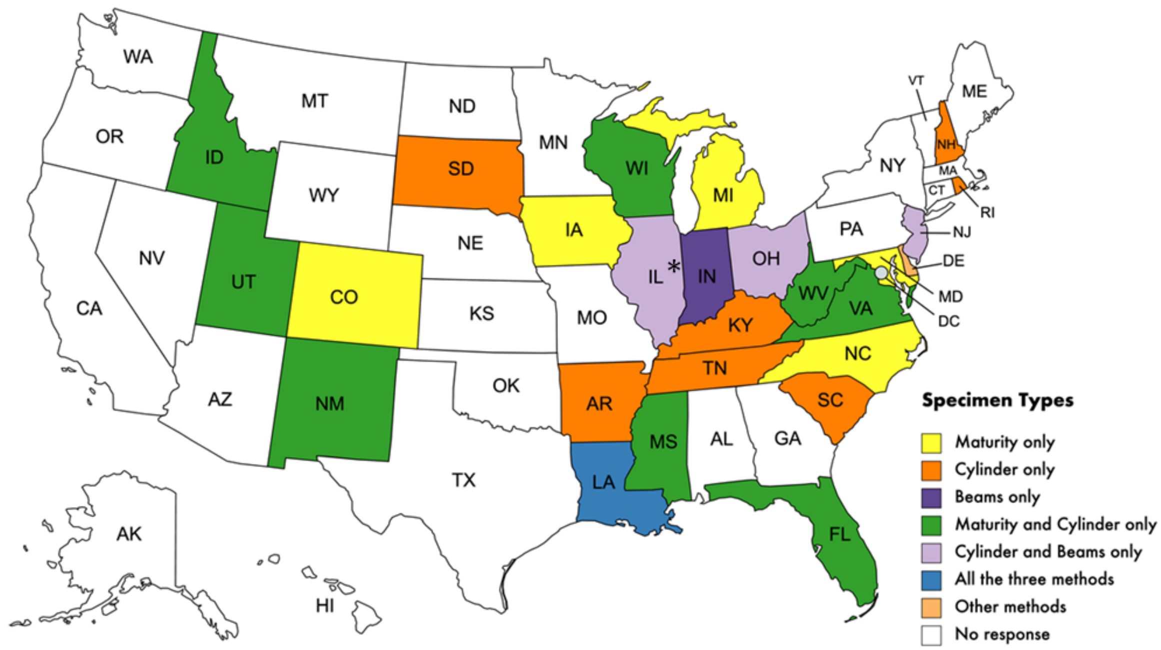


Figure 5. US Map. Specimen types used by various US states for opening pavement (including patches) to traffic sooner. (IDOT suggests both beams and cylinders; *IL Tollway suggests all three methods—cylinder, beams, and maturity.)

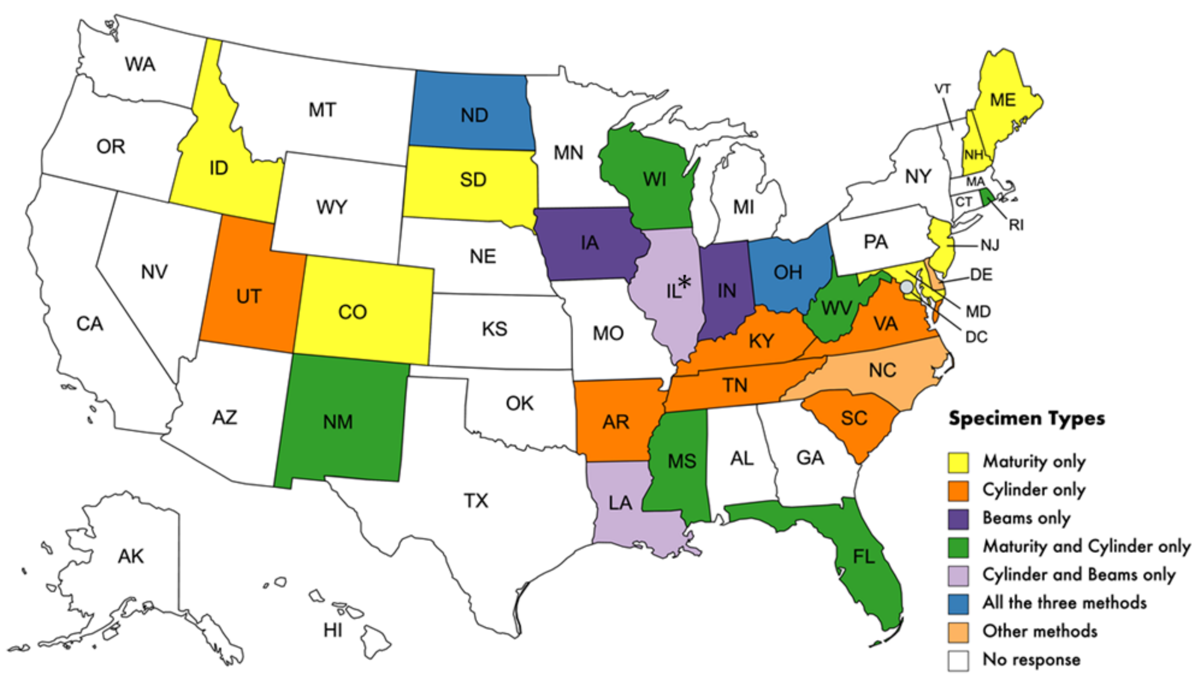


Figure 6. US Map. Specimen types used by various US states for deciding when formwork or falsework can be removed. (IDOT suggests both beams and cylinders; *IL Tollway suggests all three methods—cylinder, beams, and maturity.)

The respondent from North Carolina relied on lab-cured specimens in deciding when formwork could be removed. New Hampshire used cubes, in addition to cylinders, when the opening of pavement to traffic needed to be sooner. They did not use field curing to decide when falsework could be removed but rather used cylinders for information purposes only. Florida used the "strength versus time curve" in deciding when formwork should be removed. Arkansas used cylinders for patching and cores for pavement. In addition to cylinders, Maryland used match curing when the opening of pavement to traffic needed to be sooner. Delaware used cure cylinders for the decision of when formwork could be removed, as well as for the opening of pavement to traffic sooner. Delaware used core molds for the opening of pavement. The Ontario (Canada) Ministry of Transportation used "cylinders for early-strength determination of patches (Ontario Provincial Standard Specification (OPSS) 930/904), and maturity for pavement (autogenous cylinders OPSS 366) when the opening of pavement to traffic needs to be sooner, and OPSS 904" in deciding when falsework or formwork could be removed.

Furthermore, respondents were asked whether their agencies used a different criterion depending on the type of concrete mixes, such as pavement, patching, or bridge superstructure. Seventeen respondents did not use different criteria, while 10 respondents said they used different criteria. Out of those who use different criteria, the respondent from Ohio explained, "Pavement is beams-only 650 flex (ASTM C293 center-point)" and used beam, cylinder, or maturity for structures. The respondent from Indiana said, "Beams are used to [decide the] opening of both structural concrete and pavement. Yes, the strength targets are different for the various applications. The main exception is that cylinders are used for opening deck overlays (latex modified concrete [LMC], latex modified concrete—very early (LMC-VE), and silica fume modified)." The respondent from Florida stated that "for mass temperature, the core temperature is within 27.78°C [50°F] of ambient temperature." Also, the respondent from Arkansas explained that they use "core pavements and make cylinders for patching and bridge structures" and hardly use field curing unless they must work with below-freezing temperatures during the curing process. Maine had Class A 27.58 MPa (4 ksi) for structural elements, class LP 34.47 MPa 5 ksi for curb and barrier transition, and class P 41.37 MPa 6 ksi or more for precast. Also, Wisconsin used a minimum of 13.79 MPa (2,000 psi) for patching, a minimum of 20.68 MPa (3,000 psi) for pavement, and a minimum of 24.13 MPa (3,500 psi) for compressive strengths of opening to traffic. Virginia allowed the maturity meter for the decision to open for concrete patching, and they did not make cylinders for concrete patches but rather for all other concrete works. The Dover, Delware, respondent said cylinders were used in bridge works, and the SureCure™ cylinder-mold system was used for pavement and patching works. Mississippi's DOT wrote, "MDOT has different compressive strength requirements based on the application associated. Concrete pavements require 17.24 MPa (2,500 psi) either by field-cured cylinder or maturity meter prior to opening to traffic. Bridge superstructure elements require various compressive strength requirements (per Table 6 in Standard Specification Subsection 804.03.15). Bridge decks may be opened to traffic (i.e., stop curing) at compressive strengths exceeding 75% of the lab trial strength used to validate the proportioning of the mixture. NB: This is not 75% of the required design strength)." The Ontario (Canada) respondent indicated "maturity [used] for fast-track pavement repair, due to the short time span of construction. Everything else is based on cylinders."

SATISFACTION LEVEL WITH THE CURRENT METHOD OF FIELD-CURE STRENGTH DETERMINATION

There were 22 respondents who were satisfied with the current method of determining when to remove formwork, while 5 respondents were not. One respondent (South Carolina) explained: "Not for field poured applications. Often, early-break cylinders are standard cured, because the early-break cylinders are made at the same time as the 28-day acceptance cylinders and all of them are placed in our curing room until testing." The respondent from Indiana was not satisfied because "INDOT has historically used beams for structural applications due to the field accessibility and portability of the Rainhart beam breakers. However, compressive strength is the parameter that needs [to be] determined and cylinders would be better. INDOT has active research at Purdue University to develop in situ sensors that directly measure the modulus of concrete and are then directly correlated to strength independent of the mix design. The research continues to show significant promise, and there is a high likelihood that the sensors will replace beams and cylinders in most applications. Overlays may be a challenge due to the thin depth." Iowa used beams because it is simpler to do so. They used "multiple beam-breakers for every construction office" and stated that "curing is an issue sometimes because they may take them to a trailer, etc., if it is cold overnight. Not really representative of the structure itself."

The Illinois Tollway respondent was somewhat satisfied with the current method of determining when to remove formwork. The respondent did not have problems using the field-cured cylinders but agreed that using the maturity method would be more efficient.

Furthermore, 24 out of 27 respondents were satisfied with the current method of determining when to open pavement or pavement patches, while Indiana (the same explanation was given to when formwork should be removed) and Tennessee were not satisfied because field curing of cylinders, especially early-age concrete, did not give them the most accurate strength results. Illinois Tollway was somewhat dissatisfied because they preferred the maturing method, though there were no major issues with the cylinders. Maine used rapid set materials for patches. Table 5, Figure 7, and Figure 8 explain the breakdown of states regarding their satisfaction levels with the current methods of field-cure strength determination.

Table 5. Breakdown of Various States' Satisfaction Levels with the Current Methods Used for Determining When to Remove Formwork or Falsework or Open Pavement to Traffic

	Agency uses a different criterion depending on the type of concrete mix (such as pavement, patching, or bridge superstructure)	Satisfied with the current method of determining when to remove falsework	Satisfied with the current method of determining when to open pavement or pavement patches
Yes	AR, DE (Dover), FL, IN, ME, MS, OH, Ontario (Canada), VA, WI	AR, CO, DE (Dover), FL, ID, KY, LA, MD, ME, MS, ND, NJ, NM, OH, Ontario (Canada), RI, SD, TN, UT, VA, WI, WV	AR, CO, DE, FL, IA, ID, KY, LA, Manitoba (Canada), MD, MS, NC, ND, NJ, NM, OH, Ontario (Canada), RI, SC, SD, UT, VA, WI, WV
	37.0% (10)	81.5% (22)	82.8% (24)
No	CO, DE, IA, ID, IL Tollway*, KY, LA, MD, NC, ND, NM, RI, SC, SD, TN, UT, WV	DE, IA, IL Tollway*, IN, SC	DE (Dover), IL Tollway*, IN, ME, TN,
	63.0% (17)	18.5% (5)	17.2% (5)

* The response was from IL Tollway only (not IDOT).

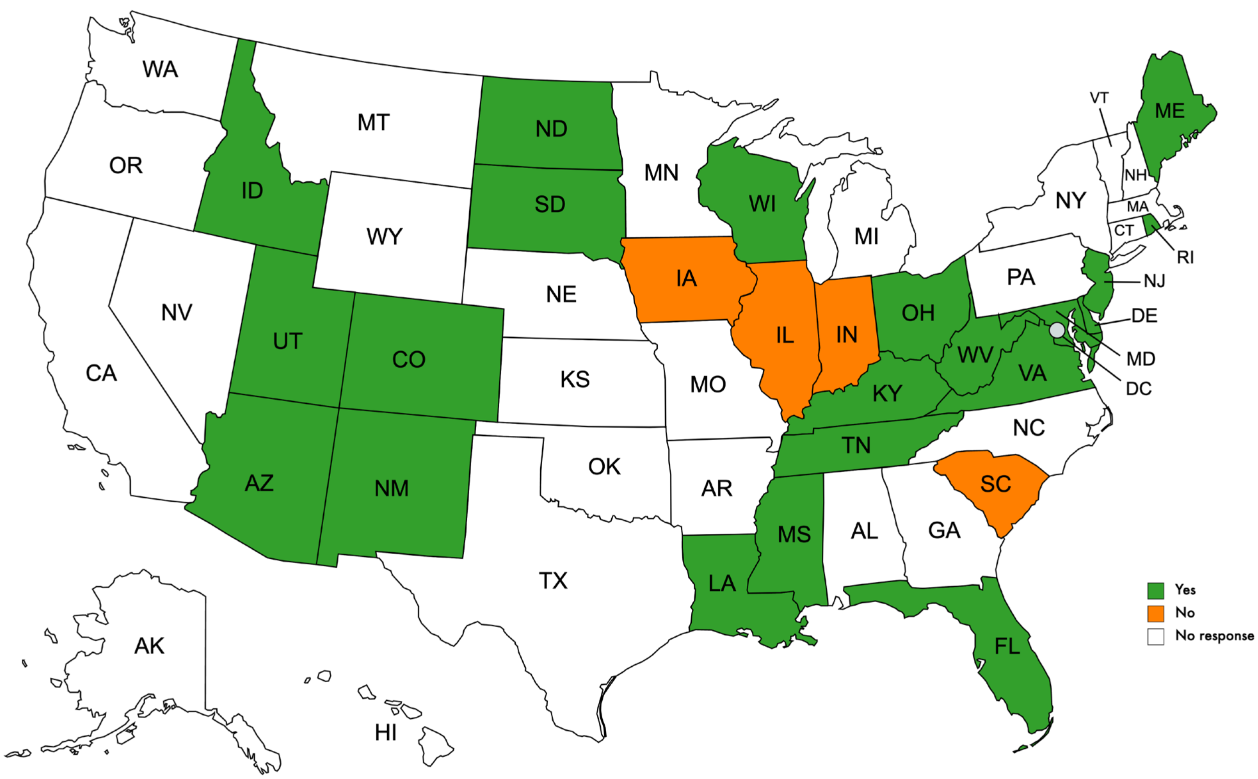


Figure 7. US Map. Satisfaction (Yes/No) of various US states with the current methods used for determining when to remove falsework. (The Illinois data is based on IL Tollway responses only.)

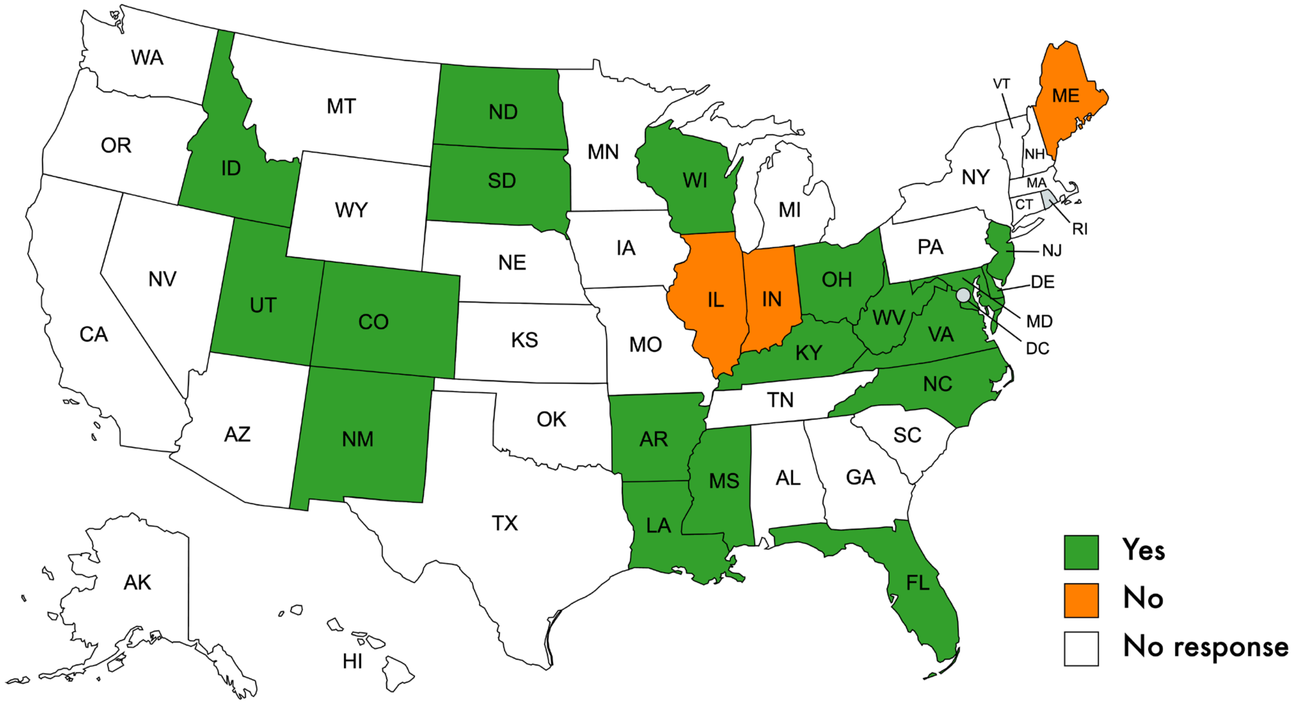


Figure 8. US Map. Satisfaction (Yes/No) of various US states with the current methods used for determining when to open pavement (including patches) to traffic. (The Illinois data is based on IL Tollway responses only.)

SIZE AND NUMBER OF FIELD-CURED CYLINDERS

In the survey, the research team asked questions related to the cylinders used for the opening of pavement (including patches) to traffic and how engineers decided when falsework or formwork could be removed. There were 24 respondents who gave the size of cylinders used for field curing, of which 14 respondents used only 100 × 200 mm only (4 × 8 in.), 3 used only 150 × 300 mm (6 × 12 in.), and 7 used both sizes. The data in Table 6 indicate the number or calculation method for 100 × 200 mm (4 × 8 in.) and 150 × 300 mm (6 × 12 in.) specimens.

Table 6. Number of Cylinder Breaks That Constitute a Test

Agency	Number or Calculation Method for 100 × 200 mm (4 × 8 in.) Cylinder	Number or Calculation Method for 150 × 300 mm (6 × 12 in.) Cylinder
AR	2	2
DE (Dover)	2 (7 days), 2 (28 days); unless asked for early breaks, then they will make more	NA
FL	Average of 3	NA
ID	2	2
IL	3	2
IL Tollway	NA	Average of 2
KY	3	2
LA	3	3
ME	Average of 2 not more than 10% different in strength	NA
MD	Average of 2	Average of 2
MN	6 (1 at 3 days, 1 at 5 days, 1 at 7 days, 1 at 14 days, and 2 at 28 days)	NA
MS	3	NA
ND	3	3
NH	1 for stripping or falsework removal and 2 (28 days) for acceptance	NA
NJ	Minimum of 2	NA
NM	Minimum of 2	NA
OH	2 for early breaks and 3 for acceptance	NA
Ontario (Canada)	6 cylinders for strength (3 acceptance–QA + 3 referee testing) 2 cores for AVS* (1 QA + 1 referee) 2 cores for RCP* (1 QA + 1 referee)	NA
SC	1 for early-break cylinders. With 28-day acceptance cylinders, 2 of the 3 cylinders making up the set are broken. If both achieve the required strength, the third is discarded. If one or both fail to reach the required strength, the third is tested and results of all three cylinders are averaged to get an average compressive strength.	Same as 4 × 6 in.
SD	NA	1
TN	2	2
UT	3	NA
VA	3	2
WI	NA	Average of 2
WV	3	3

* Concrete test methods such as Hardened Air Void Systems (AVS) and Rapid Chloride Permeability (RCP) testing. QA stands for quality assurance.

DEMOLDING TIME, CURING PERIOD, AND FIELD-CURING METHODS OF CYLINDERS

Respondents were also asked the number of days following casting when cylinder specimens were demolded. Out of 24 responses received in this section, 10 respondents said 24 hours (1 day), 2 said 48 hours (2 days), and 9 said at the time of testing. New Hampshire said it depended on when they got them, which could be a day or two. Ontario (Canada) said it depended on the application but usually 1 day, and Maryland stated as per the requirement of AASHTO T 23. Table 7 and Figure 9 explain how long a cylinder specimen is cured after being cast in every DOT.

Table 7. Demolding Time and Curing Period of Cylindrical Specimens Used by Various Agencies

Agency	Demolding Time	Curing Period After Casting
Arkansas	1 day (24 hours)	24 hours or less for very early high-strength patching 7 and 28 days for normal patching projects 7 days for removal of falsework 28 days for all concrete applications, including opening a structure to traffic
Delaware (Dover)	1 day (24 hours)	It's cured in a fog room until it is broken.
Florida	At the time of testing	24 to 48 hours for most mixes. High-strength early mixes are demolded at the time of testing (e.g., 6 hours), and extended set mixes can be demolded at 48 hours or 72 hours
Idaho	At the time of testing	We cure them based on the amount of time needed. For 7-day breaks, we cure 7 days; for 28-day breaks, we cure 28 days.
Illinois	If form work is removed, remove test specimens from their molds.	Depends on the situation calling for field curing (e.g., opening new pavement, opening a patch, deck pour sequence) and how likely the specific mix design is expected to achieve the required strength.
Illinois Tollway	At the time of testing	It is cured until it is tested. The specific time depends on the application.
Kentucky	At the time of testing	The time required to obtain the information necessary for the placement.
Louisiana	At the time of testing	Most cylinders can be kept in a moist condition prior to testing. Cylinders may be kept outside of the moist room for up to 3 hours prior to testing by covering the cylinders with the moist absorbent fabric in an environment between 20°C and 30°C (68°F and 86°F).
Maine	At the time of testing	It is field cured for as long as is needed for testing. Typically, up to 7 days.

Agency	Demolding Time	Curing Period After Casting
Maryland	None As required per AASHTO T 23	Until the time of testing
Minnesota	1 day (24 hours)	1 at 3 days, 1 at 5 days, 1 at 7 days, 1 at 14 days, and 2 at 28 days (occasionally, 56 days)
Mississippi	At the time of testing	Until the time of testing
New Hampshire	None It depends when we get them, usually a day or two	Depends on when we get them, usually 28 days plus or minus a couple of days
New Jersey	1 day (24 hours)	Most mixes are tested at 28 days; high performance concrete (HPC) is tested at 56 days
New Mexico	1 day (24 hours)	NA
North Dakota	1 day (24 hours)	Length is based on specifications.
Ohio	At the time of testing	Up to 72 hours for initial cure, due to weekends and holidays; after that, they should be in the final curing environment, be it a tank or a room at the required temperatures until the 28-day break.
Ontario (Canada)	None Typically, 1 day but depends on the application. Early-age strength determination less than 1 day	Typically, 28 days; depends on the application
South Carolina	2 days (48 hours)	Until it is supposed to be tested.
South Dakota	1 day (24 hours)	Other than demolding, the entire time until testing
Tennessee	At the time of testing	Until testing
Utah	1 day (24 days)	28 days
Virginia	2 days (48 hours)	It depends on what day-break we are looking for. For 28-day breaks, specimens are cured up until they are 28 days past cast.
West Virginia	1 day (24 hours)	Acceptance cylinders are field-cured for 24 plus or minus 8 hours, then lab cured until they are 28-days old (i.e., time of test). Field-cured cylinders are left to cure in the field until the time of the test.
Wisconsin	At the time of testing	Field-cured cylinders are cured with the concrete element being represented until removal for testing.

New Mexico and Manitoba did not provide an answer for how long cylinder specimens should be cured after being cast during the survey, though they used cylinders for field-cured specimens. Therefore, their answers are not included in Table 7 or Figure 9 (with responses showing the period after which a cylinder specimen is de-molded during field curing).

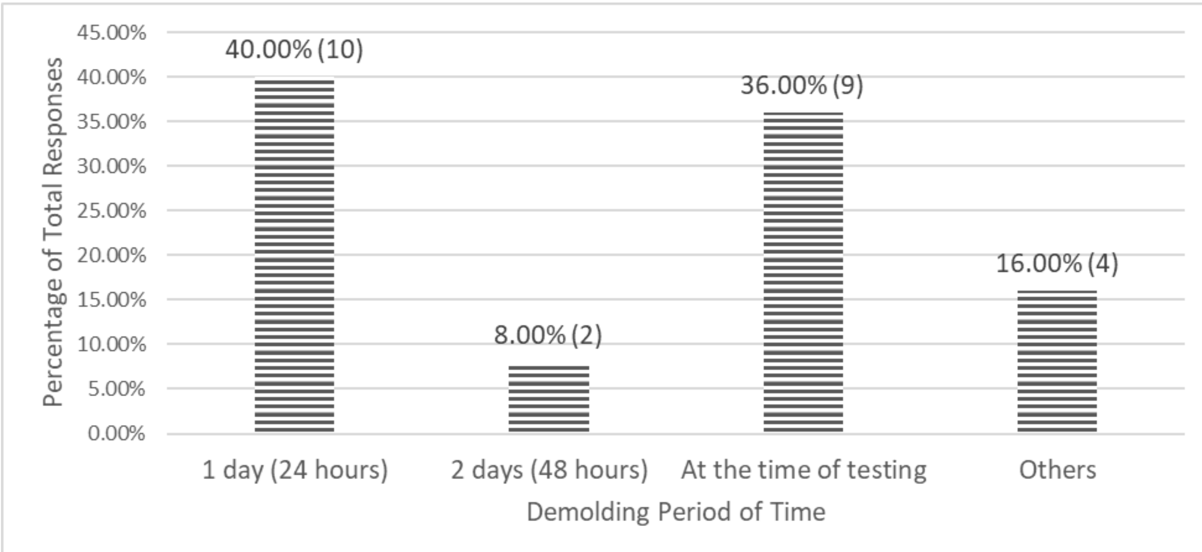


Figure 9. Histogram. Demolding time after field-cured cylindrical specimens were cast or finished (25 respondents).

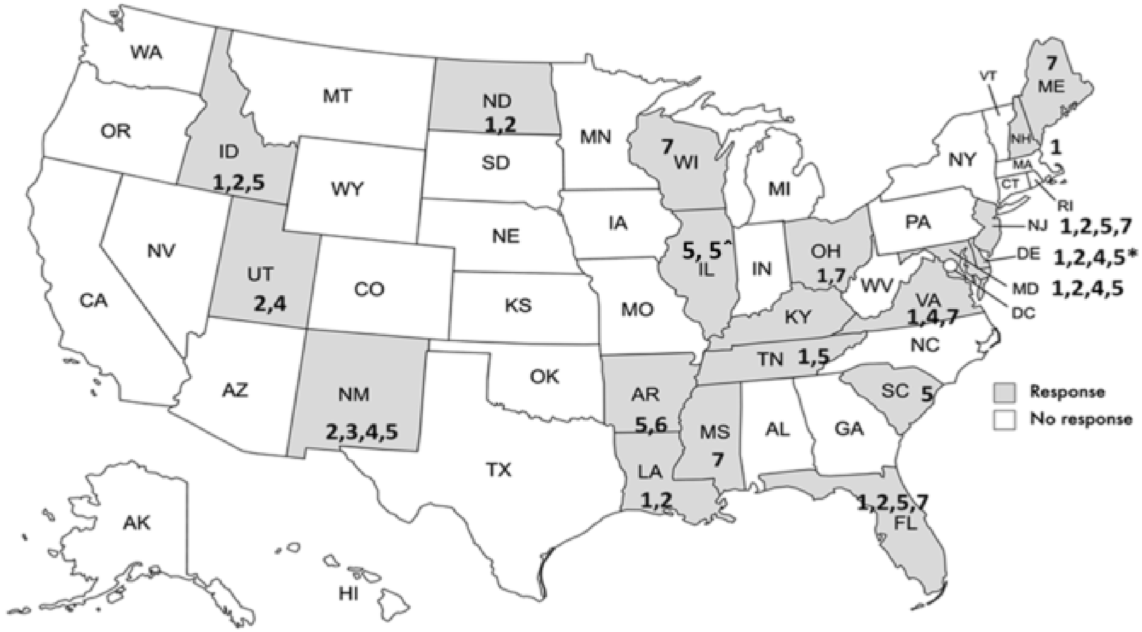
Twenty-four respondents answered the question about how a specimen was field cured. Table 8, Figure 10, and Figure 11 summarize their responses.

Table 8. Field-curing Methods of Cylindrical Specimens Used by Various Agencies

States	How Cylinder Specimen Is Field Cured	Comments
Arkansas	• Under burlap or insulation near the item/structure poured • Other (preferably on the structure instead of nearby)	ARDOT does not make or test beams; therefore, the respondent is neutral on the comparison to cylinders.
Delaware (Dover)	• Ambient air on the site near the item/structure poured • In an insulated box with other specimens (gang-cured) near the item/structure poured • Thermostatically controlled curing box (power-operated) • Under burlap or insulation near the item/structure poured	NA
Florida	• Ambient air on the site near the item/structure poured • In an insulated box with other specimens (gang-cured) near the item/structure poured • Under burlap or insulation near the item/structure poured • Other (Acceptance cylinders are cured per ASTM C31, curing box then transported to the lab. Opening-to-traffic test specimens are placed alongside the structure.)	NA
Idaho	• Ambient air on the site near the item/structure poured • In an insulated box with other specimens (gang-cured) near the item/structure poured • Under burlap or insulation near the item/structure poured	The field-cured cylinders are typically done for validating the maturity curve. These are supposed to be cured in the same manner as the cylinders that are used to develop the maturity curve.
Illinois	• After initial curing, field cylinders are cured in the same manner as the item placed, often on the pavement and under the same insulating blanket as the pavement. Field-cured cylinders are picked up from the site and tested on the same day.)	NA
Illinois Tollway	• Other (Initial curing follows Illinois-modified AASHTO T 23. After initial curing, field cylinders are cured in the same manner as the item placed. Cylinders are oriented on their side underneath protection. Field-cured cylinders are picked up from the site and tested on the same day.)	NA
Kentucky	• Ambient air on the site near the item/structure poured	NA
Louisiana	• Ambient air on the site near the item/structure poured • In an insulated box with other specimens (gang-cured) near the item/structure poured	NA

States	How Cylinder Specimen Is Field Cured	Comments
Maine	• Other (The cylinder is cured under the same conditions that the placement is.)	NA
Maryland	• Ambient air on the site near the item/structure poured • In an insulated box with other specimens (gang-cured) near the item/structure poured • Thermostatically controlled curing box (power-operated) • Under burlap or insulation near the item/structure poured	NA
Manitoba (Canada)	• Ambient air on the site near the item/structure poured • In an insulated box with other specimens (gang-cured) near the item/structure poured • Other (cylinders capped with plastic cap)	Cylindrical core specimens are sometimes taken to confirm in situ strength. A minimum of 24 MPa (3481 psi) strength is required before opening to traffic.
Mississippi	• Other ("in a manner that represents the structure, in as much as that is possible, and in no manner that would be more "favorable" than which is experienced by the structure")	NA
New Hampshire	• Ambient air on the site near the item/structure poured	NA
New Jersey	• Ambient air on the site near the item/structure poured • In an insulated box with other specimens (gang-cured) near the item/structure poured • Under burlap or insulation near the item/structure poured • Other (During the summer months, water-cured for the initial 24 hours on the jobsite. In a tub. Most contractors provide a cooler.)	"Early break" cylinders are cured on the jobsite as close as possible to the concrete item and under the same curing conditions as the item. Acceptance=test cylinders are picked up from the jobsite after the initial 24-hour cure and then are cured in the lab for the remainder of the time.
New Mexico	• In an insulated box with other specimens (gang-cured) near the item/structure poured • Damp sandpit near the item/structure poured • Thermostatically controlled curing box (power-operated) • Under burlap or insulation near the item/structure poured	NA
North Dakota	• Ambient air on the site near the item/structure poured • In an insulated box with other specimens (gang-cured) near the item/structure poured	NA
Ohio	• Ambient air on the site near the item/structure poured	NA

States	How Cylinder Specimen Is Field Cured	Comments
	• Other (on or as near to the placement as possible and with the same curing method, e.g., wet burlap, curing compound)	
South Carolina	• Under burlap or insulation near the item/structure poured	NA
South Dakota	• In an insulated box with other specimens (gang-cured) near the item/structure poured, • Under burlap or insulation near the item/structure poured	NA
Tennessee	• Ambient air on the site near the item/structure poured • Under burlap or insulation near the item/structure poured	NA
Toronto (Canada)	• In an insulated box with other specimens (gang-cured) near the item/structure poured • Thermostatically controlled curing box (power-operated) • Under burlap or insulation near the item/structure poured • Insulated cylinder mold	NA
Utah	• In an insulated box with other specimens (gang-cured) near the item/structure poured • Thermostatically controlled curing box (power-operated)	NA
Virginia	• Ambient air on the site near the item/structure poured • Thermostatically controlled curing box (power-operated) • Under burlap or insulation near the item/structure poured	NA
West Virginia	• Other (Field-cured cylinders are cured in as similar a manner as possible to that of the structure they represent. For example, if representing a pavement patch that is cured with an insulated blanket, then the cylinders would also be cured under an insulated blanket.)	The agent recently approved a specification change to require cylinders representing concrete that is to be opened to traffic in less than 8 hours to be cured in a "match-cure" box.
Wisconsin	• Under burlap or insulation near the item/structure poured	NA



1. Ambient air on the site near the item/structure poured;
2. In an insulated box with other specimens (gang-cured) near the item/structure poured;
3. Damp sandpit near the item/structure poured;
4. Thermostatically controlled curing box (power-operated);
5. Under burlap or insulation near the item/structure poured;
6. Insulated cylinder mold;
7. Other

(IL-5: The response is from IL DOT; IL-5^: The response is from IL Tollway;
DE-5*: The response is from Delaware (Dover))

Figure 10. US Map. Field-curing methods for cylindrical specimens by various US states.

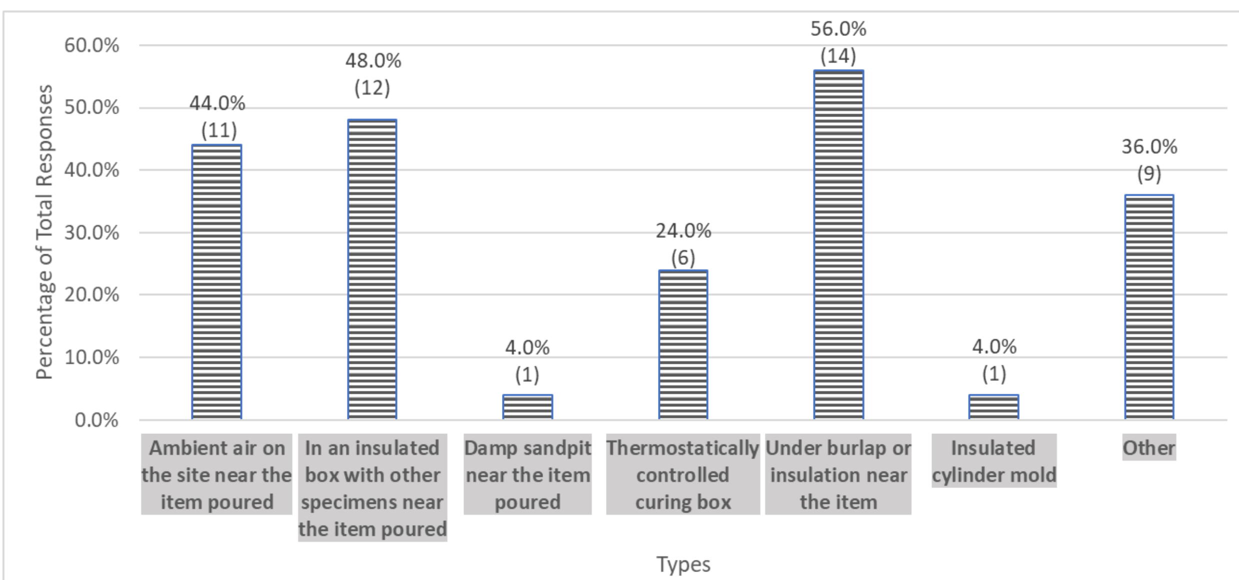


Figure 11. Histogram. Percentage of agencies using various field-curing methods for cylindrical specimens (25 respondents).

SIZE AND NUMBER OF FIELD-CURED BEAMS

The research team asked questions related to beams used for the opening of pavement (including patches) to traffic sooner, as well as in deciding when falsework or formwork could be removed. Six respondents used beams for the opening of pavement and deciding when falsework could be removed. Among them, five respondents (the DOTs of Illinois [IL DOT], Indiana, Iowa, Louisiana, and Ohio) used 150 × 150 × 500 mm (6 × 6 × 20 in.) beams, two respondents (IL DOT and ND DOT) used 150 × 150 × 760 mm (6 × 6 × 30 in.), one respondent (NJ DOT) used 150 × 150 × 530 mm (6 × 6 × 21 in.) beams. Additionally, Ohio used 150 × 150 × 1,000 mm (6 × 6 × 40 in.) beams to obtain three possible breaks, depending on the failure location of the first and second breaks. Iowa used 100 × 100 × 100 mm (4 × 4 × 4 in.) beams in addition to the 150 × 150 × 500 mm (6 × 6 × 20 in.) beams. The data in Table 9 show the details of the calculation methods used by each of these respondents. It was noticed that the information presented in Table 9 is different than Table 2, which was summarized from information available in the open literature.

Table 9. Size and Number of Beams Used for Field Curing Based on Survey Responses

States	Number of 150 × 150 × 500 mm (6 × 6 × 20 in.) Beams Used	Other Sizes and Numbers of Beams Used
Illinois	2 beams	150 × 150 × 760 mm (6 × 6 × 30 in.), 2 break per beam
Indiana	INDOT typically makes 3 to 6 beams for a pour. Only a single passing break from one beam is required.	NA
Iowa	2 beams	NA
Louisiana	2 beams	NA
New Jersey	NA	150 × 150 × 530 mm (6 × 6 × 21 in.), 2 beams
North Dakota	NA	150 × 150 × 760 mm (6 × 6 × 30 in.), 2 beams
Ohio	2 beams	NA

DEMOLDING TIME, CURING PERIOD, AND FIELD-CURING METHODS OF BEAMS

Four of the 7 respondents said that beam specimens were demolded after 24 hours, while 3 said that the specimens were demolded at the time of testing. The data in Table 10 and Figure 12 show the breakdown of the 7 responses. Table 11, Figure 13, and Figure 14 explain how a beam specimen is field cured.

Table 10. Demolding Time and Curing Period of Beams Used by Various Agencies

States	Days after Which a Beam Specimen Is Demolded	Curing Period
Illinois	At the time of testing	Cured until time of testing in the same manner as the item poured.
Indiana	1 day (24 hours)	Curing continues until the target strength is achieved.
Iowa	1 day (24 hours)	Forms for roofs of culverts may be removed when the concrete has attained an age of 3 calendar days and flexural strength of 2.41 MPa (350 psi) for spans of 1.23 meters (4 ft) or less, 2.76 MPa (400 psi) for 1.23m < span <= 1.83m (4 < span <= 6 ft), and·3.10 MPa (450 psi) for spans exceeding 1.83m (6 ft). Except when form removal is permitted in less than 5 calendar days, forms may be removed as soon after 5 calendar days as the concrete has attained the strength required**.**
Louisiana	1 day (24 hours)	Under most conditions until time of test
New Jersey	At the time of testing	NA
North Dakota	1 day (24 hours)	Length is based on specifications.
Ohio	At the time of testing	Cured until time of testing in the same manner, either by burlap, heated enclosure, or curing compound

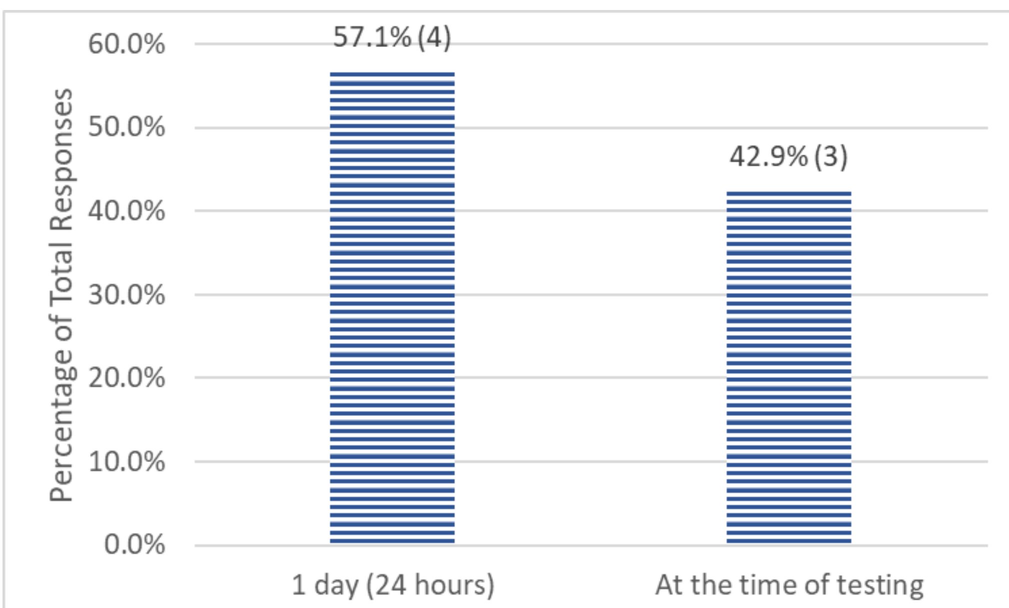
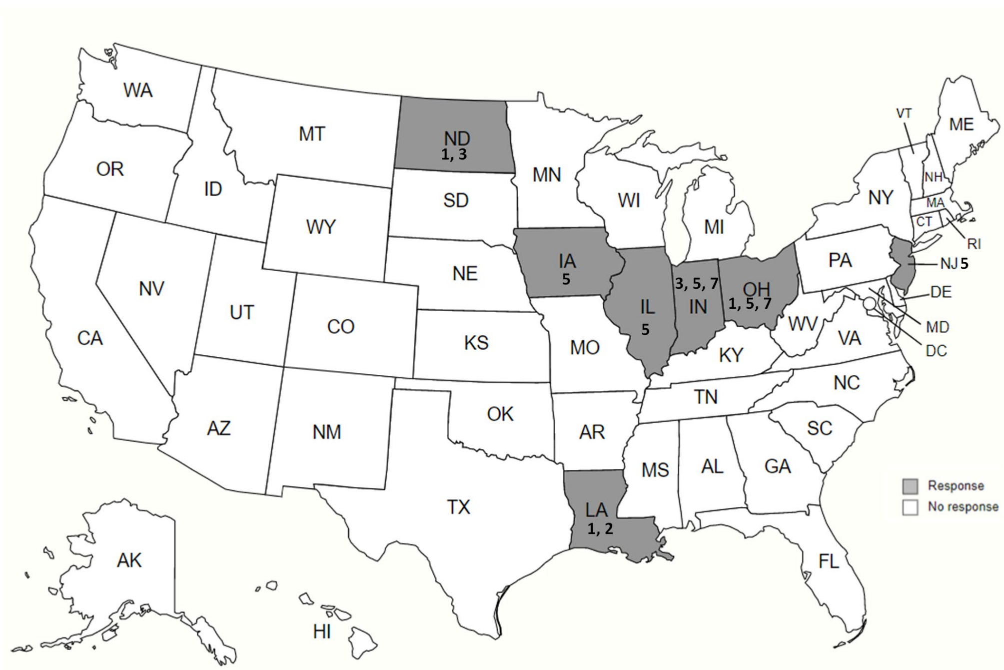


Figure 12. Histogram. How long after casting test beams agencies wait to demold them. (7 respondents; related to Table 10).

Table 11. Methods Used by Various Agencies to Field-Cure Beams

States	How is a beam specimen field cured?
Illinois	• Under insulation near the item/structure poured
Indiana	• Damp sandpit near the item/structure poured • Under burlap or insulation near the item/structure poured • Other. (For structural decks, caps, or piers, the specimen is on the deck (or caps, piers, etc.) under the curing material used on the deck (or caps, piers, etc.))
Iowa	• Under burlap or insulation near the item/structure poured
Louisiana	• Ambient air on the site near the item/structure poured • Curing box
New Jersey	• Under burlap or insulation near the item/structure poured
North Dakota	• Ambient air on the site near the item/structure poured • Damp sandpit near the item/structure poured
Ohio	• Ambient air on the site near the item/structure poured • Under burlap or insulation near the item/structure poured • Other (Typically in the same manner as the concrete it represents; in a heated enclosure if provided for item represented, or with a curing compound)



1. Ambient air on the site near the item/structure poured;
2. In an insulated box with other specimens (gang-cured) near the item/structure poured;
3. Damp sandpit near the item/structure poured;
4. Thermostatically controlled curing box (power-operated);
5. Under burlap or insulation near the item/structure poured;
6. Insulated cylinder mold;
7. Other

Figure 13. US Map. Field-curing methods used for beams by various US states (related to Table 11).

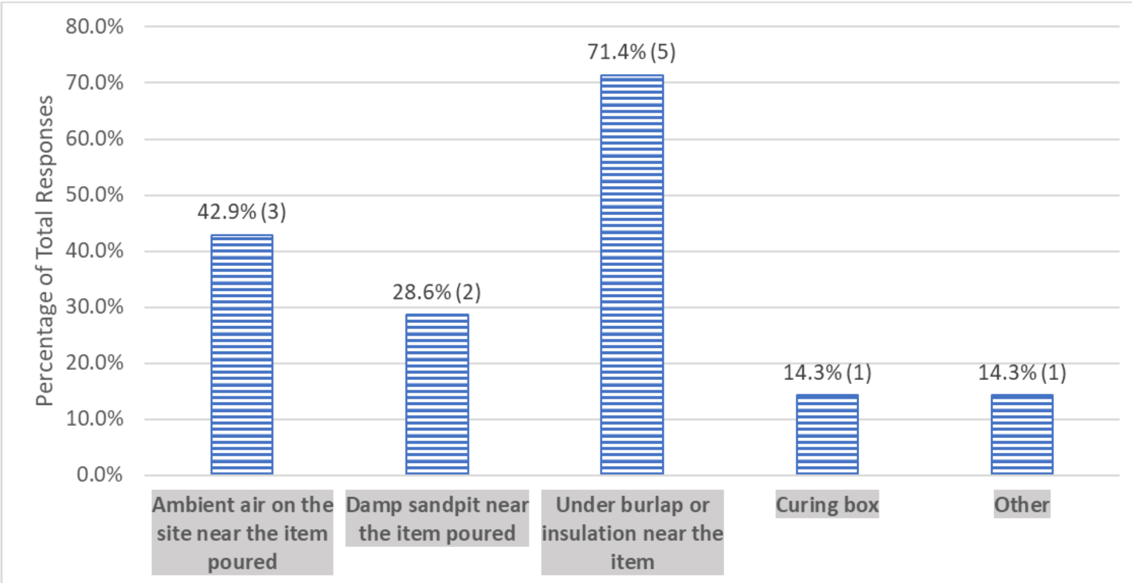


Figure 14. Histogram. Percentage of agencies using various field-curing methods for beams (7 respondents; related to Table 11).

METHOD OF KEEPING TRACK OF CONCRETE CURING AND PRIMARY CONCERN

To conclude the survey, all respondents were asked how they kept track of concrete curing; answer choices were provided to the respondents. There were 29 valid responses received for this section, out of which 10 respondents used only field reports, 8 used field reports and concrete-temperature data (embedded sensors), 2 used three methods (field reports, concrete-temperature data, and weather data), and the rest used more than three methods.

Moreover, 17 respondents said that the learning curve was their primary concern regarding a possible new curing method, while 4 respondents considered cost as their primary concern. Six respondents also stated other reasons such as reliability (Utah), the effectiveness of the methods (Indiana and Illinois), cost–benefit (Illinois Tollway), cost and construction schedule (Florida), and accuracy of the representation of the in-situ strength of the concrete element (Wisconsin). Respondents from New Hampshire and Arkansas did not respond to this question.

Finally, the Colorado respondent considered sensors as a new technology that could help field curing of concrete. The Ohio respondent also indicated that maturity, calorimetry, and curing cubes were new technologies that could help field curing of concrete. Ontario (Canada) replied “live temperature monitoring using wireless sensors with cloud access, and wireless match-curing system” to this question. Louisiana noted training and techniques for the maturity meter can help the field curing of concrete. The respondent from New Mexico stated: “I’d like to see better / increase accuracy / reliability / advances in ‘match-curing’ equipment. I think matching curing potentially could offer higher confidence levels if the lag time between adjusting test specimen internal temperature and in-place concrete temperature.” The respondent from Manitoba (Canada) stated: “Admixtures, supplementary cementitious material, internal curing, high-early-strength cement, moisture curing and proper application of curing compound, hot mixing water [in cold weather], heated aggregates [in cold weather] and use of heater [in cold weather]" were new technologies that could help the field curing of concrete. Table 12 shows the breakdown of the responses by how their agencies keep track of concrete and their primary concern regarding a possible new curing method.

Table 12. Method(s) of Keeping Track of Concrete Curing and Primary Concern(s) of Various Agencies Regarding a Possible New Method

Name	Method(s)	Primary Concern(s) Regarding a Possible New Curing Method
Arkansas	• Field reports • Weather data • Concrete temperature data (e.g., embedded sensors)	NA
Colorado	• Field reports • Concrete temperature data (e.g., sensors)	Learning curve
Delaware	• Field reports	Learning curve
Delaware (Dover)	• Field reports	Learning curve
Florida	• Field reports • Concrete temperature data (e.g., embedded sensors)	Cost, construction schedule, impact to the public, lane closures/Ministry of Transport (M.O.T)
Idaho	• Field reports • Concrete temperature data (e.g., sensors)	Learning curve
Illinois	• Field reports • Concrete temperature data (e.g., embedded sensors)	Cost, effectiveness, learning curve
Illinois Tollway.	• Photo • Field reports • Weather data • Concrete temperature data (e.g., embedded sensors) • Emails	Cost–benefit: Evaluate the benefits of the new method, check if the benefits outweigh any additional equipment, labor, and education costs.
Indiana	• Field reports • Other (INDOT uses the AASHTO program Site Manager for electronic record keeping.**)**	Effectiveness of the method
Iowa	• Concrete temperature data (e.g., sensors)	Cost
Kentucky	• Field reports	Learning curve
Louisiana	• Field reports • Concrete temperature data (e.g., sensors)	Learning curve

Name	Method(s)	Primary Concern(s) Regarding a Possible New Curing Method
Maine	• Field reports • Concrete temperature data (e.g., embedded sensors)	Learning curve
Manitoba (Canada)	• Photo • Field reports • Weather data • Concrete temperature data (e.g., embedded sensors) • Emails	Learning curve
Mississippi	• Field reports	NA
Maryland	• Field reports	Learning curve
North Dakota	• Field reports	Cost
New Hampshire	• Field reports	NA
New Jersey	• Field reports • Other (High–low thermometer)	Cost
New Mexico	• Field reports • Weather data • Concrete temperature data (e.g., embedded sensors)	Learning curve
North Carolina	• None	Learning curve
Ohio	• Field reports • Other (High–low thermometers in the coolers. Sometimes the initial curing is done with buckets and water to store 3 cylinders. Contractors are responsible for cure boxes for QC and QA cylinders. Field breaks are stored with the item they represent.)	Learning curve
Ontario (Canada)	• Photo • Field reports • Weather data • Concrete temperature data (e.g., embedded sensors) • Emails	Other (learning curve, accuracy, effectiveness, limitations)
South Carolina	• Field reports	Learning curve
Tennessee	• Field reports	Learning curve

Name	Method(s)	Primary Concern(s) Regarding a Possible New Curing Method
Virginia	• Photo • Field reports • Weather data • Concrete temperature data (e.g., embedded sensors) • Emails	Learning curve
Utah	• Field reports • Concrete temperature data (e.g., embedded sensors)	Other (reliability)
West Virginia	• Field reports • Concrete temperature data (e.g., embedded sensors) • Emails	Learning curve
Wisconsin	• Field reports	Other

SUMMARY OF SURVEY FINDINGS

Based on the survey results presented in this report, the following conclusions can be made regarding the field-curing practices for concrete specimens:

- The survey data in Table 4 revealed that most transportation agencies use field-cured cylinders (22 out of 32, 68.8%), followed by the maturity method (16 out of 32, 50.0%), for deciding the time to open a pavement to traffic. Only 5 out of 32 agencies (15.6%) use beams for the opening of pavement to traffic. Note that several agencies (17 out of 32, 53%, as shown in Figure 3) use more than one method for deciding when to open pavement to traffic sooner.

- The survey data in Table 4 also revealed that most transportation agencies use field-cured cylinders (22 out of 31, 71.0%), followed by the maturity method (12 out of 31, 38.7%), for deciding when to remove formwork or falsework. Additionally, 7 out of 31 agencies (22.6%) use beams for deciding when to remove formwork or falsework. Note that several agencies (14 out of 31, 45.0%, as shown in Figure 4) use more than one method for deciding when to remove formwork or falsework.

- Other field-curing technologies used by agencies are match curing (e.g., West Virginia in Table 9 and the survey responses from Ontario, Canada, and New Mexico in regarding the methods of keeping track of concrete curing) and the SureCure™ (e.g., the survey response from Dover, Delaware) cylinder mold system.

- According to the survey responses shown in Table 5, only 10 out of 27 responses (37.0%) agreed with using a different criterion or testing method, depending on the type of the concrete mix, such as patching, pavement, and bridge superstructure. Most transportation agencies (17 out of 27, 63.0%) use the same field-curing testing method irrespective of the type of concrete mix.

- According to the survey responses shown in Table 5, a majority of the transportation agencies were found to be satisfied with the current method used for determining when to open a pavement to traffic (22 out of 27, 81.5%) or remove formwork or falsework (24 out of 29, 82.8%). One of the major concerns among agencies dissatisfied with the current method was the curing procedure, which is not a real representation of the structure itself. For example, Connecticut DOT had such a concern (Henault, 2007).

- According to the survey responses shown in Table 6, the most common field-cured cylinder size used by the transportation agencies is 100 × 200 mm (4 × 8 in.) (22 out of 25, 88%), followed by 150 × 300 mm (6 × 12 in.) (14 out of 25, 56%). A total of 8 out of 25 respondents (32%) use both 100 mm (4 in.) and 150 mm (6 in.) cylinders for field curing. Some of the agencies stated a desire to completely transition from 150 mm (6 in.) to 100 mm (4 in.) cylinders for field curing in coming years. The number of field-cured 100 × 200 mm (4 × 8 in.) and 150 × 300 mm (6 × 12 in.) cylinders tested varied from one to three; however, most responses were in favor of three for the smaller 100 × 200 mm (4 × 8 in.) cylinders and two for the larger 150 × 300 mm (6 × 12 in.) cylinders.

- The survey responses in Table 6 demonstrated that some respondents provided curing-duration information of standard-cured specimens in place of field-cured specimens. However, some respondents clearly explained the curing duration of standard-cured as well as field-cured specimens. In general, field-cured cylinders are cured along with the concrete element being represented until the time of testing. The specific time depends on the application but typically up to 7 days.

- Based on the survey results shown in Figure 11, most of the agencies selected a combination of more than one curing technique for field-cured cylinders. Specifically, 11 out of 25 responses (44%) were found in favor of curing in ambient air on the site near the concrete item represented. Furthermore, 12 out of 25 (48%) and 6 out of 25 responses (24%) selected gang curing in an insulated box or power-operated box, respectively. Most responses (14 out of 25, 56%) were also in favor of curing cylinders under burlap or insulation near the concrete structure represented. The methods of (1) curing of cylinders in an insulated box and (2) power-operated box near the structure under burlap or insulation were often used together, which were found to be the most popular field-curing technique combination among transportation agencies surveyed in this study.

- Based on the data shown in Table 9, Illinois DOT uses both 150 × 150 × 500 mm (6 × 6 × 20 in.) beams and 150 × 150 × 760 mm (6 × 6 × 30 in.) for field curing. Ohio DOT uses 150 × 150 × 500 mm (6 × 6 × 20 in.) beams for field curing and testing; and 150 × 150 × 1,000 mm (6 × 6 × 40 in.) beams to obtain three possible breaks, depending on the failure location of the first and second breaks. Iowa DOT uses 150 × 150 × 500 mm (6 × 6 × 20 in.) beams and 100 × 100 × 100 mm (4 × 4 × 4 in.) beams for field curing and testing. The state DOTs in Indiana and Louisiana use the 150 × 150 × 500 mm (6 × 6 × 20 in.) beams. The New Jersey DOT uses 150 × 150 × 530 mm (6 × 6 × 21 in.) beams. The state DOT in North Dakota uses 150 × 150 × 760 mm (6 × 6 × 30 in.) beams. A total of 5 out of 7 respondents (71.4%) selected the 150 × 150 × 500 mm (6 × 6 × 20 in.) beam for field curing. Moreover, all responses except Indiana DOT were in favor of using two beams for field curing.

- Survey results in Figure 12 show that responding agencies (4 out of 7, 57.1%) prefer demolding beams after 1 day (24 hours), and the remaining three responses prefer demolding at the time of testing.
- Based on the survey results shown in Figure 14, 5 out of 7 (71.4%) responses indicated to place beams under burlap or insulation near the concrete item for the field curing method. The damp-sandpit method near the concrete item was selected by 2 out 7 (28.6%) responding agencies. Even though three agencies selected curing in ambient air on the site near the concrete item, that method was not used alone. The ambient-air curing method was used in combination with other methods, such as placing the beams under burlap/insulation or the damp sandpit method.
- The survey data shown in Table 12 indicates that most agencies (17 out of 29, 58.6%) reported the learning curve as the primary concern regarding a possible new curing method. A few other concerns were cost, effectiveness, reliability, and accuracy of the new method.
- New technologies of interest, as indicated by agencies in the comments of Table 12, were piezoelectric sensors, the maturity method, calorimetry, and the match-curing system.

CHAPTER 5: CONCLUSIONS

This study involved a literature review and a survey of state transportation agencies to assess the current state of the practice for field-curing methods of concrete specimens. The major findings of this effort follow:

- Both the literature review and survey results indicated that most transportation agencies use field-cured cylinders, followed by the maturity method, for deciding when to open a pavement to traffic or remove formwork or falsework.
- Both 100 × 200 mm (4 × 8 in.) and 150 × 300 mm (6 × 12 in.) sizes of field-cured cylinders are commonly used by transportation agencies. For beams, both literature and survey results showed 150 × 150 × 500 mm (6 × 6 × 20 in.) as one of the most commonly used beam sizes for field curing.
- The most commonly used field-curing method found among transportation agencies was placing the test specimens near the cast concrete and protecting them in the same manner as the concrete items represented. Specifically, cylinders are mostly field cured in an insulated box or under burlap/insulation near the concrete item. In contrast, beams are mostly field cured in a damp sandpit or under burlap/insulation near the concrete item.
- The curing period was found to depend on the time of formwork or falsework removal determination or pavement opening to traffic, as well as the type of mix.
- Other field-curing technologies used/explored by agencies are match curing, SureCure™ cylinder-mold system, piezoelectric sensors, calorimetry, and penetration-resistance tests.

REFERENCES

Alabama Department of Transportation (2012). *Portland Cement Concrete Pavement. Section 450.* Alabama Department of Transportation. Retrieved from https://www.dot.state.al.us/conweb/pdf/Specifications/2012%20GASP%20Summary/12-0152.pdf

Cable, J., Wang, K., & Ge., Z. (2003). *Investigation into improved pavement curing materials and techniques: Part 2 (Phase III)* (Report No. Iowa DOT TR-479). Center for Portland Cement Concrete Pavement Technology. Iowa Department of Transportation. Retrieved from https://intrans.iastate.edu/app/uploads/2018/03/curing2final.pdf

Calmetrix (2021). *Calorimetry applied to cement & concrete technology*. Retrieved from https://www.calmetrix.com/calorimetry-for-cement-and-concrete

Caltrans (2013). *Method of test for flexural strength of rapid strength concrete*. California Test 524. California Department of Transportation. Retrieved from https://dot.ca.gov/-/media/dot-media/programs/engineering/documents/californiatestmethods-ctm/ctm-524-a11y.pdf

Colorado Department of Transportation (2019). *Chapter – 600: Concrete & Item 600 – 19, 2019 Field Materials Manual*. Colorado Department of Transportation.

Delaware Department of Transportation (2016). *Standard specification of road and bridge construction*. Delaware Department of Transportation. Retrieved from https://deldot.gov/Publications/manuals/standard_specifications/pdfs/2016/2016_standard_specifications_08-2016.pdf

Federal Highway Administration (2021). *Monitoring concrete consistency using semi-adiabatic calorimetry*. Retrieved from https://www.fhwa.dot.gov/pavement/concrete/field.cfm

Florida Department of Transportation (2021). *Standard specifications for road and bridge construction*. Florida Department of Transportation.

Freeseman, K., Hoegh, K., & Khazanovich, L. (2016). *Concrete strength required to open traffic* (MN/RC 2016-01). Minnesota Department of Transportation, Office of Transportation System Management. Retrieved from http://www.dot.state.mn.us/research/TS/2016/201601.pdf

Georgia Department of Transportation (2016). *Making and curing concrete compression and flexure test specimens in the field*. GDT 35. Georgia Department of Transportation. Retrieved from http://www.dot.ga.gov/PartnerSmart/Business/Source/gdt/gdt035.pdf

Henault, W. J (2007). *Assessing ConnDOT's Portland cement concrete (PCC) testing methods* (Report No. 2244-F-06-8). Connecticut Department of Transportation.

Illinois Department of Transportation (2016). *Standard specifications for road and bridge construction*. Illinois Department of Transportation.

Illinois Department of Transportation (2019). *Manual of test procedures for materials*. Illinois Department of Transportation. Retrieved from https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Materials/Manual%20of%20Test%20Procedures%20for%20Materials%20December%202019.pdf

Illinois Tollway (2020). *Quality control/quality assurance of concrete mixtures*. Illinois State Toll Highway Authority.

Indiana Department of Transportation (2020). *Standard specifications*. Indiana Department of Transportation. Retrieved from https://www.in.gov/dot/div/contracts/standards/book/sep19/sep.htm

ITM 402 (2020). *Strength of Portland cement concrete pavement (PCCP) using the maturity method utilizing the time temperature factor methodology*. Indiana Department of Transportation, Office of Materials and Management. Retrieved from https://www.in.gov/indot/div/mt/itm/pubs/402_testing.pdf

Johnson, R., & Hosten, A. M. (2011), *Implementation of the concrete maturity meter for Maryland* (Report No. MD-11-SP708B4K). Maryland Department of Transportation.

Kansas Department of Transportation (2012). *Making and curing compression and flexural test specimens in the field (Kansas Test Method KT-22).* Construction Manual. Kansas Department of Transportation. Retrieved from https://www.ksdot.org/Assets/wwwksdotorg/bureaus/burConsMain/Connections/ConstManual/2012/KT-22.pdf

Krstulovich, J. M. (2021). Concrete Research Engineer, Illinois Department of Transportation, personal communication, February 1, 2021.

Louisiana Department of Transportation (2019). *Method of test for making, field-curing and transporting concrete test specimens*. Louisiana Department of Transportation and Development. DOTD TR 226. Retrieved from http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Materials_Lab/TPM_Vol_I_Part_II/TR%20226%20(9-6-19).pdf

Lu, N., & Su, Y. (2020). "When Can I Get My Concrete Project Going?" *Roads and Bridges*, April 2020. Retrieved from https://www.roadsbridges.com/real-time-sensing-technology-can-help-determine-concrete-strength-and-construction-schedules

Maine Department of Transportation (2020). *Division 500—Structures*. Maine Department of Transportation. Retrieved from https://www.maine.gov/mdot/contractor-consultant-information/ss_division_500.pdf

Manitoba Infrastructure and Transportation (2011). *Contract administration and construction inspection manual*. Manitoba Infrastructure and Transportation. Retrieved from https://www.gov.mb.ca/mit/wms/structures/pdf/manuals/contract.pdf

Manitoba Department of Transportation (2010). *Specification 1039: Specifications for Concrete Repairs specification 1039*. Retrieved from https://www.gov.mb.ca/mit/contracts/pdf/manual/1039i.pdf

Michigan Department of Transportation (2012). *Standard specifications for construction*. *Section 601 Portland cement concrete for pavements*. Michigan Department of Transportation. Retrieved from https://mdotjboss.state.mi.us/SpecProv/specBookHome.htm#1468270

Michigan Department of Transportation (2016). *Quality control and acceptance of Portland cement concrete*. 12SP-604B-07. Michigan Department of Transportation. Retrieved from https://mdotcf.state.mi.us/public/dessssp/spss_source/12SP-604A-07.pdf

Minnesota Department of Transportation (2016). *Guidance for concrete cylinders*. 2016 Inspectors Workshop. Minnesota Department of Transportation.

Mississippi Department of Transportation (2018). *Concrete field manual, materials division*, Mississippi Department of Transportation. Retrieved from https://mdot.ms.gov/documents /Materials/Standards/Manuals/MDOT%20Concrete%20Field%20Manual%20v20180907.pdf

Missouri Department of Transportation (2020). *Engineering Policy Guide (i.e. Construction and Materials Manual), Section 501.1.3.5.1 Curing*. Missouri Department of Transportation. Retrieved from https://epg.modot.org/index.php/Category:501_Concrete#501.1.3.5.1_Curing

Montana Department of Transportation (2013). *Making and curing concrete compressive and flexural strength test specimens in the field.* Methods of Sampling and Testing. MT 101-13. Montana Department of Transportation. Retrieved from https://www.mdt.mt.gov/other/webdata /external/materials/materials_manual/ARCHIVES/101_13.pdf

Nevada Department of Transportation (2019). *Synopsis of materials division testing manual for field testing*. Test Method Nev. T1021. State of Nevada Department of Transportation Construction Division. Retrieved from https://www.nevadadot.com/home/showdocument?id=16355

New Hampshire Department of Transportation (2016). *Standard specifications for road and bridge construction*. New Hampshire Department of Transportation. Retrieved from https://www.nh.gov/dot/org/projectdevelopment/highwaydesign/specifications/documents/2016NHDOTSpecBook.pdf

New Mexico State Department of Transportation (2007). Section 510. pg 223. *Standard specifications for highway and bridge construction.* New Mexico State Department of Transportation. Retrieved from https://dot.state.nm.us/content/dam/nmdot/Plans_Specs_Estimates/2007_Specs_for _Highway_and_Bridge_Construction.pdf

New York Department of Transportation (2012). *Standard specifications (US Customary Units),* Volume 2 of 4, Sections 200 - 599, New York Department of Transportation. https://www.dot.ny.gov/main/business-center/engineering/specifications/busi-e-standards-usc/usc-repository/2021_1_specs_usc_vol2.pdf

Newbolds, S. A., & Olek, J. (2001). *The Influence of curing conditions on strength properties and maturity development of concrete* (Report No. FHWA/IN/JTRP-2001/23). Indiana Department of Transportation.

North Carolina Department of Transportation (2018). *Standard specifications for roads and structures*. Section 420 Concrete Structures. North Carolina Department of Transportation. Retrieved from https://connect.ncdot.gov/resources/Specifications/StandSpecLibrary/2018 %20Standard%20Specifications%20Manual%20with%20ASTM.pdf

North Dakota Department of Transportation (2019). *Making and curing concrete test specimens in the field.* Field Sampling and Testing Manual. ND T 23. North Dakota Department of Transportation. Retrieved from https://www.dot.nd.gov/manuals/materials/testingmanual /testprocedures.pdf

Ohio Department of Transportation (2019). Item 511 Concrete for Structures, Construction and

Material Specifications, State of Ohio Department of Transportation. Retrieved from http://www.dot.state.oh.us/Divisions/ConstructionMgt/OnlineDocs/Specifications/2019CMS/2019_CMS_10162018%20Final%20to%20Printer.pdf

Ontario Ministry of Transportation (2019). *Construction specification for concrete structures*, OPSS 904 Ontario Provincial Standard Specification, Ontario Ministry of Transportation. Retrieved from https://www.library.mto.gov.on.ca/SydneyPLUS/TechPubs/Portal/tp/opsViews.aspx?lang=en-US

Pennsylvania Department of Transportation (2019). *Concrete field testing technician certification training manual.* Pennsylvania Department of Transportation. Retrieved from https://www.superpave.psu.edu/Training/Concrete/Documents/2019/2019%20Concrete%20Manual.pdf

South Dakota Department of Transportation (2019). *Method of making and curing concrete specimens in the field for compression and flexural tests*. SD 405. South Dakota Department of Transportation. Retrieved from https://dot.sd.gov/media/documents/(075)sd405.pdf

Su, Y. F., Han, G., & Lu, N. (2020). *Determining the optimal traffic opening timing through an in-situ NDT method for concrete early age properties* (Report No. FHWA/IN/JTRP-2020/02) Indiana Department of Transportation.

SureCure (2008). “Title of Web Page.” Retrieved from http://www.concretecuring.com

Tennessee Department of Transportation (2020). *Concrete field testing technician course. 2020 Manual*. Tennessee Department of Transportation. Retrieved from https://www.tn.gov/content/dam/tn/tdot/hq-materials-tests/training/training_books/Concrete_Field_Tech.pdf

The Constructor (2021). “Penetration Resistance Test on Hardened Concrete – Purpose and application,” Concrete Technology, The Constructor. Retrieved from https://theconstructor.org/concrete/penetration-resistance-test-concrete/2853/

Utah Department of Transportation (2020). *Standard specifications for road and bridge construction*. Utah Department of Transportation.

Virginia Department of Transportation (2016). *Road and bridge specifications*. Virginia Department of Transportation. Retrieved from https://www.virginiadot.org/business/resources/const/VDOT_2016_RB_Specs.pdf

Virginia Department of Transportation (2019). *Hydraulic cement concrete. Chapter IV*. Virginia Department of Transportation,. Retrieved from https://www.virginiadot.org/business/resources/Materials/bu-mat-MOI-IV.pdf

Washington State Department of Transportation (2020). *Method of making and curing concrete test specimens in the field.* Materials Manual M 46-01.33. Washington State Department of Transportation. Retrieved from https://wsdot.wa.gov/publications/manuals/fulltext/M46-01/t23.pdf

West Virginia Department of Transportation (2005). Curing Concrete Test Specimens in the Field. Materials Procedure. MP 601.04.20. West Virginia Department of Transportation. Division of Highways Materials Control, Soils and Testing Division. Retrieved from https://transportation.wv.gov/highways/mcst/Material%20Procedures/M6010420.PDF

West Virginia Department of Transportation (2020). Concrete Inspector and Technician Training Program Programmed Instruction Manual, Division of Highways, West Virginia Department of Transportation. Retrieved from http://transportation.wv.gov/highways/mcst/Documents/Technician%20Manuals/PCC%20Manual.pdf

Wisconsin Department of Transportation (2020). *Materials testing and acceptance – Concrete. Construction and Materials Manual*. Section 870. Wisconsin Department of Transportation. Retrieved from https://wisconsindot.gov/rdwy/cmm/cm-08-70.pdf

APPENDIX A: RECRUITMENT

IDOT R27-219 Concrete Field-curing Conditions and Control

Hello,

You are invited to respond to the Survey of Concrete Field-curing Conditions and Control. This survey is to gather information for the purpose to understand the current field-curing practices and specifications that transportation agencies are using. Your feedback will be used to improve current field-curing of concrete practices used by Illinois DOT that more accurately represent the strength of an in-place concrete item.

The survey will not collect personally identifiable information but will ask for demographic information. Individual responses will be kept confidential. The survey should take approximately 5 - 15 minutes to complete. Please respond by Friday, December 18, 2020, at 11:59 pm.

The link to the survey is here: https://illinoisstate.az1.qualtrics.com/jfe/form/SV_daSlh0GqsKaZ6wB

If you have any questions, please contact Dr. Pranshoo Solanki via email at psolank@ilstu.edu.

Thank you for your response.

Pranshoo Solanki, Ph.D., P.E.

APPENDIX B: PURPOSE AND DATA MANAGEMENT

IDOT R27-217 Concrete Field-curing Conditions and Control
September 23, 2020

This survey is for the purpose to understand the current field-curing practices and specifications that IDOT's Districts and other transportation agencies are using. It is okay to skip questions if they are not applicable during the survey. Some questions ask for more open-ended feedback, which allow for learning from the practitioners.

This document has the following sections:

1. Purposes and Data Management

2. Consent for the Survey. Please click the button saying "Agree and Continue" at the end of the Consent Statement, which shows your agreement to the consent. Then you will be brought to the survey questions. We will strictly follow the approved protocols for data management as explained in Section 1.

3. Form for Withdrawal of Participation (Optional). You can leave the survey at any time during the process. If you want to provide us suggestions and reasons for the withdrawal, please help to fill the form.

4. Survey Instructions and Questions.

Section 1: Purposes and Data Management

The following researchers from the Illinois State University will carry out the survey.	
Roles	**Name**
Chief Investigator	Dr. Pranshoo Solanki
Co-Investigators	Dr. Sally Xie
Student Investigator	Mr. John Awaitey, who is conducting this study as a part of graduate assistant work at the Illinois State University. This will take place under the supervision of Dr. Sally Xie.

Before you decide to take part in this study, it is important for you to understand the research purpose and its contents. You can contact a member of the research team if there is anything that is not clear or if you would like more information. This document will inform you about the research project and the tasks involved. Please use the following information to make an informed decision of whether to take part or not. Please read this information carefully.

What is the research study about?

This research is conducted to understand the current field-curing practices and specifications that IDOT's Districts and other transportation agencies are using. You are invited to take part in this research study because you have been identified as an expert/professional in the related field. To participate in this project, you need to meet the following inclusion criteria:

- Work on a transportation project; and
- Design, manufacturing, handling, or testing concrete.

Do I have to take part in this research study?

Participation in this research project is voluntary and your decision will not affect your relationship with the University. Refusal or withdrawal will involve no penalty or loss, now or in the future. If you decide you want to take part in the research study, you will be asked to click the "Agree and Continue" button, which shows your agreement to the Consent Form (shown in Section 2). We will keep a copy of this Participant Information Statement separately from the survey answers.

What does participation in this research require to do?

If you decide to take part in the research study, you will first be asked about your experience and the role of your organization in projects. The rest questions ask about your experiences of design, manufacturing, handling, or testing concrete. We will make sure that no risks or judgments will be brought by answering these questions.

The survey takes approximately 5-15 minutes. The questions are shown in Section 4. You can ask us to interpret the questions. We will not ask your name or any identification during the survey.
The survey will be kept anonymous and confidential.

Are there any risks involved?

We do not anticipate any risks beyond those that would occur in everyday life.

What are the possible benefits of participation?

By participating in this survey, you will contribute to the body of knowledge on improving concrete construction.

What will happen to information about me?

By click the “Agree and Continue” button, you consent to the research team collecting and using information about and from you for the research study. We will keep your data for seven years. We will store information about you at the faculty office computer owned by university. Your information will only be used for the purpose of this research study and it will only be disclosed with your permission. After the seven years, the data will be destroyed.

It is anticipated that the results of this research project will be published and/or presented in a variety of forums. In any publication and/or presentation, information will not be individually identifiable. Your participation in this project will be kept confidential.

How and when will I find out what the results of the research study are?

You have a right to receive feedback about the overall results of this study. You can tell us that you wish to receive feedback by email, at which point the researchers will also hold your contact details.

What happens if I want to withdraw from the research study?

If you do consent to participate, you may withdraw at any time. If you do withdraw, you will be asked to complete the optional “Form for Withdrawal of Participation” shown in Section 3 of this document. Alternatively, you can email the Research Team Contact and tell them you no longer want to participate.

If you decide to leave the research study, the researchers will not collect additional information from you. During the survey, you are free to stop the process at any time. Unless you say that you want us to keep the partial survey data, any recordings will be destroyed and the information you have provided will not be included in the study results. You may also refuse to answer any questions that you do not wish to answer during the survey.

Statement: Participation is voluntary, refusal to participate will involve no penalty or loss of benefits to which the subject is otherwise entitled, and the subject may discontinue participation at any time without penalty or loss of benefits to which the subject is otherwise entitled

Ethical review of the study

Approval from the Institutional Review Board of the Illinois State University.

Researchers' responsibility of reporting

We need to make you aware that in certain research studies, it is our legal and ethical responsibility to report illegal activity on the ISU campus, campus-controlled locations, or involving ISU students to appropriate authorities. However, we are not seeking this type of information in our study nor will you be asked questions about these issues.

Will recordings (i.e. audio, video & image) be collected?

No, recordings will not be collected in this questionnaire. If a second-round of detailed discussion is necessary based on the findings of data analysis from this survey, we will obtain a separate signature from you to indicate that you agree to be recorded. This can either be a separate signature line or a separate page.

What should I do if I have further questions about my involvement in the research study?

The person you may need to contact will depend on the nature of your query. If you want any further information concerning this project or need further assistance on the survey arrangement related to your involvement in the project, you can contact the following member/s of the research team:

Research Team Contact:

Name	John Awaitey	Dr. Pranshoo Solanki	Dr. Sally Xie
Position	Student Researcher and Data Collector	Data Analyst	Method Designer and Data Analyst
Email	jtawait@ilstu.edu	psolank@ilstu.edu	hxie@ilstu.edu

If you have any questions about your rights as a participant, or if you feel you have been placed at risk, contact the Illinois State University Research Ethics & Compliance Office at (309) 438-5527 or IRB@IllinoisState.edu.

APPENDIX C: PARTICIPANT CONSENT FORM AND SURVEY QUESTIONS

Please click the button saying "Agree and Continue" at the end of the Consent Statement, which shows your agreement to the consent. Then you will be brought to the survey questions. We will strictly follow the approved protocols for data management.

- Agreed and Proceed
- No, I do not consent

PART 1 - RESPONDENTS PROFILES

Q1. Please write the name and location (city, state) of transportation agency for which you work. Please provide your answer in the text box below.

Q1.1.How many years of concrete related experience do you have?

- Less than one year
- 1-5 years
- 6-10 years
- 11-15 years
- over 15 years

Q2. What type of concrete work are you familiar with (please select all applicable options)?

- Design
- Manufacturing
- Handling
- Testing
- Other (Please specify)

Q3. May we please contact you for additional information?.

- Yes. Please email psolank@ilstu.edu your contact details
- No

PART 2 - ISSUES OF CONCRETE FIELD OPERATION

Q1. The selection of specimen type (cylinders vs beams) affects the quality of field-cured concrete.

- Strongly agree
- Agree
- Neutral
- Disagree
- Strongly disagree

Q2. The selection of specimen size (e.g. 4 inch x 8 inch or 6 inch x 12 inch cylinders vs 20 inch or 30 inch beams) affects the quality of field-cured concrete.

- Strongly agree
- Agree
- Neutral
- Disagree
- Strongly disagree

Q3. What type of field-cured specimens does your agency use for the opening of pavement (including patches) to traffic sooner (select all that apply)?

- Cylinders
- Beams
- Maturity Method
- Other – describe
- None - describe

Q4. What type of field-cured specimens does your agency use for deciding when falsework or formwork can be removed (select all that apply)?

- Cylinders
- Beams
- Maturity

- Other – describe
- None - describe

Q5. Does your agency use a different criterion depending on the type of concrete mix (such as pavement, patching, or bridge superstructure)?

- Yes, Please explain in the textbox below
- No

Q6. Are you satisfied with the current method of determining when to remove falsework or formwork?

- Yes
- No. Please explain in the textbox below

Q7. Are you satisfied with the current method of determining when to open pavement or pavement patches?

- Yes
- No. Please explain in the textbox below

Q8 - QUESTIONS RELATED TO CYLINDERS IN PART 2

Q8.1. What size of cylinders are used for field-curing (select all that apply)?

- 4 inch x 8 inch.
- 6 inch x 12 inch.
- None of the above. Please explain

Q8.2. How many cylinders breaks constitute a test (select all that apply)?

- 4 inch x 8 inch, insert the number or describe your calculation method:
- 6 inch x12 inch, insert the number or describe your calculation method:
- Other sizes, insert the number or describe your calculation method:

Q8.3. After how many days is a cylinder specimen demolded?

- 1 day (24 hours)
- 2 days (48 hours)

- At the time of testing
- None of the above. Please explain

Q8.4. How long is a cylinder specimen cured after being cast? (Please explain in the text box below)

Q8.5. How is a cylinder specimen field-cured (select all that apply)?

- Ambient air on the site near the item/structure poured
- In an insulated box with other specimens (gang - cured) near the item/structure poured
- Damp sandpit near the item/structure poured
- Thermostatically controlled curing box (power-operated)
- Under burlap or insulation near the item/structure poured
- Insulated cylinder mold
- Other - please explain

Q8.6. Additional information, concern, or practice of cylinder specimen (if any). Please provide your answer in the text box.

Q9. QUESTIONS RELATED TO BEAMS IN PART 2

Q9.1. What size of beams are used for field-curing (select all that apply)?

- 6 inch x 6 inch x 20 inch.
- 6 inch x 6 inch x 30 inch.
- None of the above. Please explain

Q9.2. How many beams are required when field-curing (please select all that apply)?

- 6 inch x 6 inch x 20 inch, insert the number or describe your calculation method
- 6 inch x 6 inch x 30 inch, insert the number or describe your calculation method
- Other sizes, insert the number or describe your calculation method

Q9.3. After how many days is a beam specimen demolded?

- 1 day (24 hours)
- 2 days (48 hours)

- At the time of testing
- None of the above. Please explain

Q9.4. How long is a beam specimen cured after being cast? Explain in the text box.

Q9.5. How is a beam specimen field-cured (select all that apply)?

- Ambient air on the site near the item/structure poured
- Damp sandpit near the item/structure poured
- Curing box
- Under burlap or insulation near the item/structure poured
- Other - please explain

Q9.6. Additional information, concern, or practice of beam specimen (if any). Please provide your answer in the text box.

Q10. How do you keep track of concrete curing (select all that apply)?

- Photo
- Field reports
- Weather data
- Concrete temperature data (e.g. embedded sensors)
- Emails
- Others (please specify)

Q11. What is your primary concern regarding a possible new curing method?

- Cost
- Time to set up
- Learning curve
- Other (please specify)
- Not applicable

Q12. What new technologies can help the field curing of concrete? Please specify.

Q13. Please upload any additional information such as standard(s) and/or your organization's experience (current or historical) with field curing of concrete test specimens you may have.

APPENDIX D: SPECIAL PROVISION FOR QUALITY CONTROL/QUALITY ASSURANCE OF CONCRETE MIXTURES (ILLINOIS TOLLWAY)

Effective: September 15, 2014
Revised: May 11, 2020

Description. This work shall consist of providing quality control/quality assurance for concrete mixtures.

CONSTRUCTION REQUIREMENTS

Concrete mixtures shall be tested and evaluated using the Illinois DOT Recurring Special Provision for Quality Control/Quality Assurance of Concrete Mixtures, except as revised herein.

Add the following to Article 1020.16(a):

Compression Machine Requirements. All laboratories reporting compressive strength results for all PCC items shall utilize compressive testing machines that have the capability of storing results digitally for the duration of the contract and producing those results on demand. This requirement extends to Quality Control laboratories furnished by the Contractor or their subcontractors, Quality Assurance laboratories representing the Engineer, or Independent Assurance laboratories reporting directly to the Tollway. The digital readouts will be capable of displaying the following:

- Specimen identification number
- Diameter and cross-sectional area of specimen
- Specimen age at time of test
- Date and time of test
- Rate of loading to the nearest pound per second and maximum load achieved to the nearest pound of applied load.
- Compressive strength calculated to nearest pounds per square inch
- Type of fracture and any L/D corrections applied
- Test equipment and Technician Identification
- Laboratory name and location

Follow requirements of Article 1103, with the following additions:

The production facility and ready mix trucks supplying hydraulic cement concrete shall have a current Certification of Ready Mixed Concrete Production Facilities from the National Ready Mixed Concrete Association. The Contractor’s Quality Control Plan shall include documentation of NRMCA certification.

Add the following to Article 1020.16(c)(1) and 1020.16(d)(1):

Personnel conducting strength testing shall be certified as an American Concrete Institute (ACI) Concrete Strength Testing Technician.

Remove AASHTO T 177 (Standard Method of Test for Flexural Strength of Concrete) from Schedule B.

Revise Article 1020.16 Schedule B Footnote 7/ to read:

The test of record for strength shall be the day indicated in Article 1020.04. For cement aggregate mixture II, a strength requirement is not specified and testing is not required. Additional strength testing to determine early falsework and form removal, early pavement or bridge opening to traffic, or to monitor strengths is at the discretion of the Contractor. Strength shall be defined as the average of two 6 x 12 in. (150 x 300 mm) cylinder breaks for field tests. Compressive strength, as measured using Illinois Modified AASHTO T22, shall be determined using only 6-inch diameter by 12-inch long cylinders.

Cold Weather Placement of Concrete.

Replace Articles 1020.13(c) and 1020.13(d) with the following:

(c) Protection of Concrete, Other Than Structures, From Low Air Temperatures. When the official National Weather Service forecast for the construction area predicts a low of 32 °F (0 °C), or lower, or if the actual temperature drops to 32 °F (0 °C), or lower, concrete less than 72 hours old shall be provided at least the following protection.

Minimum Temperature	Protection
25 – 32 °F (-4 – 0 °C)	Two layers of polyethylene sheeting, one layer of polyethylene and one layer of burlap, or two layers of waterproof paper.
Below 25 °F (-4 °C)	6 in. (150 mm) of straw covered with one layer of polyethylene sheeting or waterproof paper.

These protective covers shall remain in place until the concrete is at least 96 hours old. When straw is required on pavement cured with membrane curing compound, the compound shall be covered with a layer of burlap, polyethylene sheeting, or waterproof paper before the straw is applied.

After September 15, there shall be available to the work within four hours, sufficient clean, dry straw to cover at least two days production. Additional straw shall be provided as needed to afford the protection required. Regardless of the precautions taken, the Contractor shall be responsible for protection of the concrete placed and any concrete damaged by cold temperatures shall be removed and replaced.

The Contractor shall submit a QC plan for cold weather placement of concrete using the Tollway A-72 Form. This form shall be submitted to the Web -Based Project Management System (WBPM) and approved by the Engineer and Tollway Materials, prior to placements requiring winter protection.

The Contractor shall produce field cured cylinders according to Illinois Modified AASHTO T-23. The Contractor shall ensure the following:

- Initial curing cylinder storage will meet Illinois Modified AASHTO T-23 standards
- After initial curing, field cylinders are cured in the same manner as the item placed. Orientation of cylinders shall be on their sides underneath protection
- Field-cured cylinders shall be picked up from the site and tested on the same day

The Contractor shall implement corrective action, as detailed in the A-72 form, in the case that field cure cylinders tested at 7 days are less than 70% of 14-day design strength.

(d) Protection of Concrete Structures From Low Air Temperatures. When the official National Weather Service forecast for the construction area predicts a low below 45 °F (7 °C), or if the actual temperature drops below 45 °F (7 °C), concrete less than 72 hours old shall be provided protection. Concrete shall also be provided protection when placed during the winter period of December 1 through March 15. The contractor shall submit a written cold weather concrete protection plan for the materials, facilities, and equipment to be used for protection. The plan shall be provided on the Illinois Tollway A-72 Form and submitted to the Web-Based Project Management System (WBPM). Concrete shall not be placed until the plan is approved by the Engineer and Tollway Materials.

The Contractor shall install temperature probes in the concrete structure. At a minimum, probes shall be placed at the core of the item and at locations of lowest expected temperatures (surface, edge, corners) in sufficient frequency to be representative of the item. Probes shall utilize a continuous temperature monitoring system capable of recording temperatures at quarter hourly intervals. Temperature data and graphs shall be reported daily for the duration of the curing period.

The Contractor shall produce field cured cylinders according to Illinois Modified AASHTO T-23. The Contractor shall ensure the following:

- Initial curing cylinder storage will meet Illinois Modified AASHTO T-23 standards
- After initial curing, field cylinders are cured in the same manner as the item placed. Orientation of cylinders shall be on their sides underneath protection
- Field-cured cylinders shall be picked up from the site and tested on the same day

The Contractor shall implement corrective action, as detailed in the A-72 form, in the case of the following scenarios:

- Temperature probe readings are below 50°F or above 90°F
- Field cure cylinders tested at 7 days are less than 70% of 14-day design strength

When directed by the Engineer, the Contractor may be required to place concrete during the winter period. When winter construction is specified, the Contractor shall proceed with the construction, including excavation, pile driving, concrete, steel erection, and all appurtenant work required for the complete construction of the item, except at times when weather conditions make such operations impracticable.

Regardless of the precautions taken, the Contractor shall be responsible for protection of the concrete placed and any concrete damaged by cold temperatures shall be removed and replaced.

(1) Protection Method I. The concrete shall be completely covered with insulating material such as fiberglass, rock wool, or other approved commercial insulating material having the minimum thermal resistance R, as defined in ASTM C 168, for the corresponding minimum dimension of the concrete unit being protected as shown in the following table.

Minimum Pour Dimension		Thermal Resistance R
in.	(mm)	
6 or less	(150 or less)	R=16
> 6 to 12	(> 150 to 300)	R=10
> 12 to 18	(> 300 to 450)	R=6
> 18	(> 450)	R=4

The insulating material manufacturer shall clearly mark the insulating material with the thermal resistance R value.

The insulating material shall be completely enclosed on sides and edges with an approved waterproof liner and shall be maintained in a serviceable condition. Any tears in the liner shall be repaired in a manner approved by the Engineer.

On formed surfaces, the insulating material shall be attached to the outside of the forms with wood cleats or other suitable means to prevent any circulation of air under the insulation and shall be in place before the concrete is placed. The blanket insulation shall be applied tightly against the forms. The edges and ends shall be attached so as to exclude air and moisture. If the blankets are provided with nailing flanges, the flanges shall be attached to the studs with cleats. Where tie rods or reinforcement bars protrude, the areas adjacent to the rods or bars shall be adequately protected in a manner satisfactory to the Engineer. Where practicable, the insulation shall overlap any previously placed concrete by at least 1 ft (300 mm). Insulation on the underside of floors on steel members shall cover the top flanges of supporting members. On horizontal surfaces, the insulating material shall be placed as soon as the concrete has set, so that the surface will not be marred and shall be covered with canvas or other waterproof covering. The insulating material shall remain in place for a period of at least seven days after the concrete is placed.

The Contractor may remove the forms, providing the temperature is 35 °F (2 °C) and rising and the Contractor is able to wrap the particular section within two hours from the time of the start of the form removal. The insulation shall remain in place for the remainder of the seven days curing period.

(2) Protection Method II. The concrete shall be enclosed in adequate housing and the air surrounding the concrete kept at a temperature of not less than 50 °F (10 °C) nor more than 80 °F (27 °C) for a period of seven days after the concrete is placed. The Contractor shall provide a quarter hourly record of temperature of the concrete during the protection period. All exposed surfaces within the housing shall be cured according to the Index Table.

The Contractor shall provide adequate fire protection where heating is in progress and such protection shall be accessible at all times. The Contractor shall maintain labor to keep the heating equipment in continuous operation.

At the close of the heating period, the temperature shall be decreased to the approximate temperature of the outside air at a rate not to exceed 15 °F (8 °C) per 12 hour period, after which the housing maybe removed. The surface of the concrete shall be permitted to dry during the cooling period.