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

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Abstract: The purpose of this research was to build up the understanding of the current state –of –the practice for field-curing methods of concrete specimens. Specifically, a comprehensive literature review and questionnaire survey were prepared to identify the selection criteria and details of field-curing methods correspondingly. The comparison of literature data and survey outcomes shows that most transportation agencies use field-cured cylinders followed by the maturity method for the decision on when to open pavement to traffic or remove form/falsework. The most commonly used field method was curing near (or on) the casted concrete in the same manner as 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. On the other hand, beams are mostly field-cured in a damp sandpit or under burlap/insulation near the concrete item. The information provided in this paper could be used by transportation agencies for determining an appropriate cost-effective field-curing technique which is representative of strength gain of the in-place concrete item.
Keywords: Curing; Concrete; Cylinders; Beams; Maturity; Formwork; Road.

1. Introduction

The hydration reaction of early-stage in-place concrete item/structure depends upon the temperature and humidity factors that affect the concrete properties significantly [1, 2]. AASHTO T23 dictates the procedure for making and curing cylinders and beams for strength testing from representative samples of fresh concrete used for in-place concrete item. A total of two types of strength specimens are recommended by AASHTO T23 – standard-cured and field-cured. While the standard-cured specimens provide acceptance for the concrete that was delivered, the field-cured specimens are used for estimation of the real-time strength of falsework/formwork removal and road openings. Standard-cured specimens are molded onsite and immediately initially cured for up to 48 hours at 60 – 80°F (16 – 27°C) and prevent moisture loss. After initial curing, specimens are transported to the testing laboratory in less than 4 hours. After initial curing, specimens are transported to the testing laboratory in less than 4 hours. Then, the specimens are final cured at a temperature of 73.5±3.5°F (23±2°C) in water storage tanks for moisture rooms conforming to ASTM C511 until the test age of 28 days.

On the other hand, AASHTO T 23 recommends no specific guidelines for curing field-cured specimens. According to AASHTO T 23, specimens should be stored in or on the structure as close as possible to the point of concrete placement. Specimens are stored on the structure in an attempt to mimic curing of concrete in the structure and tested at different times (e.g., 1, 2, 3, 7 days). However, Department of Transportations (DOTs) in the US and contractors reported that field-cured concrete specimens appear not to develop strength equivalent to in-place concrete item [3]. To fill this gap, advanced concrete curing techniques such as maturity method and match-curing were developed. However, these methods are time consuming and not cost-effective. For example, in maturity modelling, documented in ASTM C1074, concrete strength is estimated based on concrete time-strength curves or charts. In this case, developing time-strength maturity curves for each and every mix containing aggregates from different sources is not a cost-effective method for DOTs.

Considering the differences between the strengths of field-cured specimens and in-place concrete items, there is an urgent need for a cost-effective and time-efficient field-curing method of concrete specimens that can accurately represent the strength of an in-place concrete item. Therefore, the primary objective of this study was to conduct a comprehensive literature review and survey of state transportation agencies to identify the current state of practice for field-curing methods. Furthermore, a comparison was made between the survey data and the outcomes from the literature review on prevailing standards and practices. The results can help concrete construction companies to improve service and assist decision-makers to determine falsework/formwork removal and road opening times.

2. Literature review

The state-of-the-practice literature review was conducted to build sufficient background for preparing a questionnaire survey. Specifically, the literature included reports collected from Transportation Research Information Service (TRIS) and standard specifications from DOTs' webpages. Overall, a total of 36 transportation agencies including 34 US states and 2 Canadian provinces were reviewed by summarizing literature. The literature review of 36 US DOTs presented in the aforementioned sections is summarized in Tables 1 and 2 for cylinders and beams, respectively. More detailed field-curing practices used by state DOTs (in alphabetical order) is presented in Solanki et al. [3].

Table 1. A Literature Review Summary of Field-Curing Methods of Cylinders Used by Various Transportation Agencies

State	**Field-cure strength determination method**	**Cylinder Curing Method**	**Specimen Size (C-cylinder)**
Alabama [4]	Cylinder, Maturity Method	Thermostatically controlled curing box (power-operated) near the item/structure poured	C1
California [5]	Beam	-	-
Colorado [6]	Cylinder	Same as concrete item	-
Connecticut [7]	Maturity Method	-	-
Delaware [8]	Cylinder, Sure-Cure method, Match-curing Method, Maturity Method	Same as concrete item	-
Florida [9]	Cylinder, Maturity Method	Same as concrete item	-
Georgia [10]	Cylinder, Beam	Same as concrete item; Under burlap or insulation near the item/structure poured	C1, C2
Illinois [11]	Cylinder, Beam	Same as concrete item	C1, C2
Illinois Tollway [12]	Cylinder, Beam	Same as concrete item; Under burlap or insulation near the item/structure poured; Damp sandpit near the item/structure poured	C1, C2
Indiana [13]	Beam, Maturity Method	-	-
Iowa [14]	Conductivity Test, Sorptivity, Maturity Method, Moisture content, Permeability	-	-
Kansas [15]	Cylinder, Beam	Same as concrete item; Under burlap or insulation near the item/structure poured	C1, C2
Louisiana [16]	Cylinder, Beam	Same as concrete item	C1, C2
Maine [17]	Cylinder	Thermostatically controlled curing box (power-operated) but not clear if they use field-curing method or not	-
Manitoba [18]	Cylinder	In an insulated box with other specimens (gang - cured) near the item/structure poured	-
Maryland [19]	Maturity Method	-	-
Michigan [20]	Cylinder, Beam, Maturity Method, Penetration Resistance	Same as concrete item	-
Mississippi [21]	Cylinder, Maturity Method	Same as concrete item; Under burlap or insulation near the item/structure poured	-
Minnesota [22]	Cylinder, Beam	Same as concrete item; In an insulated box with other specimens (gang - cured) near the item/structure poured	C1 and C2
Missouri [23]	Cylinder	Same as concrete item; Under burlap or insulation near the item/structure poured	C1 and C2
Montana [24]	Cylinder, Beam	Same as concrete item; Thermostatically controlled curing box (power-operated) or Damp sandpit near the item/structure poured	C1 and C2

Table. 1. *(Continued)*

Nevada [25]	Cylinder	Same as concrete item; Under burlap or insulation near the item/structure poured; Damp sandpit near the item/structure poured	C1 and C2
New Hampshire [26]	Cylinder	Thermostatically controlled curing box (power-operated) near the item/structure poured; Damp sandpit near the item/structure poured	-
New Mexico [27]	Cylinder, Core testing, Windsor probe, Match-curing Method, Maturity Method	Same as concrete item	-
New York [28]	Cylinder, Maturity Method	Same as concrete item	-
North Carolina [29]	Cylinder, Maturity Method	-	-
North Dakota [30]	Cylinder, Beam	Same as concrete item; Under burlap or insulation near the item/structure poured	C1 and C2
Ohio [31]	Beam, Maturity Method	-	-
Ontario [32]	Cylinder	Same as concrete item	-
Pennsylvania [33]	Cylinder, Beam	Same as concrete item; Under burlap or insulation near the item/structure poured; Damp sandpit near the item/structure poured	C1 and C2
South Dakota [34]	Cylinder	Same as concrete item	C1 and C2
Tennessee [35]	Cylinder	Same as concrete item	C1 and C2
Utah [36]	Cylinder, Maturity Method	Same as concrete item, cylinder storage device	
Virginia [37]	Cylinder, Maturity Method	-	C1 and C2
Washington [38]	Cylinder	Same as concrete item; Thermostatically controlled curing box (power-operated) near the item/structure poured	-
West Virginia [39]	Cylinder	Same as concrete item; Under burlap or insulation near the item/structure poured; Damp sandpit near the item/structure poured	C1 and C2
Wisconsin [40]	Maturity Method	-	-

Note. C1 = 150 mm x 300 mm (6-inch x 12-inch); C2 = 100 mm x 200 mm (4-inch x 8-inch)

Table 2. A Literature Review Summary of Field-Curing Methods of Beams Used by Various Transportation Agencies

State	**Field-cure strength determination method**	**Beam Curing Method**	**Specimen Size (B-beam)**
Alabama [4]	Cylinder, Maturity Method	-	-
California [5]	Beam	Under burlap or insulation near the item/structure poured; Damp sandpit near the item/structure poured	B1
Colorado [6]	Cylinder	-	-
Connecticut [7]	Maturity Method	-	-
Delaware [8]	Cylinder, Sure-Cure method, Match-curing Method, Maturity Method	-	-
Florida [9]	Cylinder, Maturity Method	-	-
Georgia [10]	Cylinder, Beam	Same as concrete item; Damp sandpit near the item/structure poured	B1
Illinois [11]	Cylinder, Beam	Same as concrete item	B1
Illinois Tollway [12]	Cylinder, Beam	Under burlap or insulation near the item/structure poured; Damp sandpit near the item/structure poured	B1
Indiana [13]	Beam, Maturity Method	Damp sandpit near the item/structure poured	-

Table. 2. *(Continued)*

Iowa [14]	Conductivity Test, Sorptivity, Maturity Method, Moisture content, Permeability	-	-
Kansas [15]	Cylinder, Beam	Damp sandpit near the item/structure poured	B2
Louisiana [16]	Cylinder, Beam	Same as concrete item	B1
Maine [17]	Cylinder	-	-
Manitoba [18]	Cylinder	-	-
Maryland [19]	Maturity Method	-	-
Michigan [20]	Cylinder, Beam, Maturity Method, Penetration Resistance	Same as concrete item	-
Mississippi [21]	Cylinder, Maturity Method	-	-
Minnesota [22]	Cylinder, Beam	Same as concrete item	-
Missouri [23]	Cylinder	-	-
Montana [24]	Cylinder, Beam	Same as concrete item; Damp sandpit near the item/structure poured	B1
Nevada [25]	Cylinder	-	-
New Hampshire [26]	Cylinder	-	-
New Mexico [27]	Cylinder, Core testing, Windsor probe, Match-curing Method, Maturity Method	-	-
New York [28]	Cylinder, Maturity Method	-	-
North Carolina [29]	Cylinder, Maturity Method	-	-
North Dakota [30]	Cylinder, Beam	Same as concrete item; Damp sandpit near the item/structure poured	-
Ohio [31]	Beam, Maturity Method	Same as concrete item; Under burlap or insulation near the item/structure poured; Damp sandpit near the item/structure poured	B3
Ontario [32]	Cylinder	-	-
Pennsylvania [33]	Cylinder, Beam	Same as concrete item; Under burlap or insulation near the item/structure poured; Damp sandpit near the item/structure poured	B2
South Dakota [34]	Cylinder	-	-
Tennessee [35]	Cylinder	-	-
Utah [36]	Cylinder, Maturity Method	-	-
Virginia [37]	Cylinder, Maturity Method	-	-
Washington [38]	Cylinder	Ambient air on the site near the item/structure poured; Under burlap or insulation near the item/structure poured or Damp sandpit near the item/structure poured	-
West Virginia [39]	Cylinder	-	-
Wisconsin [40]	Maturity Method	-	-

Note: B1 = 150 mm x 150 mm x 500 mm (6-inch x 6-inch x 20-inch); B2 = 150 mm x 150 mm x 525 mm (6-inch x 6-inch x 21-inch); B3 = 150 mm x 150 mm x 1,000 mm (6-inch x 6-inch x 40-inch)

It is evident from Tables 1 and 2 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 form/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. Illinois Tollway was found to implement temperature monitoring and maturity method for determining field-cure strength in future. Indiana DOT is currently exploring use of piezoelectric sensors installed in pavements for determining early strength of concrete.

Both 100 mm x 200 mm (4-inch x 8-inch) and 150 mm x 300 mm (6-inch x 12-inch), were found as commonly used field-cured cylinder sizes by transportation agencies. For beams, 150 mm x 150 mm x 500 mm (6-inch x 6-

inch x 20 inch) and 150 mm x 150 mm x 525 mm (6-inch x 6-inch x 21 inch) were found to be most popular beam sizes among DOTs reviewed in this study. The curing period of field-cured specimens was not clear from the literature review as most of the literature lacked this information. However, most of the DOTs in general were in favor of curing until time of form/falsework removal determination and varied between 3 and 14 days. The preferred curing times of the structures utilizing early strength concrete mixes vary from 4 hours to 3 days.

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

3. Methodology

Qualtrics XM^{TM} survey software was used to create an online survey instrument. The designed instrument was delivered and shared as a secured website link. 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 to download and backup the data daily. Participants who did not respond to the electronic survey received a follow-up email to remind them about the survey. The collected data was verified to make sure that there should be one respondent from a state's DOT and duplicated answers were removed if there were two or more respondents from the same DOT. After the verification, there were 45 respondents in the dataset, but 13 did not provide an answer to the survey, and 1 respondent's answers were considered duplication, therefore, these answers had been removed from further analysis.

The survey consisted of two sections: participant consent form and questionnaire. The survey questionnaire consisted of three parts: respondents' profile, issues of concrete field operation, and additional feedback questions. The first part entitled respondents' profile and included three questions about participant professional background and experience. The second part entitled issues of concrete field operation and included a total of nine questions related to field-curing methods of specimens. Additional six questions were given to participants who responded yes to the question asking if their DOT uses cylinders as field-cured specimens. Similarly, additional six questions were given to participants who responded yes to the question asking if their DOT use beam as one of the field-cured specimens. Specifically, six questions were about size, number, demolding time, curing time, curing method, and additional information (if any) related to field-curing of specimens (cylinders or beams). All questions were multiple-choice along with an option to provide comments or additional information. The last part included three questions about participant's concerns related to field-curing methods and the last question for uploading additional information such as standards or documents.

4. Survey results and discussion

Overall, the survey collected data from 31 respondents representing 29 states in the US and 2 Canadian provinces. Specifically, 23 respondents had over 15 years of concrete-related experience, 3 respondents had 11-15 years of concrete experience, 4 respondents had 6-10 years of concrete-related experience, and 1 respondent had between 1 and 5 years of concrete experience. All the respondents were familiar with at least one of the following types of concrete work: design, testing, manufacturing, and handing.

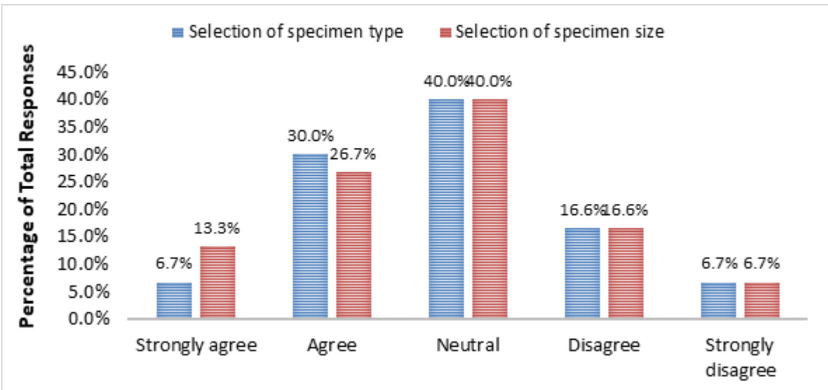

Fig. 1. Selection of specimen type or size versus the quality of field-cured concrete (31 respondents)

Firstly, when asked whether the selection of specimen type (cylinders vs beams) 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 respondents strongly agreed, 9 respondents agreed, 13 respondents answered neutral, 5 respondents disagreed, and 2 respondents strongly disagreed (as shown in Figure 1). Also, respondents were asked whether the selection of the specimen size e.g., 100 mm x 200 mm or 150 mm x 300 mm cylinders vs. 500 mm or 760 mm beams (e.g., 4-inch x 8-inch or 6-inch x 12-inch cylinders vs. 20-inch or 30-inch beams) could affect the quality of field-cured concrete, and to what extent? Out of the 30 valid responses received, 4 respondents strongly agreed to the statement, 8 respondents agreed, 11 respondents were neutral, 5 respondents disagreed, and 2 respondents strongly disagreed (shown in Figure 1).

4.1 Types of field-cured strength determination methods used

Figure 2 shows the responses to the question of the type of field-cure strength determination method used by agencies for the opening of pavement to traffic sooner. The survey revealed that the majority of transportation agencies used field-cured cylinders (23 out of 31, 74.2%) followed by the maturity method (17 out of 31, 54.8%) for deciding when to open pavement to traffic. Only 5 out of 31 agencies (16.1%) used beams for the opening of pavement to traffic. It is also important to note that several agencies (16 out of 31, 51.6%) used more than one method for deciding when to open pavement to traffic sooner.

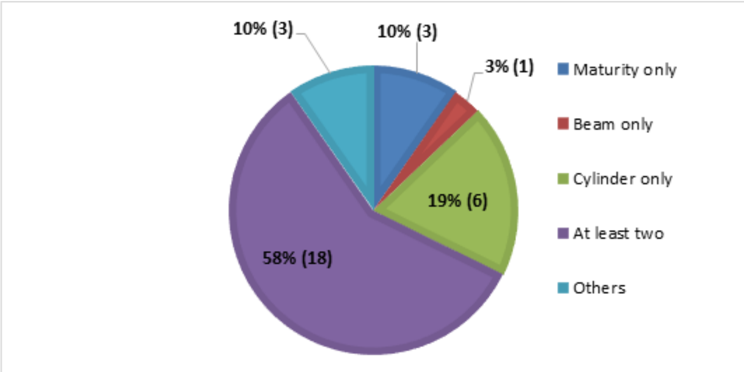

Fig. 2. Types of field-cure strength determination methods used by agencies in opening pavement to traffic sooner (31 respondents)

Figure 3 shows the responses to the question of the type of field-cure strength determination method used by agencies for the form/falsework removal decision. The survey revealed that the majority of transportation agencies used field-cured cylinders (24 out of 30, 80%) followed by the maturity method (10 out of 30, 33.3%) for deciding form/falsework removal time. Only 3 out of 30 agencies (10%) used beams for deciding when to remove form/falsework. Additionally, several agencies (9 out of 30, 30%) used more than one method for deciding when to remove form/falsework removal.

Figures 4 and 5 show pavement opening and form/falsework responses respectively, on a US map. Both Illinois DOT and Ohio DOT used both beam and cylinders (light purple color in Figure 4) for opening pavement. Several state DOTs used both maturity and cylinder methods (green color in Figure 4) for deciding when to open pavement to traffic. On the other hand, Indiana DOT used only beams and several DOTs (Colorado, Michigan, Iowa, North Carolina, Maryland) used only cylinders for the opening pavement to traffic.

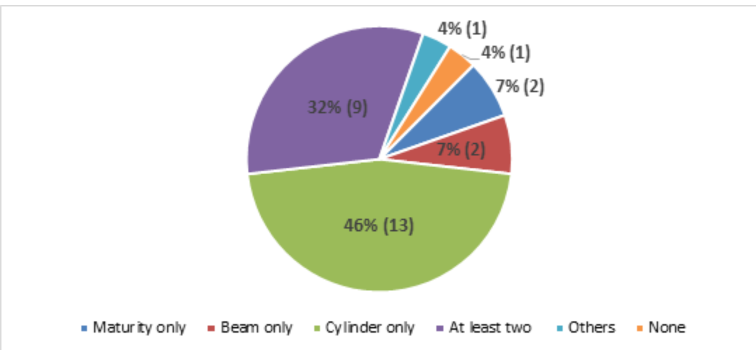

Fig. 3. Types of field-cure strength determination methods used by agencies in form/falsework removal decisions (30 respondents)

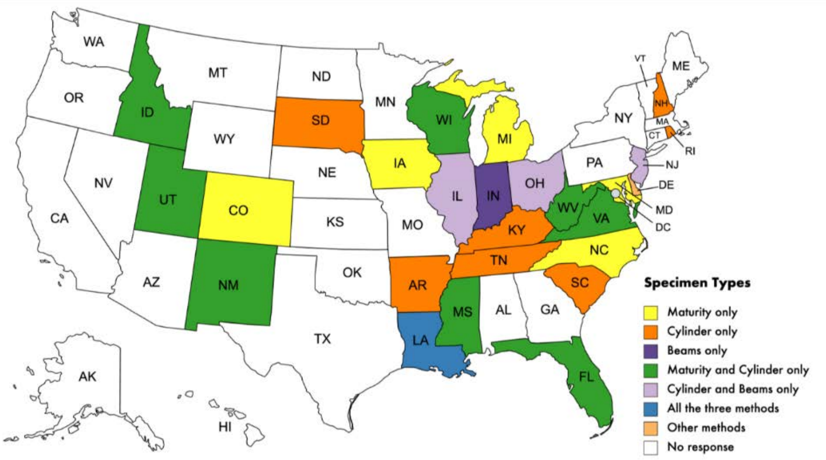

Fig. 4. Specimen types used by transportation agencies for opening pavement (including patches) to traffic sooner

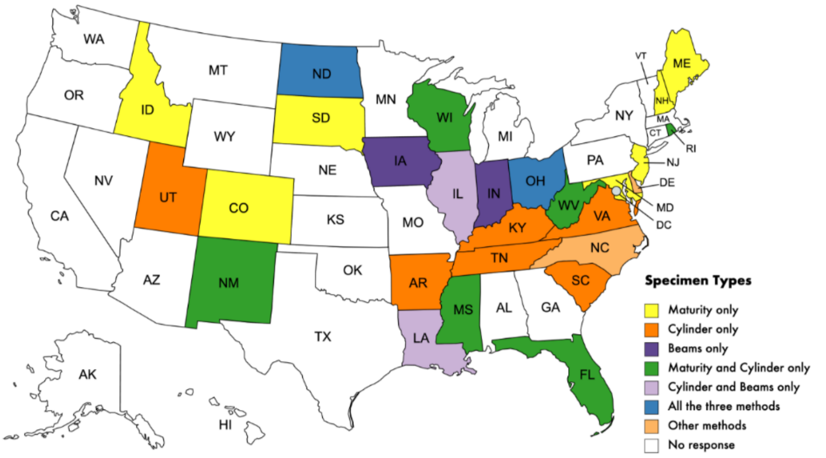

Fig. 5. Specimen types used by transportation agencies for deciding when form/falsework can be removed

The respondent from North Carolina relied on lab-cured specimens in deciding when formwork could be removed. New Hampshire also used cubes in addition to cylinders when the opening of pavement to traffic needed to be sooner. They did not use field-cure to decide when falsework could be removed but cylinders for information purposes only. Florida used the maturity method 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 the opening of pavement to traffic sooner. Delaware also used core molds for the opening of pavement. Toronto (Canada) DOT used cylinders for early strength determination of patches and a maturity method for pavement when the opening of pavement to traffic needed to be sooner, in deciding when falsework for formwork could be removed.

Furthermore, respondents were asked whether their agencies use a different criterion depending on the type of concrete mixes, such as pavement, patching, or bridge superstructure. According to survey responses, only 10 out of 29 responses (34.5%) agreed with using a different criterion or testing method depending on the type of the concrete mix such as patching, pavement, and bridge superstructure. Out of those who used different criteria, Ohio used beam, cylinder, or maturity for structures, while Indiana used beams for both structural concrete and pavement. However, the strength targets should be different for the various applications. Arkansas was found to use core for pavements and make cylinders for patching and bridge structures. Maine had Class A 28 MPa (4000 psi) for structural elements, class LP 35 MPa (5000 psi) for curb and barrier transition, and class P 41 MPa (6000 psi) or more for precast. Also, Wisconsin used a minimum of 14 MPa (2000 psi) for patching, a minimum of 21 MPa

(3000 psi) for pavement, and a minimum of 24 MPa (3500 psi) for compressive strengths of opening to traffic. Virginia allowed maturity meters for the decision of open-up for concrete patching, and they did not make cylinders for concrete patches, but for all other concrete works. In the case of the response from Dover, Delaware, cylinders were used in bridge works, and match-curing system for pavement and patching works. Mississippi DOT requires 17 MPa (2500 psi) either by field-cured cylinder or maturity meter prior to opening to traffic. 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. Toronto (Canada) indicated use of cylinders for deciding when to remove form/falsework.

4.2 Satisfaction level with the current method of field-cure strength determination

Figures 6 and 7 show satisfaction levels of transportation agencies with the current methods used for determining when to open pavement to traffic and remove form/falsework, respectively, on a US map. A majority (87%) of transportation agencies were found to be satisfied with the current method used for determining when to open pavement to traffic or remove form/falsework. Specifically, 24 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 provide 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.

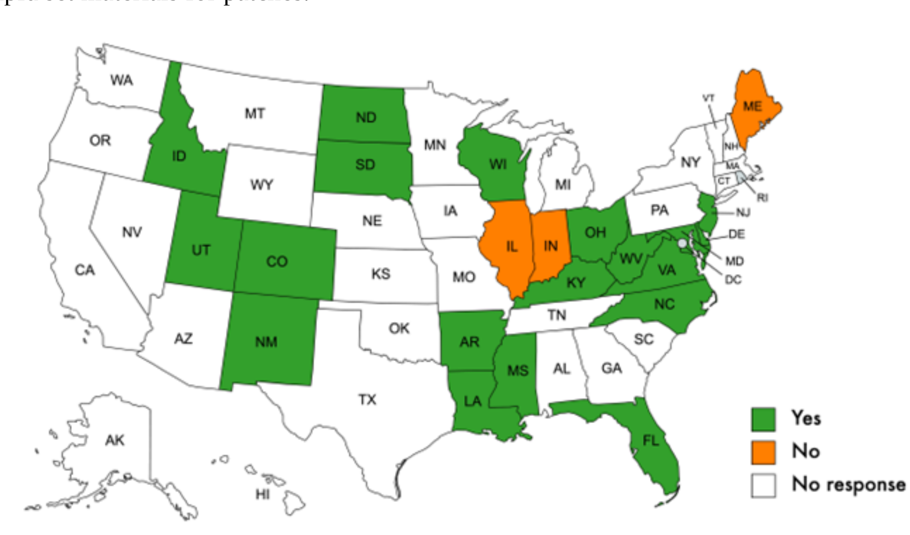

Fig. 6. Satisfaction levels of transportation agencies with the current methods used for determining when to open pavement (including patches) to traffic

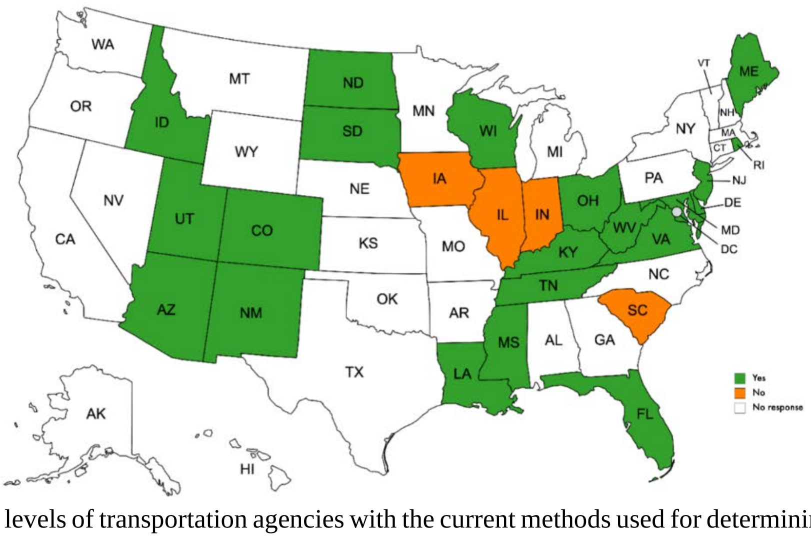

Fig. 7. Satisfaction levels of transportation agencies with the current methods used for determining when to remove form/falsework

Overall, 22 respondents were satisfied with the current method of determining when to remove form/falsework while 5 respondents were not satisfied with the current determination method. One respondent explained that early-break cylinders were standard cured, because the early break cylinders were made at the same time as the 28-day acceptance cylinders and all of them were placed in one curing room until testing. Indiana DOT was found to historically use beams for structural applications due to the field accessibility and portability of the beam breakers. Indiana DOT has one active research at Purdue University (Su et al., 2020) 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. Iowa DOT uses beams but found curing an issue sometimes because specimens may be taken into a trailer, if it is cold overnight, which is not representative of the structure itself.

4.3 Field-cured cylinders

4.3.1 Size and Number

The most common field-cured cylinder size used by the transportation agencies is 100 mm x 200 mm (4-inch x 8-inch) (22 out of 25, 88%) followed by 150 mm x 300 mm (6-inch x 12-inch) (11 out of 25, 44%). A total of 8 out of 25 respondents (32%) use both 100 mm (4-inch) as well as 150 mm (6-inch) cylinders for field-curing. Some of the agencies commented to completely transition from 150 mm (6-inch) to 100 mm (4-inch) cylinders for field-curing in coming years. The number of field-cured 100 mm x 200 mm (4-inch x 8-inch) and 150 mm x 300 mm (6-inch x 12-inch) cylinders tested varied from one to three. However, most responses were in favor of three – 100 mm x 200 mm (4-inch x 8-inch) and two – 150 mm x 300 mm (6-inch x 12-inch) cylinders.

4.3.2 Demolding Time, Curing Period and Field-curing Methods

Respondents were also asked the number of days after which cylinder specimen was demolded. Out of 24 responses received, 10 responded (41.7%) 24 hours, 2 responded (8.3%) 48 hours, 9 responded (37.5%) as at the time of testing. It appeared from survey responses that some respondents provided curing duration information of standard-cured specimens in place of field-cured specimens. However, some of the respondents clearly explained the curing duration of standard-cured as well as field-cured specimens. In general, survey responses showed that field-cured cylinders are cured with the concrete element being represented until the time of testing. The specific time depends on the application but is typically up to 7 days.

Figure 8 shows field-curing methods used by various transportation agencies for cylindrical specimens on the US map. Based on the survey results, most of the agencies selected a combination of more than one curing technique for field-cured cylinders. Specifically, 14 out of 25 responses (56%) were found in favor of curing in ambient air on the site near the concrete item represented. Furthermore, 13 out of 25 (52%) and 6 out of 25 responses (24%) selected gang-curing in an insulated box and power-operated box, respectively. Most of the responses (13 out of 25, 52%) were also in favor of curing cylinders under burlap or insulation near the concrete structure represented. A combination of curing of cylinders in an insulated box or power-operated box near the structure under burlap or insulation was found to be the most popular field-curing technique among transportation agencies surveyed in this study.

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

*Illinois Tollway or Delaware (Dover)

Fig. 8. Field-curing methods used for cylindrical specimens by transportation agencies

4.4 Field-cured beams

4.4.1 Size and Number

A total of 4 out of 6 respondents (66.7%) selected 150 mm x 150 mm x 500 mm (6-inch x 6-inch x 20-inch) beam for field-curing. Other beam sizes selected were 100 mm x 100 mm x 350 mm (4-inch x 4-inch x 14-inch), 150 mm x 150 mm x 525 mm (6-inch x 6-inch x 21-inch), 150 mm x 150 mm x 760 mm (6-inch x 6-inch x 30-inch), and 150 mm x 150 mm x 1000 mm (6-inch x 6-inch x 40-inch). Moreover, all responses except one were in favor of two beams for field-curing. Ohio DOT used 150 mm x 150 mm x 1000 mm (6-inch x 6-inch x 40-inch) beams to obtain three breaks depending on the failure location of the first and second breaks. Iowa DOT used 100 mm x 100 mm x 100 mm (4-inch x 4-inch x 4-inch) in addition to the 150 mm x 150 mm x 500 mm (6-inch x 6-inch x 20-inch) ones.

4.4.2 Demolding Time, Curing Period and Field-curing Methods

Survey results showed that responding agencies (4 out of 6, 66.7%) prefer demolding beam after 1 day (24 hours), and the remaining two responses prefer demolding at the time of testing. Many agencies indicated that curing is continued until the time of testing. Figure 9 shows field-curing methods used by various transportation agencies for beams on the US map. The most popular (4 out of 6, 66.7%) field-curing method used for beams was found to be under burlap or insulation near the concrete item. The damp sand pit method near the concrete item was selected by 2 out 6 (33.3%) responding agencies. Even though three agencies selected curing in ambient air on the site near the concrete item, it was not used alone. The ambient air curing method was used in combination with other methods such as under burlap/insulation and damp sandpit method.

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

*Illinois Tollway

Fig. 9. Field-curing methods used for beams by transportation agencies

4.5 Primary concerns and new technologies

To conclude the survey, all the respondents were asked primary concerns regarding a possible new curing method. It was found from the survey that most of the agencies (17 out of 26, 65.4%) reported the learning curve as the primary concern regarding a possible new curing method. Five (5) respondents also stated other reasons such as reliability (Utah), the effectiveness of the methods (Indiana), cost-benefit (Illinois Tollway), cost and construction schedule (Florida), and accuracy of the representation of the in-situ strength of the concrete element (Wisconsin).

Finally, the respondent from Colorado DOT considered sensors as a new technology that could help field-curing of concrete. Ohio DOT also indicated that maturity, calorimetry, and curing cubes were new technologies that could help field-curing of concrete. Toronto (Canada) suggested live temperature monitoring using wireless sensors with cloud access, and a wireless match curing system. Louisiana noted training and techniques for maturity meter can help field-curing of concrete. The respondents from New Mexico indicated better match-curing equipment. Manitoba (Canada) responded 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) as new technologies that could help the field-curing of concrete.

5. Conclusions and recommendations

This study involved a comprehensive 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 include the following:

1) Both literature review and survey results indicated that most transportation agencies use field-cured cylinders followed by the maturity method for deciding when to open pavement to traffic or remove form/falsework.

2) Both 100 mm x 200 mm (4-inch x 8-inch) and 150 mm x 300 mm (6-inch x 12-inch) are commonly used field-cured cylinder sizes by transportation agencies. For beams, both literature and survey results showed 150 mm x 150 mm x 500 mm (6-inch x 6-inch x 20-inch) as one of the most used beam sizes for field-curing.

3) The most used field-curing method found among transportation agencies was near the casted concrete in the same manner as concrete items represented. Specifically, cylinders are mostly field cured in an insulated box or under burlap/insulation near the concrete item. On the other hand, beams are mostly field cured in a damp sandpit or under burlap/insulation near the concrete item.

4) The curing period was found to depend on the time of form/falsework removal determination or pavement opening to traffic, and type of mix.

5) Some of the other field-curing technologies used/explored by agencies are match-curing, piezoelectric sensors, calorimetry, and penetration resistance tests.

6) The literature and survey results of this study could be used for determining an appropriate field-curing technique which is representative of strength gain of the in-place concrete item. Further, this information could help in making confident decisions of road openings and falsework/formwork removal and lead to the direct savings of agency cost through time-efficient construction.

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