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

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16. Abstract

The American Association of State Highway and Transportation Officials R 100 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 combined laboratory and field study was to evaluate field-curing methods of concrete specimens for estimating the early opening strength of an in-place concrete item. The researchers used one Illinois Department of Transportation class PV mix to cast cylinders, beams, and in-place concrete slabs on October 2021 and February 2022 at an Illinois State University concrete experiment site. Concrete cylinders were cured using three methods: ambient air (Method #C1), insulated box/cooler (Method #C2), and power-operated box (Method #C3). Beams were cured using two methods: ambient air (Method #B1) and insulated plywood box (Method #B2). The cast-in-place specimens from each slab and cylinder were tested for compressive strength, and beams were tested for flexural strength after 1, 3, and 7 days of curing. One cylinder and one beam in each curing method along with slabs were embedded with sensors to collect temperature variation with time. Only Methods #C1, #C2, and #B1 were selected for evaluating further in the field, and data were collected from an IDOT District 5 box culvert demonstration project. Laboratory results showed that Method #C2 curing of 150 mm (6 in.) cylinders estimated early (1 to 3 days) compressive strength of an in-place concrete item within an acceptable range. For estimating the 7-day strength of an in-place concrete item, Method #C1 produced acceptable results. Further statistical analysis supported the results observed in the laboratory and field.

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Special thanks to all District 3, District 4, and District 5 Illinois Department of Transportation personnel who provided assistance with the field demonstration project. This project involved construction of a box culvert near Armstrong, Illinois. For the field demonstration project, the reader is also referred to the following publication by the Illinois Center for Transportation for research conducted on reducing concrete curing time, R27-213: Reducing Concrete Cure Times for Bridge Substructure Components and Box Culverts, by Faisal Qadri and Nishant Garg.

EXECUTIVE SUMMARY

The American Association of State Highway and Transportation Officials (AASHTO) R 100 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 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, the primary objective of this combined laboratory and field study was to evaluate field-curing methods of concrete specimens for estimating the early opening strength of in-place concrete items.

For the laboratory, one IDOT Class PV (pavements) mix was used. Concrete was poured on October 1, 2021, and February 25, 2022. Three small 600 × 600 × 200 mm (24 × 24 × 8 in.) cast-in-place test slabs, three large 900 × 900 × 300 mm (36 × 36 × 12 in.) cast-in-place test slabs, 30 100 × 200 mm (4 × 8 in.) cylinders, 30 150 × 300 mm (6 × 12 in.) cylinders, and 15 150 × 150 × 500 mm (6 × 6 × 20 in.) beams were prepared during each pour in this study. Each small and large slab consisted of four 100 × 200 mm (4 × 8 in.) and four 150 × 300 mm (6 × 12 in.) cast-in-place (CIP) cylinder molds, respectively, inside the slab formwork in accordance with modified ASTM C873 (Popovics et al., 2014). Concrete cylinders were cured using three methods: ambient air (Method #C1), insulated box/cooler (Method #C2), and power-operated box (Method #C3). Beams were cured using two methods: ambient air (Method #B1) and insulated plywood box (Method #B2). The CIP specimens from each slab and cylinder were tested for compressive strength, and beams were tested for flexural strength after 1, 3, and 7 days of curing. One cylinder and one beam in each curing method and all slabs were embedded with sensors for collecting temperature variation with time.

Laboratory results showed that ambient air curing (Method #C1) of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders underestimated early strength (1 to 3 days) of an in-place concrete item within 88%–89% and 81%–89%, respectively, for the October 2021 cast (3-day ambient air temperature ranging between 15.5 and 35.5°C [59.9 and 95.9°F]). Furthermore, for the February 2022 cast (3-day ambient air temperature ranging between −10.5 and 13.0°C [13.1 and 55.4°F]), ambient air curing (Method #C1) underestimated early strength of an in-place concrete item within 16%–70% and 23%–78% for 100 mm (4 in.) and 150 mm (6 in.) cylinders, respectively. Ambient air curing of 100 mm (4 in.) and 150 mm (6 in.) cylinders (Method #C1) estimated 7-day strength of an in-place concrete item within the acceptable range of 94%–101% and 101%–105% for the October 2021 and February 2022 cast, respectively.

Insulated box curing (Method #C2) of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders estimated early strength (1 to 3 days) of an in-place concrete item within acceptable range of 95%–110% and 105%–108%, respectively, for the October 2021 cast. For the February 2022 cast, insulated box curing

(Method #C2) cured 100 mm (4 in.) cylinders underestimated early strength of an in-place concrete item within 66%–78% and 150 mm (6 in.) cylinder estimated strength within acceptable range of 100%–102%. Insulated box curing (Method #C2) of 100 mm (4 in.) and 150 mm (6 in.) cylinders estimated 7-day strength of an in-place concrete item by 91% and 112%, respectively, for the October 2021 cast and by 94% and 106%, respectively, for the February 2022 cast.

Power-operated box curing (Method #C3) of 100 mm (4 in.) and 150 mm (6 in.) cylinders estimated early strength (1 to 3 days) of an in-place concrete item within an acceptable range of 99%–104% and 99%–107%, respectively, for the October 2021 cast. For the February 2022 cast, power-operated box (Method #C3) overestimated early strength within the unacceptable range of 101%–148% and 113%–146% for 100 mm (4 in.) and 150 mm (6 in.) cylinders, respectively. Power-operated box curing (Method #C3) of 100 mm (4 in.) and 150 mm (6 in.) cylinders estimated 7-day strength of an in-place concrete item by 100% and 106%, respectively, for the October 2021 cast and by 89% and 110%, respectively, for the February 2022 cast. Therefore, 150 mm (6 in.) cylinders cured using either Method #C2 or Method #C3 slightly overestimated the strength of an in-place concrete item.

Ambient air (Method #B1) and insulated plywood box (Method #B2) curing of beams underestimated the strength of an in-place concrete item due to relatively low temperature inside the beams compared to an in-place concrete item. Based on the laboratory tests, Methods #C1, #C2, and #B1 were selected for further evaluation in the field.

Field data were collected from a box culvert demonstration (IDOT District 5) project. For the box culvert project, an IDOT class SI (structural, non-superstructure) mix with a shortened cure period was used. (See Appendix A for more information.) The concrete was poured in two stages: without a rheology-controlling admixture (Stage I) and with a rheology-controlling admixture, (Stage II). The Stage I mixes were poured in the field on May 12, May 20, May 27, and June 8 of 2022. The Stage II mixes were poured in the field on June 21, August 11, and August 22 of 2022. The concrete specimens prepared in the field were tested after 2, 3, and 7 days of curing.

The data from the box culvert demonstration project showed that early strength estimated by insulated box (Method #C2) cylinders was higher than the corresponding early strength estimated by ambient air curing of cylinders (Method #C1). The 7-day strength estimated by Method #C2 was approximately similar or less than the corresponding strength estimated by Method #C1. Method #C1 provided higher temperature differences between cured cylinders and in-pour compared to corresponding differences between Method #C2 cylinders and in-pour concrete temperature. This finding indicates that Method #C2 cylinders mimic in-pour temperature better than Method #C1 cylinders. For the cast on May 20, 2022 (Stage I), August 11, 2022 (Stage II), and August 22, 2022 (Stage II), Method #C2 overheated cured specimens. The magnitude of overheating was higher for 150 mm (6 in.) cylinders compared to corresponding 100 mm (4 in.) cylinders when specimens were placed in separate coolers. However, the magnitude of overheating was similar when both 150 mm (6 in.) and 100 mm (4 in.) cylinders were placed in the same cooler. This behavior may result in overestimation of in-place concrete strength estimated by Method #C2. The ambient air cured beams (Method #B1) experienced the lowest temperature among all cured specimens tested and the temperature was lower than in-pour temperature and similar to ambient air temperature. Therefore, beams may not be a good strength indicator of in-place concrete strength.

The statistical analysis of laboratory data showed that the compressive strength estimated by 100 mm (4 in.) and 150 mm (6 in.) cylinders cured using Method #C1 was not significantly different. Therefore, any cylinder size could be used for curing specimens using Method #C1. However, the compressive strength estimated by 100 mm (4 in.) and 150 mm (6 in.) cylinders cured using Method #C2 was significantly different. Further, statistical analysis showed that the compressive strengths of cylinders cured using Methods #C1 and #C2 had significant differences on Day 1 for both October 2021 and February 2022 data, significant differences on Day 3 for only February 2022 data, and no significant differences on Day 7 for both October 2021 and February 2022 data. The statistical analysis further showed that the compressive strengths of cylinders cured using Method #C2 and corresponding cast-in-place cylinders (in-place concrete item strength) had no significant differences in early strength (1 to 3 days) and 7-day strength for both October 2021 and February 2022 data. Moreover, statistical analysis showed that the compressive strength of cylinders cured using Methods #C2 and #C3 had significant differences in early strength (1 to 3 days) for only the February 2022 data and no significant differences in 7-day strength for both October 2021 and February 2022 data.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

The American Association of State Highway and Transportation Officials (AASHTO) R 100 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 longer to develop strength than beams. This trait may result in the contractor reverting to using beams for the sake of opening the pavement to traffic or loading structures 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 laboratory study to develop a cost-effective and time-efficient field-curing method of specimens that can accurately estimate the strength of an in-place concrete item. The laboratory study was validated by analyzing field data collected from IDOT projects.

The report is organized as follows. Chapter 2 explains the materials and methods, including laboratory procedures, data collection, and IDOT project locations. Chapter 3 presents data from the laboratory and field as well as statistical analysis, including hypothesis testing and correlations. Chapter 4 concludes this report. There are two appendices in this report: special provision for box culvert concrete (Appendix A) and correlation analysis (Appendix B).

CHAPTER 2: MATERIALS AND METHODS

LABORATORY MATERIALS AND METHODS

This section discusses the various laboratory materials and methods used for conducting this study as well as the specimen casting procedure.

Concrete Mixes

This study used an IDOT Class PV (pavements) mix for pavement. The mix design had a design water-to-cement ratio (w/c) of 0.42, cement content of 255 kg/m^3 (430 lb/yd^3), fly ash content of 86 kg/m^3 (145 lb/yd^3), coarse aggregate content of 1067 kg/m^3 (1798 lb/yd^3), and fine aggregate content of 720 kg/m^3 (1213 lb/yd^3). Table 1 presents a summary of the actual quantity of concrete ingredients batched. Three types of admixtures—namely, air entrainer, water reducer, and retarder—were used. The specified slump range of the fresh mixture was between 89 and 114 mm (3.5 and 4.5 in.). The target entrained air content was 6.5%, and the allowable air content range was 5.0% to 8.0%. The design requirements of 14-day compressive and flexural strengths were a minimum 24 MPa (3500 psi) and 4.5 MPa (650 psi), respectively. Due to the relatively large volume of concrete used in this study (approximately 3 m^3 [4.0 yd^3]), central-mixed concrete was ordered from a local ready-mix concrete supplier, which was approximately 6.44 km (4 miles) from the concrete experiment site. Concrete was poured on October 1, 2021, and February 25, 2022. Once received, each concrete batch was tested for w/c, slump, and air content to make sure it was within the required specifications before casting specimens. Three small 600 × 600 × 200 mm (24 × 24 × 8 in.) cast-in-place test slabs, three large 900 × 900 × 300 mm (36 × 36 × 12 in.) cast-in-place test slabs, 30 100 × 200 mm (4 × 8 in.) cylinders, 30 150 × 300 mm (6 × 12 in.) cylinders, and 15 150 × 150 × 500 mm (6 × 6 × 20 in.) beams were prepared during each pour in this study. To mimic field conditions, all slabs, cylinders, and beams were cured outside in the parking lot area (the concrete experiment site) of the Turner Hall building at Illinois State University (ISU). Specimens were tested after 1, 3, and 7 days of curing.

Temperature Sensors

The self-powered temperature sensors used in this study were obtained from the COMMAND Center and came in small button sizes. Each sensor can continuously collect and store temperature readings for two years with 2,048 data points of memory. Once a sensor reaches its internal capacity of 2,048 total temperature readings, new data continue to be collected but will roll over and overwrite the oldest data. For this study, the sensors were configured to measure concrete temperatures at 15-minute intervals. The sensors come in a customized lead wire length of 2.4 m (8 ft.) and are covered for protection from water. Sensors were installed during concrete pouring at the center of slabs, concrete cylinders, and beams. The temperature data were downloaded on the laptop at the end of the curing period (1, 3, and 7 days) by connecting the lead wire to a laptop using a USB cable.

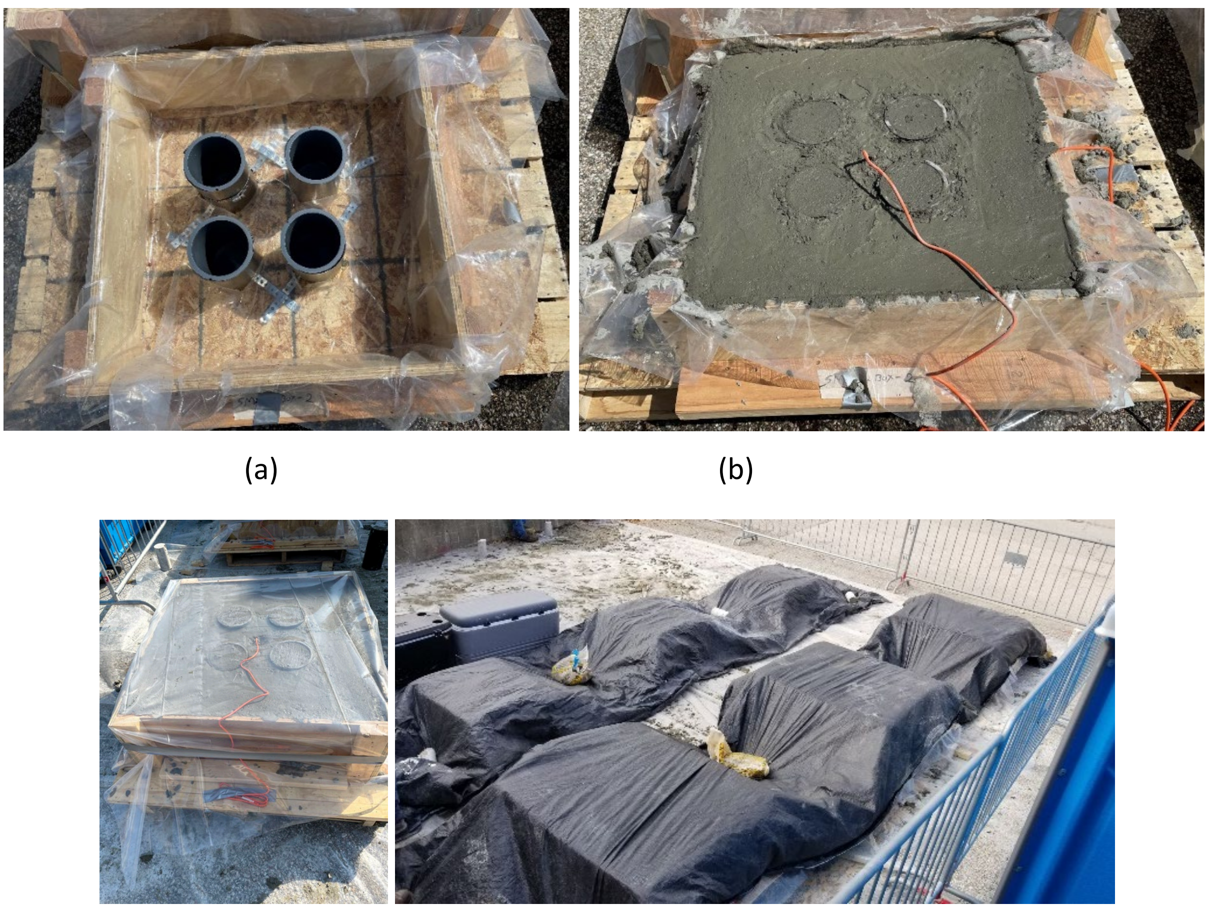
Table 1. Concrete Mix Proportions

Concrete Mixtures	Quantity Batched Per Cubic Yard									
	Cement (lb)	Fly Ash (lb)	Water (gal)	FA[1] (lb)	CA[2] (lb)	AEA[3] (fl oz)	Water reducer (fl oz)	Retarder (fl oz)	HWRW[4] (fl oz)	RCA[5] (fl oz)
ISU Mix (10/1/2021)	430	142.5	29.1	1260	1790	20	20.25	11.25	–	–
ISU Mix (2/25/2022)	432.5	145	30.35	1280	1800	12.5	20.25	–	–	–
Box Culvert Field Demo Stage I (5/12/2022)	630[6]	–	28.3	1174[6]	1831[6]	6.5	22.1	15.8	28.4	–
Box Culvert Field Demo Stage I (5/20/2022)	630[6]	–	27.3	1152[6]	1848[6]	6.9	25.2	15.8	42.7	–
Box Culvert Field Demo Stage I (5/27/2022)	630[6]	–	29.2	1152[6]	1848[6]	6.2	25.2	–	–	–
Box Culvert Field Demo Stage I (6/8/2022)	630[6]	–	28.3	1152[6]	1848[6]	5.4	22.7	–	12.8	–
Box Culvert Field Demo Stage II (7/21/2022)	630[6]	–	31.5	1166[6]	1812[6]	10	22.0	6.3	14.2	31.5
Box Culvert Field Demo Stage II (8/11/2022)	630[6]	–	31.7	1166[6]	1812[6]	10	25.1	15.8	21.3	31.5
Box Culvert Field Demo Stage II (8/22/2022)	630[6]	–	29.0	1166[6]	1812[6]	10	25.1	15.8	21.3	31.5

[1] Fine aggregate; [2] Coarse aggregate; [3] Air Entraining Admixture; [4] High-Range Water Reducer; [5] Rheology-Controlling Admixture; [6] Theoretical batch weight provided since actual batch weight was unavailable

Casting of Slabs

To mimic concrete pavement, three small 600 × 600 × 200 mm (24 × 24 × 8 in.) and three large 900 × 900 × 300 mm (36 × 36 × 12 in.) slabs were cast using the concrete mix. Each small and large slab consisted of four 100 × 200 mm (4 × 8 in.) and four 150 × 300 mm (6 × 12 in.) cast-in-place (CIP) cylinder molds, respectively, inside the slab formwork in accordance with modified ASTM C873 (Popovics et al., 2014) (Figure 1a). Each special mold consisted of an outer cylindrical, an adjustable steel sleeve with straps tied to the plywood of the slab, and an inner standard plastic cylinder mold. Each slab was poured in two lifts and compacted with a battery-operated vibrating rod. The CIP cylinders were consolidated outside the slab by vibrating in two lifts in accordance with the AASHTO R 100 test method. After slab consolidation, the CIP cylinders were placed inside the metal sleeves. After pouring and placing the CIP cylinders, a temperature sensor was embedded at the center of the slab and then the slab was covered with polyethylene sheeting for curing until the day of testing. Additionally, the slab was sealed with a 2.5 cm (1/2 in.) curing blanket (R value = 5.7) on the top to ensure better (i.e., less gradient) heat distribution within the CIP specimens (Popovics et al., 2014). Photos of the slabs immediately after casting, covered with a plastic sheet, and covered with a blanket on top of a plastic sheet during curing are shown in Figure 1b, Figure 1c, and Figure 1d, respectively. One small slab and one large slab were opened on each testing day after curing to extract four 100 mm (4 in.) and four 150 mm (6 in.) CIP cylinders, respectively. Coring was also conducted on small and large slabs on the day it was opened to extract four 100 mm (4 in.) and four 150 mm (6 in.) cores, respectively. Small and large slabs 1, 2, and 3 were opened on day 1, 2, and 3, respectively. Only the three best CIP and three best cores out of four CIP cylinders and four cores were tested, and the average compressive strength was reported in this study. Figures 2 and 3 show drawings of small and large slabs, respectively, with embedded sensors, CIP cylinders, and coring locations.



(a) (b)

(c) (d)

Figure 1. Photos. Slab with four cast-in-place cylinders (a) before casting, (b) after casting, (c) covered with a plastic sheet, and (d) covered with a blanket under curing.

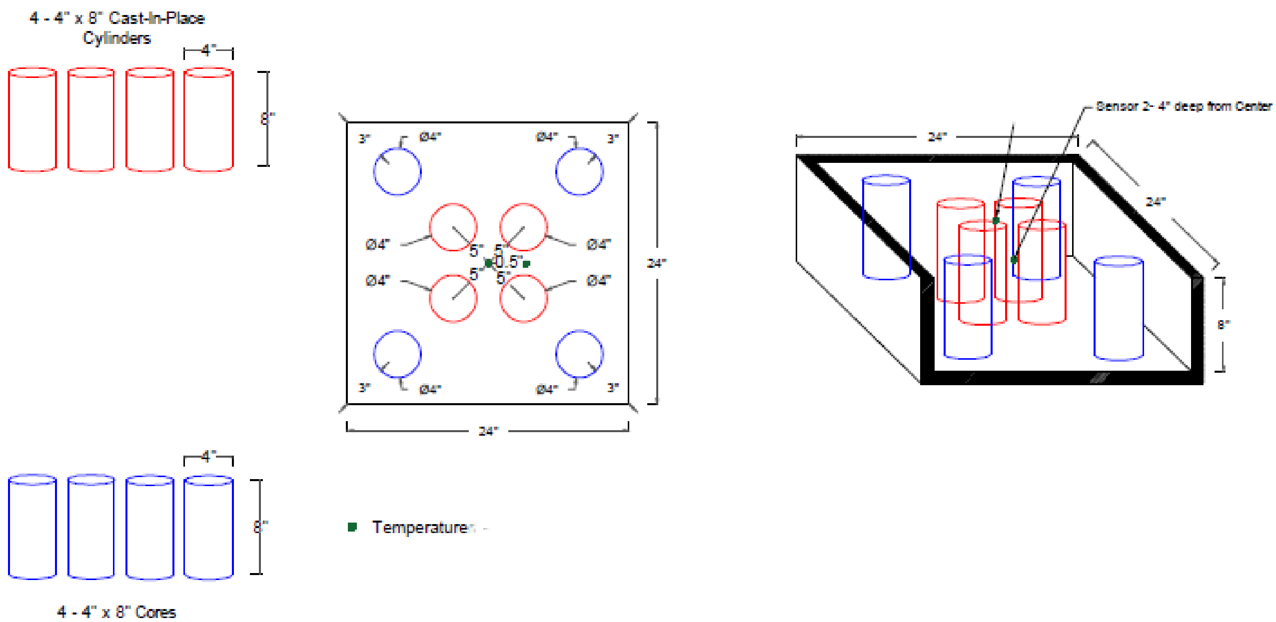


Figure 2. Drawing. Small 600 × 600 × 200 mm (24 × 24 × 8 in.) slab with embedded sensor, CIP cylinders, and coring locations.

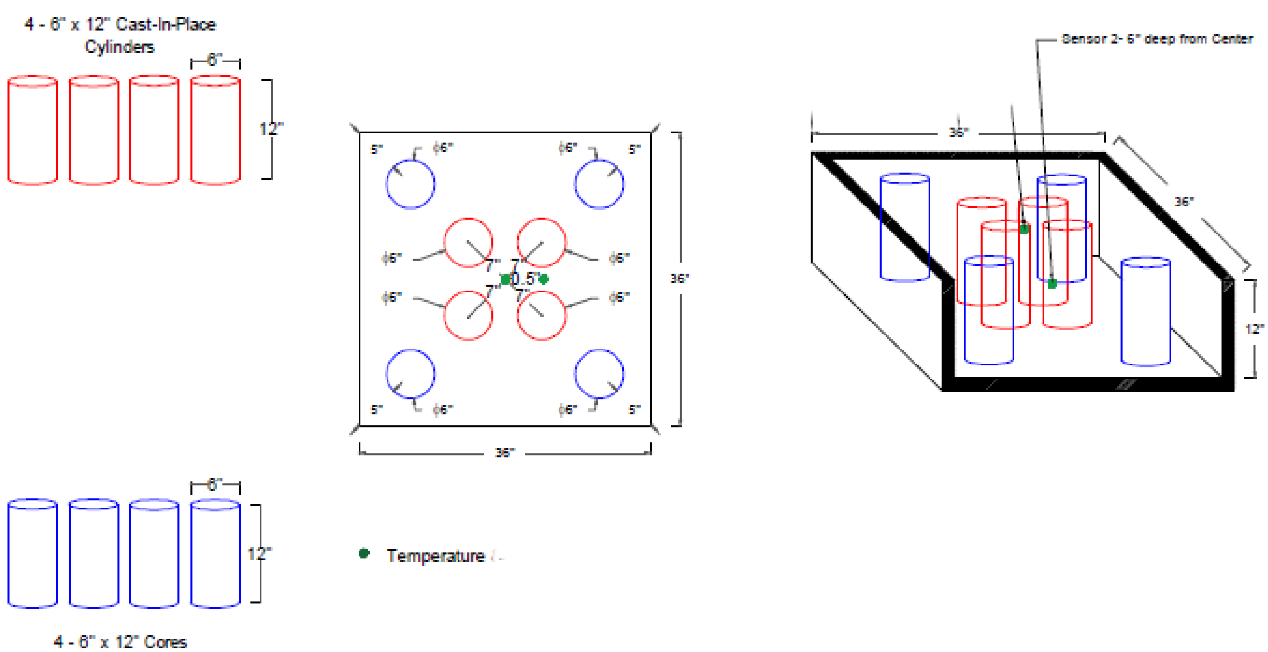


Figure 3. Drawing. Large 900 × 900 × 300 mm (36 × 36 × 12 in.) slab with embedded sensor, CIP cylinders, and coring locations.

Casting of Cylinders

Both 100 mm (4 in.) and 150 mm (6 in.) cylinders were consolidated by vibrating in two lifts in accordance with the AASHTO R 100 test method. After casting, concrete cylinders were cured using the following three cost-effective curing methods:

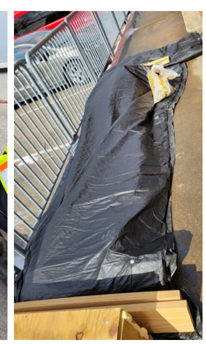
- Method #C1 (Figure 4a): Cured in ambient air in direct sunlight on the lab loading dock of the outdoor concrete experiment site and stripped on the day of the test ($1.64 per plastic cylinder mold). For the February 2022 cast (Figure 4b), cylinders were covered with a 2.5 cm (1/2 in.) curing blanket (R value = 5.7) due to extremely cold weather, consistent with IDOT practice.

- Method #C2 (Figure 4c and 4d): Gang-cured (10 in a box) in an insulated box (cooler) in direct sunlight in the parking lot of the outdoor concrete experiment site and stripped on the day of the test ($1.64 per plastic cylinder mold + $70 cooler, which is reusable). The cooler used was rated as a "5-day cooler," which keeps ice for up to 5 days in temperatures as high as 32°C (90°F).

- Method #C3 (Figure 4e and 4f): Gang-cured (10 in a box) in a thermostatically controlled curing box (power-operated) in direct sunlight in the parking lot of the outdoor concrete experiment site and stripped on the day of the test ($1.64 per plastic cylinder mold + $1,185 reusable box + power supply). Power was kept on for 24 hours at 21°C (70°F) after casting of cylinders and then turned off.

Each curing method consisted of 10 specimens. Of the 10 specimens, nine specimens were tested for compressive strength after 1, 3, and 7 days of curing. Three replicates were tested on each day. The remaining specimen was embedded with a sensor for monitoring temperature with time.

(a)



(b)

(c)

(d)

(e) (f)

Figure 4. Photos. Cylinders under curing for (a) Method #C1—October 2021, (b) Method #C1—February 2022, (c) 100 mm (4 in.) Method #C2, (d) 150 mm (6 in.) Method #C2, (e) 100 mm (4 in.) Method #C3, and (f) 150 mm (6 in.) Method #C3.

Casting of Beams

Each 500 mm (20 in.) long beam was cast in a steel mold in one lift and consolidated by vibrating in accordance with the AASHTO R 100 test method. After casting, all concrete beams were covered using an insulated wet curing cover (see Figure 5a) and cured using two types of cost-effective methods (discussed below). It is also important to note that all beams were demolded after 24 hours of casting and placed back for curing, consistent with IDOT practice.

- Method #B1 (Figure 5a): Cured in ambient air in direct sunlight on the lab loading dock of the outdoor concrete experiment site ($158.50 per beam mold, which is reusable). For the February 2022 cast, beams were covered with a 2.5 cm (1/2 in.) curing blanket (R value = 5.7) due to extremely cold weather, consistent with IDOT practice.

- Method #B2 (Figure 5b without top lid, Figure 5c with top lid): Gang-cured in a beam box in direct sunlight in the parking lot of the outdoor concrete experiment site ($138.60 per box, which is reusable). Five beam boxes were manufactured in the lab using foam board (R value = 10) sandwiched in two plywood sheets for providing insulation to beams (total R value = 12) (see Figure 5c). Two beams were placed inside each box.

Seven and eight beams were prepared for Method #B1 and Method #B2, respectively. Of the seven beams, six beams were tested for third-point flexural strength after 1, 3, and 7 days of curing, and duplicates were tested each day. The remaining beam was embedded with a sensor for monitoring temperature with time. One extra beam for Method #B2 was prepared to accommodate two beams inside each box for consistency.

(a) (b) (c)

Figure 5. Photos. Beams under curing for (a) Method #B1—October 2021, (b) Method #B2 without a top lid, (c) Method #B2 with a top lid.

Properties of Concrete Mixes

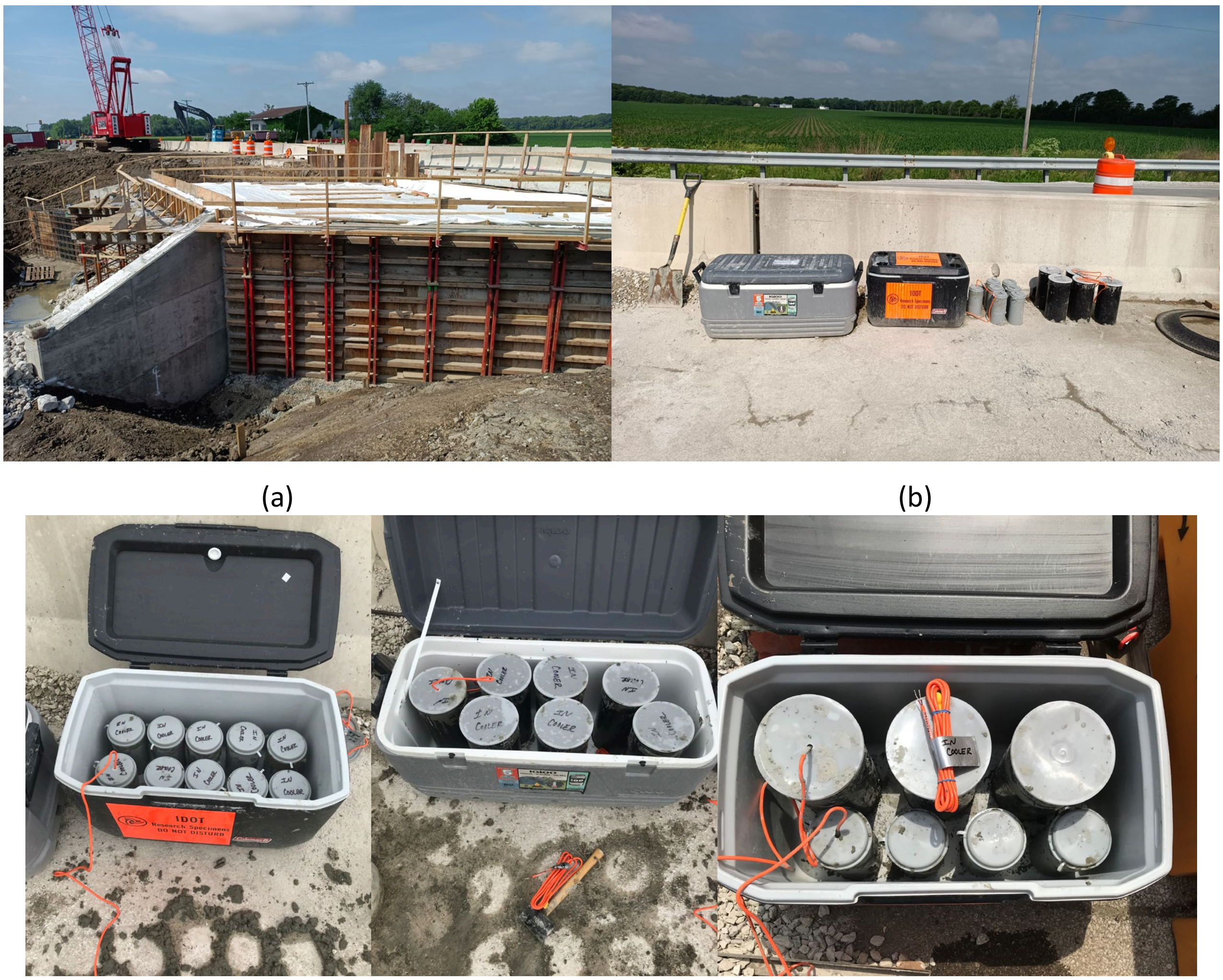
Both fresh properties and hardened properties of concrete were evaluated in this study. The workability of the fresh concrete mix was evaluated by conducting slump tests in accordance with the AASHTO T 119 test procedure. Then, the unit weight was obtained by pouring concrete into the container in three layers of equal volume in accordance with the AASHTO T 121 test procedure. Further, the same container was used for measuring the air content of the concrete mix by using the pressure in accordance with the AASHTO T 152 test method. The hardened concrete cylinders were tested for compressive strength. The CIP cylinders, cores, and cured cylinders, as well as beams were first measured for their volumes and then weighed to calculate the density of each specimen. This was done to ensure consistent quality of the specimens and to obtain accurate strength results. Then, cylinders were tested for compressive strength in accordance with the AASHTO T 122 test method by using a Universal Testing Machine. Beams were tested for flexural strength after 1, 3, and 7 days of curing (duplicates were tested on each day) by subjecting beams to third-point loading in accordance with the AASHTO T 97 test method.

FIELD DATA COLLECTION

Field data were collected from an IDOT District 5 box culvert demonstration project. Further details about the project location, construction, and data collected are discussed in subsequent sections.

Box Culvert Project

The box culvert project site is in IDOT District 5 near Armstrong, Illinois, on IL 49, approximately 0.8 km (0.5 miles) north of US 136 East. Figure 6a shows a photo of the construction site. For this project, an IDOT Class SI mix (with a shortened cure period) was used. The mix design had an initial target w/c of 0.38, cement content of 374 kg/m^3 (630 lb/yd^3), coarse aggregate content of 1086 kg/m^3 (1831 lb/yd^3), and fine aggregate content of 697 kg/m^3 (1174 lb/yd^3). Table 1 presents a summary of the actual quantity of concrete ingredients batched for batches poured on various dates. Five types of admixtures—namely, air entrainer, water reducer, retarder, superplasticizer, and rheology-controlling admixture—were used. (See Table 1 for proportions used.) The design requirements of 3-day compressive and flexural strengths were a minimum 24 MPa (3500 psi) and 4.5 MPa (650 psi), respectively. The concrete was poured in two stages: without a rheology-controlling admixture (Stage I) and with a rheology-controlling admixture at 44 oz. per cubic yard (Stage II). For Stage II, the rheology-controlling admixture contained calcium-silicate-hydrate (C-S-H) based seeds, which will enhance concrete strength. Refer to Qadri and Garg (2023) for more information. Appendix A provides the special provision with additional mix design information.



(a) (b)

(c) (d) (e)

Figure 6. Photos. View of (a) box culvert construction site, (b) specimen curing location taken on June 11, 2022, (c) example of 4 in. cylinders cured using Method#C2 on 6/8/2022 and 8/22/2022, (d) example of 6 in. cylinders cured using Method#C2 on 6/8/2022 and 8/22/2022, and (e) example of 4 in. and 6 in. cylinders cured together using Method#C2 on 5/20/2022 and 8/11/2022.

All specimens were prepared and cured at the site on concrete pouring day. Figure 6b shows a photo of the specimen curing location. Further, Stage I (without rheology-controlling admixture) pouring dates as well as specimen preparation and curing details are provided below:

- May 12, 2022: 325 mm (13 in.) Box Culvert Floor poured with the sensor located in the center of the slab and a few feet from the end of the slab.
  - University of Illinois Urbana-Champaign made 21 100 × 200 mm (4 × 8 in.) cylinders, which were demolded after one day and kept in water. Three replicates were tested after 2, 3, 7, 14, 28, 56, and 97 days of curing (refer to Qadri and Garg [2013] for more information).
  - Method #B1: Two replicates of 500 mm (20 in.) long beams were tested after 2, 3, and 7 days of curing (total = 6 beams + 1 beam with a sensor).
- May 20, 2022: 275 mm (11 in.) Box Culvert Center Wall poured with the sensor located a couple feet down from the top of the wall, and a couple feet from the end of the wall.
  - Method #C2: Three replicates of 100 × 200 mm (4 × 8 in.) cylinders (total = 3 cylinders + 1 cylinder with a sensor) and two replicates of 150 × 300 mm (6 × 12 in.) cylinders (total = 2 cylinders + 1 cylinder with a sensor) were placed in the same cooler and tested after 3 days (Figure 6e).
  - Method #B1: Two replicates of 500 mm (20 in.) long beams were tested after 2, 3, and 7 days of curing (total = 6 beams + 1 beam with a sensor).
- May 27, 2022: 275 mm (11 in.) Box Culvert North and South Walls were poured with no sensors.
  - Method #B1: Two replicates of 500 mm (20 in.) long beams were tested after 2, 3, and 7 days of curing (total = 6 beams + 1 beam with a sensor)
- June 8, 2022: 300 mm (12 in.) Box Culvert Lid poured with the sensor located in the center of the slab, and a couple feet from the end of the slab.
  - Method #C1: Three replicates of 100 × 200 mm (4 × 8 in.) cylinders were tested after 2, 3, and 7 days of curing (total = 9 cylinders + 1 cylinder with a sensor).
  - Method #C1: Two replicates of 150 × 300 mm (6 × 12 in.) cylinders were tested after 2, 3, and 7 days of curing (total = 6 cylinders + 1 cylinder with a sensor).
  - Method #C2: Three replicates of 100 × 200 mm (4 × 8 in.) cylinders were tested after 2, 3, and 7 days of curing (total = 9 cylinders + 1 cylinder with a sensor) (Figure 6c).
  - Method #C2: Two replicates of 150 × 300 mm (6 × 12 in.) cylinders were tested after 2, 3, and 7 days of curing (total = 6 cylinders + 1 cylinder with a sensor) (Figure 6d).

- Method #B1: Two replicates of 500 mm (20 in.) long beams were tested after 2, 3, and 7 days of curing (total = 6 beams + 1 beam with a sensor).

The Stage II (with rheology-controlling admixture) pouring dates and specimen preparation and curing details are provided below:

- July 21, 2022: 325 mm (13 in.) Box Culvert Floor poured with the sensor located in the center of the slab, and a few feet from the end of the slab.
  - University of Illinois Urbana-Champaign made 21 100 × 200 mm (4 × 8 in.) cylinders, which were demolded after one day and kept in water. Three replicates were tested after 2, 3, 7, 14, 28, 56, and 97 days of curing (refer to Qadri and Garg [2023] for more information).
  - Method #B1: Two replicates of 500 mm (20 in.) long beams were tested after 2, 3, and 7 days of curing (total = 6 beams + 1 beam with a sensor).
- August 11, 2022: 275 mm (11 in.) Box Culvert North, Center, and South Walls poured with the sensor located a couple of feet down from the top of the center wall, and a couple of feet from the end of the wall.
  - Method #C2: Three replicates of 100 × 200 mm (4 × 8 in.) cylinders (total = 3 cylinders + 1 cylinder with a sensor) and two replicates of 150 × 300 mm (6 × 12 in.) cylinders (total = 2 cylinders + 1 cylinder with a sensor) were placed in the same cooler and tested after 3 days (Figure 6e).
  - Method #B1: Two replicates of 500 mm (20 in.) long beams were tested after 2, 3, and 7 days of curing (total = 6 beams + 1 beam with a sensor).
- August 22, 2022: 300 mm (12 in.) Box Culvert Lid poured with the sensor located in the center of the slab, and a couple feet from the end of the slab.
  - Method #C1: Three replicates of 100 × 200 mm (4 × 8 in.) cylinders were tested after 2, 3, and 7 days of curing (total = 9 cylinders + 1 cylinder with a sensor).
  - Method #C1: Two replicates of 150 × 300 mm (6 × 12 in.) cylinders were tested after 2, 3, and 7 days of curing (total = 6 cylinders + 1 cylinder with a sensor).
  - Method #C2: Three replicates of 100 × 200 mm (4 × 8 in.) cylinders were tested after 2, 3, and 7 days of curing (total = 9 cylinders + 1 cylinder with a sensor) (Figure 6c).
  - Method #C2: Two replicates of 150 × 300 mm (6 × 12 in.) cylinders were tested after 2, 3, and 7 days of curing (total = 6 cylinders + 1 cylinder with a sensor) (Figure 6d).
  - Method #B1: Two replicates of 500 mm (20 in.) long beams were tested after 2, 3, and 7 days of curing (total = 6 beams + 1 beam with a sensor).

CHAPTER 3: RESULTS AND DISCUSSION

LABORATORY DATA

Concrete was poured at ISU on October 1, 2021, and February 25, 2022, for preparing slabs, cylinders, and beams. The fresh properties of concrete pour, compressive strength of cylinders, flexural strength of beams, and variation of temperature in specimens is discussed in subsequent sections.

Fresh Properties and Quality Control

Table 2 presents a summary of fresh properties of all concrete mixes included in this study. The average slump and air content of the concrete mix received on October 1, 2021, were 108 mm (4.25 in.) and 6.9%, respectively. The test for water content of freshly mixed concrete using microwave oven drying in accordance with AASHTO T 318 resulted in w/c of 0.416. To ensure consistent mixture properties, a set of three 100 × 200 mm (4 × 8 in.) quality control (QC) cylinders were poured and cured inside the laboratory in a cooler under controlled temperature and humidity conditions. These cylinders were tested the next day after 24 hours of curing. For the October 2021 cast, QC cylinders produced an average 1-day compressive strength of 18.9 MPa (2741 psi.). The average slump and air content of the concrete mix received on February 25, 2022, were 70 mm (2.75 in.) and 6.4%, respectively. The w/c ratio for the February 2022 pour was 0.418, as determined in accordance with AASHTO T 318. Further, the QC cylinders produced an average 1-day compressive strength of 17.7 MPa (2566 psi).

Table 2. Concrete Mix Fresh Properties

Concrete Mix	Slump (in.)	Air Content %	Concrete Temperature (°F)	Air Temperature (°F)	Water-to-Cement Ratio
ISU Mix (10/1/2021)	4.25	6.9	76.7	66.6	0.416*
ISU Mix (2/25/2022)	2.75	6.4	60.5	22	0.418*
Box Culvert Field Demo Stage I (5/12/2022)	6.5	5.1	88	91	0.38[1]
Box Culvert Field Demo Stage I (5/20/2022)	–	8.0	82	85	0.37[1]
Box Culvert Field Demo Stage I (5/27/2022)	–	5.0	73	58	0.39[1]
Box Culvert Field Demo Stage I (6/8/2022)	6.5	5.9	74	65	0.38[1]
Box Culvert Field Demo Stage II (7/21/2022)	4.75	5.4	80	65	0.42[1]
Box Culvert Field Demo Stage II (8/11/2022)	7.5	5.6	84	88	0.43[1]
Box Culvert Field Demo Stage II (8/22/2022)	6.5	5.3	84	77	0.39[1]

*Determined using microwave oven drying method (AASHTO T 318); [1]The calculated water-to-cement ratio includes water from the admixtures. It was assumed 70% of the chemical admixture dosage was water.

Strength and Temperature Variation

October 2021 Cast

Table 3 summarizes all average compressive strength results from October 2021. Further results are discussed in subsequent sections.

Table 3. A Summary of Compressive Strength Results for October 2021 Cast

Curing Days	Cast-In-Place (CIP)		Cores		Method #C1		Method #C2		Method #C3	
	100 mm (4 in.)	150 mm (6 in.)	100 mm (4 in.)	150 mm (6 in.)	100 mm (4 in.)	150 mm (6 in.)	100 mm (4 in.)	150 mm (6 in.)	100 mm (4 in.)	150 mm (6 in.)
Compressive Strength (psi)										
Day 1	3277	3714	4304	3830	2876	3005	3603	4016	3419	3980
Day 3	4605	4714	5099	4031	4117	4217	4369	4935	4574	4669
Day 7	5361	5017	5827	4962	5024	5051	4890	5629	5383	5308
Compressive Strength (MPa)										
Day 1	22.6	25.6	29.7	26.4	19.8	20.7	24.8	27.7	23.6	27.4
Day 3	31.7	32.5	35.1	27.8	28.4	29.1	30.1	34.0	31.5	32.2
Day 7	36.9	34.6	40.2	34.2	34.6	34.8	33.7	38.8	37.1	36.6

100 mm (4 in.) Cylinders

Table 3 and Figure 7 present the variation of compressive strength of 100 mm (4 in.) cured and CIP cylinders with respect to curing days for the October 21 cast. Figure 8 presents the variation of the temperature inside cylinders cured using various methods, 7-day cured small/large slabs, and ambient air temperature. As demonstrated in Figure 7, Method #C1 estimated lowest 1-day and 3-day strength among all three curing methods. As indicated in Figure 8, this could be attributed to the lower temperature inside the cylinders cured using Method #C1 compared to the slab.

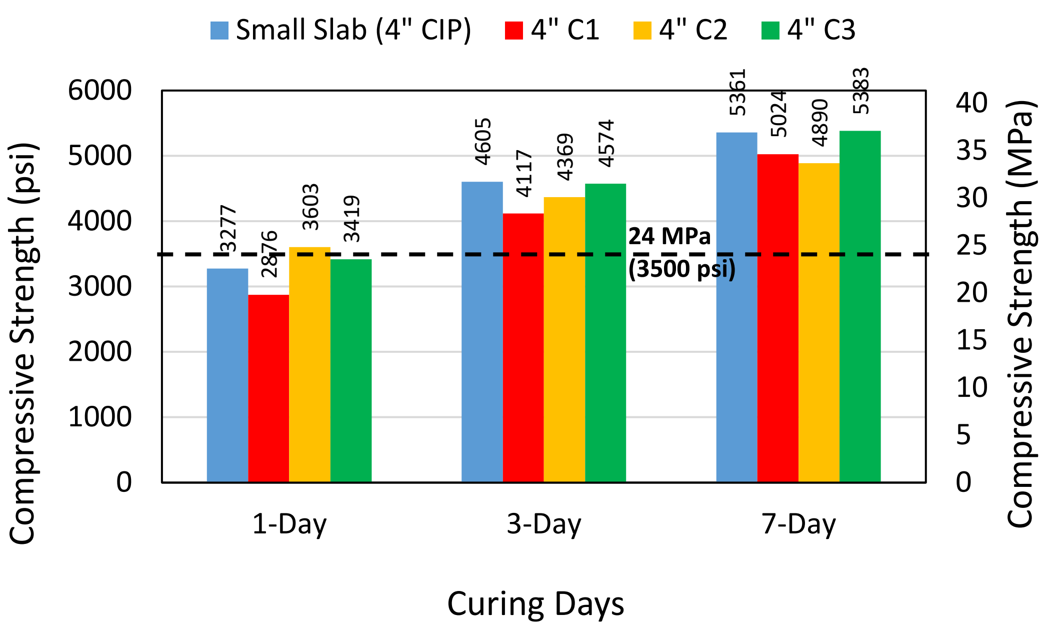


Figure 7. Chart. Compressive strength of 100 mm (4 in.) cylinders for the October 2021 cast.

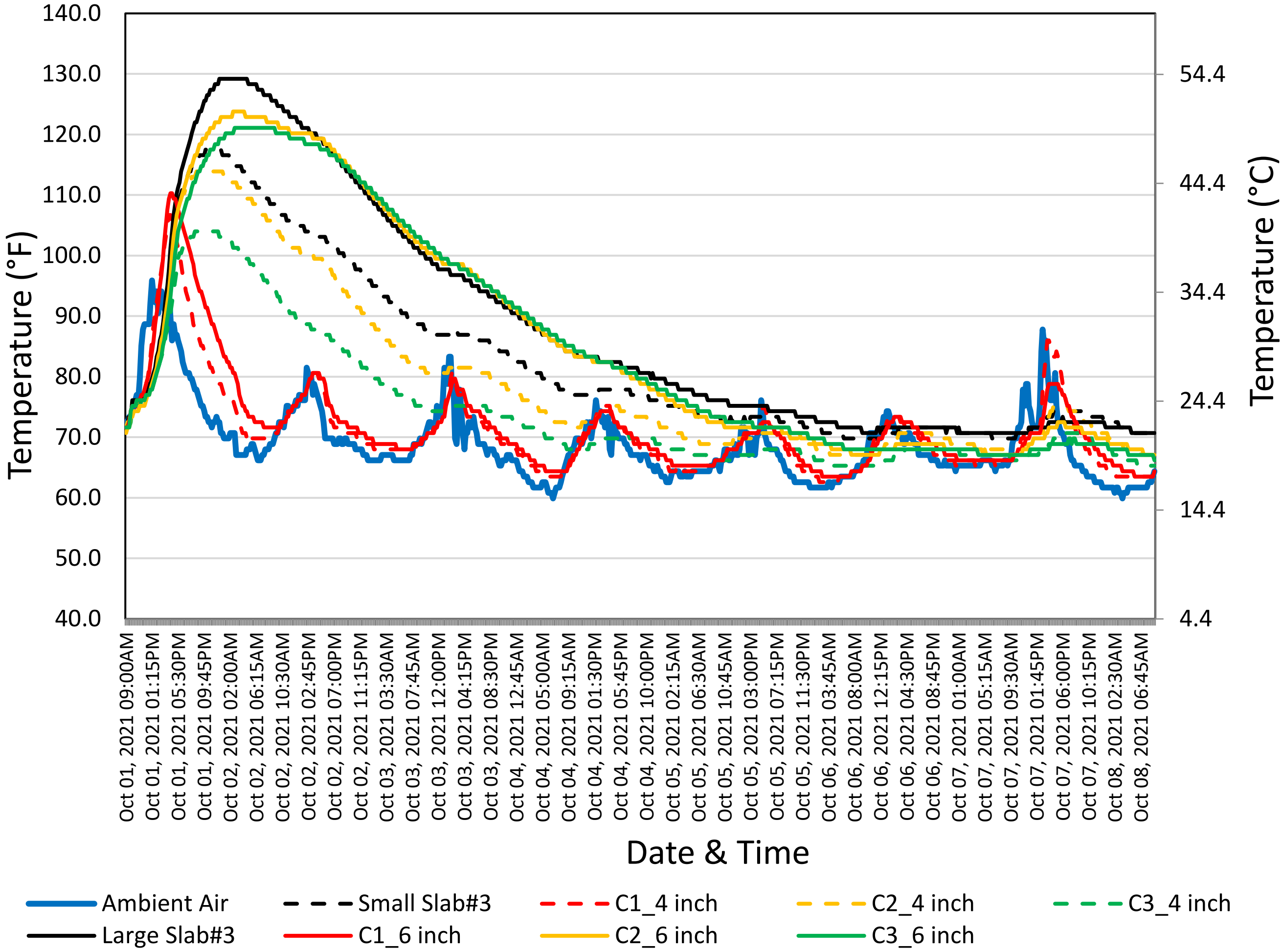


Figure 8. Graph. Temperature variation with time of specimens for the October 2021 cast.

Table 4. Difference in the Strength of 100 mm (4 in.) and 150 mm (6 in.) Cured Specimens and Corresponding CIP Specimens for the October 2021 Cast

Curing Days	Curing Method#											
	4" C1		4" C2		4" C3		6" C1		6" C2		6" C3	
	MPa	psi	MPa	psi	MPa	psi	MPa	psi	MPa	psi	MPa	psi
	[100 mm (4 in.) cured specimen strength] minus [100 mm (4 in.) CIP strength from small slab]						[150 mm (6 in.) cured specimen strength] minus [150 mm (6 in.) CIP strength from large slab]					
Day 1	−2.8	−401	2.2	327	1.0	142	−4.9	−709	2.1	302	1.8	266
Day 3	−3.4	−488	−1.6	−236	−0.2	−31	−3.4	−497	1.5	221	−0.3	−45
Day 7	−2.3	−336	−3.2	−471	0.2	23	0.2	34	4.2	613	2.0	292

Method #C3 followed by Method #C2 estimated compressive strength closest to the CIP cylinders. Table 4 shows the difference in the strength of 100 mm (4 in.) cured specimens and the corresponding 100 mm (4 in.) CIP specimens that were extracted from small slabs for the October 2021 cast. For example, the average compressive strength of 100 mm (4 in.) specimens cured using Method #C1 and CIP extracted from the small slab on Day 1 was 2876 psi (19.8 MPa) and 3277 psi (22.6 MPa), respectively. Therefore, the difference in the strength of 100 mm (4 in.) cured specimens and the corresponding 100 mm (4 in.) CIP specimens is –401 psi (–2.8 MPa) (2876 psi – 3277 psi = –401 psi, i.e., 19.8 MPa – 22.6 MPa = –2.8 MPa). Table 4 demonstrates that 1-, 3-, and 7-day strength estimated by Method #C3 was within +1 MPa (+142 psi), −0.2 MPa (−31 psi), and +0.2 MPa (+23 psi) compared to the strengths of corresponding CIP cylinders. For Method #C2, the 1-, 3-, and 7-day strength estimated was within +2.3 MPa (+327 psi), −1.6 MPa (−236 psi), and −3.2 MPa (−471 psi) compared to the strengths of corresponding CIP cylinders.

Further, Method #C2 provided higher 1-day strength values compared to corresponding cylinders cured using Method #C3. This could be attributed to slightly higher temperature values at the beginning inside cylinders cured using Method #C2 compared to Method #C3. During the first 24 hours, the average temperature difference between Methods #C2 and #C3 was 4.2°C (7.6°F) (see Figure 8). One reason for the higher temperature inside Method #C2 could be the thicker insulated walls of the cooler compared to the power-operated box used for Method #C3. It is also interesting to note that concrete attained more than the required 14-day compressive strength of 24 MPa (3500 psi) on day 1, as indicated by Method #C2 results.

150 mm (6 in.) Cylinders

Figure 9 presents the variation of compressive strength of 150 mm (6 in.) cured and CIP cylinders with respect to curing days for the October 2021 cast. Similar to the 100 mm (4 in.) cylinders observation, Method #C1 estimated the lowest 1-, 3-, and 7-day strength. This could be attributed to cylinders cured using Method #C1 having the lowest temperature among all curing methods. Table 4 shows the difference in the strength of 150 mm (6 in.) cured specimens and the corresponding 150 mm (6 in.) CIP specimens extracted from large slabs for the October 2021 cast. Table 4 demonstrates that on day 7, Method #C1, compared to Methods #C2 and #C3, had an estimated strength closest to the corresponding CIP cylinders (within +0.2 MPa [+34 psi]).

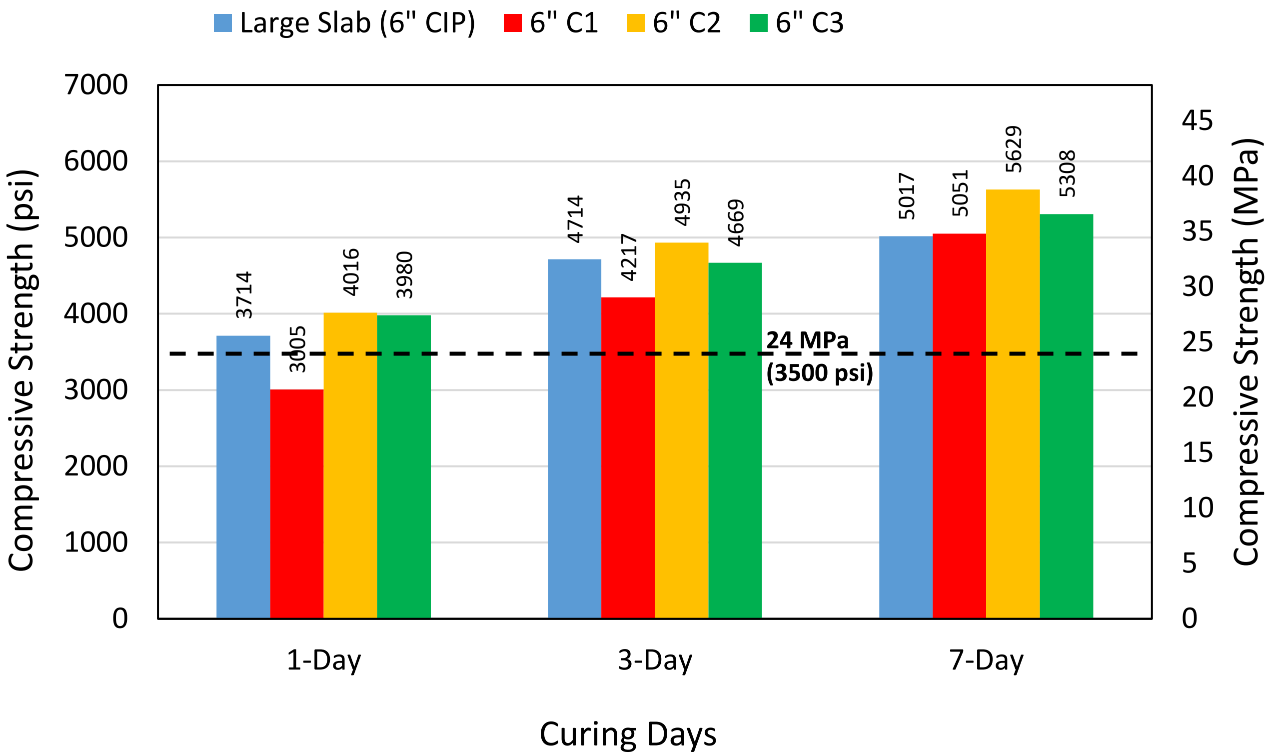


Figure 9. Chart. Compressive strength of 150 mm (6 in.) cylinders for the October 2021 cast.

Method #C3 followed by Method #C2 estimated 1-day and 3-day compressive strength closest to CIP cylinders (Table 4). Specifically, 1-day and 3-day strength estimated by Method #C3 was within +1.8 MPa (+266 psi) and −0.3 MPa (−45 psi), respectively, compared to the strength of corresponding CIP cylinders. For Method #C2, the 1-day and 3-day strength estimated was within +2.1 MPa (+302 psi) and +1.5 MPa (+221 psi) compared to the strength of corresponding CIP cylinders.

Further, Method #C2 provided the highest 1-, 3-, and 7-day strength values compared to corresponding cylinders cured using Method #C3. This could be attributed to slightly higher temperature values inside cylinders cured using Method #C2 compared to Method #C3. In the first 24 hours, there was an average temperature difference of 1.2°C (2.2°F) (see Figure 8). Note that concrete attained more than the required 14-day compressive strength of 24 MPa (3500 psi) on day 1, as indicated by CIP and Method #C2 and #C3 cylinders.

February 2022 Cast

Table 5 summarizes all average compressive strength results from the February 2022 cast. Further results are discussed in subsequent sections.

Table 5. A Summary of Compressive Strength Results for February 2022 Cast

Curing Days	Cast-In-Place (CIP)		Cores		Method #C1		Method #C2		Method #C3	
	100 mm (4 in.)	150 mm (6 in.)	100 mm (4 in.)	150 mm (6 in.)	100 mm (4 in.)	150 mm (6 in.)	100 mm (4 in.)	150 mm (6 in.)	100 mm (4 in.)	150 mm (6 in.)
Compressive Strength (psi)										
Day 1	1894	1913	1813	1484	300	431	1255	1955	2803	2801
Day 3	3777	3628	3641	2995	2631	2815	2957	3635	3797	4093
Day 7	5270	4850	5262	4063	5326	5099	4947	5154	4669	5325
Compressive Strength (MPa)										
Day 1	13.0	13.2	12.5	10.2	2.1	3.0	8.6	13.5	19.3	19.3
Day 3	26.0	25.0	25.1	20.6	18.1	19.4	20.4	25.0	26.2	28.2
Day 7	36.3	33.4	36.3	28.0	36.7	35.1	34.1	35.5	32.2	36.7

100 mm (4 in.) Cylinders

Table 5 and Figure 10 present the variation of compressive strength of 100 mm (4 in.) cured and CIP cylinders with respect to curing days for the February 2022 cast. Figure 11 presents the variation of temperature inside cylinders cured using various methods, 7-day cured small/large slabs, beams, and ambient air temperature. Figure 10 demonstrates that Method #C1 estimated the lowest 1-day and 3-day strength. This behavior could be attributed to the lower temperature inside the cylinders cured using Method #C1 compared to the slab (Figure 11). Table 6 shows the difference in the strength of 100 mm (4 in.) cured specimens and corresponding 100 mm (4 in.) CIP specimens extracted from small slabs for the February 2022 cast. Table 6 demonstrates that on day 7, Method #C1, compared to Methods #C2 and #C3, had an estimated strength closest to the corresponding CIP cylinders (within +0.4 MPa [+56 psi]).

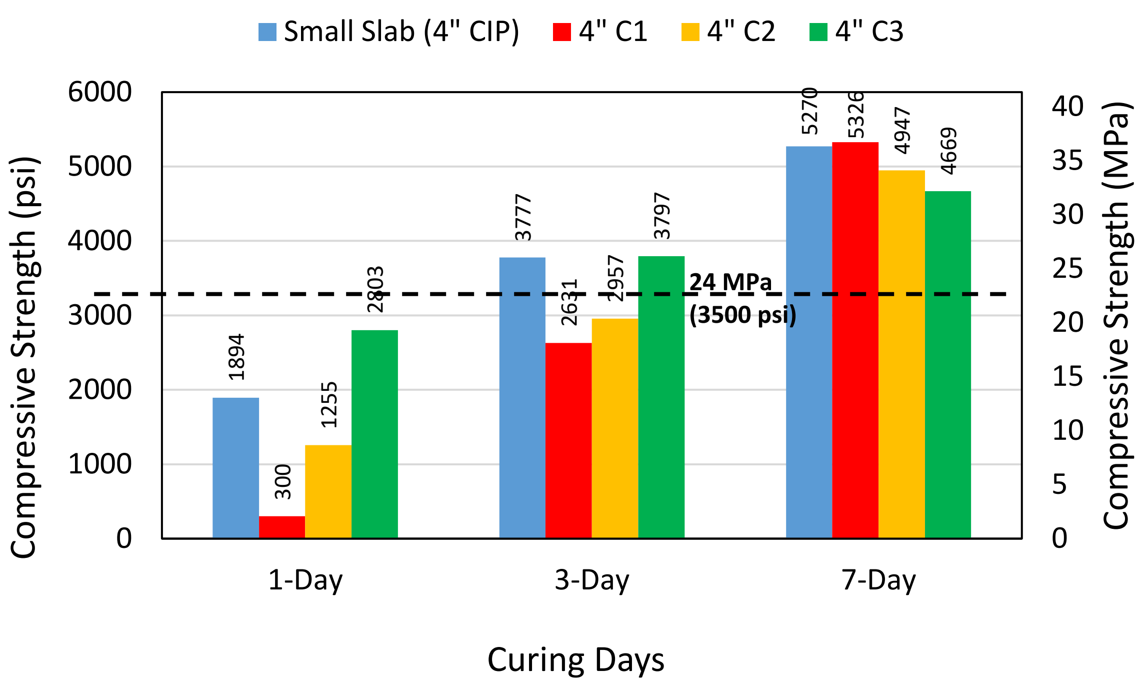


Figure 10. Chart. Compressive strength of 100 mm (4 in.) cylinders for the February 2022 cast.

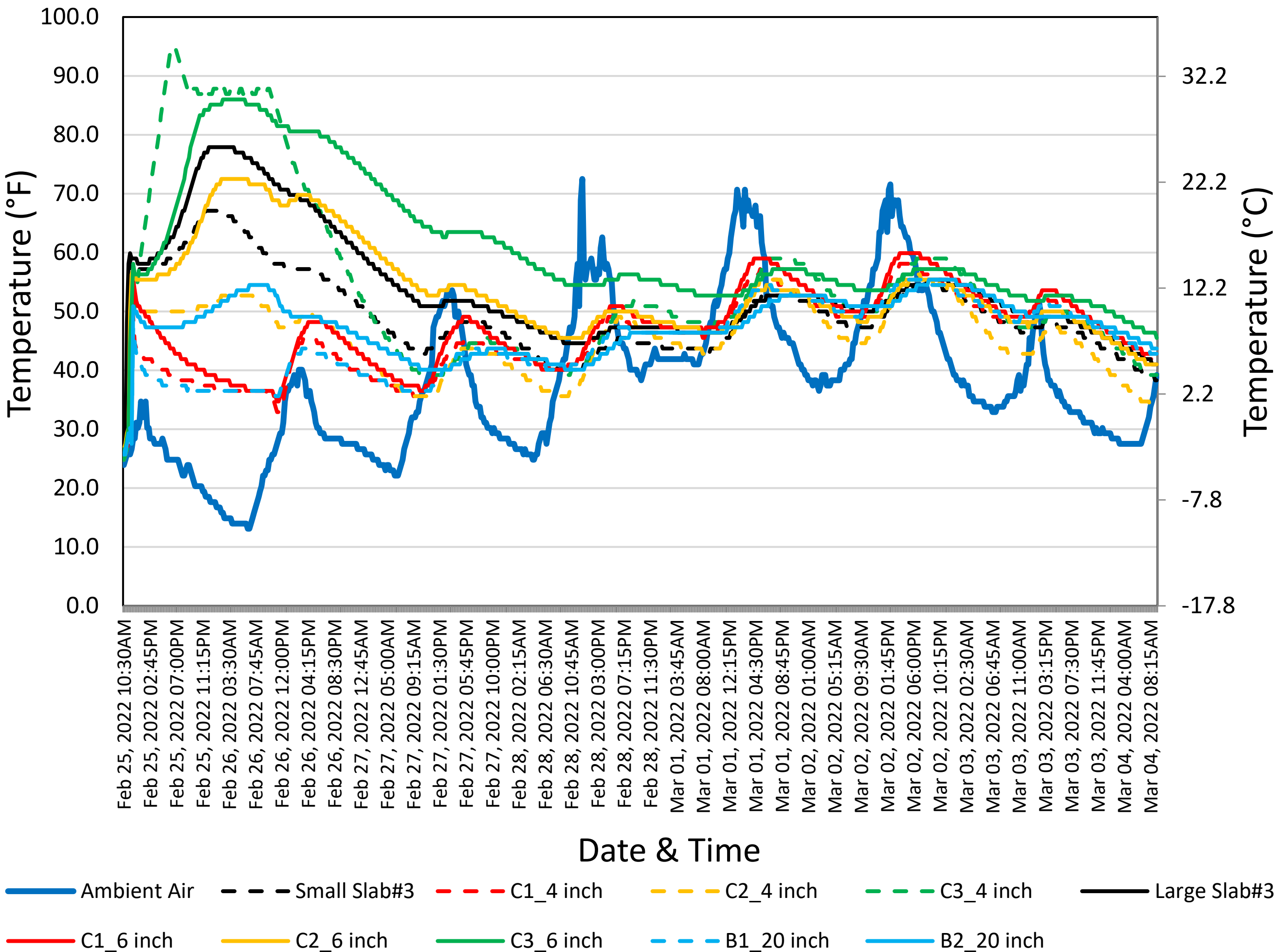


Figure 11. Graph. Temperature variation with time of specimens for the February 2022 cast.

Table 6. Difference in the Strength of 100 mm (4 in.) and 150 mm (6 in.) Cured Specimens and Corresponding CIP Specimens for the February 2022 Cast

Curing Days	Curing Method#											
	4" C1		4" C2		4" C3		6" C1		6" C2		6" C3	
	MPa	psi	MPa	psi	MPa	psi	MPa	psi	MPa	psi	MPa	psi
	[100 mm (4 in.) cured specimen strength] minus [100 mm (4 in.) CIP strength from small slab]						[150 mm (6 in.) cured specimen strength] minus [150 mm (6 in.) CIP strength from large slab]					
Day 1	−11.0	−1593	−4.4	−638	6.3	910	−10.2	−1482	0.3	42	6.1	888
Day 3	−7.9	−1145	−5.6	−820	0.1	20	−5.6	−813	0.1	7	3.2	465
Day 7	0.4	56	−2.2	−323	−4.1	−602	1.7	249	2.1	304	3.3	475

Method #C2 estimated the 1-day compressive strength closest to the corresponding CIP cylinders. Specifically, Methods #C2 and #C3 underestimated and overestimated 1-day strength by −4.4 MPa (−638 psi) and + 6.3 MPa (+ 910 psi), respectively. The better estimation of 1-day strength by Method

#C2 compared to Method #C3 could be attributed to temperature differences. In the first 24 hours, Method #C3 provided slightly warmer temperatures (an average 24 hour temperature difference of +17.1°C [+30.7°F]) compared to Method #C2 due to power-operated heating which resulted in overestimation of in-place strength.

Further, Method #C3 followed by Method #C2 estimated 3-day strength closest to the CIP cylinders, which was within +0.1 MPa (+20 psi) for Method #C3 and within −5.6 MPa (−820 psi) for Method #C2. However, Method #C3 again overestimated 3-day strength, and, therefore, Method#C3 may not be a good option for estimating early strength in cold weather. Note that the concrete slab attained more than the required 14-day compressive strength of 24 MPa (3500 psi) on day 3, as indicated by CIP cylinders and estimated by Method #C3.

150 mm (6 in.) Cylinders

Figure 12 presents the variation of compressive strength of 150 mm (6 in.) cured and CIP cylinders with respect to curing days for the February 2022 cast. Figure 12 demonstrates that Method #C1 estimated the lowest 1-, 3-, and 7-day strength among all three curing methods. The significant difference in 1-day and 3-day strength values of Method #C1 compared to CIP cylinders could be attributed to lower temperature inside the cylinders cured using Method #C1 compared to the slab. Table 6 shows the difference in the strength of 150 mm (6 in.) cured specimens and corresponding 150 mm (6 in.) CIP specimens extracted from large slabs for the February 2022 cast. Table 6 demonstrates that on day 7, Method #C1, compared to Methods #C2 and #C3, had an estimated strength closest to the corresponding CIP cylinders (within +1.7 MPa [+249 psi]).

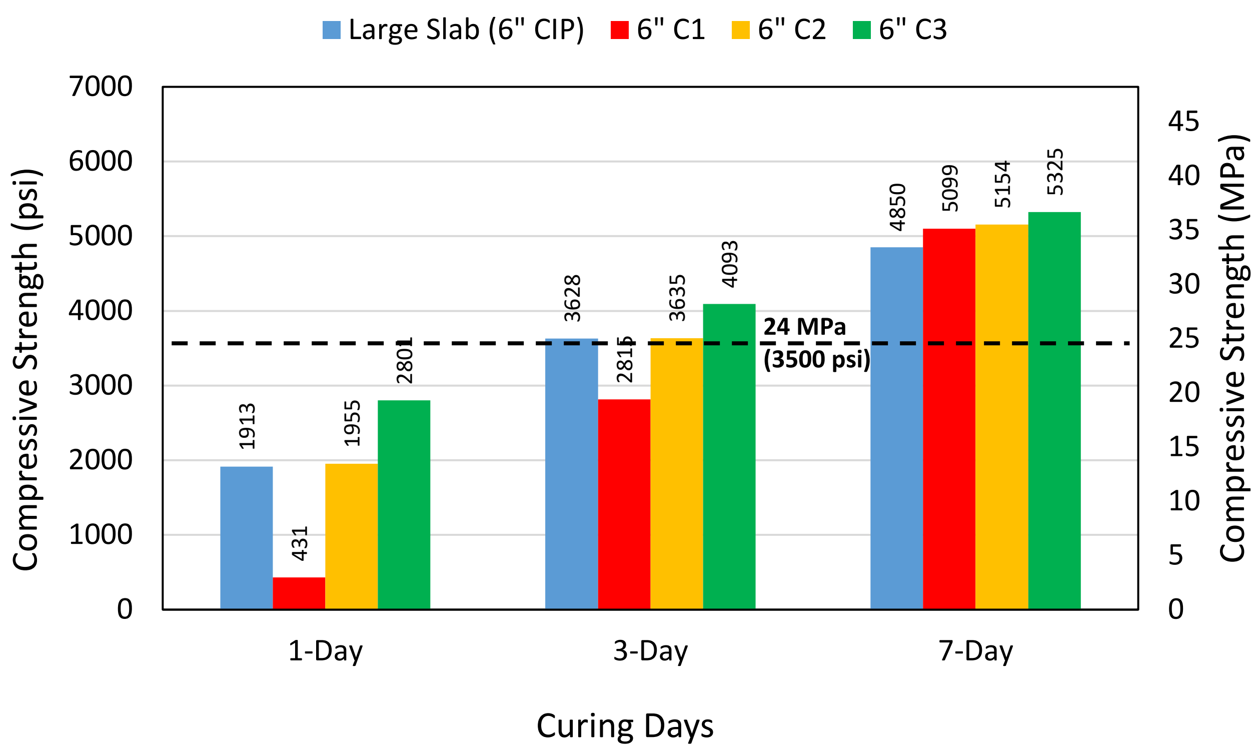


Figure 12. Chart. Compressive strength of 150 mm (6 in.) cylinders for the February 2022 cast.

Method #C2 estimated 1-day and 3-day compressive strength closest to the CIP cylinders. Specifically, the 1-day and 3-day strength estimated by Method #C2 was within +0.3 MPa (+42 psi) and +0.1 MPa (+7 psi), respectively, compared to the strength of corresponding CIP cylinders. This behavior of better estimation of 1-day and 3-day strength by Method #C2 compared to Method #C3 could be attributed to temperature differences. In the first 24 hours, Method #C3 provided slightly warmer temperatures (first 24 hour average temperature difference of +5.6°C [+10.0°F]) compared to Method #C2 due to power-operated heating, resulting in overestimation of strength (Figure 11). For instance, Method #C3 overestimated in-place 1-day, 3-day, and 7-day compressive strength by +6.1 MPa (+888 psi), +3.2 MPa (+465 psi), and +3.3 MPa (+475 psi), respectively. Therefore, Method#C3 may not be a good option for estimating early strength in cold weather. Note that concrete attained more than the required 14-day compressive strength of 24 MPa (3500 psi) on day 3, as indicated by CIP cylinders and estimated by Methods #C2 and #C3.

500 mm (20 in.) Beams

Table 7 summarizes all average flexural strength results from the October 2021 and February 2022 casts. Further results are discussed in subsequent sections. Figure 13 presents the variation of flexural strength of 500 mm (20 in.) cured beams with respect to curing days for the October 2021 and February 2022 casts. Figure 13 demonstrates that for the October 2021 cast, Method #B1 estimated slightly higher 1-day and 3-day flexural strength compared to Method #B2 (within 0.3 MPa [50 psi]). In contrast, the 7-day flexural strength estimated by Method #B2 was slightly higher than the corresponding flexural strength estimated by Method #B1 (within 0.2 MPa [35 psi]).

Table 7. A Summary of Flexural Strength Results for October 2021 and February 2022 Casts

Curing Days	October 2021 Cast		February 2022 Cast	
	Method #B1	Method #B2	Method #B1	Method #B2
Flexural Strength (psi)				
Day 1	526	476	78	201
Day 3	670	654	393	503
Day 7	636	671	573	601
Flexural Strength (MPa)				
Day 1	3.6	3.3	0.5	1.4
Day 3	4.6	4.5	2.7	3.5
Day 7	4.4	4.6	3.9	4.1

Note: All beams were tested for third-point flexural strength by using Universal Testing Machine

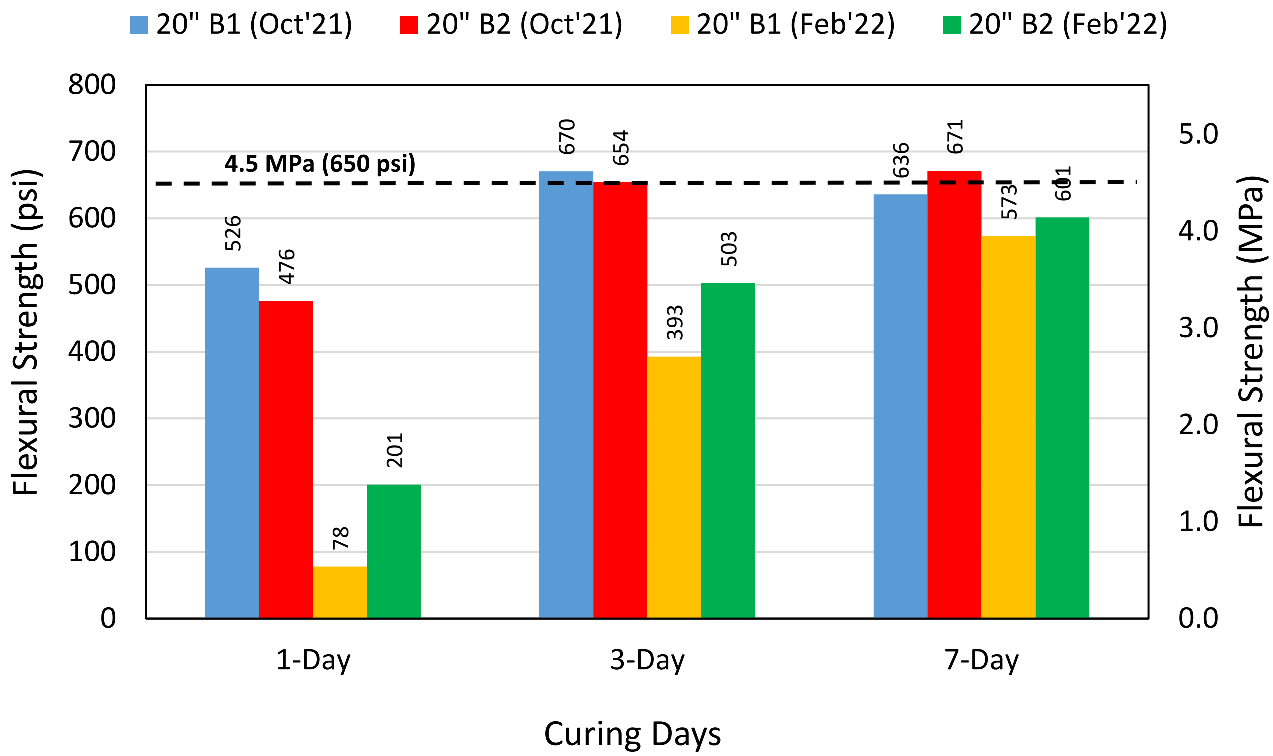


Figure 13. Chart. Flexural strength of 500 mm (20 in.) beams for October 2021 and February 2022 casts.

For the February 2022 cast, Method #B2 consistently estimated higher 1-, 3-, and 7-day flexural strength compared to Method #B1. The 1-, 3-, and 7-day strength estimated by Method #B2 was within +0.8 MPa (+123 psi), +0.7 MPa (+110 psi), and +0.2 MPa (+28 psi), respectively, compared to the strength of corresponding Method #B1 beams. This higher flexural strength could be attributed to higher temperature inside beams cured using Method #B2 compared to Method #B1 (see Figure 11). In the first 24 hours, Method #B2 provided an average warmer temperature of +6.7°C (+12.1°F) compared to corresponding Method #B1 beams.

A comparison of the temperature inside a 7-day cured large slab and cured beams from Figure 11 shows that both Method #B1 and #B2 provided a temperature trend similar to cast slabs. However, Method #B1 and #B2 beams experienced colder temperatures compared to slabs. For instance, Method #B1 and #B2 beams experienced an average temperature difference of −11.5°C (−20.7°F) and −7.9°C (−14.2°F) in the first 72 hours, respectively, compared to the large slab.

Note that concrete attained more than the required 14-day flexural strength of 4.5 MPa (650 psi) on day 3 for the October 2021 cast. However, for the February 2022 cast, concrete never attained the required 14-day flexural strength, which is contrary to observations made for cylinders. This could be attributed to the relatively lower temperature inside cured beams compared to cured cylinders. For instance, Method #B2 beams experienced an average lower temperature of −7.4°C (−13.4°F) in the first 72 hours compared to Method #C2 cylinders (Figure 11).

DISCUSSION OF LABORATORY DATA

For further analysis and discussion of laboratory data, Table 8 summarizes the average of 1-, 3-, and 7-day temperature difference and percent strength change between cured cylinders and slabs. For comparison, Table 8 also presents the minimum, maximum, and average ambient air temperature.

Small Versus Large Slab

Table 8 demonstrates that the large slab experienced higher temperature compared to the corresponding small slab cast during the same time. For instance, an average 3-day temperature difference between the large and small slab was +5.7°C (+10.3°F) and +4.2°C (+7.5°F) for the October 2021 and February 2022 casts, respectively. Peak temperatures experienced by the small and large slabs in October 2021 were 47.5°C (117.5°F) and 53°C (127.4°F), respectively. Peak temperatures experienced by the small and large slabs in February 2022 were 19.5°C (67.1°F) and 25.5°C (77.9°F), respectively. The increase in the temperature of concrete with size is consistent with observations reported by Harrison (1981). The study shows temperature rises to 37.7°C (100°F) for high cement content concrete mixes (Harrison, 1981). Therefore, the higher temperature rise provided by the larger slab is expected to be more common and a better representation of the pavement.

100 mm (4 in.) Versus 150 mm (6 in.) Cylinders

A comparison of Figure 7 and Figure 9 shows that the 1-day and 3-day compressive strength of 150 mm (6 in.) cylinders was higher than the corresponding 100 mm (4 in.) cylinders for the October 2021 cast. For instance, the difference in 150 mm (6 in.) and 100 mm (4 in.) strength for 1-day cured cylinders was +3 MPa (+437 psi) for CIP cylinders, 0.9 MPa (+129 psi) for Method #C1 cylinders, +2.8 MPa (+413 psi) for Method #C2 cylinders, and +3.9 MPa (+561 psi) for Method #C3 cylinders. Similarly, for the February 2022 cast, Figures 10 and 12 show that the 1-day compressive strength of 150 mm (6 in.) cylinders was higher than the corresponding 100 mm (4 in.) cylinders except for Method #C3 cylinders. The higher strength of 150 mm (6 in.) cylinders compared to 100 mm (4 in.) cylinders is contrary to expected behavior. The literature indicates that smaller size specimens tend to show higher strength compared to corresponding larger size specimens (Day, 1994; Malhotra, 1976). For example, Malhotra (1976) tested both 100 mm (4 in.) and 150 mm (6 in.) cylinders at a curing age ranging from 3 days to about 8 months (3 days, 7 days, 14 days, 28 days, 42 days, 60 days, 90 days, 120 days, 218 days). Further the difference in the strength of two sizes of cylinders was found to increase with an increase in the strength level of concrete. This difference in behavior could be attributed to the higher temperature generated by larger concrete mass in 150 mm (6 in.) cylinders compared to 100 mm (4 in.) cylinders (see Table 8). For instance, the average 3-day temperature difference between 150 mm (6 in.) and the corresponding 100 mm (4 in.) Method #C2 cylinders for the October 2021 and February 2022 casts were +7.6°C (+13.7°F) and +8.2°C (+14.7°F), respectively (Table 8).

Table 8. A Summary of Temperature Difference and Percent Strength Change Between Cured Cylinders and Slabs for October 2021 and February 2022 Casts

Curing Days	Ambient Air Temperature (°F)			Curing Method#							
				4" C1	4" C2	4" C3	Small slab	6" C1	6" C2	6" C3	Large slab
	Min	Max	Average	Average temperature (°F)							
October 2021 Cast											
Day 1	66.2	95.9	76.8	81.6	101.5	93.8	103.5	85.5	107.6	105.4	111.6
Day 3	59.9	95.9	71.8	74.5	90.8	83.4	95.2	76.2	104.5	103.8	105.5
Day 7	59.9	95.9	69.0	70.9	79.1	74.5	82.5	71.8	85.8	85.5	87.8
February 2022 Cast											
Day 1	13.1	34.7	22.1	37.9	49.9	80.8	60.4	40.5	63.2	73.3	68.7
Day 3	13.1	55.4	29.4	39.8	44.2	60.1	52.2	42.1	58.9	69.5	59.7
Day 7	13.1	72.5	37.9	45.4	45.6	54.8	49.5	47.2	53.6	60.8	53.9
Curing Days	Ambient Air Temperature			[Average cured 4" specimen temperature] minus [Average cured small slab temperature]				[Average cured 6" specimen temperature] minus [Average cured large slab temperature]			
October 2021 Cast											
Day 1	66.2	95.9	76.8	−21.9	−2.0	−9.7	—	−26.1	−4.0	−6.2	—
Day 3	59.9	95.9	71.8	−20.7	−4.4	−11.8	—	−29.3	−1.0	−1.7	—
Day 7	59.9	95.9	69.0	−11.6	−3.4	−8.1	—	−16.1	−2.0	−2.3	—
February 2022 Cast											
Day 1	13.1	34.7	22.1	−22.5	−10.5	20.4	—	−28.2	−5.5	4.6	—
Day 3	13.1	55.4	29.4	−12.4	−8.0	7.9	—	−17.6	−0.8	9.8	—
Day 7	13.1	72.5	37.9	−4.1	−3.9	5.3	—	−6.7	−0.3	6.9	—
Curing Days	Ambient Air Temperature			[Average cured 4" specimen temperature] minus [Average cured large slab temperature]							
October 2021 Cast											
Day 1	66.2	95.9	76.8	−30.0	−10.1	−17.8	—	—	—	—	—
Day 3	59.9	95.9	71.8	−31.0	−14.7	−22.1	—	—	—	—	—
Day 7	59.9	95.9	69.0	−16.9	−8.7	−13.4	—	—	—	—	—
February 2022 Cast											
Day 1	13.1	34.7	22.1	−30.8	−18.8	12.1	—	—	—	—	—
Day 3	13.1	55.4	29.4	−19.9	−15.5	0.4	—	—	—	—	—
Day 7	13.1	72.5	37.9	−8.5	−8.3	0.9	—	—	—	—	—
Curing Days	Ambient Air Temperature			% Strength Change = (Method#C1 or #C2 or #C3 strength × 100/ slab strength*)							
October 2021 Cast											
Day 1	66.2	95.9	76.8	88	110	104	—	81	108	107	—
Day 3	59.9	95.9	71.8	89	95	99	—	89	105	99	—
Day 7	59.9	95.9	69.0	94	91	100	—	101	112	106	—
February 2022 Cast											
Day 1	13.1	34.7	22.1	16	66	148	—	23	102	146	—
Day 3	13.1	55.4	29.4	70	78	101	—	78	100	113	—
Day 7	13.1	72.5	37.9	101	94	89	—	105	106	110	—

*Slab strength was determined by testing cast-in-place (CIP) cylinders extracted from slabs.

Table 8 presents a summary of the 1-, 3-, and 7-day average of the temperature difference between cured 100 mm (4 in.) or 150 mm (6 in.) cylinders and a large slab. The results in Table 8 demonstrate that the temperature difference between 100 mm (4 in.) cured cylinders and the corresponding large slab was higher than the temperature difference between 150 mm (6 in.) cured cylinders and the corresponding large slab. For example, for the October 2021 cast, the average 3-day temperature difference between 100 mm (4 in.) Method #C2 cylinders and the large slab was (–25.9°C) −14.7°F while the average 3-day temperature difference between 150 mm (6 in.) Method #C2 cylinders and the large slab was −18.3°C (−1.0°F). So, 150 mm (6 in.) cylinders appear to mimic the temperature profile of pavement (the large slab) better than 100 mm (4 in.) cylinders. Therefore, 150 mm (6 in.) cylinders could be conservatively used for estimating the early opening strength of an in-place concrete item.

Method #C1 Versus Method #C2 Versus Method #C3

Table 8 presents a summary of the 1-, 3-, and 7-day percent strength changes between cured 100 mm (4 in.) or 150 mm (6 in.) cylinders and the corresponding slab. The results in Table 8 demonstrate that Methods #C2 and #C3 are better at estimating early strength (1 to 3 days) of a concrete item compared to Method #C1. Methods #C1, #C2, and #C3 cylinders of 100 mm (4 in.) estimated the early strength of a concrete item (i.e., small slab) within 88%–89%, 95%–110%, and 99%–104% for the October 2021 cast, respectively. Methods #C1, #C2, and #C3 cylinders of 150 mm (6 in.) estimated the early strength of a concrete item (i.e., large slab) within 81%–89%, 105%–108%, and 99%–107% for the October 2021 cast, respectively. For the February 2022 cast, Methods #C1, #C2, and #C3 100 mm (4 in.) cylinders estimated the early strength of a concrete item (i.e., small slab) within 16%–70%, 66%–78%, and 101%–148%, respectively. Further, Methods #C1, #C2, and #C3 cylinders of 150 mm (6 in.) estimated the early strength of a concrete item (i.e., large slab) within 23%–78%, 100%–102%, and 113%–146% for the February 2022 cast, respectively. On the contrary, Method #C1 cylinders were found to estimate the 7-day strength of a concrete item within an acceptable range of 94%–101% and 101%–105% for 100 mm (4 in.) and 150 mm (6 in.) cylinders, respectively. The 150 mm (6 in.) cylinders cured using Methods #C2 and #C3 overestimated the 7-day strength. For instance, Method #C2 150 mm (6 in.) cylinders overestimated the 7-day strength by 112% and 106% for the October 2021 and February 2022 casts, respectively. On the other hand, Method #C3 150 mm (6 in.) cylinders overestimated the 7-day strength by 106% and 110% for the October 2021 and February 2022 casts, respectively.

The abovementioned behavior could be attributed to higher temperature differences between Method #C1 cylinders and small/large slabs (except 7-day temperature for the February 2022 cast) (see Table 8). The temperature difference between Method #C2 cylinders and small/large slabs was either lower or similar to the corresponding temperature difference between Method #C3 cylinders and small/large slabs (Table 8). For example, for the October 2021 cast, 100 mm (4 in.) Method #C2 and #C3 cylinders experienced an average 3-day temperature difference of −2.4°C (−4.4°F) and −6.6°C (−11.8°F), respectively, compared to the small slab (Table 8). For the February 2022 cast, 150 mm (6 in.) Method #C2 and #C3 cylinders experienced an average 3-day temperature difference of −0.4°C (−0.8°F) and +5.4°C (+9.8°F), respectively, compared to the large slab (Table 8). The results in Table 8 also demonstrate that Method #C3 overheated specimens compared to slabs for the February 2022 cast. It is also important to note that Method #C2 is more cost-effective, requires no power, and is easier to handle/transport than Method #C3. Therefore, only Methods #C1 and #C2 were selected for further evaluation in the field, as discussed in subsequent sections.

Traffic Opening Times—Cylinders Versus Beams

The concrete mix used in this study requires a minimum compressive strength of 24 MPa (3500 psi) or flexural strength of 4.5 MPa (650 psi) of a field-cured specimen before pavement can be opened to traffic. Therefore, based on 150 mm (6 in.) compressive strength results of Method #C2, pavement cast in October 2021 and February 2022 can be opened to traffic on day 1 and day 3, respectively. However, based on flexural strength results of Methods #B1 and #B2, pavement cast in October 2021 can be opened to traffic on day 3, which is two days later than the corresponding compressive strength results of Method #C2. However, for the February 2022 cast, the beams never attained the required 14-day flexural strength within the 7-day curing period. This could be attributed to the relatively low temperature inside cured beams compared to cured cylinders and slabs.

FIELD DATA

Field data were collected from an IDOT District 5 box culvert demonstration project. The compressive strength of cylinders, flexural strength of beams, and variation of temperature in specimens is discussed in subsequent sections. It is also important to note here that beams were tested for center-point flexural strength by using a hand-operated beam breaker. This center-point loading test was conducted in accordance with the AASHTO T 177 test method. This method is different than the one used in the laboratory (third-point loading was used for the laboratory data).

IDOT District 5 Box Culvert Demonstration Project

Table 2 summarizes the fresh properties of concrete mixes from the box culvert project. All average compressive strength and flexural strength results from the box culvert project are summarized in Table 9. Further results are discussed in subsequent paragraphs.

Table 9. A Summary of Compressive and Flexural Strength Results for the Box Culvert Project

Method Type	Specimen Size	psi			MPa		
		2-Day	3-Day	7-Day	2-Day	3-Day	7-Day
Pouring Details		*Box Culvert Floor on 5/12/2022 (Stage 1: Without RCA)*					
Water cured[*]	100 mm (4 in.)	3708	5305	5406	25.5	36.6	37.2
Method #B1[#,*]	500 mm (20 in.)	655	711	800	4.5	4.9	5.5
Pouring Details		*Box Culvert Center Wall on 5/20/2022 (Stage 1: Without RCA)*					
Method #C2[2]	100 mm (4 in.)	NA	4720	NA	NA	32.5	NA
	150 mm (6 in.)	NA	4600	NA	NA	31.7	NA
Method #B1[#,*]	500 mm (20 in.)	650	734	911	4.5	5.1	6.3
Pouring Details		*Box Culvert N & S Walls on 5/27/2022 (Stage 1: Without RCA)*					
Method #B1[#,*]	500 mm (20 in.)	734	733	856		5.1	5.9
Pouring Details		*Box Culvert Lid on 6/8/2022 (Stage 1: Without RCA)*					
Method #C1	100 mm (4 in.)	4086	4493	5325	28.2	31.0	36.7
	150 mm (6 in.)	3817	4089	5299	26.3	28.2	36.5
Method #C2[1]	100 mm (4 in.)	4344	4502	5460	29.9	31.0	37.6
	150 mm (6 in.)	4279	4736	4923	29.5	32.6	33.9
Method #B1[#,*]	500 mm (20 in.)	667	734	789	4.6	5.1	5.4
Pouring Details		*Box Culvert Floor on 7/21/2022 (Stage 2: With RCA)*					
Water cured[*]	100 mm (4 in.)	5354	6010	6886	36.9	41.4	47.4
Method #B1[#,*]	500 mm (20 in.)	811	911	889	5.6	6.3	6.1
Pouring Details		*Box Culvert Walls on 8/11/2022 (Stage 2: With RCA)*					
Method #C2[2]	100 mm (4 in.)	NA	5875	NA	NA	40.5	NA
	150 mm (6 in.)	NA	5874	NA	NA	40.5	NA
Method #B1[#,*]	500 mm (20 in.)	667	800	889	4.6	5.5	6.1
Pouring Details		*Box Culvert Lid on 8/22/2022 (Stage 2: With RCA)*					
Method #C1	100 mm (4 in.)	4927	5974	7096	33.9	41.2	48.9
	150 mm (6 in.)	5295	5772	6703	36.5	39.8	46.2
Method #C2[1]	100 mm (4 in.)	6069	6333	6794	41.8	43.6	46.8
	150 mm (6 in.)	6070	6267	6498	41.8	43.2	44.8
Method #B1[#,*]	500 mm (20 in.)	750	734	823	5.2	5.1	5.7

[*]Specimens were demolded after one day and then kept in a water tank until the day of testing.
[#]All beams were tested for flexural strength by using a hand-operated beam breaker with center-point loading.
[1]All 4 in. specimens were kept in one cooler and all 6 in. specimens were kept in a separate cooler (see the "Field Data Collection" section in Chapter 2 for details)
[2]All 4 in. and 6 in. specimens were kept together in the same cooler (see the "Field Data Collection" section in Chapter 2 for details).

May 2022 Cast (Stage I Mix)

The compressive strength results from the cast on May 20, 2022, using the Stage I mix are presented in Table 9 and Figure 14. Figure 15 presents the flexural strength variation of Method #B1 cured beams that were cast on May 12, May 20, and May 27 of 2022. Figure 16 presents the variation of temperature inside beams, in-pour, and ambient air temperature for the cast on May 12, 2022. Figure 17 shows the variation of the temperature inside cured cylinders, beam, in-pour, and ambient air temperature for the cast on May 20, 2022.

For May 20, 2022 cast, both four 100 mm (4 in.) and three 150 mm (6 in.) cylinders were kept in the same cooler and cured using Method #C2. Then, specimens were tested after three days of curing. Both 100 mm (4 in.) and 150 mm (6 in.) specimens provided approximately similar compressive strength. This could be attributed to similar temperature variation inside 100 mm (4 in.) and 150 mm (6 in.) specimens, as shown in Figure 17. Note that 100 mm (4 in.) and 150 mm (6 in.) cylinders produced temperatures ranging slightly higher than in-pour temperature (Figure 17). This slightly higher temperature caused by Method #C2 could result in overestimation of in-place concrete strength. Figure 17 also shows that out of all specimens tested for the cast on May 20, 2022, beams experienced the lowest temperature, and the trend was similar to ambient air temperature.

For both 100 mm (4 in.) and 150 mm (6 in.) specimens from the cast on May 20, 2022, concrete showed compressive strength greater than the required compressive strength of 24 MPa (3500 psi) on day 3 (Figure 14). Figure 15 demonstrates that the concrete showed flexural strength greater than the required flexural strength of 650 psi on day 2 for all casts on May 12, May 20, and May 27 of 2022.

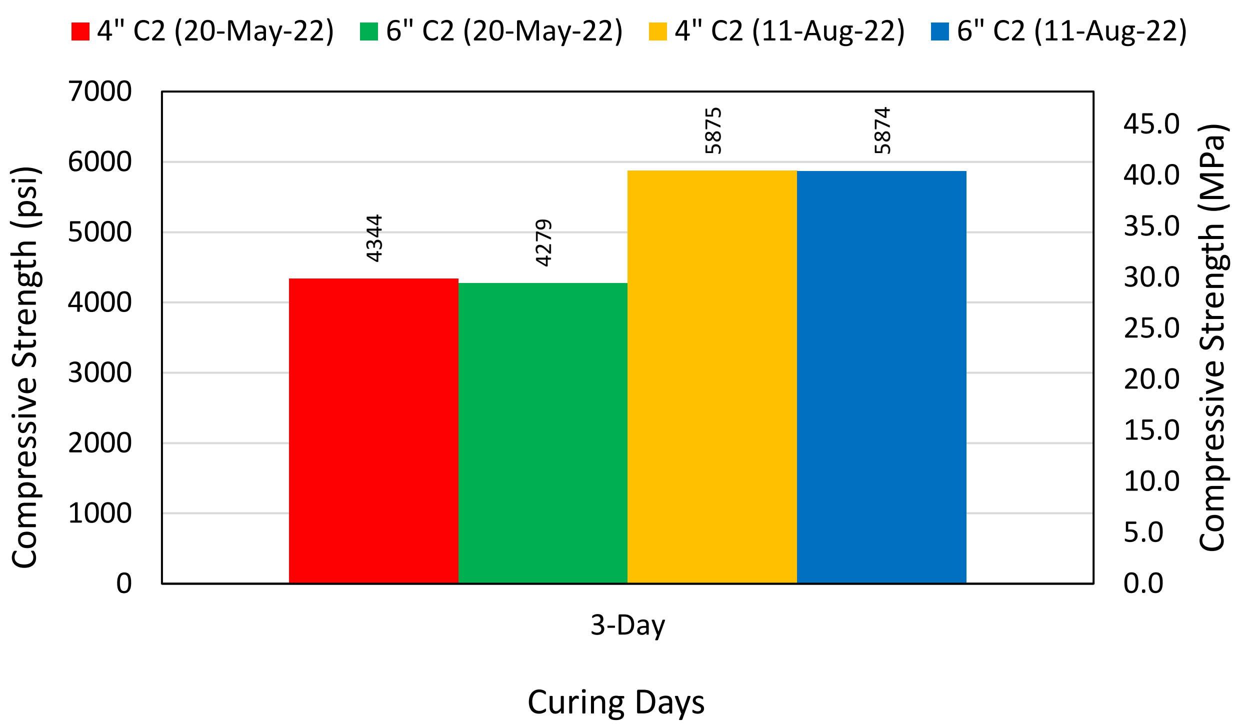


Figure 14. Chart. Compressive strength of 100 mm (4 in.) and 150 mm (6 in.) cylinders for the May 20 and August 11, 2022, cast.

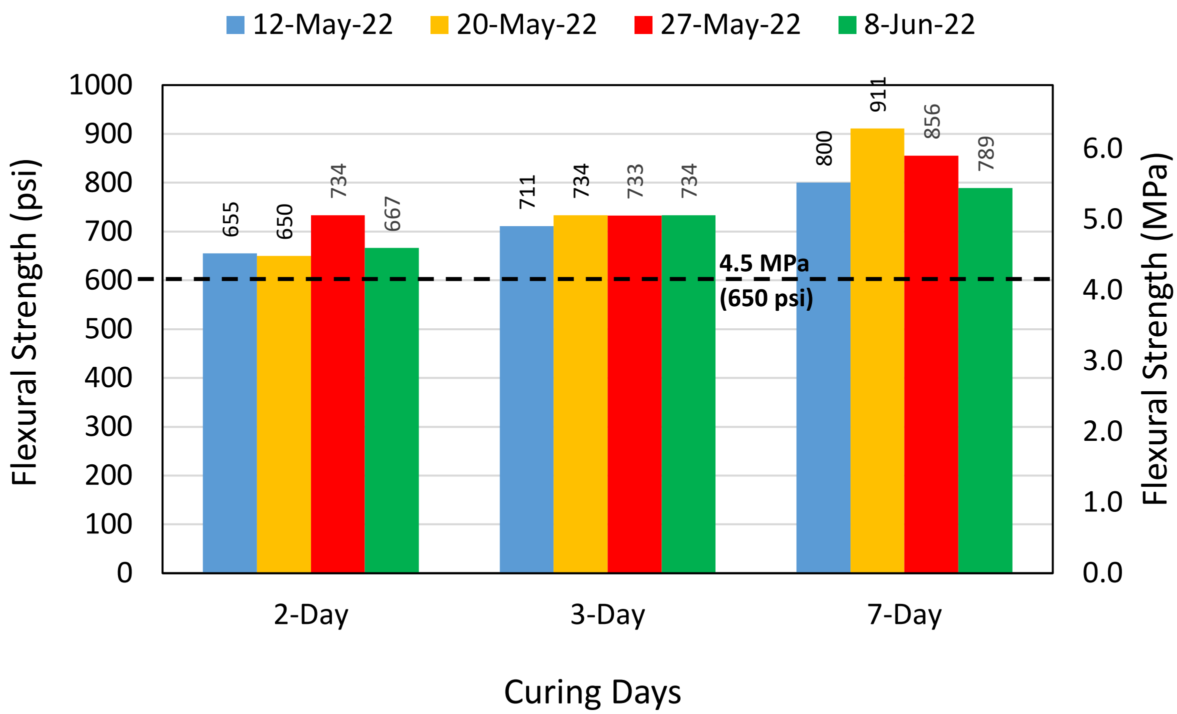


Figure 15. Chart. Flexural strength of 500 mm (20 in.) beams for the May and June 2022 cast.

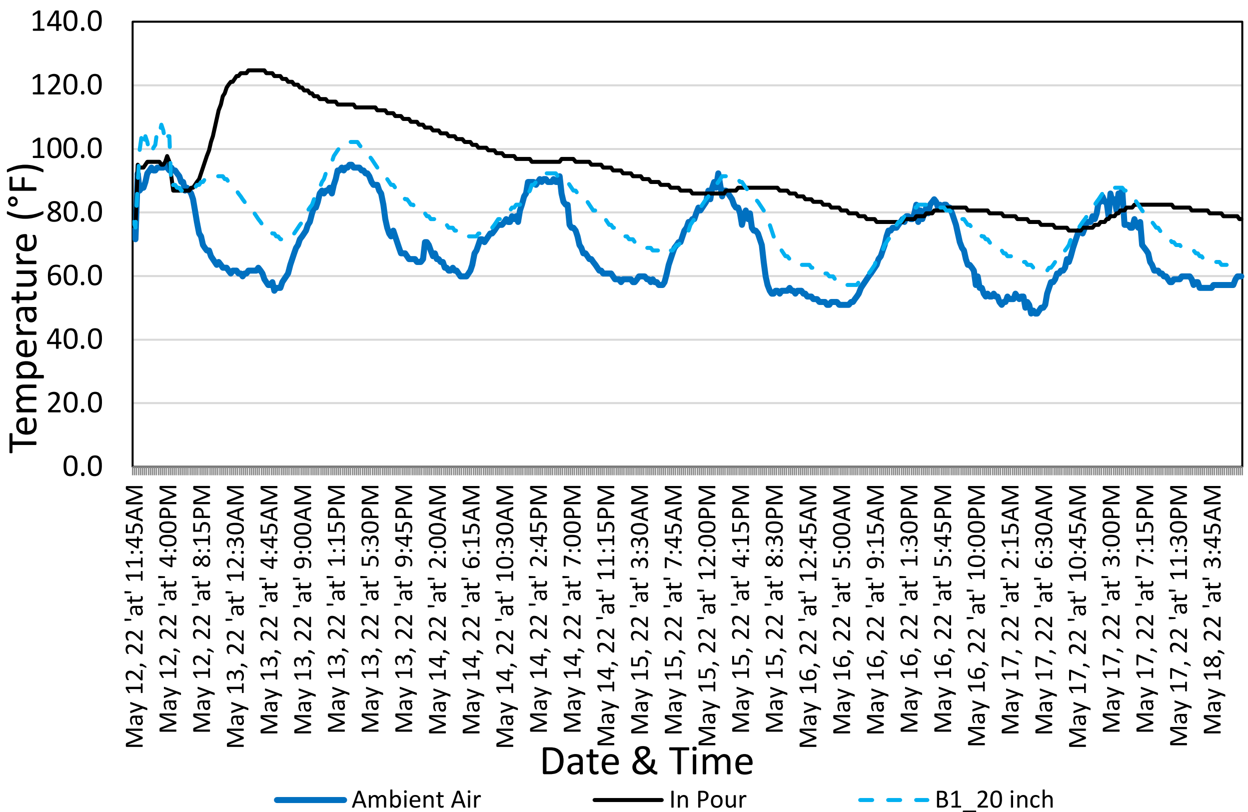


Figure 16. Graph. Temperature variation with time of specimens for the May 12, 2022, cast.

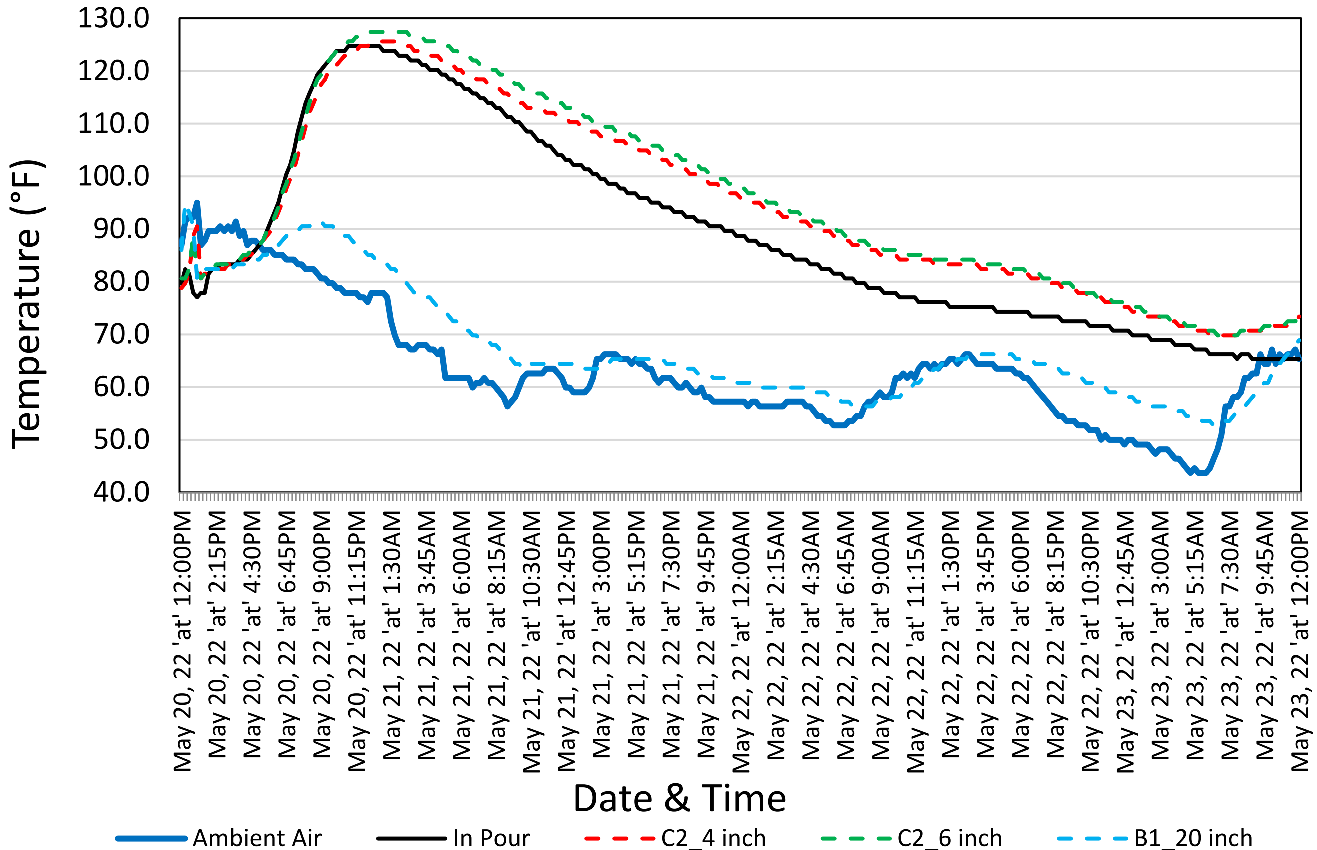


Figure 17. Graph. Temperature variation with time of specimens for the cast on May 20, 2022.

June 2022 Cast (Stage I Mix)

Figure 18 presents the variation of compressive strength of 100 mm (4 in.) and 150 mm (6 in.) cured cylinders with respect to curing days for the cast on June 8, 2022. Figure 19 presents the variation of the temperature inside cured cylinders, beam, in-pour, and ambient air temperature. Figure 18 demonstrates that Method #C1 estimated the lowest 2-, 3-, and 7-day strength among both methods. This could be attributed to low temperature inside cylinders cured using Method #C1 (Figure 19). For both 100 mm (4 in.) and 150 mm (6 in.) specimens, concrete showed strength greater than the required compressive strength of 24 MPa (3500 psi) on day 2. Figure 15 shows that the concrete showed flexural strength greater than the required flexural strength of 650 psi on day 2. Figure 19 shows that 150 mm (6 in.) cylinders cured using Method #C2 provided temperature closest to in-pour temperature among all specimens tested.

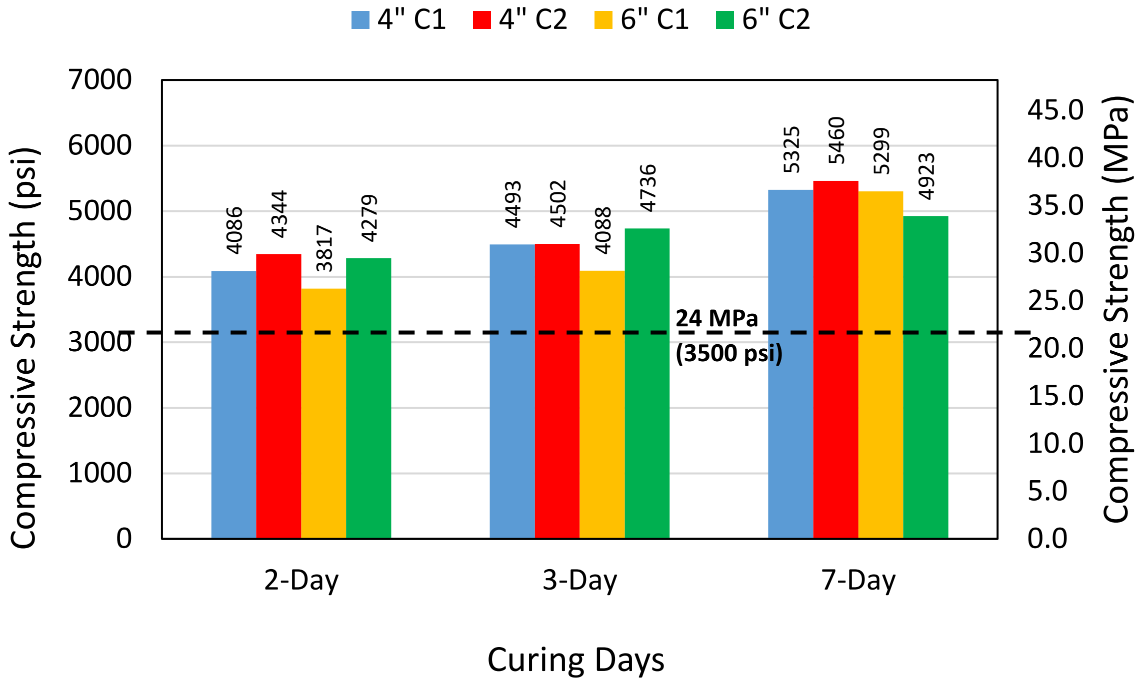


Figure 18. Chart. Compressive strength of 100 mm (4 in.) and 150 mm (6 in.) cylinders for the June 8, 2022, cast.

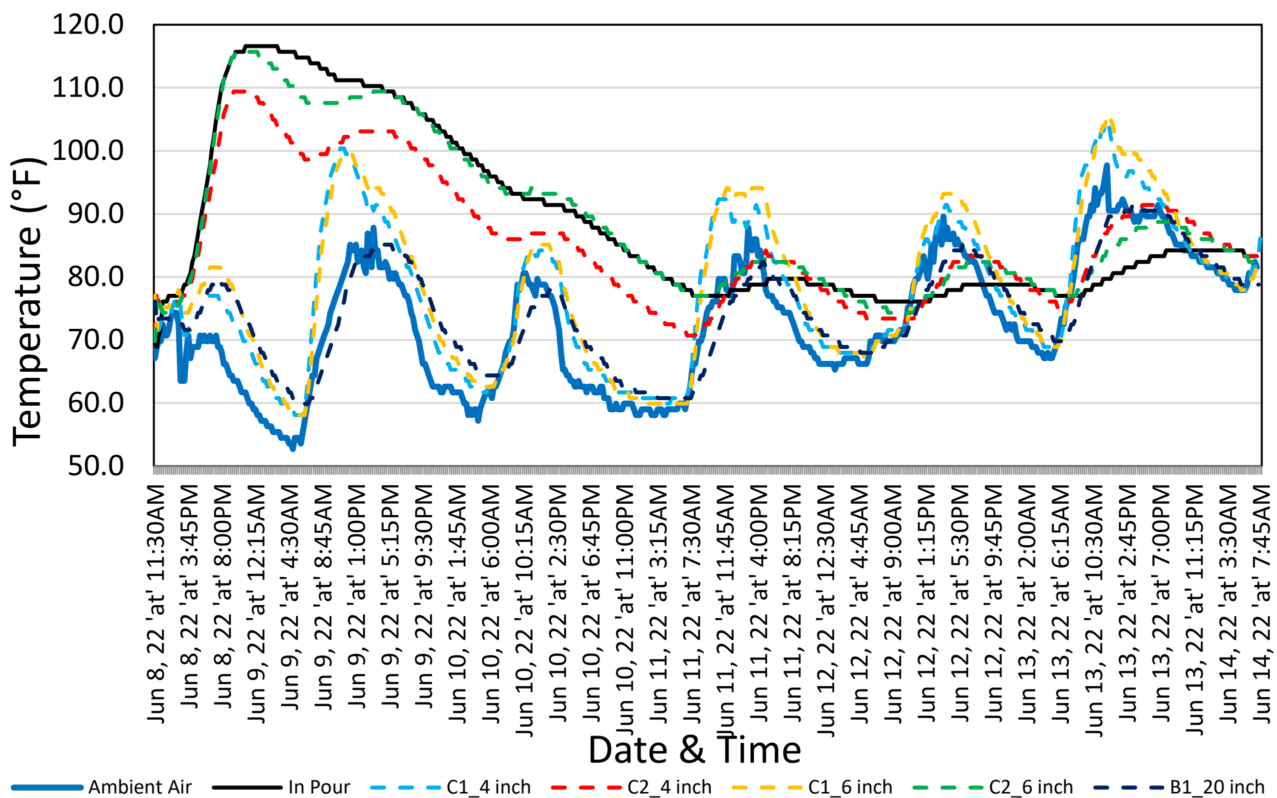


Figure 19. Graph. Temperature variation with time of specimens for the cast on June 8, 2022.

July and August 2022 Cast (Stage II Mix)

Figure 20 presents the variation of compressive strength of 100 mm (4 in.) and 150 mm (6 in.) cured cylinders with respect to curing days for the cast on August 22, 2022. Figure 21 presents the variation of flexural strength of Method #B1 cured beams for casts on July 21, August 11, and August 22 of 2022. Figure 22 show the variation of the temperature inside beam and in-pour for the July 21 cast. Figures 23 and 24 show the variation of the temperature inside cured cylinders, beam, in-pour, and ambient air temperature for the August 11 and August 22 casts, respectively. The compressive strength results from the August 11 cast using Stage II mix are presented in Table 9 and Figure 14.

Figure 20 demonstrated that Method #C1 estimated the lowest 2-, 3-, and 7-day strength among both methods. This could be attributed to the low temperature inside cylinders cured using Method #C1 (Figure 19). For both 100 mm (4 in.) and 150 mm (6 in.) specimens, concrete showed strength greater than the required compressive strength of 24 MPa (3500 psi) on day 2. According to Figure 21, concrete showed flexural strength greater than the required flexural strength of 4.5 MPa (650 psi) on day 2 for all casts on July 21, August 11, and August 22 of 2022.

For the May 20, 2022, and August 11, 2022, casts, both four 100 mm (4 in.) and three 150 mm (6 in.) cylinders were kept in the same cooler and cured using Method #C2. Then, specimens were tested after three days of curing, and the results are presented in Figure 14. Both 100 mm (4 in.) and 150 mm (6 in.) specimens provided approximately similar compressive strength. This could be attributed to similar temperature variation inside 100 mm (4 in.) and 150 mm (6 in.) specimens, as shown in Figure 17 for the May 20, 2022, cast and Figure 23 for the August 11, 2022, cast. Note that 100 mm (4 in.) and 150 mm (6 in.) cylinders produced temperature ranging slightly higher than in-pour temperature for casts on May 20, 2022 (Figure 17) and August 11, 2022 (Figure 23). Using Method #C2 could result in overestimation of in-place strength. For both 100 mm (4 in.) and 150 mm (6 in.) specimens, concrete showed compressive strength greater than the required compressive strength of 24 MPa (3500 psi) on day 3.

For August 22, 2022 cast, Figure 24 shows that both 100 mm (4 in.) and 150 mm (6 in.) cylinders cured using Method #C2 provided temperatures slightly higher compared to the in-pour temperature. This could result in overestimation of in-place strength.

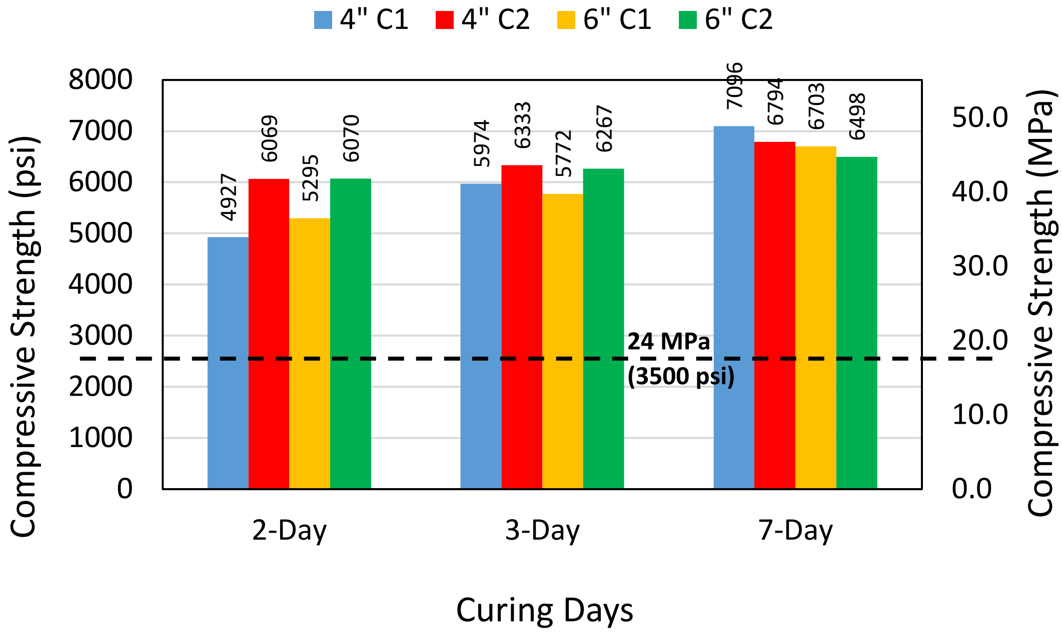


Figure 20. Chart. Compressive strength of 100 mm (4 in.) and 150 mm (6 in.) cylinders for the cast on August 22, 2022.

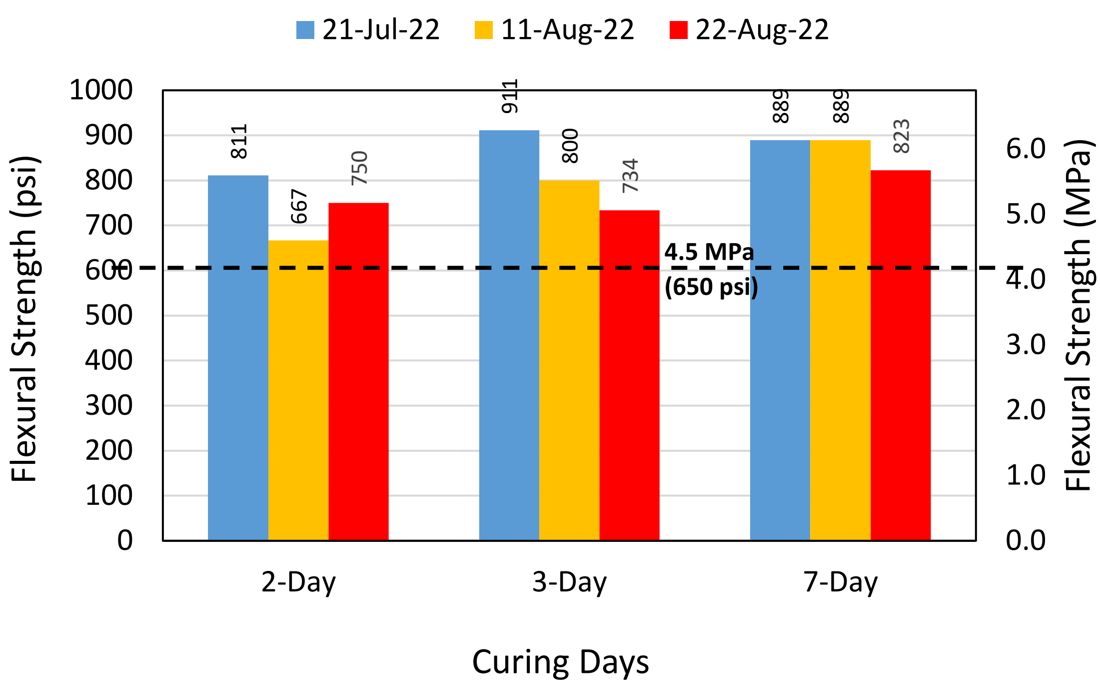


Figure 21. Chart. Flexural strength of 500 mm (20 in.) beams for the July and August 2022 cast.

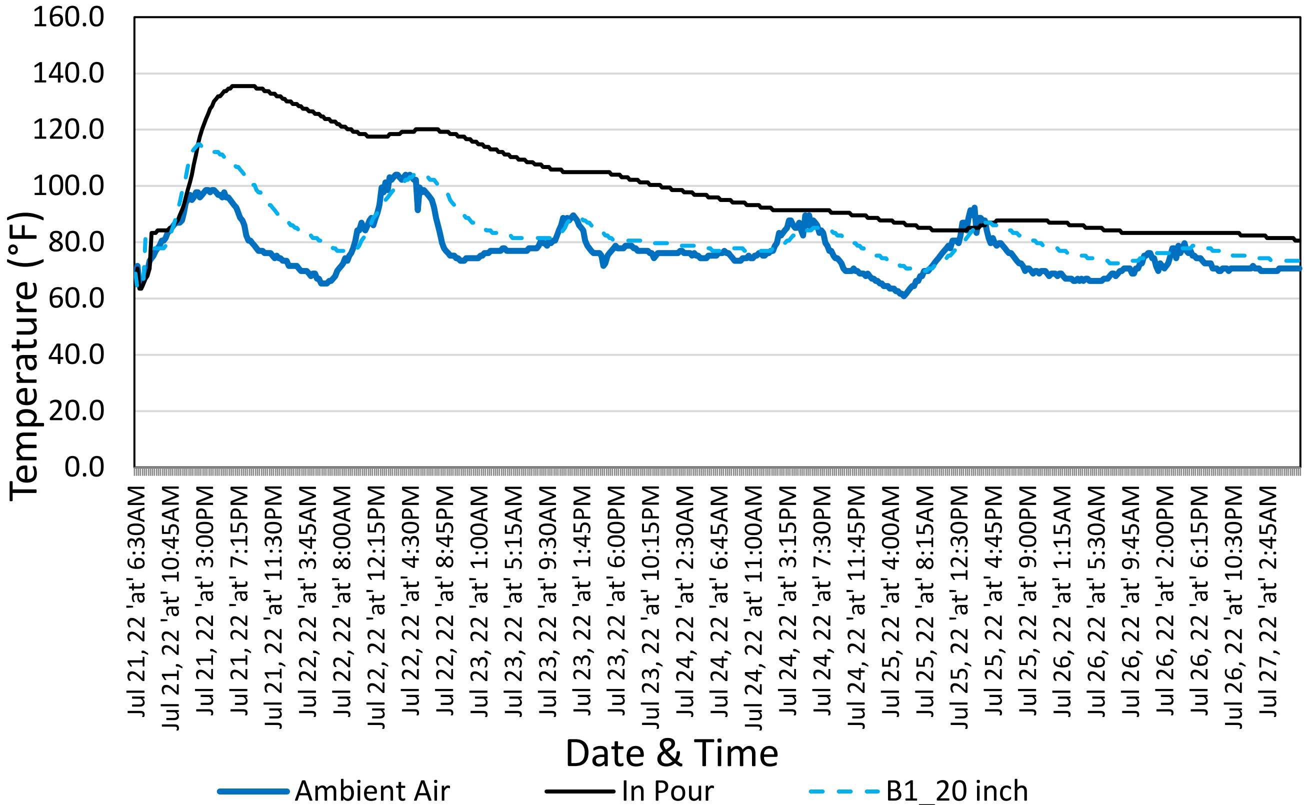


Figure 22. Graph. Temperature variation with time of specimens for the cast on July 21, 2022.

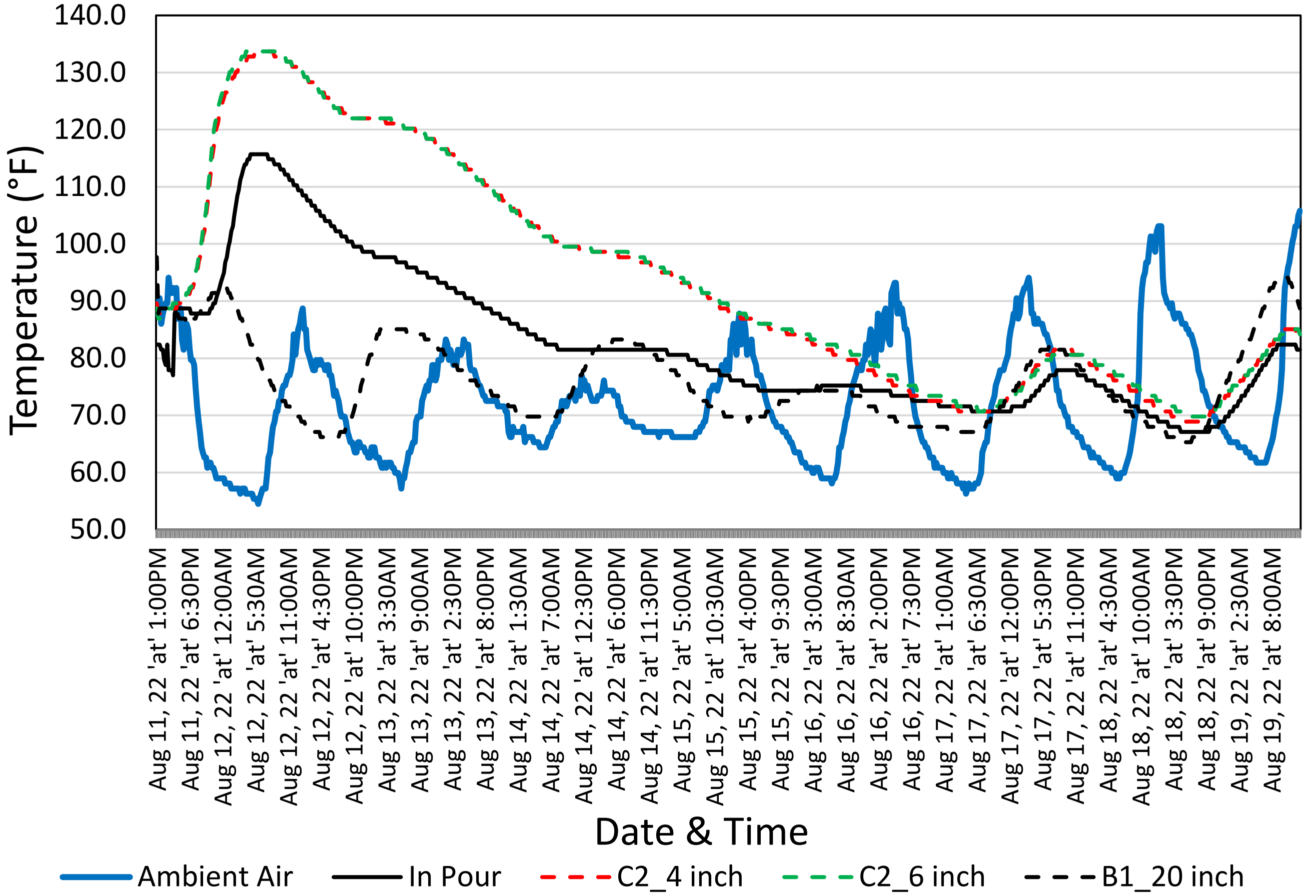


Figure 23. Graph. Temperature variation with time of specimens for the cast on August 11, 2022.

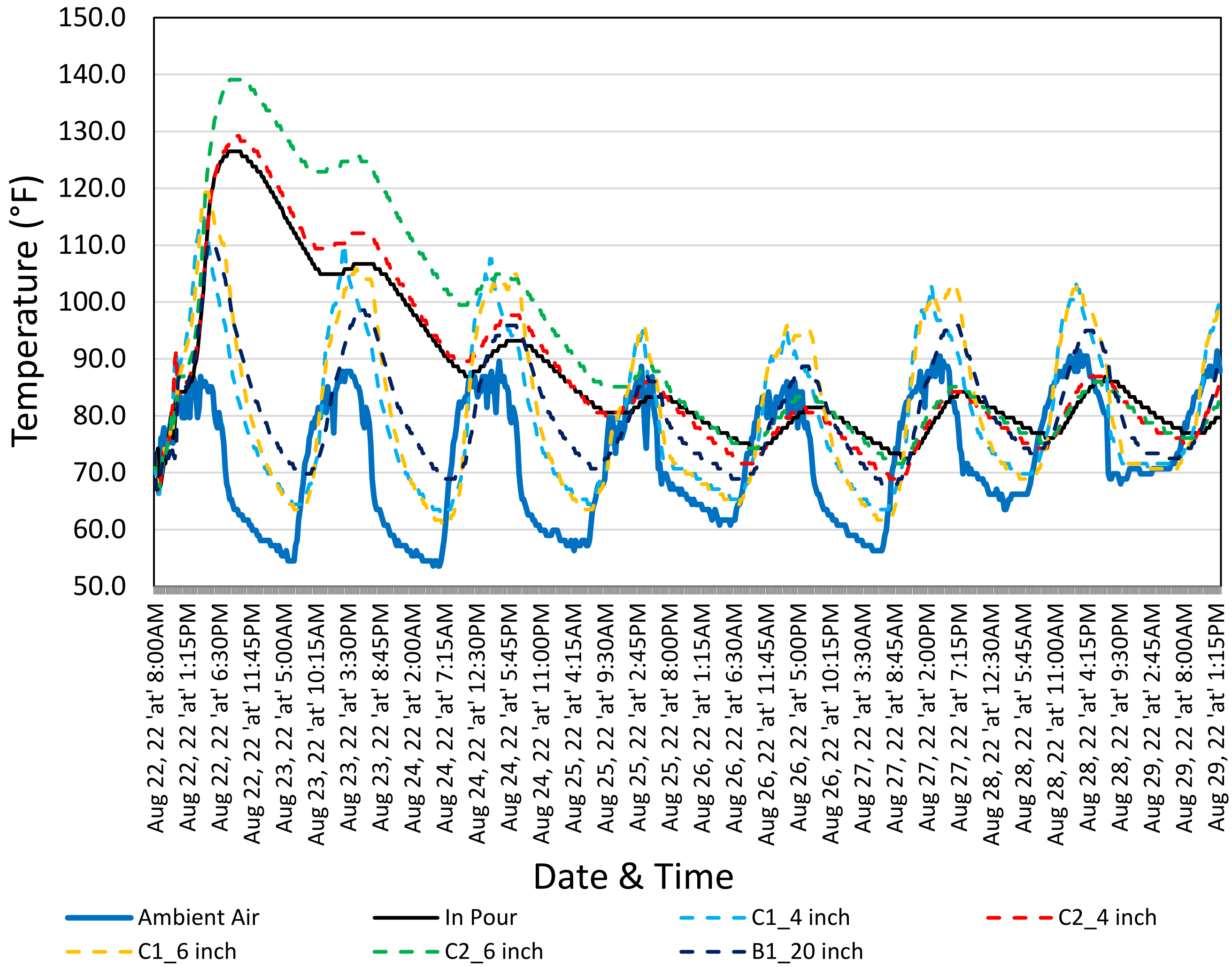


Figure 24. Graph. Temperature variation with time of specimens for the cast on August 22, 2022.

DISCUSSION OF FIELD DATA

Box Culvert Project

For further analysis and discussion of field data, Table 10 summarizes the average 1-, 2-, 3-, and 7-day temperature difference between cured cylinders and in-pour for the box culvert project. Further, the percent strength change between cured Method #C1 and #C2 cylinders is also presented in Table 10. For comparison, Table 10 also presents the minimum, maximum, and average ambient air temperature.

Table 10. A Summary of Temperature Difference and Percent Strength Change for Box Culvert Project

Curing Days	Ambient Air Temperature (°F)			Curing Method#					% Strength Change*	
				4" C1	4" C2	6" C1	6" C2	In-pour	4"	6"
	Min	Max	Average	Average temperature (°F)					%	
Box Culvert Center Wall on 5/20/2022 (Stage I: Without RCA)										
1-Day	56.3	95.0	75.0	NA	109.2	NA	111.1	107.9	NA	NA
2-Day	52.7	95.0	67.1	NA	102.9	NA	104.6	98.4	NA	NA
3-Day	43.7	95.0	63.7	NA	94.1	NA	95.4	89.2	NA	NA
7-Day	43.7	95.0	63.7	NA	94.1	NA	95.4	89.2	NA	NA
Box Culvert Lid on 6/8/2022 (Stage I: Without RCA)										
1-Day	52.7	81.5	65.2	73.3	96.3	74.6	101.6	104.1	NA	NA
2-Day	52.7	87.8	68.3	75.0	95.7	76.3	101.7	103.3	106	112
3-Day	52.7	87.8	67.2	73.3	89.9	74.3	96.0	96.8	100	116
7-Day	52.7	97.7	72.7	77.4	85.9	78.6	88.9	88.5	103	93
Box Culvert Center Wall on 8/11/2022 (Stage II: With RCA)										
1-Day	54.5	94.1	70.3	NA	116.1	NA	116.7	99.8	NA	NA
2-Day	54.5	94.1	70.2	NA	119.2	NA	119.5	99.6	NA	NA
3-Day	54.5	94.1	70.9	NA	115.0	NA	115.1	95.1	NA	NA
7-Day	54.5	103.1	71.5	NA	96.2	NA	96.6	83.9	NA	NA
Box Culvert Lid on 8/22/2022 (Stage II: With RCA)										
1-Day	54.5	86.9	69.6	82.7	109.2	85.00	116.9	107.4	NA	NA
2-Day	53.6	87.8	69.4	81.5	106.9	83.2	116.8	104.4	123	115
3-Day	53.6	89.6	69.8	81.4	101.7	83.1	110.7	99.3	106	109
7-Day	53.6	91.4	72.3	79.9	88.2	81.2	92.9	87.8	96	97
Curing Days	Ambient Air Temperature			[Average cured 4" or 6" specimen temperature] minus [Average in-pour temperature]						
Box Culvert Center Wall on 5/20/2022 (Stage I: Without RCA)										
1-Day	56.3	95.0	75.0	NA	1.3	NA	3.2	NA	NA	NA
2-Day	52.7	95.0	67.1	NA	4.5	NA	6.2	NA	NA	NA
3-Day	43.7	95.0	63.7	NA	4.9	NA	6.2	NA	NA	NA
7-Day	43.7	95.0	63.7	NA	4.9	NA	6.2	NA	NA	NA
Box Culvert Lid on 6/8/2022 (Stage I: Without RCA)										
1-Day	52.7	81.5	65.2	-30.8	-7.8	-29.5	-2.5	NA	NA	NA
2-Day	52.7	87.8	68.3	-28.3	-7.6	-26.9	-1.6	NA	NA	NA
3-Day	52.7	87.8	67.2	-23.5	-6.9	-22.6	-0.8	NA	NA	NA
7-Day	52.7	97.7	72.7	-11.1	-2.6	-9.9	0.3	NA	NA	NA
Box Culvert Center Wall on 8/11/2022 (Stage II: With RCA)										
1-Day	54.5	94.1	70.3	NA	16.3	NA	16.9	NA	NA	NA
2-Day	54.5	94.1	70.2	NA	19.6	NA	19.9	NA	NA	NA
3-Day	54.5	94.1	70.9	NA	19.9	NA	20.0	NA	NA	NA
7-Day	54.5	103.1	71.5	NA	12.3	NA	12.7	NA	NA	NA
Box Culvert Lid on 8/22/2022 (Stage II: With RCA)										
1-Day	54.5	86.9	69.6	-24.7	1.8	-22.4	9.5	NA	NA	NA
2-Day	53.6	87.8	69.4	-22.9	2.5	-21.2	12.3	NA	NA	NA
3-Day	53.6	89.6	69.8	-17.9	2.4	-16.3	11.4	NA	NA	NA
7-Day	53.6	91.4	72.3	-7.8	0.5	-6.6	5.1	NA	NA	NA

*% Strength Change = (Method#C2 strength x 100/ Method#C1 strength); NA: Not applicable

For the cast on August 22, 2002 (Stage II), Table 10 demonstrates that the early strength (1 to 3 days) estimated by Method #C2 is higher than the corresponding strength estimated by Method #C1. However, the percent strength change between Methods #C1 and #C2 is higher for the 2-day strength followed by the 3-day strength. For instance, the 2- and 3-day strength estimated by 100 mm (4 in.) Method #C2 was 123% and 106% higher, respectively, than the corresponding 100 mm (4 in.) Method #C1 strength. For 150 mm (6 in.) cylinders, the 2- and 3-day strength estimated by Method #C2 was 115% and 109% higher, respectively, than the corresponding Method #C1 strength.

Further, for the cast on June 8, 2022 (Stage I) and August 22, 2022 (Stage II), the 7-day strength estimated by Method #C2 was approximately similar or less than the corresponding strength estimated by Method #C1. For instance, the 7-day strength estimated by 100 mm (4 in.) Method #C2 was 96%–103% of the corresponding 100 mm (4 in.) Method #C1 strength. For 150 mm (6 in.) cylinders, the 7-day strength estimated by Method #C2 was 93%–97% of the corresponding Method #C1 strength.

Table 10 also presents temperature differences between cured cylinders and in-pour temperature. Negative values indicate higher temperature inside in-pour compared to cured cylinders. Method #C1 provided higher temperature differences between cured cylinders and in-pour compared to Method #C2 cylinders. This finding indicates that Method #C2 cylinders mimic in-pour temperature better than Method #C1 cylinders.

For the cast on June 8, 2022 (Stage I), the temperature differences between cured 100 mm (4 in.) cylinders and in-pour temperature was higher than the corresponding temperature differences between cured 150 mm (6 in.) cylinders and in-pour temperature. For example, the temperature difference for 100 mm (4 in.) Method #C1 cylinders and in-pour temperature was −17.1°C (−30.8°F) for day 1, and the temperature difference for 150 mm (6 in.) Method #C1 cylinders and in-pour temperature was −16.4°C (−29.5°F) for day 1.

For the cast on May 20, 2022 (Stage I), August 11, 2022 (Stage II), and August 22, 2022 (Stage II) Method #C2 overheated cured specimens and the magnitude of overheating was higher for 150 mm (6 in.) cylinders compared to corresponding 100 mm (4 in.) cylinders. For example, for the cast on August 22, 2022, the temperature difference for 100 mm (4 in.) Method #C2 cylinders and in-pour temperature was +1°C (+1.8°F) for day 1, and the temperature difference for 150 mm (6 in.) Method #C2 cylinders and in-pour temperature was +5.3°C (+9.5°F) for day 1.

Table 11 summarizes all laboratory and field demo mixes along with the number of curing days required to attain the required design compressive and flexural strength. Both compressive strength data from Methods #C1 and #C2 were collected only on four of nine casts presented in Table 11. Out of the four casts, only one cast (ISU cast on October 1, 2021) showed that Method #C1 cylinders took a longer time to attain design strength compared to the corresponding Method #C2 cylinders. One cast—ISU cast on February 25, 2022—demonstrated that 100 mm (4 in.) cylinders of Methods #C1 and #C2 took the same time to attain design strength but 150 mm (6 in.) cylinders of Method #C1 took a longer time to attain design strength compared to the corresponding 150 mm (6 in.) cylinders of Method #C2.

Both compressive strength data from Method #C2 and flexural strength data from Method #B1 were collected only on six of the nine casts presented in Table 11. Of the six casts, data from two ISU laboratory casts and one box culvert cast—June 8, 2022 (Stage I)—showed that Method #B1 cured beams took more time to attain design strength compared to corresponding 100 mm (4 in.) or 150 mm (6 in.) Method #C2 cured cylinders. This behavior could be attributed to the lower temperature of Method #B1 beams compared to Method #C2 cylinders. It is also important to note here that ISU beams were tested third-point using a Universal testing machine while box culvert beams were tested center-point using a portable hand-operated machine.

Both compressive strength data from Method #C1 and flexural strength data from Method #B1 were collected only on four of nine casts presented in Table 11. Of the four casts, the ISU cast on February 25, 2022, and the box culvert cast on June 8, 2022, had ambient cured beams taking a longer time to attain design strength than corresponding ambient cured cylinders. The remaining two casts (ISU cast on October 1, 2021, and box culvert cast on August 22, 2022) showed both ambient cured beams and cylinders taking a similar time to attain design strength.

Table 11. A Summary of Number of Curing Days Required for Design Compressive and Flexural Strength for Various Laboratory and Field Mixes

Pouring Date	Pouring Location	Mix Type	Design Compressive Strength (psi)	Design Flexural Strength (psi)	Curing Method#				
					4" C1	4" C2	6" C1	6" C2	20" B1
10/1/2021	ISU	PV	3500	650	3 Days	1 Day	3 Days	1 Day	3 Days
2/25/2022	ISU	PV	3500	650	7 Days	7 Days	7 Days	3 Days	> 7 Days
5/12/2022	Box Culvert	SI (Stage I)	3500	650	NA	NA	NA	NA	7 Days
5/20/2022	Box Culvert	SI (Stage I)	3500	650	NA	< 3 Days	NA	< 3 Days	2 Days
5/27/2022	Box Culvert	SI (Stage I)	3500	650	NA	NA	NA	NA	7 Days
6/8/2022	Box Culvert	SI (Stage I)	3500	650	< 2 Days	< 2 Days	< 2 Days	< 2 Days	2 Days
7/21/2022	Box Culvert	SI (Stage II)	3500	650	NA	NA	NA	NA	< 2 Days
8/11/2022	Box Culvert	SI (Stage II)	3500	650	NA	< 3 Days	NA	< 3 Days	2 Days
8/22/2022	Box Culvert	SI (Stage II)	3500	650	< 2 Days	< 2 Days	< 2 Days	< 2 Days	< 2 Days

NA: Not Available

CORRELATION ANALYSIS AND DISCUSSION

Hypothesis

The previous research discussions presented the specimens' strengths and changes due to temperature variations and curing method designs. The following correlation analysis examines the strength and curing method relationships between different types of test specimens. The purpose is to improve the understanding of the linear or nonlinear correlation models so that people can perform reliable and practical comparisons of concrete strengths when using different cylinder diameters or estimate early flexural strengths using early compressive strengths. The compressive and flexural strengths of 210 specimens (105 specimens were poured on October 1, 2021, and 105 specimens were poured on Feburary 25, 2022) were from an ISU laboratory, which were analyzed to develop correlations according to the following hypotheses. The compressive strengths of the cylinders and the flexural strengths of the beams are shown in Figures 7, 9, 10, 12, and 13.

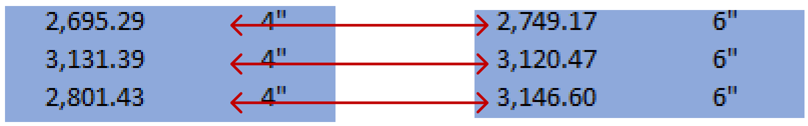
This section only focuses on the laboratory data because the materials and methods for laboratory testing were consistent with the research design. For example, ISU beams were tested using a third-point method versus the field beams, which were tested with a portable hand-operated center-point beam breaker (see note #3 of Table 9).

- H.1. The compressive strengths of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders (using only Method #C1 data)
    - H.1.a. Linear
    - H.1.b. Nonlinear
- H.2. The compressive strengths of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders (using only Method #C2 data)
    - H.2.a. Linear
    - H.2.b. Nonlinear
- H.3. Flexural strength of a 500 mm (20 in.) beam and compressive strength of 100 mm (4 in.) cylinders (using only Method #C1 data). Use Method #B1 for the beam's flexural strength.
    - H.3.a. Linear
    - H.3.b. Nonlinear
- H.4. Flexural strength of a 500 mm (20 in.) beam and compressive strength of 100 mm (4 in.) cylinders (using only Method #C2 data). Use Method #B1 for the beam's flexural strength.
    - H.4.a. Linear
    - H.4.b. Nonlinear
- H.5. Flexural strength of a 500 mm (20 in.) beam and compressive strength of 150 mm (6 in.) cylinders (using only Method #C1 data). Use Method #B1 for the beam's flexural strength.
    - H.5.a. Linear
    - H.5.b. Nonlinear
- H.6. Flexural strength of a 500 mm (20 in.) beam and compressive strength of 150 mm (6 in.) cylinders (using only Method #C2 data). Use Method #B1 for the beam's flexural strength.
    - H.6.a. Linear
    - H.6.b. Nonlinear

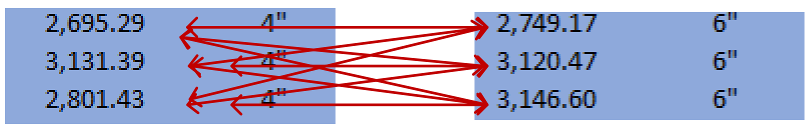
Data Extraction and Crossmatching

A pair of (x, y) coordinates are plotted to help understand the correlation between the two variables. For example, taking the compressive strength of a 100 mm (4 in.) cylinder as the x coordinate and the compressive strength of a 150 mm (6 in.) cylinder as the y coordinate, a pair of (x, y) coordinates is generated for the group of experiment results collected from the concrete cylinders cured using Method #C1. These pairs of coordinates can be plotted on a scatter chart for correlation analysis. Figure 25 shows the steps of data extraction and pair-matching process.

This research project implements a crossmatching method to create coordinate pairs. As shown in Figure 25, three pairs of (x, y) coordinates are generated from simple matching (see Figure 25a), and nine pairs of (x, y) coordinates are generated from crossmatching (see Figure 25b). Using crossmatching can significantly increase the number of data points for a scatter plot chart. The approach can help increase validation accuracy and reduce the possibility of model overfitting (de Rooij & Weeda, 2020). Furthermore, the crossmatching procedure is only on the data points collected on the same day. For example, the compressive strength of a 100 mm (4 in.) cylinder is only paired with the compressive strength of a 150 mm (6 in.) cylinder cast on 10/1/2021 and tested on the same day. Hence, the data points of October pours are not combined or paired with the data points of February pours.



(a) Result of simple matching



(b) Result of crossmatching

Figure 25. Crossmatching for (x, y) coordinates.

Correlation Analysis

After crossmatching, the individually extracted results are verified as correct. Then, the individual data files are combined into one Excel file to analyze the correlations. Appendix B includes the details of correlation analysis and the measurements to compare the precisions of the correlation estimates. Figure 26 shows the R-squared (R^2) value calculation for the coefficient of determination. The higher the R-squared value, the better a model's goodness of fit. The R-squared value means how much in the percentage of the variation in the y values is accounted for by the x values.

$$R^2 = 1 - \frac{sum\ squared\ regression\ (SSR)}{total\ sum\ of\ squares\ (SST)} = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2}$$

Figure 26. Equation. R-squared calculation.

In the equation for the R-squared calculation (Figure 26), y_i is the observed data, $\bar{y}$ is the mean of the observed data, and $\hat{y}_i$ is the regression estimate.

Table 12 summarizes the results of the best correlation for each hypothesis H.1. to H.6. As discussed by Chicco et al. (2021), R-squared measurements are informative for correlation and regression analysis evaluation. The evaluation results in Table 12 indicate that it is reliable to compare the compressive strengths of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders when they are cured in ambient air in direct sunlight (using Method #C1) or gang-cured in an insulated box (using Method #C2).

Table 12. Correlation Results Summary

Index	Accepted Hypothesis	X	Y	Model	R^2
4 vs 6 in. Cylinder, C1	(H.1.a) The compressive strengths of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders (using only Method #C1 data) are linear.	4 in. compressive strength	6 in. compressive strength	Y = 1.0013X	0.9961
4 vs 6 in. Cylinder, C2	(H.2.a) The compressive strengths of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders (using only Method #C2 data) are linear.	4 in. compressive strength	6 in. compressive strength	Y = 1.1228X	0.9904
4 vs 20 in. C-B, C1	(H.3.b) The flexural strengths of the 500 mm (20 in.) beams (using only Method #B1 data) and the compressive strengths of the 100 mm (4 in.) cylinders (using Method #C1 data) are nonlinear.	4 in. compressive strength	20 in. flexural strength	$Y = 9.0684\sqrt{X}$	0.9862
4 vs 20 in. C-B, C2	(H.4.a) The flexural strength of the 500 mm (20 in.) beam (using only Method #B1 data) and the compressive strength of the 100 mm (4 in.) cylinders (using Method #C2 data) are linear.	4 in. compressive strength	20 in. flexural strength	Y = 0.1350X	0.9820
6 vs 20 in. C-B, C1	(H.5.b) The flexural strength of the 500 mm (20 in.) beams (using only Method #B1 data) and the compressive strengths of the 150 mm (6 in.) cylinders (using Method #C1 data) are nonlinear.	6 in. compressive strength	20 in. flexural strength	$Y = 8.9941\sqrt{X}$	0.9865
6 vs 20 in. C-B, C2	(H.6.a) The flexural strengths of the 500 mm (20 in.) beams (using only Method #B1 data) and the compressive strengths of the 150 mm (6 in.) cylinders (using Method #C2 data) are linear.	6 in. compressive strength	20 in. flexural strength	Y = 0.1198X	0.9835

Note: 1. C-B stands for Cylinder-Beam

The strength data is based on day 1, day 3, and day 7 testing results on the specimens cast on October 1, 2021, and February 25, 2022. The analysis aims to find out whether there are linear or nonlinear relationships between the strengths of the group of 100 mm (4 in.) cylinders, the group of 150 mm (6 in.) cylinders, and the group 500 mm (20 in.) beams using Method #C1, Method #C2, and Method #B1.

The following observations are based on the results in Table 12. The estimate of compressive strengths and flexural strengths of in-place concrete using 100 mm (4 in.) cylinders, 150 mm (6 in.) cylinders, and 500 mm (20 in.) beams are presented in Figures 7, 9, 10, 12, and 13. Hence, the following discussions are for the correlations between testing specimens, not for the evaluation of the accuracy of the strength estimates of in-place concrete.

- The compressive strengths of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders are in linear correlations when they are cured using ambient air curing (Method #C1). The ambient air temperatures during the curing days were between 59.9°F and 95.9°F (cast on October 1, 2021) and 13.1°F and 72.5°F (cast on February 25, 2022), as shown in Table 8.

- If ambient air curing (Method #C1) is used, the coefficient of the linear correlation equation for the compressive strengths of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders is calculated as 1.0013 (approximately equals 1), which indicates that 100 mm (4 in.) cylinders predict the same estimates of the compressive strengths of 150 mm (6 in.) cylinders.

- The compressive strengths of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders are in linear correlations when they are cured using insulated box curing (Method #C2). The ambient air temperatures during the curing days were between 59.9°F and 95.9°F (cast on October 1, 2021) and 13.1°F and 72.5°F (cast on February 25, 2022), as shown in Table 8.

- If using insulated box curing (Method #C2), the coefficient of the linear correlation equation for the compressive strengths of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders is calculated as 1.1228 (> 1), which indicates that 100 mm (4 in.) cylinders predict lower estimates of the compressive strength compared to the strength estimates of 150 mm (6 in.) cylinders.

- It is reliable to use the compressive strengths of 100 mm (4 in.) cylinders or 150 mm (6 in.) cylinders (cured using Method #C1 or Method #C2) to predict the flexural strengths of 500 mm (20 in.) beams when cast in October or February.

- If ambient air curing (Method #C1) is used, the flexural strengths of the 500 mm (20 in.) beams (using only Method #B1 data) and the compressive strengths of the cylinders (100 mm (4 in.) cylinders or 150 mm (6 in.)) are nonlinear. The nonlinear equation can be approximated as $Y = 9\sqrt{X}$ since 9.0684 and 8.9941 can be approximated as 9.

- If using insulated box curing (Method #C2), the flexural strengths of the 500 mm (20 in.) beams (using only Method #B1 data) and the compressive strengths of the cylinders (100 mm [4 in.] cylinders or 150 mm [6 in.]) are linear. When using the compressive strengths of 100 mm (4 in.) cylinders, the coefficient is 0.1350 (13.5%). When using the compressive strengths of 150 mm (6 in.) cylinders, the coefficient is 0.1198 (11.98%). The difference in the coefficient values is consistent with the results that 100 mm (4 in.) cylinders have lower compressive strengths than 150 mm (6 in.) cylinders. Hence, the coefficient of the correlation equation when using the compressive strengths of 100 mm (4 in.) cylinders need to be higher.

COMPARISON OF CYLINDER CURING METHODS

The comparison of cylinder curing methods in Table 13 is between Method #C1 and Method #C2. Table 13 shows whether there are significant differences in compressive strength when the cylinders were cured using these curing methods, where the data were collected from the ISU laboratory. The strength data is based on day 1, day 3, and day 7 testing results on specimens cast on October 1, 2021, and February 25, 2022.

In general, 100 mm (4 in.) cylinders have different means of compressive strength when using Method #C1 versus Method #C2. Similarly, the means of the compressive strength of 150 mm (6 in.) cylinders are different when using Method #C1 versus Method #C2. Cylinder sizes, whether 100 mm (4 in.) or 150 mm (6 in.), make no difference in the compressive strengths when using Method #C1.

However, cylinder sizes of 100 mm (4 in.) and 150 mm (6 in.) make a significant difference in the compressive strengths when using Method #C2. These results confirm the correlation analysis results from Table 12.

Table 13. Hypothesis Tests on the Mean Differences of Compressive Strengths Based on ISU Laboratory Data

#	Hypothesis	Result
H.7	Hypothesis (null): The mean of the compressive strengths of 100 mm (4 in.) cylinders for Method#C1 was the same as the mean of the compressive strengths of 100 mm (4 in.) cylinders tested for Method#C2. Sample C1-4-in: N = 18, mean = 3379, s.d. = 1755, SE Mean = 414 Sample C2-4-in: N = 18, mean = 3670, s.d. = 1345, SE Mean = 317 95% CI for Paired Difference: (−547, −36)	18 data points T-Value = −2.40; P-Value = 0.028 P-Value < 0.05 **Significant Difference**
H.8	Hypothesis (null): The mean of the compressive strengths of 150 mm (6 in.) cylinders for Method#C1 was the same as the mean of the compressive strengths of 150 mm (6 in.) cylinders tested for Method#C2. Sample C1-6-in: N = 18, mean = 3436, s.d. = 1663, SE Mean = 392 Sample C2-6-in: N = 18, mean = 4221, s.d. = 1263, SE Mean = 298 95% CI for Paired Difference: (−1045, −524)	18 data points T-Value = −6.36; P-Value = 0.000 P-Value < 0.05 **Significant Difference**
H.9	Hypothesis (null): The mean of the compressive strengths of 100 mm (4 in.) cylinders for Method#C1 was the same as the mean of the compressive strengths of 150 mm (6 in.) cylinders for Method#C1. Sample C1-4-in: N = 18, mean = 3379, s.d. = 1755, SE Mean = 414 Sample C1-6-in: N = 18, mean = 3436, s.d. = 1663, SE Mean = 392 95% CI for Paired Difference: (−178.1, 63.8)	18 data points T-Value = -1.00; P-Value = 0.333 P-Value > 0.05 **No Difference**
H.10	Hypothesis (null): The mean of the compressive strengths of 100 mm (4 in.) cylinders for Method#C2 was the same as the mean of the compressive strengths of 150 mm (6 in.) cylinders for Method#C2. Sample C2-4-in: N = 18, mean = 3436, s.d. = 1663, SE Mean = 392 Sample C2-6-in: N = 18, mean = 4221, s.d. = 1263, SE Mean = 298 95% CI for Paired Difference: (−1045, −524)	18 data points T-Value = −6.36; P-Value = 0.000 P-Value < 0.05 **Significant Difference**

Note: “N” is the sample size, and “s.d.” stands for standard deviation.

The following discussion uses a paired t-test (confidence interval = 95%) for each hypothesis. Each null hypothesis states that all means are equal. The corresponding alternative hypothesis is that the means are not equal. The significance level is 0.05. If a calculated p-value is greater than 0.05, the corresponding null hypothesis is accepted (i.e., no difference). Otherwise, the null hypothesis is rejected, and the alternate hypothesis is accepted (i.e., significant difference). Table 14 lists the details of the hypothesis testing, based on data collected from the ISU laboratory.

Table 14. Hypothesis Testing Summary of Daily Curing Methods Differences Based Only on ISU Laboratory Data (Collected in October 2021 and February 2022)

Name	Details	Results
Day 1, Method#C1 versus Method#C2	Hypothesis (null): On Day 1, the mean of the compressive strengths of cylinders using the curing Method#C1 was the same as the mean of the compressive strengths of cylinders using the curing Method#C2. Sample Day1-C1: N = 12, mean = 1653, s.d. = 1354, SE Mean = 391 Sample Day1-C2: N = 12, mean = 2707, s.d. = 1194, SE Mean = 345 95% CI for Paired Difference: (-1274, -834)	12 data points T-Value = -10.55; P-Value = 0.000 P-Value < 0.05 **Significant Difference**
Day 3, Method#C1 versus Method#C2	Hypothesis (null): On Day 3, the mean of the compressive strengths of cylinders using the curing Method#C1 was the same as the mean of the compressive strengths of cylinders using the curing Method#C2. Sample Day3-C1: N = 12, mean = 3445, s.d. = 762, SE Mean = 220 Sample Day3-C2: N = 12, mean = 3974, s.d. = 809, SE Mean = 234 95% CI for Paired Difference: (-759, -299)	12 data points T-Value = -5.07; P-Value = 0.000 P-Value < 0.05 **Significant Difference**
Day 7, Method#C1 versus Method#C2	Hypothesis (null): On Day 7, the mean of the compressive strengths of cylinders using the curing Method#C1 was the same as the mean of the compressive strengths of cylinders using the curing Method#C2. Sample Day7-C1: N = 12, mean = 5125, s.d. = 216, SE Mean = 62 Sample Day7-C2: N = 12, mean = 5155, s.d. = 400, SE Mean = 116 95% CI for Paired Difference: (-319, 259)	12 data points T-Value = -0.23; P-Value = 0.824 P-Value > 0.05 **No Difference**
Day 1, Method#C1 versus Method#C3	Hypothesis (null): On Day 1, the mean of the compressive strengths of cylinders using the curing Method#C1 was the same as the mean of the compressive strengths of cylinders using the curing Method#C3. Sample Day1-C1: N = 12, mean = 1653, s.d. = 1354, SE Mean = 391 Sample Day1-C3: N = 12, mean = 3251, s.d. = 537, SE Mean = 155 95% CI for Paired Difference: (-2182, -1013)	12 data points T-Value = -6.02; P-Value = 0.000 P-Value < 0.05 **Significant Difference**
Day 3, Method#C1 versus Method#C3	Hypothesis (null): On Day 3, the mean of the compressive strengths of cylinders using the curing Method#C1 was the same as the mean of the compressive strengths of cylinders using the curing Method#C3. Sample Day3-C1: N = 12, mean = 3445, s.d. = 762, SE Mean = 220 Sample Day3-C3: N = 12, mean = 4283, s.d. = 508, SE Mean = 147 95% CI for Paired Difference: (-1178, -449)	12 data points T-Value = -5.43; P-Value = 0.000 P-Value < 0.05 **Significant Difference**
Day 7, Method#C1 versus Method#C3	Hypothesis (null): On Day 7, the mean of the compressive strengths of cylinders using the curing Method#C1 was the same as the mean of the compressive strengths of cylinders using the curing Method#C3. Sample Day7-C1: N = 12, mean = 5125, s.d. = 216, SE Mean = 62 Sample Day7-C3: N = 12, mean = 5171, s.d. = 350, SE Mean = 101 95% CI for Paired Difference: (-360, 268)	12 data points T-Value = -0.32; P-Value = 0.752 P-Value > 0.05 **No Difference**
Day 1, Method#C1 versus CIP	Hypothesis (null): On Day 1, the mean of the compressive strengths of cylinders using the curing Method#C1 was the same as the mean of the compressive strengths of cylinders using CIP. Sample Day1-C1: N = 12, mean = 1653, s.d. = 1354, SE Mean = 391 Sample Day1-CIP: N = 12, mean = 2699, s.d. = 854, SE Mean = 246 95% CI for Paired Difference: (-1406, -687)	12 data points T-Value = -6.41; P-Value = 0.000 P-Value < 0.05 **Significant Difference**

Name	Details	Results
Day 3, Method#C1 versus CIP	Hypothesis (null): On Day 3, the mean of the compressive strengths of cylinders using the curing Method#C1 was the same as the mean of the compressive strengths of cylinders using CIP. Sample Day3-C1: N = 12, mean = 3445, s.d. = 762, SE Mean = 220 Sample Day3-CIP: N = 12, mean = 4181, s.d. = 542, SE Mean = 156 95% CI for Paired Difference: (-943.5, -528.4)	12 data points T-Value = -7.80; P-Value = 0.000 P-Value < 0.05 **Significant Difference**
Day 7, Method#C1 versus CIP	Hypothesis (null): On Day 7, the mean of the compressive strengths of cylinders using the curing Method#C1 was the same as the mean of the compressive strengths of cylinders using CIP. Sample Day7-C1: N = 12, mean = 5125.1, s.d. = 215.8, SE Mean = 62.3 Sample Day7-CIP: N = 12, mean = 5124.4, s.d. = 228.0, SE Mean = 65.8 95% CI for Paired Difference: (-205.6, 207.0)	12 data points T-Value = 0.01; P-Value = 0.994 P-Value > 0.05 **No Difference**
Day 1, Method#C2 versus Method#C3	Hypothesis (null): On Day 1, the mean of the compressive strengths of cylinders using the curing Method#C2 was the same as the mean of the compressive strengths of cylinders using the curing Method#C3. Sample Day1-C2: N = 12, mean = 2707, s.d. = 1194, SE Mean = 345 Sample Day1-C3: N = 12, mean = 3251, s.d. = 537, SE Mean = 155 95% CI for Paired Difference: (-1028, -59)	12 data points T-Value = -2.47; P-Value = 0.031 P-Value < 0.05 **Significant Difference**
Day 3, Method#C2 versus Method#C3	Hypothesis (null): On Day 3, the mean of the compressive strengths of cylinders using the curing Method#C2 was the same as the mean of the compressive strengths of cylinders using the curing Method#C3. Sample Day3-C2: N = 12, mean = 3974, s.d. = 809, SE Mean = 234 Sample Day3-C3: N = 12, mean = 4283, s.d. = 508, SE Mean = 147 95% CI for Paired Difference: (-692, 74)	12 data points T-Value = -1.77; P-Value = 0.104. P-Value > 0.05 **No Difference**
Day 7, Method#C2 versus Method#C3	Hypothesis (null): On Day 7, the mean of the compressive strengths of cylinders using the curing Method#C2 was the same as the mean of the compressive strengths of cylinders using the curing Method#C3. Sample Day7-C2: N = 12, mean = 5155, s.d. = 400, SE Mean = 116 Sample Day7-C3: N = 12, mean = 5171, s.d. = 350, SE Mean = 101 95% CI for Paired Difference: (-327, 295)	12 data points T-Value = -0.11; P-Value = 0.911. P-Value > 0.05 **No Difference**
Day 1, Method#C2 versus CIP	Hypothesis (null): On Day 1, the mean of the compressive strengths of cylinders using the curing Method#C2 was the same as the mean of the compressive strengths of cylinders using CIP. Sample Day1-C2: N = 12, mean = 2707, s.d. = 1194, SE Mean = 345 Sample Day1-CIP: N = 12, mean = 2699, s.d. = 854, SE Mean = 246 95% CI for Paired Difference: (-259, 275)	12 data points T-Value = 0.07; P-Value = 0.948 P-Value > 0.05 **No Difference**
Day 3, Method#C2 versus CIP	Hypothesis (null): On Day 3, the mean of the compressive strengths of cylinders using the curing Method#C2 was the same as the mean of the compressive strengths of cylinders using CIP. Sample Day3-C2: N = 12, mean = 3974, s.d. = 809, SE Mean = 234 Sample Day3-CIP: N = 12, mean = 4181, s.d. = 542, SE Mean = 156 95% CI for Paired Difference: (-537, 123)	12 data points T-Value = -1.38; P-Value = 0.195. P-Value > 0.05 **No Difference**

Name	Details	Results
Day 7, Method#C2 versus CIP	Hypothesis (null): On Day 7, the mean of the compressive strengths of cylinders using the curing Method#C2 was the same as the mean of the compressive strengths of cylinders using CIP. Sample Day7-C2: N = 12, mean = 5155, s.d. = 400, SE Mean = 116 Sample Day7-CIP: N = 12, mean = 5124, s.d. = 228, SE Mean = 66 95% CI for Paired Difference: (-324, 385)	12 data points T-Value = 0.19; P-Value = 0.853 P-Value > 0.05 **No Difference**
Day 1, Method#C3 versus CIP	Hypothesis (null): On Day 1, the mean of the compressive strengths of cylinders using the curing Method#C3 was the same as the mean of the compressive strengths of cylinders using CIP. Sample Day1-C3: N = 12, mean = 3251, s.d. = 537, SE Mean = 155 Sample Day1-CIP: N = 12, mean = 2699, s.d. = 854, SE Mean = 246 95% CI for Paired Difference: (284, 819)	12 data points T-Value = 4.53; P-Value = 0.001 P-Value < 0.05 **Significant Difference**
Day 3, Method#C3 versus CIP	Hypothesis (null): On Day 3, the mean of the compressive strengths of cylinders using the curing Method#C3 was the same as the mean of the compressive strengths of cylinders using CIP. Sample Day3-C3: N = 12, mean = 4283, s.d. = 508, SE Mean = 147 Sample Day3-CIP: N = 12, mean = 4181, s.d. = 542, SE Mean = 156 95% CI for Paired Difference: (-243, 448)	12 data points T-Value = 0.65; P-Value = 0.528. P-Value > 0.05 **No Difference**
Day 7, Method#C3 versus CIP	Hypothesis (null): On Day 7, the mean of the compressive strengths of cylinders using the curing Method#C3 was the same as the mean of the compressive strengths of cylinders using CIP. Sample Day7-C3: N = 12, mean = 5171, s.d. = 350, SE Mean = 101 Sample Day7-CIP: N = 12, mean = 5124, s.d. = 228, SE Mean = 66 95% CI for Paired Difference: (-253, 347)	12 data points T-Value = 0.34; P-Value = 0.737 P-Value > 0.05 **No Difference**

The results in Table 14 support the following observations:

- After 1-day curing, the cylinder samples' compressive strength means are considered not significantly different when using the following curing methods: Method #C2 and CIP.

- After 3-day curing, the cylinder samples' compressive strength means are considered not significantly different when using the following curing methods: Method #C2 and Method #C3, Method #C2 and CIP, as well as Method #C3 and CIP.

- After 7-day curing, the cylinder samples' compressive strength means are considered not significantly different when using the following curing methods: Method #C1 and Method #C2, Method #C1 and Method #C3, Method #C1 and CIP, Method #C2 and Method #C3, Method #C2 and CIP, as well as Method #C3 and CIP.

- Table 14 suggests that Method #C1 and CIP showed the lowest T-value and highest P-value compared to the 7-day strength estimated by Method #C2 and CIP. A T-value measures the size of the difference relative to the variation in the sample data. A low T-value indicates less evidence against the null hypothesis. In other words, a high T-value indicates that there is greater evidence that there is a significant difference. Hence, the estimates from the specimens cured using Method #C1 and the measurements from the specimens cured using CIP have no difference.

Therefore, the mean compressive strength of cylinders (both 100 mm [4 in.] and 150 mm [6 in.]) using insulated boxes (Method #C2) is considered not significantly different from the mean of the compressive strength of cylinders cast in place after 1 day, 3 days, and 7 days, respectively.

The statistical analyses in Tables 13 and 14 are paired t tests. The paired t tests are used to compare the means between two related groups of samples. For example, in Table 14, we want to compare the compressive strengths of cylinders using curing Method #C1 and the compressive strengths of cylinders using curing Method #C2 when they are tested on day 1. We want to know whether the curing methods have an impact on the compressive strengths of cylinders.

To answer this question, the compressive strengths of 12 cylinders cured using Method #C1 and the compressive strengths of 12 cylinders cured using Method #C2 were measured on day 1. This gives 12 sets of values for Method #C1 and 12 sets of values for Method #C2. In such situations, the paired t test can be used to compare the mean weights in the two groups. Specifically, paired t-test analysis is performed as follow:

- Calculate the difference between each pair of values.
- Compute the mean and the standard deviation of the differences.
- Compare the average difference to 0. If there is any significant difference between the two pairs of samples, then the mean of difference is expected to be far from 0.

The assumption of the paired t test is that the differences of the pairs are approximately normally distributed. However, the samples were not sufficiently large (usually $n1 > 30$ and $n2 > 30$) to justify the use of paired t tests based on the Central Limit Theorem. A nonparametric test called Mann Whitney U Test is appropriate to compare two independent samples when the data is not normally distributed, and the samples are small. The Mann Whitney U tests in Tables 15 is to analyze whether two samples are likely to derive from the same population. In other words, the Mann Whitney U tests compare the medians between the two populations to examine whether the two populations have the same shape, while paired t tests calculate the mean of differences. Another advantage of the Mann Whitney U tests is that the two samples under consideration do not necessarily need to have the same number of instances while paired t tests require that the two samples under consideration should have the same number of observations or instances.

Table 15 shows the analysis of the Mann Whitney tests because of sample sizes. Items 1, 2, and 3 are for the comparisons of the compressive strengths of cylinders cured using Method #C1 and the compressive strengths of the cylinders cured using Method #C2 when they were tested on days 1, 3, and 7. Items 4, 5, and 6 are for the comparisons of the compressive strengths of cylinders cured using Method #C2 and the compressive strengths of the cylinders cured using Method CIP when they were tested on days 1, 3, and 7. Items 7, 8, and 9 are for the comparisons of the compressive strengths of cylinders cured using Method #C2 and the compressive strengths of the cylinders cured using Method #C3 when they were tested on days 1, 3, and 7. Items 10, 11, and 12 are for the comparisons of the compressive strengths of cylinders cured using Method #C3 and the compressive strengths of the cylinders cured using Method CIP when they were tested on days 1, 3, and 7. The data were collected from the ISU laboratory and categorized by testing days, curing methods, and cast seasons.

Table 15. Test Result Analysis Categorized by Testing Days, Curing Methods, and Cast Seasons

Comparisons	Estimation for Difference, Descriptive Statistics, and Test Results	Difference
1. The compressive strengths of cylinders cured using Method #C1 and tested on Day 1 are significantly different from the compressive strengths of the cylinders cured using Method #C2 and tested on Day 1.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = -963.12; CI for Difference: (-1707.91, -293.40) Achieved Confidence = 95.36%; N = 12; Median: C1=1593.87, C2=2716.17 W-Value = 114.00; P-Value = 0.040 (<0.05)	Significant difference
b. Use only October 2021 data.	Difference Estimation = -904.95; CI for Difference: (-1229.60, -552.70) Achieved Confidence = 95.47%; N = 6; Median: C1=2960.95, C2=3782.50 W-Value = 21.00; P-Value = 0.005 (<0.05)	Significant difference
c. Use only February 2022 data.	Difference Estimation = -1213.96; CI for Difference: (-1641.55, -846.40) Achieved Confidence = 95.47%; N = 6; Median: C1=359.36, C2=1593.14 W-Value = 21.00; P-Value = 0.005 (<0.05)	Significant difference
2. The compressive strengths of cylinders cured using Method #C1 and tested on Day 3 are significantly different from the compressive strengths of the cylinders cured using Method #C2 and tested on Day 3.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = -571.46; CI for Difference: (-1230.31, 136.70) Achieved Confidence = 95.36%; N = 12; Median: C1=3530.00, C2=3979.17 W-Value = 123.00; P-Value = 0.126 (>0.05)	**No significant difference**
b. Use only October 2021 data.	Difference Estimation = -594.10; CI for Difference: (-881.50, 38.00) Achieved Confidence = 95.47%; N = 6; Median: C1=4127.00, C2=4737.05 W-Value = 28.00; P-Value = 0.093 (>0.05)	**No significant difference**
c. Use only February 2022 data.	Difference Estimation = -473.02; CI for Difference: (-953.37, -195.98) Achieved Confidence = 95.47%; N = 6; Median: C1=2697.73, C2=3251.90 W-Value = 23.00; P-Value = 0.013 (<0.05)	Significant difference
3. The compressive strengths of cylinders cured using Method #C1 and tested on Day 7 are significantly different from the compressive strengths of the cylinders cured using Method #C2 and tested on Day 7.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = -10.49; CI for Difference: (-309.96, 220.33) Achieved Confidence = 95.36%; N = 12; Median: C1=5144.73, C2=5131.29 W-Value = 150.00; P-Value = 1.000 (>0.05)	**No significant difference**
b. Use only October 2021 data.	Difference Estimation = -295.15; CI for Difference: (-764.30, 345.20) Achieved Confidence = 95.47%; N = 6; Median: C1=5081.65, C2=5376.80 W-Value = 31.00; P-Value = 0.230 (>0.05)	**No significant difference**
c. Use only February 2022 data.	Difference Estimation = -138.03; CI for Difference: (-38.40, 361.19) Achieved Confidence = 95.47%; N = 6; Median: C1=5177.30, C2=5048.33 W-Value = 49.00; P-Value = 0.128 (>0.05)	**No significant difference**
4. The compressive strengths of cylinders cured using Method #C2 and tested on Day 1 are significantly different from the compressive strengths of the cylinders cured using Method CIP and tested on Day 1.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = 41.54; CI for Difference: (-828.77, 954.60) Achieved Confidence = 95.36%; N = 12; Median: C2=2716.17, CIP=2623.36 W-Value = 154.00; P-Value = 0.840 (>0.05)	**No significant difference**

Comparisons	Estimation for Difference, Descriptive Statistics, and Test Results	Difference
b. Use only October 2021 data.	Difference Estimation = 306.75; CI for Difference: (-40.90, -698.60)	**No significant difference**
	Achieved Confidence = 95.47%; N = 6; Median: C2=3782.50, CIP=3579.95	
	W-Value = 48.00; P-Value = 0.173 (>0.05)	
c. Use only February 2022 data.	Difference Estimation = -319.95; CI for Difference: (-669.06, 94.45)	**No significant difference**
	Achieved Confidence = 95.47%; N = 6; Median: C2=1593.14, CIP=1902.92	
	W-Value = 34.00; P-Value = 0.471 (>0.05)	
5. The compressive strengths of cylinders cured using Method #C2 and tested on Day 3 are significantly different from the compressive strengths of the cylinders cured using Method CIP and tested on Day 3.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = -206.84; CI for Difference: (-846.74, 440.47)	**No significant difference**
	Achieved Confidence = 95.36%; N = 12; Median: C2=3979.17, CIP=4219.59	
	W-Value = 142.00; P-Value = 0.665 (>0.05)	
b. Use only October 2021 data.	Difference Estimation = 15.00; CI for Difference: (-546.30, 461.60)	**No significant difference**
	Achieved Confidence = 95.47%; N = 6; Median: C2=4737.05, CIP=4687.80	
	W-Value = 41.00; P-Value = 0.810 (>0.05)	
c. Use only February 2022 data.	Difference Estimation = -417.95; CI for Difference: (-877.83, 86.24)	**No significant difference**
	Achieved Confidence = 95.47%; N = 6; Median: C2=3251.90, CIP=3737.77	
	W-Value = 29.00; P-Value = 0.128 (>0.05)	
6. The compressive strengths of cylinders cured using Method #C2 and tested on Day 7 are significantly different from the compressive strengths of the cylinders cured using Method CIP and tested on Day 7.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = 36.78; CI for Difference: (-225.53, 316.76)	**No significant difference**
	Achieved Confidence = 95.36%; N = 12; Median: C2=5131.29, CIP=5135.95	
	W-Value = 152.00; P-Value = 0.931 (>0.05)	
b. Use only October 2021 data.	Difference Estimation = 193.90; CI for Difference: (-617.10, -592.90)	**No significant difference**
	Achieved Confidence = 95.47%; N = 6; Median: C2=5376.80, CIP=5135.95	
	W-Value = 42.00; P-Value = 0.689 (>0.05)	
c. Use only February 2022 data.	Difference Estimation = -11.47; CI for Difference: (-294.31, 325.47)	**No significant difference**
	Achieved Confidence = 95.47%; N = 6; Median: C2=5048.33, CIP=5030.66	
	W-Value = 36.00; P-Value = 0.688 (>0.05)	
7. The compressive strengths of cylinders cured using Method #C2 and tested on Day 1 are significantly different from the compressive strengths of the cylinders cured using Method #C3 and tested on Day 1.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = -694.95; CI for Difference: (-1557.73, 643.36)	**No significant difference**
	Achieved Confidence = 95.36%; N = 12; Median: C2=2716.16, C3=3099.39	
	W-Value = 133.00; P-Value = 0.341 (>0.05)	
b. Use only October 2021 data.	Difference Estimation = 111.40; CI for Difference: (-322.33, 545.13)	**No significant difference**
	Achieved Confidence = 95.47%; N = 6; Median: C2=3782.46, C3=3810.80	
	W-Value = 40.00; P-Value = 0.936 (>0.05)	
c. Use only February 2022 data.	Difference Estimation = -1254.14; CI for Difference: (-1568.29, -784.46)	Significant difference
	Achieved Confidence = 95.47%; N = 6; Median: C2=1593.14, C3=2786.71	
	W-Value = 21.00; P-Value = 0.005 (<0.05)	

Comparisons	Estimation for Difference, Descriptive Statistics, and Test Results	Difference
8. The compressive strengths of cylinders cured using Method #C2 and tested on Day 3 are significantly different from the compressive strengths of the cylinders cured using Method #C3 and tested on Day 3.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = -513.16; CI for Difference: (-1157.32, 183.18) Achieved Confidence = 95.36%; N = 12; Median: C2=3979.17, C3=4187.61 W-Value = 126.00; P-Value = 0.175 (>0.05)	**No significant difference**
b. Use only October 2021 data.	Difference Estimation = 85.76; CI for Difference: (-546.34, 667.44) Achieved Confidence = 95.47%; N = 6; Median: C2=4737.06, C3=4615.80 W-Value = 41.00; P-Value = 0.810 (>0.05)	**No significant difference**
c. Use only February 2022 data.	Difference Estimation = -707.53; CI for Difference: (-1126.60, -193.16) Achieved Confidence = 95.47%; N = 6; Median: C2=3251.90, C3=3920.96 W-Value = 23.00; P-Value = 0.013 (<0.05)	Significant difference
9. The compressive strengths of cylinders cured using Method #C2 and tested on Day 7 are significantly different from the compressive strengths of the cylinders cured using Method #C3 and tested on Day 7.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = -64.64; CI for Difference: (-372.72, 325.00) Achieved Confidence = 95.36%; N = 12; Median: C2=5131.29, C3=5295.42 W-Value = 146.00; P-Value = 0.840 (>0.05)	**No significant difference**
b. Use only October 2021 data.	Difference Estimation = 51.41; CI for Difference: (-875.81, 405.48) Achieved Confidence = 95.47%; N = 6; Median: C2=5376.81, C3=5318.93 W-Value = 42.00; P-Value = 0.689 (>0.05)	**No significant difference**
c. Use only February 2022 data.	Difference Estimation = 217.48; CI for Difference: (-470.73, 461.23) Achieved Confidence = 95.47%; N = 6; Median: C2=5048.33, C3=4841.25 W-Value = 44.00; P-Value = 0.471 (>0.05)	**No significant difference**
10. The compressive strengths of cylinders cured using Method #C3 and tested on Day 1 are significantly different from the compressive strengths of the cylinders cured using Method CIP and tested on Day 1.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = 709.87; CI for Difference: (-373.07, 1109.39) Achieved Confidence = 95.36%; N = 12; Median: C3=3099.39, CIP=2623.36 W-Value = 177.00; P-Value = 0.126 (>0.05)	**No significant difference**
b. Use only October 2021 data.	Difference Estimation = 176.87; CI for Difference: (-386.08, 691.42) Achieved Confidence = 95.47%; N = 6; Median: C3=3810.80, CIP=3579.95 W-Value = 48.00; P-Value = 0.173 (>0.05)	**No significant difference**
c. Use only February 2022 data.	Difference Estimation = 893.95; CI for Difference: (770.54, 1070.50) Achieved Confidence = 95.47%; N = 6; Median: C3=2786.71, CIP=1902.92 W-Value = 57.00; P-Value = 0.005 (<0.05)	Significant difference
11. The compressive strengths of cylinders cured using Method #C3 and tested on Day 3 are significantly different from the compressive strengths of the cylinders cured using Method CIP and tested on Day 3.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = 290.21; CI for Difference: (-351.80, 740.59) Achieved Confidence = 95.36%; N = 12; Median: C3=4187.61, CIP=4219.59 W-Value = 168.00; P-Value = 0.312 (>0.05)	**No significant difference**

Comparisons	Estimation for Difference, Descriptive Statistics, and Test Results	Difference
b. Use only October 2021 data.	Difference Estimation = -72.00; CI for Difference: (-626.06, 569.15)	**No significant difference**
	Achieved Confidence = 95.47%; N = 6; Median: C3=4615.80, CIP=4687.80	
	W-Value = 37.00; P-Value = 0.810 (>0.05)	
c. Use only February 2022 data.	Difference Estimation = 210.08; CI for Difference: (-63.79, 480.75)	**No significant difference**
	Achieved Confidence = 95.47%; N = 6; Median: C3=3920.96, CIP=3737.77	
	W-Value = 49.00; P-Value = 0.128 (>0.05)	
12. The compressive strengths of cylinders cured using Method #C3 and tested on Day 7 are significantly different from the compressive strengths of the cylinders cured using Method CIP and tested on Day 7.		
a. Use both October 2021 and February 2022 data.	Difference Estimation = 83.55; CI for Difference: (-227.01, 373.29)	**No significant difference**
	Achieved Confidence = 95.36%; N = 12; Median: C3=5295.42, CIP=5135.95	
	W-Value = 161.00; P-Value = 0.544 (>0.05)	
b. Use only October 2021 data.	Difference Estimation = 192.58; CI for Difference: (-127.40, 379.49)	**No significant difference**
	Achieved Confidence = 95.47%; N = 6; Median: C3=5318.93, CIP=5135.95	
	W-Value = 47.00; P-Value = 0.230 (>0.05)	
c. Use only February 2022 data.	Difference Estimation = -151.79; CI for Difference: (-585.43, 613.57)	**No significant difference**
	Achieved Confidence = 95.47%; N = 6; Median: C3=4841.25, CIP=5030.66	
	W-Value = 36.00; P-Value = 0.689 (>0.05)	

The results in Table 15 support the following observations:

- The compressive strengths of cylinders cured using Method #C1 and Method #C2 have a significant difference on day 1 for both October 2021 and February 2022 data.
- The compressive strengths of cylinders cured using Method #C1 and Method #C2 have a significant difference on day 3 for only February 2022 data.
- The compressive strengths of cylinders cured using Method #C1 and Method #C2 have no significant difference on day 7 for both October 2021 and February 2022 data.
- The compressive strengths of cylinders cured using Method #C2 and cast-in-place cylinders representing in-place concrete strength have no significant difference on day 1, day 3, and day 7 for both October 2021 and February 2022 data.
- The compressive strengths of cylinders cured using Method #C2 and Method #C3 have a significant difference on day 1 for only February 2022 data.
- The compressive strengths of cylinders cured using Method #C2 and Method #C3 have a significant difference on day 3 for only February 2022 data.

- The compressive strengths of cylinders cured using Method #C2 and Method #C3 have no significant difference on day 7 for both October 2021 and February 2022 data.

- The compressive strengths of cylinders cured using Method #C3 and Method CIP have a significant difference on day 1 for only February 2022 data.

- The compressive strengths of cylinders cured using Method #C3 and Method CIP have no significant difference on day 3 for both October 2021 and February 2022 data. However, using day 3 data, Item 11.c shows that the estimated strength difference between the Method #C3 data and the Method CIP data is 210.08; while Item 5.c shows that the estimated strength difference between the Method #C2 data and the Method CIP data is –417.95. The two values indicate that compressive strengths of cylinders cured using Method #C3 tend to be overestimated.

- The compressive strengths of cylinders cured using Method #C3 and Method CIP have no significant difference on day 7 for both October 2021 and February 2022 data.

CHAPTER 4: CONCLUSIONS

LABORATORY DATA

The laboratory study evaluated cost-effective field-curing methods of concrete cylinders (Methods #C1, #C2, #C3) and beams (Methods #B1, #B2) during October 2021 and February 2022. The key findings of the laboratory study presented in this report are summarized as follows:

- Ambient air curing (Method #C1) of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders underestimated early strength (1 to 3 days) of an in-place concrete item within 88%–89% and 81%–89%, respectively, for the October 2021 cast (3-day ambient air temperature ranging between 15.5 and 35.5°C [59.9 and 95.9°F]) (Table 8). Furthermore, for the February 2022 cast (3-day ambient air temperature ranging between −10.5 and 13.0°C [13.1 and 55.4°F]), ambient air curing (Method #C1) underestimated early strength of an in-place concrete item within 16%–70% and 23%–78% (Table 8) for 100 mm (4 in.) and 150 mm (6 in.) cylinders, respectively.

- Insulated box curing (Method #C2) of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders estimated early strength (1 to 3 days) of an in-place concrete item within acceptable range of 95%–110% and 105%–108%, respectively, for the October 2021 cast (Table 8). For the February 2022 cast, insulated box curing (Method #C2) cured 100 mm (4 in.) cylinders underestimated early strength of an in-place concrete item within 66%–78% and 150 mm (6 in.) cylinder estimated strength within acceptable range of 100%–102% (Table 8). Therefore, only 150 mm (6 in.) cylinders cured using Method #C2 may be a good option for estimating early strength of an in-place concrete item in cold weather (3-day ambient air temperature ranging between −10.5 and 13.0°C [13.1 and 55.4°F]).

- Power-operated box curing (Method #C3) of 100 mm (4 in.) and 150 mm (6 in.) cylinders estimated early strength (1 to 3 days) of an in-place concrete item within an acceptable range of 99%–104% and 99%–107% (Table 8), respectively, for the October 2021 cast. For the February 2022 cast, power-operated box (Method #C3) overestimated early strength within the unacceptable range of 101%–148% and 113%–146% for 100 mm (4 in.) and 150 mm (6 in.) cylinders, respectively. Therefore, Method #C3 may not be a good option for estimating early strength in cold weather (3-day ambient air temperature ranging between −10.5 and 13.0°C [13.1 and 55.4°F]).

- Ambient air curing of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders (Method #C1) estimated 7-day strength of an in-place concrete item within the acceptable range of 94%–101% and 101%–105% for October 2021 and February 2022 cast, respectively (Table 8).

- Insulated box curing (Method #C2) of 100 mm (4 in.) and 150 mm (6 in.) cylinders estimated 7-day strength of an in-place concrete item by 91% and 112%, respectively, for the October 2021 cast and by 94% and 106%, respectively, for the February 2022 cast

(Table 8). Power-operated box curing (Method #C3) of 100 mm (4 in.) and 150 mm (6 in.) cylinders estimated 7-day strength of an in-place concrete item by 100% and 106%, respectively, for the October 2021 cast and by 89% and 110%, respectively, for the February 2022 cast (Table 8). Therefore, 150 mm (6 in.) cylinders cured using either Method #C2 or Method #C3 slightly overestimated the 7-day strength of an in-place concrete item.

- For the October 2021 cast, the 150 mm (6 in.) cylinders cured using all three methods mimicked the temperature profile of an in-place concrete item better than corresponding 100 mm (4 in.) cylinders and 500 mm (20 in.) beams. For the February 2022 cast, the 150 mm (6 in.) cylinders cured using only Methods #C1 and #C2 mimicked the temperature profile of an in-place concrete item better than corresponding 100 mm (4 in.) cylinders and 500 mm (20 in.) beams (Table 8). Further, for the October 2021 cast, the temperature difference between insulated box (Method #C2) cylinders and in-place concrete was either lower or similar to the temperature difference between the corresponding power-operated box (Method #C3) cylinders and in-place concrete items. However, for the February 2022 cast, the temperature difference between insulated box (Method #C2) cylinders and in-place concrete was significantly lower compared to the temperature difference between the corresponding power-operated box (Method #C3) cylinders and in-place concrete item.

- For both October 2021 and February 2022 casts, ambient air (Method #B1) and insulated plywood box (Method #B2) curing of beams underestimated the strength of concrete due to relatively low temperature inside beams compared to an in-place concrete item strength indicated by cast-in-place cylinders.

- Statistical analysis showed that 100 mm (4 in.) and 150 mm (6 in.) cylinders cured using Method #C1 estimated strength that was not significantly different (Table 13). Therefore, any cylinder size could be used for curing specimens using Method #C1. However, cylinder sizes of 100 mm (4 in.) and 150 mm (6 in.) make a significant difference in the estimated compressive strength when using Method #C2.

- Statistical analysis showed that the compressive strengths of cylinders cured using Methods #C1 and #C2 had significant differences on day 1 for both October 2021 and February 2022 data, significant differences on day 3 for only February 2022 data, and no significant differences on day 7 for both October 2021 and February 2022 data (Table 14). Further, statistical analysis showed that the compressive strengths of cylinders cured using Method #C2 and corresponding cast-in-place cylinders (in-place concrete item strength) had no significant differences in early strength (1 to 3 days) and 7-day strength for both October 2021 and February 2022 data. Moreover, statistical analysis showed that the compressive strength of cylinders cured using Methods #C2 and #C3 had significant differences in early strength (1 to 3 days) for only the February 2022 data and no significant differences in 7-day strength for both October 2021 and February 2022 data.

FIELD DATA

Based on the laboratory study results, only Methods #C1, #C2, and #B1 were selected for further evaluation in the field. Field data was collected from an IDOT District 5 box culvert demonstration project. The key findings of the field study presented in this report are summarized as follows:

- The early strength estimated by insulated box (Method #C2) cylinders was higher than the corresponding early strength estimated by ambient air curing of cylinders (Method #C1). The percent difference in the strength of Method #C1 and #C2 cylinders was higher for 2-day followed by 3-day (Table 10). The 7-day strength estimated by Method #C2 was approximately similar or less than the corresponding strength estimated by Method #C1.

- Method #C1 provided higher temperature differences between cured cylinders and in-pour compared to corresponding difference between Method #C2 cylinders and in-pour concrete temperature. This finding indicates that Method #C2 cylinders mimic in-pour temperature better than Method #C1 cylinders (Table 10).

- Out of four casts from the field with Method #C2 data, three casts showed that Method #C2 cured specimens experienced higher temperatures compared to corresponding in-pour temperature. Specifically, for the cast on May 20, 2022 (3-day ambient air temperature ranging between 6.5 and 35°C [43.7 and 95.0°F]), August 11, 2022 (3-day ambient air temperature ranging between 12.5 and 34.5°C [54.5 and 94.1°F]), and August 22, 2022 (3-day ambient air temperature ranging between 12 and 32°C [53.6 and 89.6°F]), Method #C2 overheated cured specimens by an average temperature difference of +3.4°C (+6.2°F), +11.1°C (+20°F), and +6.3°C (+11.4°F), respectively, for 150 mm (6 in.) specimens. The magnitude of overheating was higher for 150 mm (6 in.) cylinders compared to corresponding 100 mm (4 in.) cylinders when specimens were placed in separate coolers. However, the magnitude of overheating was similar when both 150 mm (6 in.) and 100 mm (4 in.) cylinders were placed in the same cooler. This behavior may result in overestimation of in-place concrete strength estimated by Method #C2. For the cast on June 8, 2022 (3-day ambient air temperature ranging between 11.5 and 31°C [52.7 and 87.8°F]), Method #C2 slightly underheated specimens by an average temperature difference of −3.8°C (−6.9°F) for 100 mm (4 in.) and of −0.4°C (−0.8°F) for 150 mm (6 in.) specimens.

- Figures 16, 17, 19, 22, 23, and 24 show that beams experienced the lowest temperature among all cured specimens tested and the temperature was lower than in-pour temperature and similar to ambient air temperature. Therefore, beams may not be a good strength indicator of in-place concrete strength.

CORRELATIONS AND HYPOTHESIS TESTING

Based on the correlation analyses and hypothesis testing presented in Chapter 3, the key findings are summarized as follows:

- Table 12 suggests that the compressive strengths of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders when using ambient air curing (Method #C1) are proportional and covary. They have approximately the same estimates of compressive strength. Hence, cylinder size does not affect the correlation for Method #C1.

- Table 12 suggests that the compressive strengths of 100 mm (4 in.) cylinders and 150 mm (6 in.) cylinders when using insulated box curing (Method #C2) are proportional and covary. The 100 mm (4 in.) cylinders predict lower estimates of compressive strength compared to the strength estimates of 150 mm (6 in.) cylinders.

- Table 12 suggests that if ambient air curing (Method #C1) is used, the flexural strengths of the 500 mm (20 in.) beams (using only Method #B1 data) can be estimated as 9 multiplied by the square root of the compressive strengths of the cylinders (100 mm [4 in.] cylinders or 150 mm [6 in.]). Hence, cylinder size does not affect the correlation.

- Table 12 suggests that if insulated box curing (Method #C2) is used, the flexural strengths of the 500 mm (20 in.) beams (using only Method #B1 data) can be estimated as 0.1350 multiplied by the compressive strengths of the 100 mm (4 in.) cylinders or 0.1198 multiplied by the compressive strengths of the 150 mm (6 in.) cylinders.

- Based on both October 2021 and February 2022 data, Table 13 suggests that the compressive strength estimated by 100 mm (4 in.) and 150 mm (6 in.) cylinders cured using Method #C1 was not significantly different. On the other hand, Table 13 suggests that the compressive strength estimated by 100 mm (4 in.) and 150 mm (6 in.) cylinders cured using Method #C2 was significantly different.

- Based on sample means, Table 14 suggests that the compressive strengths of cylinders using insulated box curing (Method #C2) had no significant differences in the mean after 1 day and 3 days of curing from the ones using cast-in-place (CIP) curing. Hence, it is acceptable to use the compressive strengths of the cylinders cured in an insulated box to estimate the early (1 to 3 days) compressive strengths of an in-place concrete item.

- Based on sample means, Table 14 suggests that the 7-day strength estimated by both Method #C1 or #C2 and CIP showed no significant differences.

- Based on sample means, Table 14 suggests that Method #C1 can have more accurate estimates of the 7-day compressive strength of an in-place concrete item than Method #C2. Hence, it is recommended to use the compressive strengths of the cylinders cured in ambient air (Method #C1) for estimating 7-day strength of an in-place concrete item.

- Based on sample medians, Table 15 suggests that the compressive strengths of cylinders cured using Methods #C1 and #C2 had significant differences on day 1 for both October 2021 and February 2022 data, significant differences on day 3 for only February 2022 data, and no significant differences on day 7 for both October 2021 and February 2022 data.

- Table 15 suggests that the compressive strengths of cylinders cured using Method #C2 and corresponding cast-in-place cylinders (in-place concrete item strength) had no significant differences in early strength (1 to 3 days) and 7-day strength for both October 2021 and February 2022 data.

- The compressive strength of cylinders cured using Methods #C2 and #C3 had significant differences in early strength (1 to 3 days) for only the February 2022 data and no significant differences in 7-day strength for both October 2021 and February 2022 data (Table 15).

- The compressive strength of cylinders cured using Method #C3 and cast-in-place cylinders had significant differences in 1-day strength for only February 2022 data (Table 15). However, the compressive strengths of cylinders cured using Method #C3 and cast-in-place cylinders had no significant differences in 7-day strength for both October 2021 and February 2022 data. Therefore, Method #C3 may not be a good option for predicting early strength of an in-place concrete item in cold weather.

RECOMMENDATION

The current IDOT specification (Article 1020.09) states the following:

For strength specimens, the Contractor shall provide a field curing box for initial curing and a water storage tank for final curing. The field curing box will be required when an air temperature below 60°F (16°C) is expected during the initial curing period. The device shall maintain the initial curing temperature range specified in Illinois Modified AASHTO T 23, and may be insulated or power operated as appropriate.

The proposed IDOT specification (Article 1020.09) is as follows:

For strength specimens, the Contractor shall provide a field curing box for initial curing and a water storage tank for final curing. The field curing box will be required when an air temperature below 60°F (16°C) is expected during the initial curing period for standard curing. The device shall maintain the initial curing temperature range specified in Illinois Modified AASHTO T 23, and may be insulated or power operated as appropriate. An acceptable insulated device is a 5-day chest cooler.

For standard curing when the air temperature will be below 60°F (16°C), a power-operated box shall be set at 60°F (16°C) to 63°F (17°C), and strength specimens shall be transported to the testing facility the next day but no later than 32 hours after casting. For the insulated device, strength specimens may be transported to the testing facility the next day but no later than 48 hours after casting.

In the case of field curing when strength specimens remain in the field until testing is complete, an insulated device shall be used when an air temperature below 70°F (21°C) is expected during the first 24 hours. The power operated box is prohibited.

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APPENDIX A: SPECIAL PROVISION FOR CAST-IN-PLACE BOX CULVERT CONCRETE (CLASS SI – Short Cure Period (SCP))

The following is the special provision for the box culvert demonstration project. The box culvert (Structure # 092-2045) was completed under Illinois Department of Transportation Contract # 70905. The box culvert is located on Illinois Route 49, 0.8 km (0.5 miles) north of US 136 East in Vermilion County.

Effective: August 13, 2021

<u>Description.</u>

The Contractor is advised this is a demonstration project for a new concrete mix design. This work shall consist of the construction of a cast-in-place box culvert using Class SI concrete with a cure period in the range of 24 to 72 hours for Stage I and Stage II, as well as construction of trial batches for concrete testing with disposal of the excess concrete. The work shall be according to the applicable portions of Section 540 of the Standard Specifications.

<u>Materials.</u>

The materials shall be according to Article 540.02(a) except the following revisions shall apply to Section 1020.

For Stage 1 construction of the box culvert, the Class SI mix design parameters per Article 1020.04 (Table 1) are revised as follows: the cement factor shall be a minimum 6.05 cwt/cu yd (360 kg/cu m) and a maximum 6.50 cwt/cu yd (385 kg/cu m); the water/cement ratio shall be 0.36 to 0.38, the strength shall be a minimum 3500 psi (24,000 kPa) compressive or 650 psi (4500 kPa) flexural at 72 hours; and a high range water-reducing admixture shall be used.

For Stage II construction of the box culvert, the Class SI mix design parameters shall be the same as Stage I except the rheology-controlling admixture (X2) will also be required. The dosage shall be in the 7-10 oz/cwt. (456-652 ml/100 kg) range. A technical representative shall be available for assistance when establishing the dosage rate.

For each concrete pour, the Engineer will perform all concrete testing. Sufficient compressive and flexural strength specimens will be molded to perform six separate compressive tests and six separate flexural tests.

The curing period for Culverts as indicated in Article 1020.13 shall be revised to end at 72 hours. However, this specified curing period may be terminated earlier if the concrete has attained 80 percent of the specified mix design strength. The minimum cure period shall be 24 hours.

Trial Batch.

A trial batch for the Class SI – SCP concrete shall be scheduled a minimum of 21 calendar days prior to anticipated use for Stage I construction of the box culvert and 14 calendar days prior to anticipated use for Stage II. The trial batch shall be performed in the presence of the Engineer, and the Engineer will perform all testing.

A minimum 4 cubic yard (3.0 cubic meter) trial batch shall be produced and placed off site. The Contractor may propose alternative locations for approval by the Engineer. The trial batch will be evaluated for slump, air content, and strength without the rheology-controlling admixture. Sufficient compressive and flexural strength specimens will be molded to perform nine separate compressive tests and nine separate flexural tests.

The same trial batch will subsequently be evaluated for slump, air content, and strength with the rheology-controlling admixture. Sufficient compressive and flexural strength specimens will be molded to perform nine separate compressive tests and nine separate flexural tests.

Based on one or more trial batches, the final admixture dosages and mix design parameters will be determined and approved by the Engineer. A mix design capable of obtaining the full specified strength at 72 hours will be selected.

Instrumentation.

The Engineer shall have free access for installation of thermocouples and other instrumentation on or within the structure. The testing equipment will be provided by the Engineer. As a minimum, three thermocouples per pour will be installed. Two will be installed in the concrete and one will be used to measure ambient air temperature. This information is for determining the maximum temperature differential as discussed under Falsework and Form Removal. The Contractor shall cooperate with the Engineer and take necessary steps to prevent damage to the instrumentation.

Falsework and Form Removal

Falsework and form removal shall be according to Articles 503.05 and 503.06 except only flexural strength test results will be accepted for self-supporting box culvert components. The cure period shall be as specified under Materials herein.

When the Contractor performs form removal, the maximum temperature differential between the internal concrete core and the ambient air temperature shall not exceed 50 °F (28 °C). If this maximum temperature differential is exceeded, the Contractor shall wait until the concrete is within the maximum temperature differential range before form removal is performed. The Engineer will provide the heat of hydration temperature differential information.

Method of Measurement.

Cast-in-place concrete box culverts will be measured for payment according to Article 540.07.

Concrete for cast-in-place box culverts which contain a rheology-controlling admixture will be measured for payment in cubic yards (cubic meters) as specified in Article 540.07

Trial batches will be measured for payment in units of each.

Basis of Payment.

Cast-in-place concrete box culverts will be paid for according to Article 540.08.

Cast-in-place concrete box culverts which contain a rheology-controlling admixture will be paid for at the contract unit price per cubic yard (cubic meter) for CONCRETE BOX CULVERTS (RHEOLOGY-CONTROLLING ADMIXTURE).

Trial batches will be paid for at the contract unit price per each for TRIAL BATCH.

APPENDIX B: CORRELATION ANALYSIS

For correlation analysis, MATLAB (R2022a) software was used to find the accurate and practical engineering equations of the correlation models for the hypotheses stated in the section of Correlation Analysis and Discussion in Chapter 3 Results and Discussion. The titles of the following sections are consistent with the order of the hypotheses in Chapter 3.

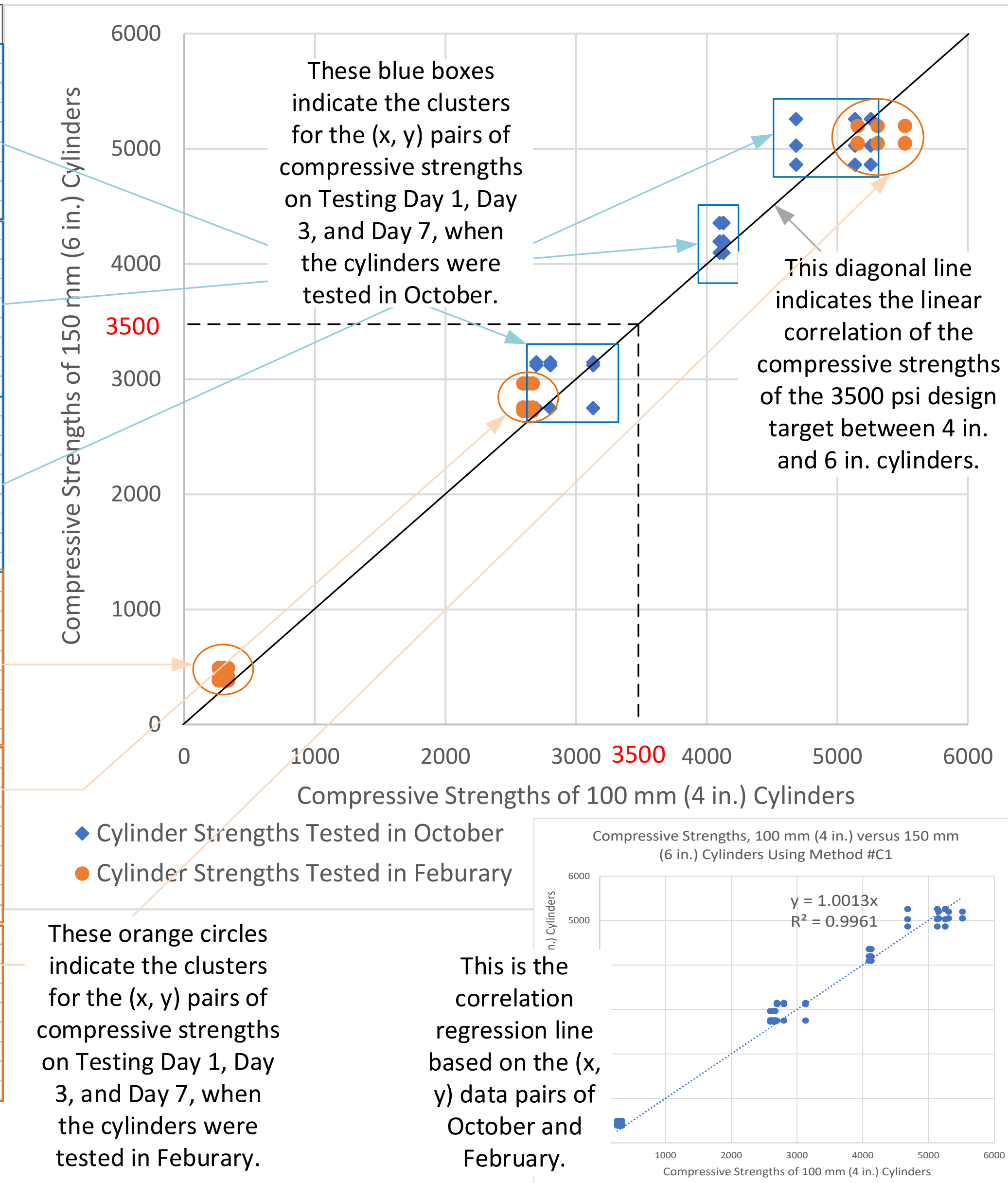
As explained in Table 10 and the Hypothesis section of Chapter 3, the correlation analysis focuses only on the data from ISU laboratory for all the following hypothesis testing, correlation analysis, and evaluation. The test days are Day 1, Day 3, and Day 7.

H1: CORRELATION ANALYSIS: 100 MM (4 IN.) VS. 150 MM (6 IN.) CYLINDERS USING ONLY METHOD #C1.

Figure 27 explains the correlation analysis process for the compressive strengths of 100 mm (4 in.) and 150 mm (6 in.) cylinders using Method #C1.

Four indicators are used to examine the performances of correlation equations, including R-squared, root-mean-square error (RMSE, see Figure 27), mean absolute error (MAE), and mean absolute percentage error (MAPE). The R-squared indicator is widely used to measure the strength of the relationship between the prediction of a linear model and its dependent variable. It can tell how well a regression model describes observed data. The main purpose of using an R-squared indicator is to avoid overfitting a model, preventing the model from picking up noises. Nevertheless, the criteria value of R-squared depends on the context. In this research project, the R-squared indicator is set to 0.8 or higher.

x	y	Testing Day	Month of Year
2695.29	2749.17	1	October
2695.29	3120.47	1	October
2695.29	3146.6	1	October
3131.39	2749.17	1	October
3131.39	3120.47	1	October
3131.39	3146.6	1	October
2801.43	2749.17	1	October
2801.43	3120.47	1	October
2801.43	3146.6	1	October
4128.5	4357.92	3	October
4128.5	4196.19	3	October
4128.5	4097.53	3	October
4097.51	4357.92	3	October
4097.51	4196.19	3	October
4097.51	4097.53	3	October
4125.54	4357.92	3	October
4125.54	4196.19	3	October
4125.54	4097.53	3	October
5134.9	4864.83	7	October
5134.9	5259.19	7	October
5134.9	5028.36	7	October
4683.24	4864.83	7	October
4683.24	5259.19	7	October
4683.24	5028.36	7	October
5254.58	4864.83	7	October
5254.58	5259.19	7	October
5254.58	5028.36	7	October
299.62	492.43	1	February
299.62	383.49	1	February
299.62	416.97	1	February
335.23	492.43	1	February
335.23	383.49	1	February
335.23	416.97	1	February
265.92	492.43	1	February
265.92	383.49	1	February
265.92	416.97	1	February
2630.39	2754.37	3	February
2630.39	2962.5	3	February
2630.39	2726.92	3	February
2668.53	2754.37	3	February
2668.53	2962.5	3	February
2668.53	2726.92	3	February
2595.25	2754.37	3	February
2595.25	2962.5	3	February
2595.25	2726.92	3	February
5517.06	5048.4	7	February
5517.06	5049.31	7	February
5517.06	5200.04	7	February
5154.56	5048.4	7	February
5154.56	5049.31	7	February
5154.56	5200.04	7	February
5307.13	5048.4	7	February
5307.13	5049.31	7	February
5307.13	5200.04	7	February



$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{N}}$$

Figure 27. Equation. Root-mean-square error calculation.

Table 16 includes the considerations of acceptable tradeoffs of accuracy and reliability compared to the linear and nonlinear models. Additionally, the initial compressive strengths of 100 mm (4 in.) and 150 mm (6 in.) cylinders should be zero.

Table 16. Comparison of Linear vs Nonlinear Correlation Models of the Compressive Strengths of 100 mm (4 in.) and 150 mm (6 in.) Method #C1 Cured Cylinders

	Linear Model	Nonlinear Model	Modified Linear Model	Evaluation
Model Equation	**y = 228.0869 + 0.9325*x**	y = 1.14e-09 + 1.23e-06*x + 0.001*x2 -4.63e-07*x3 + 7.27e-11*x4 - 4.03e-15*x5	y = x	The linear model is better in simplicity and easiness to use.
C.I.	95%	95%	95%	Same
Correlation Type	Pearson's	Pearson's	Modified Pearson's correlation	—
Number of Data Points	186	186	186	Same
Correlations	0.987	0.987	0.987	Same
r	**0.987**	0.984	0.9847	A higher value is preferred
R^2	**0.975**	0.967	0.9696	A higher value is preferred
RMSE	**251.241**	286.537	276.4787	A smaller value is preferred
MAE	**196.986**	234.593	216.3038	A smaller value is preferred
MAPE	0.065	0.11	0.0734	A smaller value is preferred

Note 1: The bold numbers are the selected best values of the measurements.

The modified Pearson's correlation method in Table 16 follows the Wilkinson-Rogers notation to describe regression in a simplified manner by making specific coefficient values into zeros. The modified Pearson's correlation method identifies the response variable based on the previous linear and nonlinear correlation analyses.

It is a deviation if the calculation is for estimating residuals of the data sample, where i = variable, N = number of non-missing data points, y_i=actual observations time series, and $\hat{y}_i$ = estimated time series.

$$MAE = \frac{\sum_{i=1}^{N} |\hat{y}_i - y_i|}{N}$$

Figure 28. Equation. Mean absolute error.

$$MAPE = \frac{1}{N} \sum_{i=1}^{N} \frac{|\hat{y}_i - y_i|}{y_i}$$

Figure 29. Equation. Mean absolute percentage error.

Table 17 compares the model performances of the linear and nonlinear equations of the correlation models of the compressive strengths of 100 mm (4 in.) and 150 mm (6 in.) cylinders cured using Method #C2. The results indicate that the linear model is simpler, easier to use, and better performing than the nonlinear model. Table 17 also provides a simplified engineering equation of the correlation model with acceptable tradeoffs of accuracy and reliability compared to the linear and nonlinear models. Additionally, the initial compressive strengths of 100 mm (4 in.) and 150 mm (6 in.) cylinders should be zero in the modified linear model.

Table 17. Comparison of Linear vs Nonlinear Correlation Models of the Compressive Strengths of 100 mm (4 in.) and 150 mm (6 in.) Method #C2 Cured Cylinders

	Linear Model	**Nonlinear Model**	**Modified Linear Model**
Model Equation	**y = 1067.0 + 0.81*x**	y = 9.227e-10 + 1.365e-06*x + 0.0013*x2 - 4.784e-07*x3 + 6.891e-11*x4 – 3.514e-15*x5	y = 1.1*x
C.I.	95%	95%	95%
Correlation Type	Spearman, Pearson’s	Spearman, Pearson’s	Modified Pearson’s correlation
Number of Data Points	192	192	192
Correlations	0.955	0.955	0.955
r	**0.955**	0.951	0.8762
R^2	**0.913**	0.904	0.7677
RMSE	329.983	345.441	**38.8653**
MAE	**260.41**	273.818	421.8578
MAPE	**0.062**	0.073	0.0965

Note 1: The bold numbers are the selected best values of the measurements.

Table 18 compares the model performances of the linear and nonlinear equations of the correlation models of the compressive strengths of 100 mm (4 in.) cylinders versus the flexural strengths of 500 mm (20 in.) beams cured using Method #C1. After the comparison of the linear and nonlinear models given in Table 18, a simplified engineering equation of the correlation model with acceptable accuracy and reliability is derived. Even though the linear model is simpler and easier to use, the results indicate that the modified nonlinear model of y = 10.3 * sqrt(x) has the best performance and accuracy.

Table 18. Comparison of Linear vs Nonlinear Correlation Models of the Compressive Strengths of 100 mm (4 in.) Method #C1 Cured Cylinders vs the Flexural Strengths of 500 mm (20 in.) Beams

	Linear Model	**Modified Linear Model**	**Modified Nonlinear Model**	**Empirical Relationship***	**Nonlinear Model**	**Evaluation**
Model Equation	y = 243.0 + 0.1*x	y = 0.1513*x	**y = $10.295\sqrt{x}$**	y = $7.5\sqrt{x}$	y = 2.688e-10 + 2.168e-06*x + 0.0003*x^2 - 1.194e-07*x^3 + 1.853e-11*x^4 – 9.975e-16*x^5	Simplicity and easiness to use
C.I.	95%	N/A	N/A	N/A	95%	Same
Correlation Type	Spearman's, Pearson's	y-intercept = 0	Empirical	Empirical	Spearman's, Pearson's	–
Number of Data Points	204	204	204	204	204	Same
Correlations	0.815	N/A	N/A	N/A	0.815	Same
r	0.811	0.2043	**0.8320**	0.4683	0.807	A higher value is preferred
R^2	0.665	0.0417	**0.6923**	0.2193	0.655	A higher value is preferred
RMSE	115.284	12.6962	**83.4149**	203.398	117.063	A smaller value is preferred
MAE	86.528	136.8531	**51.1558**	135.0444	89.419	A smaller value is preferred
MAPE	0.221	0.2856	**0.1124**	0.2433	0.207	A smaller value is preferred

* The empirical relationship y = $0.62\sqrt{x}$ is based on the American Concrete Institute standard (Yusuf et al., 2016), where y is the flexural strength at 28 days in N/mm^2 and x is cylinder compressive strength at 28 days in N/mm^2. Since 1 N/mm^2 = 145.038 psi, the equation can be transformed to y = 7.4668*$\sqrt{x} \approx 7.5\sqrt{x}$,where y and x are in psi.
Note 1: The bold numbers are the selected best values of the measurements.

Table 19 compares the model performances of the linear and nonlinear equations of the correlation models of the compressive strengths of 100 mm (4 in.) cylinders versus the flexural strengths of 500 mm (20 in.) beams cured using Method #C2. The linear model is simpler and easier to use, and the results indicate that the modified linear model of y = 0.1441 * x has the best performance and accuracy.

Table 19. Comparison of Linear vs Nonlinear Correlation Models of the Compressive Strengths of 100 mm (4 in.) Method #C2 Cured Cylinders vs the Flexural Strengths of 500 mm (20 in.) Beams

	Linear Model	**Modified Linear Model**	**Modified Nonlinear Model**	**Empirical Relationship***	**Nonlinear Model**	**Evaluation**
Model Equation	y = 60.1909 + 0.1310*x	**y = 0.1441*x**	y = 9.6534*$\sqrt{x}$	y = 7.5$\sqrt{x}$	y = 7.685e-11 + 1.434e-07*x + 0.0001*x^2 - 2.303e-08*x^3 + 1.961e-12*x^4 – 6.598e-17*x^5	Simplicity and easiness to use
C.I.	95%	95%	N/A	N/A	95%	Same
Correlation Type	Spearman's, Pearson's	Spearman's, Pearson's	Empirical	Empirical	Spearman's, Pearson's	—
Number of Data Points	204	204	204	204	204	Same
Correlations	0.882	N/A	N/A	N/A	0.882	Same
r	0.88	0.8775	0.8491	0.3888	**0.918**	A higher value is preferred
R^2	0.779	0.7700	0.7210	0.1512	**0.84**	A higher value is preferred
RMSE	91.82	93.7361	90.3098	136.7675	**78.17**	A smaller value is preferred
MAE	76.783	76.2581	63.7829	107.0069	**63.023**	A smaller value is preferred
MAPE	0.179	0.1579	0.2343	0.2389	**0.128**	A smaller value is preferred

* The empirical relationship y = 0.62$\sqrt{x}$ is based on the American Concrete Institute standard (Yusuf et al., 2016), where y is the flexural strength at 28 days in N/mm^2, and x is cylinder compressive strength at 28 days in N/mm^2. Since 1 N/mm^2 = 145.038 psi, the equation can be transformed to y = 7.4668*$\sqrt{x} \approx 7.5\sqrt{x}$,where y and x are in psi.
Note 1: The bold numbers are the selected best values of the measurements.

Table 20 compares the model performances of the linear and nonlinear equations of the correlation models of the compressive strengths of 150 mm (6 in.) cylinders versus the flexural strengths of 500 mm (20 in.) beams cured using Method#C1. After the comparison of the linear and nonlinear models given in Table 20, a simplified engineering equation of the correlation model with acceptable accuracy and reliability is derived. The linear model is the simplest and easy to use, and the results indicate that the modified nonlinear model of y = 10.223$\sqrt{x}$ has the best performance and accuracy.

Table 20. Comparison of Linear vs Nonlinear Correlation Models of the Compressive Strengths of 150 mm (6 in.) Method #C1 Cured Cylinders vs the Flexural Strengths of 500 mm (20 in.) Beams

	Linear Model	**Modified Linear Model**	**Modified Nonlinear Model**	**Empirical Relationship***	**Nonlinear Model**	**Evaluation**
Model Equation	y = 200.0741 + 0.1075*x	y = 0.1538*x	**y = 10.223$\sqrt{x}$**	y = 7.5$\sqrt{x}$	y = 3.196e-10 + 2.595e-07*x + 0.0003*x^2 -1.329e-07*x^3 + 2.211e-11*x^4 – 1.277e-15*x^5	The linear model is better in simplicity and easiness to use.
C.I.	95%	N/A	N/A	N/A	95%	Same
Correlation Type	Spearman's, Pearson's	Empirical	Empirical	Empirical	Spearman's, Pearson's	—
Number of Data Points	160	160	160	160	160	Same
Correlations	0.870	N/A	N/A	N/A	0.870	Same
r	0.874	0.7679	**0.8917**	0.3247	0.871	A higher value is preferred
R^2	0.757	0.5897	**0.7951**	0.1054	0.752	A higher value is preferred
RMSE	97.246	126.3815	**89.3034**	186.6171	98.315	A smaller value is preferred
MAE	78.593	107.5218	**71.4273**	160.6865	81.634	A smaller value is preferred
MAPE	0.204	0.2097	**0.1775**	0.2830	0.178	A smaller value is preferred

* The empirical relationship y = 0.62$\sqrt{x}$ is based on the American Concrete Institute standard (Yusuf et al., 2016), where y is the flexural strength at 28 days in N/mm^2 and x is cylinder compressive strength at 28 days in N/mm^2. Since 1 N/mm^2 = 145.038 psi, the equation can be transformed to y = 7.4668*$\sqrt{x} \approx 7.5\sqrt{x}$,where y and x are in psi.
Note 1: The bold numbers are the selected best values of the measurements.

Table 21 compares the model performances of the linear and nonlinear equations of the correlation models of the compressive strengths of 150 mm (6 in.) cylinders versus the flexural strengths of 500 mm (20 in.) beams cured using Method #C2. After the comparison of the linear and nonlinear models given in Table 21, a simplified engineering equation of the correlation model with acceptable accuracy and reliability is derived. The linear model is simplest and easy to use, and the results indicate that the modified linear model of y = 0.1336*x has the best performance and accuracy.

Table 21. Comparison of Linear vs Nonlinear Correlation Models of the Compressive Strengths of 150 mm (6 in.) Method #C2 Cured Cylinders vs the Flexural Strengths of 500 mm (20 in.) Beams

	Linear Model	Modified Linear Model	Modified Nonlinear Model	Empirical Relationship*	Nonlinear Model	Evaluation
Model Equation	y = -82.3472 + 0.1509*x	**y = 0.1336*x**	y = 9.1201*$\sqrt{x}$	y = 7.5*$\sqrt{x}$	y = 8.855e-12 + 1.325e-08*x + 1.297e-05*x^2 + 1.329e-08*x^3 - 6.129e-12*x^4 + 4.075e-16*x^5	The linear model is better in simplicity and easiness to use.
C.I.	95%	N/A	N/A	N/A	95%	Same
Correlation Type	Spearman's, Pearson's	Empirical	Empirical	Empirical	Spearman's, Pearson's	—
Number of Data Points	160	160	160	160	160	Same
Correlations	0.886	N/A	N/A	N/A	0.886	Same
r	0.884	0.8801	0.7651	0.3247	**0.912**	A higher value is preferred
R^2	0.786	0.7746	0.5854	0.1054	**0.833**	A higher value is preferred
RMSE	91.348	93.6739	127.0456	186.6171	**80.621**	A smaller value is preferred
MAE	74.57	77.7733	99.3854	160.6865	**64.313**	A smaller value is preferred
MAPE	0.177	0.2130	0.3429	0.2830	**0.141**	A smaller value is preferred

* The empirical relationship y = 0.62$\sqrt{x}$ is based on the American Concrete Institute standard (Yusuf et al., 2016), where y is the flexural strength at 28 days in N/mm^2 and x is cylinder compressive strength at 28 days in N/mm^2. Since 1 N/mm^2 = 145.038 psi, the equation can be transformed to y = 7.4668*$\sqrt{x} \approx 7.5\sqrt{x}$,where y and x are in psi. Note 1: The bold numbers are the selected best values of the measurements.

Based on the correlation analyses in Tables 16 to 21, some correlations are recommended. Table 22 summarizes all results of the best correlation for each hypothesis to determine which method is better for predicting the strengths of an in-place concrete item.

Table 22. Correlation Results Summary

	4 vs 6 in. Cylinder, C1	**4 vs 6 in. Cylinder, C2**	**4 vs 20 in. C-B, C1**	**4 vs 20 in. C-B, C2**	**6 vs 20 in. C-B, C1**	**6 vs 20 in. C-B, C2**
X	4 in. compressive strength	4 in. compressive strength	4 in. compressive strength	4 in. compressive strength	6 in. compressive strength	6 in. compressive strength
Y	6 in. compressive strength	6 in. compressive strength	20 in. flexural strength	20 in. flexural strength	20 in. flexural strength	20 in. flexural strength
Model	Y = 0.9836*X	Y = 1.0361*X	Y = 10.295*$\sqrt{x}$	Y = 0.1441*X	Y = 10.223*$\sqrt{x}$	Y = 0.1336*X
R-Squared	0.9955	0.9903	0.6923	0.7700	0.7951	0.786
RMSE	—	—	83.4149	93.7361	89.3034	91.348
MAE	—	—	51.1558	76.2581	71.4273	74.57
MAPE	—	—	0.1124	0.1579	0.1775	0.177

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