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STATE OF PRACTICE FOR CONCRETE CYLINDER MATCH CURING AND EFFECT OF TEST CYLINDER SIZE

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State of Practice for Concrete Cylinder Match Curing and the Effect of Test Cylinder Size

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16. Abstract
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EXECUTIVE SUMMARY

The prestressed concrete element industry is interested in exploring the application of different types of match-curing technologies and in using 4 x 8-in. (100 x 200-mm) cylinders to measure concrete compressive strength instead of the standard 6 x 12-in. (150 x 300-mm) cylinders. Application of this new technology creates potential for cost savings to the producer and the Illinois Department of Transportation (IDOT) as improved knowledge of concrete strength development allows more efficient and accurate stress release and form removal times, normally within 24 hours after casting. The technology associated with match-curing cylinders is somewhat new, and little information is available on the use of temperature-controlled chambers for match curing. This study explores the effects of match-curing performance specifically taking into consideration the insulated jacket mold and air chamber technologies, as well as the effect of cylinder size. This research effort consists of five objectives: (1) review of the literature, current industry practice, and available technology; (2) purchase, assembly, and verification of the effectiveness of match-curing technology; (3) study of the effect of system temperature control on match-cured (water bath) strength results; (4) study of the utility of using match-curing technologies (insulated jacket mold and air chamber) to estimate 1-day, in-place compressive strength; and (5) study of the effect of cylinder size on match-cure strength results.

For the experimental work, concrete satisfying IDOT Class PS concrete specifications was cast in 4-in. (100-mm) diameter cylinders, 6-in. (150-mm) diameter cylinders, and large-slab samples; in some cases, ready-mix concrete was used. Standard mixing, casting, and material testing procedures were employed in the construction of these samples. Type T thermocouple sensors with a multichannel data acquisition system were used to monitor temperatures with a precision of 1 °F (0.56 °C). In-place concrete strength was measured using cast-in-place cylinders drawn from large-slab samples with preliminary tests showing that the cast-in-place cylinders accurately represented the temperature profile of the surrounding concrete in the slab. Three types of match-curing technology were studied: a water bath system (non-commercial), an air chamber system (non-commercial), and an insulated jacket mold system (a commercial product manufactured by Products Engineering).

Rigorous statistical analysis was used to evaluate experimental results, revealing transient disruption (significant loss of temperature control over a short period of time) to have a much larger influence on 24-hour strength than constant offset error when error area (error maturity) is compared. Absolute temperature error is likely a better standard of comparison across these two error types. It appears that the temperature-control criteria in AASHTO standard procedure PP 54-06 are appropriate for obtaining accurate representation of in-place strength for both 4 and 6-in. (100 and 150-mm) diameter cylinders using an air chamber or insulated jacket mold. Results show that air chambers are more likely to exhibit transient disruption error and be warmer than in-place, while insulated jacket systems are more likely to exhibit constant offset error and to be colder than in-place. Although 4 and 6-in. (100 and 150-mm) match-cure cylinders exhibit lower average concrete strength for air chamber and insulated jacket mold systems when compared to in-place concrete strength, they are statistically equivalent at the 95% confidence level as long as temperature-control errors are maintained within reason (AASHTO PP 54-06), though these control standards may be slightly conservative for air chamber systems.

In general, 4-in. (100-mm) cylinders show higher average strength regardless of curing type. Furthermore, there appears to be a cylinder-size effect for match-cure performance: generally, 6-in. (150-mm) cylinders are not as accurate for in-place strength, which appears to be the case for both air chamber and insulated jacket systems. Despite these observed size

effects, reasonable agreement with in-place strength is observed, as match-cured strength from both cylinder sizes did match in-place from a 95% confidence statistical point of view. Based on the literature review, experimental findings, and conclusions obtained in this project, we recommend that properly controlled match-curing procedures be deployed with confidence for both air chamber and insulated jacket systems using either 4 or 6-in. (100 or 150-mm) cylinders. In particular, we suggest that the AASHTO PP 54-06 standard practice for match curing be deployed once the proposed minor changes to that practice are implemented.

CONTENTS

CHAPTER 1 INTRODUCTION

The prestressed concrete element industry is interested in exploring the application of different types of match curing technologies. Match curing is a process whereby concrete test specimens are cured at the same temperature as the product by means of monitoring the concrete temperature in both the product and the test specimens, as well as applying heat to the test specimens, as needed, to match the concrete temperature in the product. By having the temperature of the companion cylinder match the product, a more accurate assessment of concrete strength is obtained, as compared with standard-cure (non-temperature-controlled) companion cylinders. This study is necessary to compare the performance of insulated jacket specimens and specimens in an air chamber with the actual concrete strengths of the “product” they represent. Also, the influence of temperature-control error in the match-curing system needs to be investigated. The technology associated with match-curing cylinders is somewhat new, and little information is available on using temperature-controlled chambers for match curing.

Furthermore, the industry would like to use 4 x 8-in. (100 x 200 mm) cylinders instead of the standard 6 x 12-in. (150 x 300 mm) cylinders to measure concrete compressive strength. Although smaller 4 x 8-in. (100 x 200 mm) cylinders cannot be used with large aggregate sizes, and accepted testing practice dictates that more small cylinders should be tested to ensure confidence in the results due to the expected higher variability of these results, 4 x 8-in. (100 x 200 mm) cylinders offer notable benefits over larger test cylinders: ease of handling, lower storage space requirements, lower material consumption, and lower test-machine capacity needs. Thus, there is strong potential for cost savings to the producer and the Illinois Department of Transportation (IDOT) if smaller cylinders are used. It is known, however, that measured strength values obtained from standard and small cylinders are not equivalent. Therefore, it is necessary to explore the effects of cylinder size on match-curing performance.

CHAPTER 2 CURRENT STATE OF UNDERSTANDING AND PRACTICE

To help guide and supplement the project, several sources of information were investigated. These included a review of technical literature, testing standards, and other documents related to the cylinder-size issue.

2.1 CYLINDER SIZE

2.1.1 Literature Review

The basic effects of test cylinder size on the measured compressive strength are well known. Smaller samples tend to provide higher average values of compressive strength (Neville 1996). This behavior is driven by the size-effect phenomenon associated with the fracture of brittle and quasi-brittle materials (Kim et al. 1999; Yi et al. 2006). The magnitude of the measured average strength change as a function of cylinder size depends primarily on the compressive strength of the concrete, where higher compressive strengths (generally above 7,000 psi) tend to lead to markedly higher measured values of strength for small cylinders (Vandegrift and Schindler 2006; Elfahal and Krauthammer 2005). Vandegrift and Schindler use the parameter K_s to denote the ratio of 4 x 8-in. cylinder strength to 6 x 12-in. cylinder strength:

$$f_{c_4} = f_{c_6} \times K_s \quad (1)$$

where f_{c_4} = compressive strength of a 4 x 8-in. cylinder, f_{c_6}= compressive strength of a 6 x 12-in. cylinder, and K_s= the strength conversion factor, correlating the 4 x 8-in. cylinder to the 6 x 12-in. cylinder strength. Researchers report that the value K_s increases with increasing compressive strength, ranging from about 1.03 for normal-strength concrete (compressive strength around 6,000 psi) to 1.10 for high-strength concrete (compressive strength ranging from 8,000 to 13,000 psi) (Elfahal and Krauthammer 2005). Lessard et al. (1993) compared compressive strength values from 6 x 12-in. and 4 x 8-in. cylinders for high-strength concrete. They report that the average compressive strength of 4 x 8-in. cylinders is approximately 5% greater than 6 x 12-in. cylinders; that is, $K_s \approx 1.05$. These research findings are supported by real-world testing data for normal-strength concrete through the Cement and Concrete Reference Laboratory (CCRL) program at the National Institute for Standards and Technology (NIST). CCRL offers laboratory testing-proficiency evaluations in which many testing laboratories participate. The semiannual testing-proficiency reports from CCRL collect test data from hundreds of testing laboratories and thus provide a good statistical basis to evaluate distinctions in 7-day, compressive strength laboratory data from 4 x 8-in. and 6 x 12-in. cylinders (CCRL 2011); each laboratory uses consistent materials and mixture design for normal-strength concrete in the study. The results from the past seven (2008 to 2011) CCRL semiannual reports show that 4 x 8-in. cylinders provided average strength values that are consistently higher (K_s ranging from 1.06 to 1.10, with an average of 1.085) than those obtained from 6 x 12-in. cylinders.

In addition, the maximum size of coarse aggregate in a concrete mixture should also be considered because it influences the size-effect phenomenon (Kim et al. 1999). Concrete used with 4 x 8-in. cylinders should have a maximum aggregate size of 1 inch (Forstie and Schnormeier 1981).

Cylinder size has also been reported to affect the variability of compressive strength test results, although the magnitude of this effect remains unclear. In general, higher levels of test variability result from smaller sample sizes. The CCRL data from the past seven semiannual reports (2008 to 2011) illustrate the complexity of this issue. The CCRL requires three 4 x 8-in. cylinders be tested to obtain an average strength value, whereas testing of only two 6 x 12-in. cylinders is required. The variability of normal-strength concrete strength data was slightly but consistently higher for the 4 x 8-in. cylinders, compared with that of 6 x 12-in. cylinders, when expressed as standard deviation. However, when the variability was expressed in terms of coefficient of variation (standard deviation normalized to strength), the results from the two cylinder sizes were approximately equivalent (CCRL 2011). The effect of concrete strength on this behavior is unclear. Some researchers have reported that the coefficient of variation from a set of three 4 x 8-in. cylinders is equivalent to, or even smaller than, that for 6 x 12-in. cylinders for high-strength concrete (Lessard et al. 1993). However, a more recent study suggests that the variability of concrete strength values does depend on the cylinder size and also the strength value itself (Taghaddos et al. 2010). The data from this study are shown in Figure 1. These results are based on a comparative concrete testing program administered by the Alberta Ready-mixed Concrete Association (ARMCA) and conducted by 15 laboratories in Canada over 10 years. More than 2,700 concrete strength testing results from a 10-year ARMCA program were analyzed. Despite the high level of scatter in the data, two trends are seen: Within-laboratory standard deviation increases as the average strength value increases and cylinder size decreases.

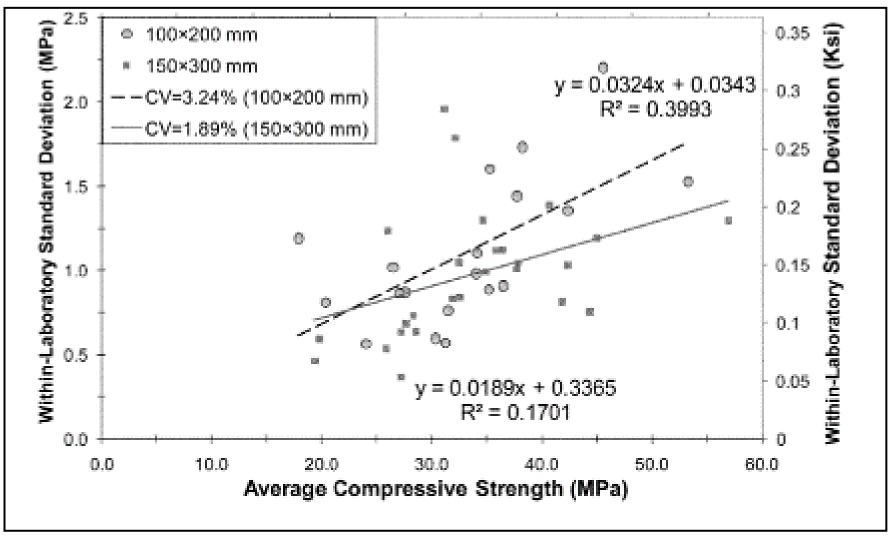


Figure 1. Within-laboratory standard deviation of data versus compressive strength for standard- and small-size test cylinders; test data from ARMCA program (Taghaddos et al. 2010). Note: 1 mm = 0.0394 in.

The data are also shown in Table 1 in terms of a comparison of within-laboratory and between-laboratory coefficient of variation (COV) for 4 x 8-in. and 6 x 12-in. cylinders. When equivalent cases are compared (e.g., same curing conditions, laboratory comparisons, and number of strength tests), the average COV of small cylinders is larger than that of larger cylinders. These findings are reflected in the researchers' suggestions for proposed within-laboratory and between-laboratory COV and the acceptable range of cylinders cured under field conditions, where smaller cylinders are expected to show larger COVs. They also propose acceptable COV levels, based on statistical confidence, for two- and three-cylinder strength tests, shown in Table 2.

Table 1. Within-Laboratory and Between-Laboratory COVs from ARMCA Program and Other Studies (Curing Conditions in Parentheses) (Taghaddos et al. 2010)

Study	COV			
	100 x 200 mm (4 x 8 in.)		150 x 300 mm (6 x 12 in.)	
	Within-laboratory	Between-laboratory	Within-laboratory	Between-laboratory
ARMCA	3.24 (Field)	6.41 (Field)	1.89 (Field)	5.05 (Field)
ASTM C39/C39M-09a	3.2 (Laboratory)	—	2.9 (Field)	5.00
Gray (1990)	—	—	3.6 (Laboratory)	5.3 (Laboratory)
Detwiler and Bickley (1993)	—	—	1.9	8.4
Kennedy et al. (1995)	—	—	3.0 (Field)	7.4 (Field)
Lobo (2005, 2006, 2007)	3.1 (Laboratory)	6.2 (Laboratory)	2.5 (Laboratory)	5.2 (Laboratory)
Detwiler et al. (2006)	2.86 (Field)	4.71 (Field)	—	—

Table 2. Proposed Within-Laboratory and Between-Laboratory COV and Acceptable Range of Two-Cylinder Strength Cured Under Field Conditions (Taghaddos et al. 2010)

Cylinder size, mm (in.)	Strength range, MPa (psi)	COV		95% Limits			
				Two-cylinder		Three-cylinder	
		Within-laboratory	Between-laboratory	Within-laboratory	Between-laboratory	Within-laboratory	Between-laboratory
100 x 200 (4 x 8)	17 to 54 (2500 to 7800)	3.24	6.41	9.1	17.9	10.7	21.2
150 x 300 (6 x 12)	19 to 57 (2750 to 8250)	1.89	5.05	5.3	14.1	6.2	16.7

Because of the observed strength variability effect, test standards and codes provide guidance about the number of test-sample replicas needed to obtain reliable strength estimates. AASHTO specifications (AASHTO 2008) state that a compressive strength test shall consist of the average strength of at least two 6 x 12-in. or at least three 4 x 8-in. test cylinders fabricated from material taken from a single randomly selected batch of properly molded concrete. Furthermore, a minimum of three cylinders shall be fabricated for each strength test, regardless of cylinder size, if the specified strength exceeds 5.0 ksi (AASHTO 2008). The ACI 318 building code also requires that a compressive strength test shall consist of the average strength of at least two 6 x 12-in. or at least three 4 x 8-in. test cylinders, although no provision is made for more samples for high-strength concrete (ACI 2008). ACI 318, R5.6.3.2, also specifies that "the cylinder size should be agreed upon by the owner, licensed design professional, and testing agency before construction (ACI 2008)." IDOT requires in its specifications that only 6 x 12-in. cylinders may be used to determine compressive strength of a concrete batch obtained from an average of two standard cylinders.

2.1.2 South Carolina DOT Survey of Practice

The South Carolina Department of Transportation (SCDOT) has carried out a survey of state DOT practice for small-cylinder strength correction (SCDOT 2010). Thirty-three states responded to the survey. Most states (90%) allow the use of 4 x 8-in. cylinders for strength testing of precast and prestressed concrete elements. However, most of these states restrict the use of 4 x 8-in. cylinders when the maximum aggregate size is greater than 1 in. None of the states surveyed apply a correction factor to convert strength values from 4 x 8-in. to 6 x 12-in. samples.

2.1.3 Missouri DOT Report

In the SCDOT survey described above, information from the state of Missouri was not included. The practice in that state was found in a separate report (Hake 2004). Missouri applies a correction factor to modify strength values from 4 x 8-in. to 6 x 12-in. cylinder results. It allows the use of 4 x 8-in. cylinders with a correction factor of 0.94 (i.e., K_s = 1. 06) for Missouri DOT Class A-1, prestressed concrete at the plant with a semi-controlled environment. Figure 2 shows results of compressive strength tests with different cylinder sizes, as reported by Missouri DOT. The Missouri results also indicate that 4 x 8-in. cylinders do not result in significantly greater within-test variability than do 6 x 12-in. samples. Based on their data, they conclude: "There is little justification for future specifications to require the testing of three rather than two cylinders when 100-mm (4-in.) plastic molds are used." However, these results were not reviewed using a rigorous technical peer-review system.

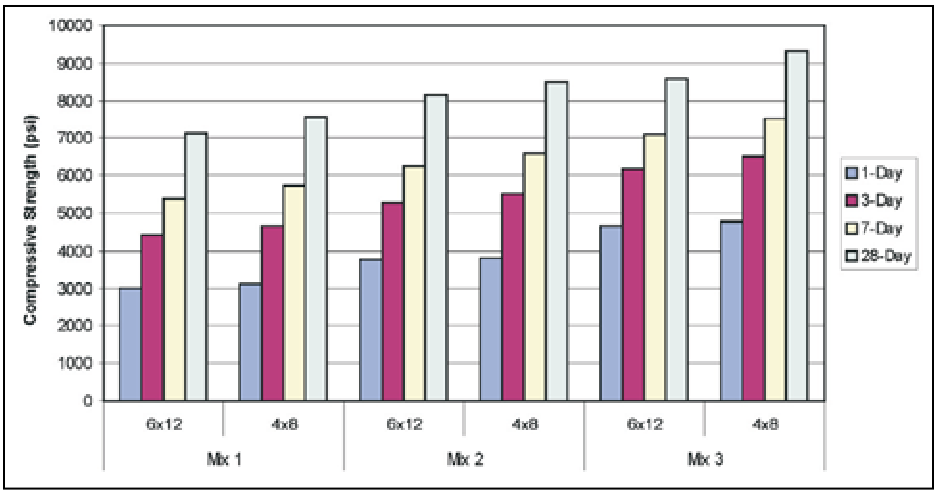


Figure 2. Average compressive strength for standard and small cylinders (Hake 2004).

2.2 MATCH CURING

To help guide and supplement the project, several sources of information were investigated. These included a review of technical literature, testing standards, and other documents related to the issue.

2.2.1 Literature Review

Generally, increasing concrete cure temperatures leads to increased strength development, but excessively high temperature (> 160°F or 71°C) may lead to increased material permeability and decreased strength (Kehl and Carrasquillo 1998). Match curing is a process whereby concrete test specimens are cured at the same temperature as the product by means of monitoring the concrete temperature in the product with an embedded reference sensor and controlling heat applied to the test specimens, as needed, to match the measured concrete temperature in the product. It follows that match-cured test samples are more representative of the strength within a structure than standard-cure companion cylinders. ASTM moist-cure and member-cured companion cylinders tend to underestimate early strength (e.g., 1-day). However, there are conflicting reports about the effect on late strength (e.g., > 56 days) (Myers and Carrasquillo 1999; Roller et al. 2003).

Match curing has a long history. Since the late 1920s, researchers in the United Kingdom and the United States monitored temperature conditions within concrete and matched curing specimens following the same temperature profile. The tests were undertaken to examine the effects of cement types, different cement contents, and different concrete placing temperatures upon the temperature rise and strength development of temperature-matched cure (TMC) specimens compared to standard-cure environments. In the 1970s, match-cure systems were developed for field use. This method has become more prevalent over the last 30 years, principally to determine appropriate formwork striking time or prestress transfer time (Cannon 1986; Kehl and Carrasquillo 1998). It must be emphasized that match curing does not reproduce in situ conditions; but by matching the temperature changes, it does eliminate one of the main reasons for the difference in properties between reference specimens and on-site concrete (Williams 1986).

Match curing is accomplished by the use of temperature-controlled insulated cylinder jacket molds or temperature-controlled curing chambers (either air or water). With controlled curing chambers, the environment within the chamber (either air or water) is automatically adjusted, based on the sensed temperature within a specimen, to match the temperature of a concrete reference, for example, an in-place slab or structure. With insulated jacket molds, however, the temperature of the interior surface of the mold (external surface of the sample) is adjusted to match the temperature of the concrete reference. Water bath systems have been used with success in laboratory studies, especially when smaller concrete samples are used. Well-controlled water bath systems can be assembled at reasonable cost using aquarium heaters and pumps (to obtain a uniform heat flux inside the water bath) and existing temperature controllers (Bert 2005; Khan 1995). Two self-constructed (not commercially produced) water bath systems are shown in Figures 3 and 4, respectively. Other studies show that match-cure strength results from water bath systems compare well to that obtained by in-place, semi-destructive, pull-out tests at 2 days after casting (Reddy 2008).

Figure 3. Laboratory equipment for water bath match curing (Reddy 2008).

The specimens in water bath should be properly sealed to protect the concrete from water immediately after casting. The initial water temperature inside the bath should be about the same as the mix constituents. The water bath temperature-matched curing is achieved by measuring the temperature at the center of the control cylinder and heating the surrounding water to match the temperature of the hydrating concrete cylinder.

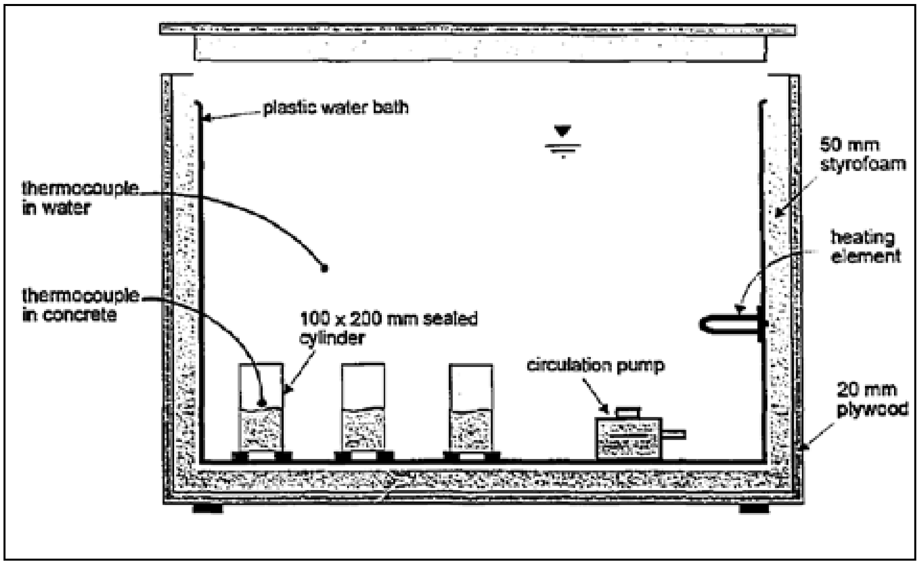


Figure 4. Testing setup for water bath equipment (Khan 1995).

More recently, the performance of insulated jacket mold and air chamber systems have been evaluated for match-curing application by the precast and prestressed concrete industry (TxDOT 2000) and concrete pavements (Olek 2001). Both types of systems are commercially available; an example of insulated jacket mold equipment is shown in Figure 5. Experimental studies confirm that match-cured samples provide more representative strength estimates of the concrete element than standard-cured companion specimens at early age; standard-cured companion samples tend to underestimate in-place concrete strength. At later ages, the standard-cured companion samples tend to overestimate in-place concrete strength, but there is some disagreement about the extent of this effect. The trend for elastic modulus of concrete is similar to that of compressive strength. The location of the embedded reference sensor within a single concrete element has some effect on the measured temperature profile, and this, in turn, will affect the match-cured cylinder. As shown in Figure 6, larger and voluminous sections (such as the girder end block) exhibit higher internal temperatures than slender sections (such as the girder web) (TxDOT 2000). Regardless of this variability, match-cured cylinders are more representative of concrete in the member than are standard-cured companion samples, providing a more accurate representation of the maturity of the concrete.

Figure 5. Commercially available equipment for match curing using the insulated jacket molds (TxDOT 2000).

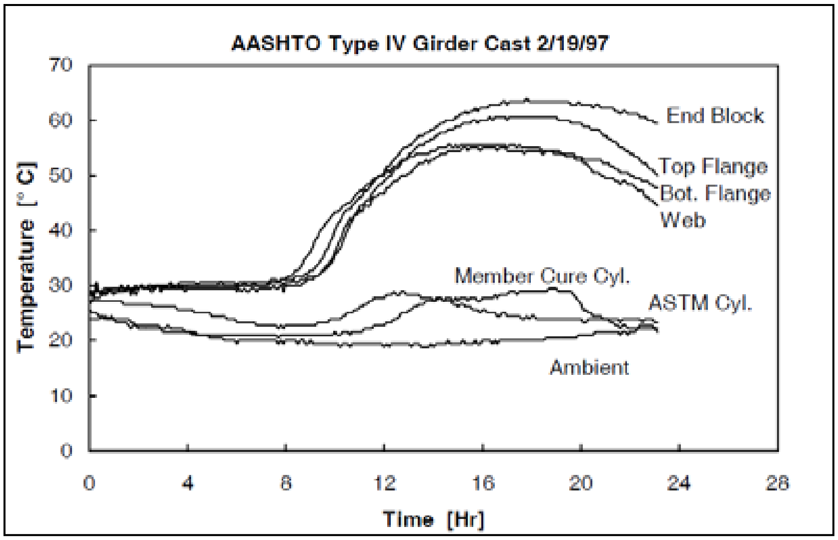


Figure 6. Obtained concrete-specimen temperature profiles at different locations within a girder, compared to standard curing procedures (TxDOT 2000). Note: °F = 9/5°C + 32.

One disadvantage of the commercially available insulated jacket mold systems is that they can accommodate only cylindrical specimens of typical size but not beam specimens or odd-sized cylinders (Olek 2001). Chamber systems can accommodate any sample type, assuming the chamber volume is sufficient. Commercially available controlled air chamber temperature-matched curing test systems are fairly expensive. However, controlled air chamber match curing systems can be assembled at reasonable cost using off-the-shelf components, as shown in Figure 7. It has been reported, though, that the temperature control of the self-developed (non-commercial) air chamber system was at times less than desired, especially because most match-curing systems do not provide controlled cooling to the environment (Olek 2001). The problem stems from the lag time for the samples within the chamber to match the temperature of the reference sensor embedded in the concrete product. This lag usually causes the temperature of the matched sample to exceed the temperature of the reference thermocouple and is especially significant in air chamber systems because air exhibits low thermal inertia. This temperature difference may cause notable overestimation of the strength of the concrete within the tested product element. Additional studies are needed to determine whether the extra expense of improving air chamber match-cure systems is worth the increase in accuracy when simple, more primitive methods like sandpit curing provide satisfactory results in many cases. In sandpit curing, companion samples are buried and maintained in moist sand nearby the monitored concrete product until the time of testing. This type of curing has been used by the Indiana Department of Transportation to monitor pavement samples (Olek 2001).

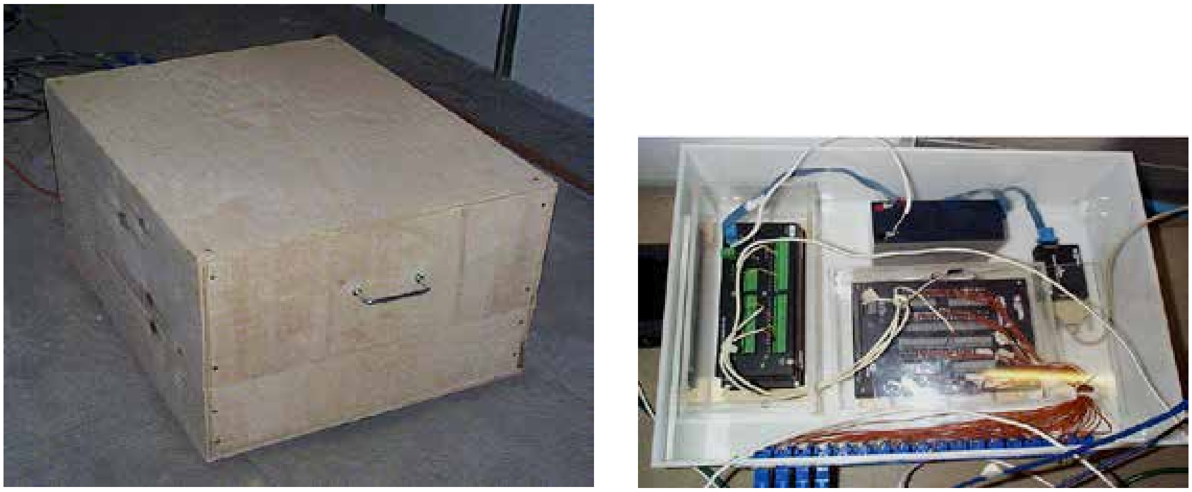


Figure 7. Assembled curing box for air chamber match curing, assembled using off-the-shelf components (Olek 2001).

A recent study evaluates the effects of concrete curing temperatures on compressive strength development in high-strength concrete (Roller et al. 2003). In this work, concrete temperatures within five AASHTO Type III bridge girders with a specified compressive strength of 10,000 psi were monitored. Results from standard 6 x 12-in. companion cylinders (cured alongside the girder) are compared to insulated jacket mold cylinders with a match-cure system. The command temperatures for the match-cure system were obtained from a specific location in the girder, where several different locations within the girder were considered, as shown in Figure 8. Temperatures within high-strength concrete members can vary considerably from one location to another, both within the cross section and along the length of the girder. These variations are caused by the conduction of heat out of the concrete through adjacent steel elements (such as the formwork and prestressing strand) and heat loss through insulated tarpaulins typically used to cover the casting bed. As expected, temperatures in the bottom flange at midspan were substantially greater than those measured near the girder end. It is evident that there was a considerable amount of heat loss at the girder end. Thus, it is important to select an appropriate location to sample temperature within the girder; this critical location is usually defined as a region with the slowest and lowest overall temperature rise (Russell 2004). For most I-beams and bulb-tee girders, this location is likely at the top flange.

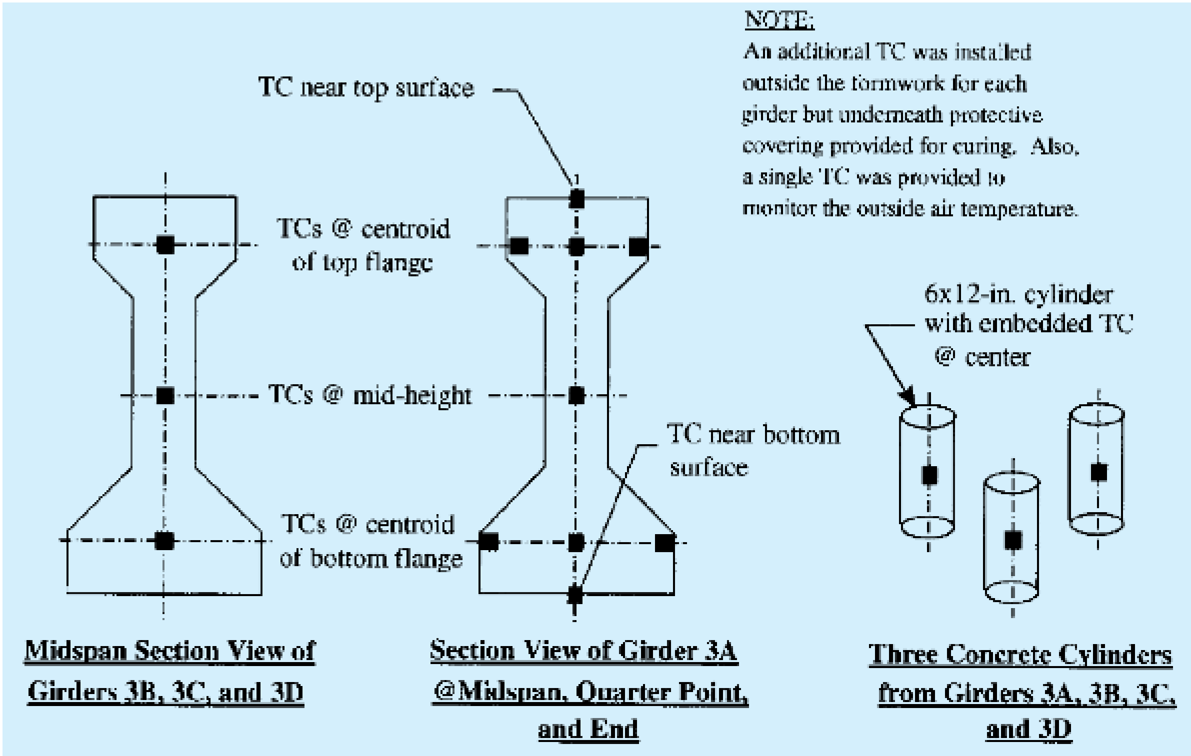


Figure 8. Thermocouple instrumentation (Roller et al. 2003).

As shown in Table 3 and Figure 9, compressive strengths of the match-cured cylinders were consistently higher than for the standard companion cylinders: The average compressive strength of the matched-cured cylinders is approximately 10% higher than the standard at 56 and 90 days. Roller et al. concluded that standard cylinders could underestimate the compressive strength of the girder concrete. Accurate measurement of concrete compressive strength requires test cylinders to be cured under conditions that are the same as those in the member they represent, especially for compressive strength exceeding 8,000 psi (55 MPa) (Roller et al. 2003).

2.2.2 Test Standard and Recommendations

AASHTO has a current designation regarding match curing (AASHTO PP 54-06) that allows for ±4°F (±2°C) tolerance in the temperature difference between the test cylinder and the structural member interior (AASHTO 2006). The AASHTO test requires temperature sensor, controller, and insulated molds with heating elements. Either 4 x 8-in. or 6 x 12-in. cylinder molds are accepted for concrete with 1-in. nominal maximum aggregate size. For larger aggregates, only 6 x 12-in. cylinders are allowed. The molds must be sealed to prevent moisture loss. The temperature of companion cylinders at the mold wall must be maintained within ±4°F (±2°C) of the temperature in the concrete element. Sealed cylinder molds, either 4 x 8-in. with 1-in. maximum aggregate size or 6 x 12-in. with 2-in. maximum aggregate size, should be used. A minimum of two 6 x 12-in. or three 4 x 8-in. cylinders shall be made for each strength test when the specified strength does not exceed 5000 psi (34 MPa). A minimum of three cylinders shall be made for each strength test when the specified strength exceeds 5000 psi (34 MPa). No explicit duration for match curing is specified, and only heating control is specified (not cooling). It should be noted that no particular match-curing approach is ruled out, but only insulated cylinder molds are specifically mentioned and accommodated in this standard.

Table 3. Compressive Strength and Modulus of Elasticity for Match and Field Curing (Roller et al. 2003)

Concrete property	Curing method	Girder	Concrete age				
			Release	7 days	28 days	56 days	90 days
Compressive strength, psi	Match	A	9,110	8,910	10,620	11,350	12,040
		B	8,210	9,850	10,520	11,400	12,420
		C	8,510	9,100	11,160	12,180	11,570
		D	7,630	9,140	9,960	—	11,760
		Avg.	8,360	9,250	10,570	11,640	11,950
	Field	A	6,470	8,360	9,080	9,580	10,220
		B	6,840	8,590	10,490	10,600	11,600
		C	7,790	8,000	9,670	10,280	10,520
		D	7,000	8,140	9,210	9,930	10,320
		Avg.	7,020	8,270	9,610	10,100	10,670
Modulus of elasticity, ksi	Match	A	5,800	6,050	5,750	6,000	6,000
		B	5,750	5,550	5,600	5,750	5,750
		C	5,650	6,050	6,200	6,200	6,150
		D	5,400	6,000	5,600	—	6,150
		Avg.	5,650	5,900	5,800	6,000	6,000
	Field	A	5,000	5,850	6,050	6,050	6,300
		B	5,450	5,500	5,750	5,900	6,250
		C	5,450	6,000	5,950	5,850	5,800
		D	5,400	6,400	5,800	6,100	5,600
		Avg.	5,350	5,950	5,900	6,000	6,000

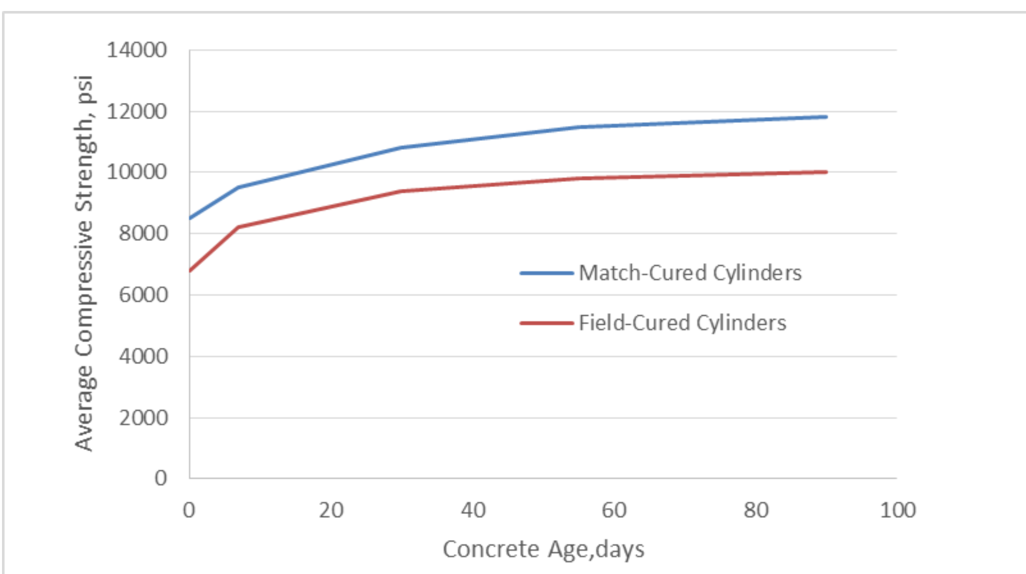


Figure 9. Compressive strength of match-cured and field-cured cylinders (Roller et al. 2003).

A test standard for water bath match curing has been established in the United Kingdom (BSI 1996). In that standard, an unsealed mold is immersed in a controlled-temperature water bath until the time of the test. The temperature of the water bath must be maintained within ±2°F (±1°C) of that in the concrete element, and the heater capacity must perform at least at 50 °F/h (28 °C/h). A water agitating device is required, and the system should function up to a temperature of 176°F (80°C). Compared with the AASHTO standard, this standard specifies more precise temperature control and defines a very specific procedure.

A test-procedure recommendation for match curing has been offered by the Texas Department of Transportation (TxDOT 2000). The test procedure is specified for insulated jacket mold match-cure systems, for use with precast or prestressed concrete products. The apparatus controller should hold the temperature of the mold within ±2°F (±1°C) of the reference-temperature profile. Type T shielded wire thermocouples of at least 20 awg (0.03196 inches dia. = 0.812 mm dia.) are required. Predefined temperature profiles can be used, but they should not deviate any more than ±5.4°F (±3°C) from the actual internal temperature profile for the first 18 hours. Concrete for match-cure cylinders should be taken from within 60 inches (1.52 m) of the thermocouple wire location, and a minimum of six match-cure cylinders should be made for each concrete batch. The match-cure cylinders should be covered to prevent heat and moisture loss.

2.3 SUMMARY

The effects of cylindrical sample size on compressive strength results are well known: smaller samples tend to exhibit higher average strength. Smaller sample size also tends to show more variation in the results, but this behavior is not as clearly established. Both of these behaviors are affected by the compressive strength of the concrete, with high-strength concrete showing larger differences in strength and, possibly, more variable data. However, many design codes and state transportation agencies neglect the difference in strength values between 4 x 8-in. samples and 6 x 12-in. samples because the difference is normally on the order of only several percent. Many agencies require a higher number of 4 x 8–in. samples (usually three) to be tested to establish a strength value because of the expected, although not definitively established, increased variability of the results.

Temperature-matched curing for concrete has been an established practice for decades, and several robust test standards and recommendations have been developed. There are three principal temperature match-curing systems in use: water bath, air chamber, and insulated jacket molds. All three types of match curing have been shown to provide test samples that more accurately represent the strength of in-place concrete in an element, compared with conventionally cured samples. Commercially available testing systems for all three exist. The insulated jacket systems are usually lowest in cost, although water bath and air chamber systems can be assembled using off-the-shelf components at reasonable cost. Each of the three systems have benefits and drawbacks. Relatively little research has been done to compare the effectiveness of the three types of match-curing systems nor the effect of sample size on match-curing results; more research is needed in these areas.

CHAPTER 3 EXPERIMENTAL PROCEDURES AND DETAILS

3.1 CONCRETE MIXTURES AND STANDARD TESTING PROCEDURES

3.1.1 IDOT-Specified Mix Designs

Mixtures that satisfy specifications for IDOT Class PS concrete were used in this work. This mixture class is assigned to precast, prestressed members. The PS specifications call for mixtures with a water to cement ratio (w/c) between 0.32 and 0.44 and a cement content between 565 and 705 lb/cu yd (335 and 418 kg/m^3). The slump of the fresh mixture should be between 1 and 4 in. (2.5 cm and 10 cm); the upper value can be increased to 7 in. (18 cm) if a high-range water reducer is used and up to 8½ in. (22 cm) if a polycarboxylate-type admixture is used. Entrained air is required with an air content between 5.0% and 8.0%. The coarse aggregate gradation should be either CA11, CA13, CA 14, or CA16, with a nominal maximum aggregate size of ¾ inch (2 cm). The design 28-day compressive strength is at least 5,000 psi.

For concrete mixed in-house at the University of Illinois, we proposed a mixture with 650 lb/cu yd (386 kg/m^3) of Type I cement and a 0.38 w/c ratio. A well-graded sand and ¾-in. (2 cm) crushed limestone were used as aggregates. The mixture proportions by mass were 1:0.38:2.84:1.72 [cement:water:fine aggregate:coarse aggregate (c:w:fa:ca)]. Superplasticizer and air-entraining admixtures were used as needed to meet IDOT performance specifications; in this regard, two different mixtures were considered, with different dosages of admixtures in each. The dosages and detail on the admixtures are given in Tables 4 and 5 for mixtures 1 and 2, respectively. The slump (ASTM C 143 procedure), air content (pressure method; ASTM C 231 procedure), and temperature of the fresh concrete were measured and recorded for each batch. For mixture 1, the measured slump was 2.5 in. (6.4 cm) and air was 8% by volume. Although these values satisfy IDOT specifications for structural concrete, we aimed to use higher slump (6 to 8 in.) (15 to 20 cm) and lower air content (5% to 6%) to better simulate standard practice at a prestressed concrete plant. Thus, the admixture dosages were adjusted accordingly for mixture 2, where the test results showed that slump was 7.1 in. (18 cm), and air was 6.3% by volume. Again, these values satisfy IDOT specifications for structural concrete. Therefore, mixture 2 was used as our standard mixture for all concrete cast in-house at the University of Illinois.

Table 4. Description and Dosage of Admixtures Used in Mixture 1

Admixture	Description	Dosage (ml/100 kg cement)	Dosage (fl oz / 100 lb cement)
Air Entrainer	ASTM C 260 (Grace Daravair 1400)	97.7	1.5
Super-Plasticizer	ASTM C 494 Types A&F/ASTM C 1017 Type I (Grace ADVA Cast 575)	450.0	6.9

Table 5. Description and Dosage of Admixtures Used in Mixture 2

Admixture	Description	Dosage (ml/100 kg cement)	Dosage (fl oz / 100 lb cement)
Air Entrainer	ASTM C 260 (Grace Daravair 1400)	58.6	0.9
Super-Plasticizer	ASTM C 494 Types A&F/ASTM C 1017 Type I (Grace ADVA Cast 575)	848.0	13.0

Considering the relatively large volume of concrete to be used in some portions of this study, ready-mix concrete was ordered from a local commercial supplier, Prairie Materials. A mixture that was nearly identical to that mixed in-house was provided.

The w/c was 0.38, with a cement content of 651 lb/cu yd. (386 kg/m^3).The mixture proportions by mass were 1:0.38:2.77:1.60 (c:w:fa:ca), where well-graded sand and ¾-in. (1.9-cm) crushed limestone aggregate were used. The slump was measured at delivery, and then a polycarboxylate high-range water reducer was added until the desired slump was achieved; the test procedures are described below. The target slump value was between 8 and 8.5 in. (20 and 22 cm).The air content was also measured at delivery, where the target value of the air content was between 5.5% and 7.5%. Six batches of ready-mix concrete were used. The properties of the mixtures are shown in Table 6.

Table 6. Ready-Mix Concrete Material Properties

	RMC1	RMC2	RMC3	RMC4	RMC5	RMC6
Air (%)	5.8	6.4	5.7	6.4	7.1	7.4
Slump (in.)	8.2	8.1	8.5	8.0	8.3	8.2
Slump (cm)	20.8	20.6	21.6	20.3	21.1	20.8

3.1.2 Mixing (ASTM C 192)

We followed a standard mixing procedure for all concrete produced in the laboratory. All mix components were mixed in a drum mixer with water at ambient room temperature maintained at an average of 73.4°F (23°C). Preparation of concrete was done in accordance with ASTM C 192 test procedures for laboratory made specimens, specifically the provision for machine mixing of concrete. The coarse aggregate and a portion of the mixing water were placed in the mixer. Fine aggregate, cement, and the remaining water were added while the mixer was running. The initial mixing process was completed in 3 minutes, followed by a 2-minute rest period, and a final 3-minute mixing period.

3.1.3 Material Tests

3.1.3.1 Slump (ASTM C 143)

Slump tests were performed in accordance with ASTM C 143 test procedure. For this test, a slump cone mold, plastic board, $^5/_8$-in. (1.6-cm) tamping rod, and ruler were used to test the concrete. The mold and plastic board were first dampened with the mold held firmly in place on the board. Concrete was then poured into the mold in layers of about one-third of the cone volume. After each layer, the concrete was rodded 25 times with the tamping rod. Care was taken to ensure the rodding process was performed over the entire surface to ensure adequate consolidation. Upon the pouring and rodding of the final layer, the concrete was leveled to ensure an accurate top layer height for later measurements. The mold was immediately lifted above the board in a quick, vertical motion. The slump was found as the vertical distance between the height of the cone and the height of the concrete sample. The entirety of this test was performed in approximately 2½ minutes, and the mold was not disturbed at any time.

3.1.3.2 Unit Weight (ASTM C 138)

First, unit weight was obtained using the ASTM C 138 test procedure. The sample was then tested for air content. This measurement sequence increased efficiency because the same container could be used for both tests. The weight of the empty container was recorded. Concrete was then poured into the container in three layers of equal volume; each layer was rodded 25 times with a $^{5}/_{8}$-in. (1.6-cm) tamping rod, and the container was struck with a mallet 10 to 15 times before subsequent layers were added. After the final layer was poured and consolidated, excess concrete was removed using the tamping rod as a screed, and the final weight was recorded. The difference between the final weight and the empty container weight was the weight of the concrete. Unit weights were found to be the weight of the concrete divided by the volume of the container.

3.1.3.3 Air Content (ASTM C 231)

Once unit weight measurements were taken, air pressure was found using a Type B meter in accordance with ASTM C 231 test procedure. The pressure gauge was inspected to ensure it was clean and able to properly form a seal. The apparatus was placed on the bowl with both petcocks opened. Water was injected through one petcock until it escaped through the other to ensure no air was trapped in the apparatus. The container was then hit with a mallet to release any residual trapped air. An initial pressure was obtained through pumping; if the pressure was over the indicator line, the air bleeder valve was used to release some of the pressure. The petcocks were closed and the air valve opened. The percentage of air in the sample was recorded and later reduced by 0.7% per the calibration requirements for limestone.

3.1.3.4 Casting and Curing (ASTM C 192)

For each mix prepared, cylinders were cast in accordance with ASTM C 192 test procedure for laboratory specimens. The cylindrical molds were first sprayed with form oil to allow easy removal of cured specimens. The molds were placed on a flat surface and filled through the layering and rodding procedure prescribed by the standard. After layering and consolidating was complete, the top of the mold was struck level; and the cylinder was left to cure uncovered. The curing process varied because it was specific to the test being performed.

3.1.3.5 Compressive Strength (ASTM C 39)

In accordance with ASTM C 39, the cured specimens were first measured to obtain the final volume and then weighed and the density of each cylinder computed. This was done to ensure consistent quality of the specimens, specifically with regard to density (and entrained air), and accurate strength results.

Compression strength was found in accordance with ASTM C 39 test procedure. A FORNEY compression machine was used and was in compliance with the standard. For all cylinders, unbound caps were used in accordance with the ASTM C 1231 test procedure. The load rate was 35 psi/s (0.25 MPa/s) or within the acceptable range. The peak compression load was obtained from the compression testing machine and used, with the previously obtained dimensions, to calculate the peak compressive stress.

3.1.4 Water Bath Tests

A detailed description of the water bath equipment and tests can be found in Section 3.3. The water bath match-cure equipment was used to apply a controlled, predefined temperature profile to cylindrical samples immersed in a water bath. In one series of tests, a typical temperature profile was manipulated with different types of “error” to examine the effects of this error on the strength results. In another case, the water bath was used to provide a constant-temperature curing environment for companion cylinder samples.

3.1.5 In-Place Strength Tests

A detailed description of the cast-in-place procedures can be found in Sections 3.5 and 5.2.

3.2 TEMPERATURE-PROFILE MEASUREMENTS

3.2.1 Sensors and DAQ

The internal concrete temperatures were measured using embedded thermocouples. A thermocouple is a thermoelectric temperature sensor formed by two dissimilar metallic wires joined at a probe tip and extended to a known junction. The electrical potential of the joined system is related to the temperature at the connection tip. Typical thermocouples are shown in Figure 10 (Efunda). Throughout the years, a wide range of thermocouples have been developed to be used in different applications; the most prevalent are the Type T and Type K thermocouples; and both have been deployed successfully to measure internal concrete temperatures. The Type K thermocouple is composed of a Chromel (90% Ni, 10% Cr) positive leg and Alumel (95% Ni, 2% Mn, 2% Al, 1% Si) negative leg, while the Type T thermocouple is made of a copper positive leg and Constantan (copper–nickel alloy) negative leg. Typically, Type K thermocouples are used in applications where temperatures range between -328 to 2462°F (-200 and 1350°C) and have sensitivities of 40.6 μV/°C (measured at 25°C). Type T thermocouples are effective between -328 to 752°F (-200 and 400°C) (Efunda). Table 7 shows basic thermocouple properties, including error and sensitivity. Although Type T thermocouples have the same sensitivity as Type K, the two conductors that make up Type T thermocouples are not ferromagnetic, and as a result have no Curie point. Therefore, lower variability/error is obtained with a Type T thermocouple when used within its temperature range and should thus be more reliable (Dowell 2010). For these reasons, Type T thermocouples are used in this study to measure temperatures for our study. However, we point out that Type K thermocouples are embedded in the air chamber temperature-control system.

Figure 10. Thermocouple wire types: Type T (left) and Type K (right) (Efunda).

Table 7. Basic Thermocouple Properties (Efunda)

ISA	Material (+ & -)	Temperature Range °C (°F)	Sensitivity at 25°C (77°F) µV/°C (µV/°F)	Error*	App.**
K	Chromel & Alumel (Ni-Cr & Ni-Al)	-270~1350 (-450~2500)	40.6 -22.6	LT: ±2.2~1.1°C(±4~2°F) HT: ±0.375~0.75%	I,O
T	Copper & Constantan (Cu & Cu-Ni)	-270~400 (-450~750)	40.6 -22.6	LT: ±1~2% HT: ±1.5% or ±0.42°C(±0.75°F)	I,O,R,V

*LT= Low temperature range, HT= High temperature range
**I = Inert media, O = Oxidizing media, R = Reducing media, V = Vacuum
(Constantan, Alumel, and Chromel are trade names of their respective owners.)

Electrical potential data from the thermocouples were monitored with an Omega TC-08 data acquisition (DAQ) unit, where the potential data were converted to a temperature. The data are transferred to a networked computer for analysis and storage. This DAQ module can measure temperature from -454 to 3308°F (-270 to 1820°C) and accepts both Types K and T thermocouples. A maximum of ten data readings per second are possible, and the system has 0.9°F (0.5°C) temperature resolution. This DAQ is capable of measuring eight channel inputs simultaneously. During the tests described here, temperature data were collected every 30 seconds for a total of 48 hours.

The purpose of this test was to verify the accuracy and precision of our data acquisition (DAQ TC-08) and Type T thermocouple system. The data obtained from our thermocouples and DAQ system were compared with that obtained by an independent digital thermometer for tests on hot water. As shown in Figure 11, a small water container (11.8 x 11.8 x 7.87-in. = 300 x 300 x 200-mm) was set up, and the sensors from the two measurement systems (our DAQ with Type T thermocouple and the Taylor digital thermometer) were placed inside. To get reasonable and constant results, the probes of the two sensors were centrally located within the bath at the same height. Hot water [initial water temperature of 121.1°F (49.5°C)] was placed in the chamber and allowed to cool naturally; the water temperature was measured every 30 seconds for 70 minutes during this cooling process.

As illustrated in Figure 12, the results showed the expected gradual decrease in temperature of the water. The water temperature approached the ambient temperature of 77°F (25°C) after several hours. There was a small difference in the reported temperature, indicating some discrepancy in accuracy between the sensor types; however, this difference between the reported temperatures became smaller over time as the temperature decreased. The maximum difference of temperature was 1°F (0.55°C), but after 10 minutes of testing, the maximum difference reduced to less than 0.5°F (0.3°C). Assuming that the digital thermometer provided inherently accurate results, we concluded that our DAQ and thermocouple system reported temperatures that were accurate within 1°F (0.55°C). This value is in agreement with expected values shown in Table 7.

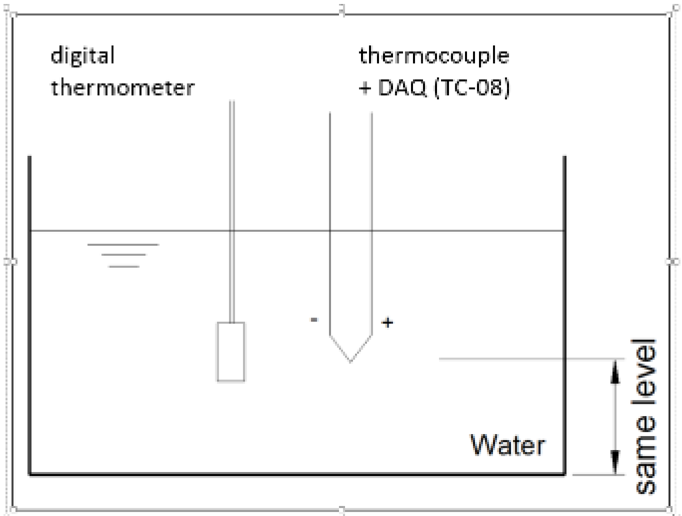


Figure 11. Verification test with digital thermometer:
Illustration of testing setup in hot water.

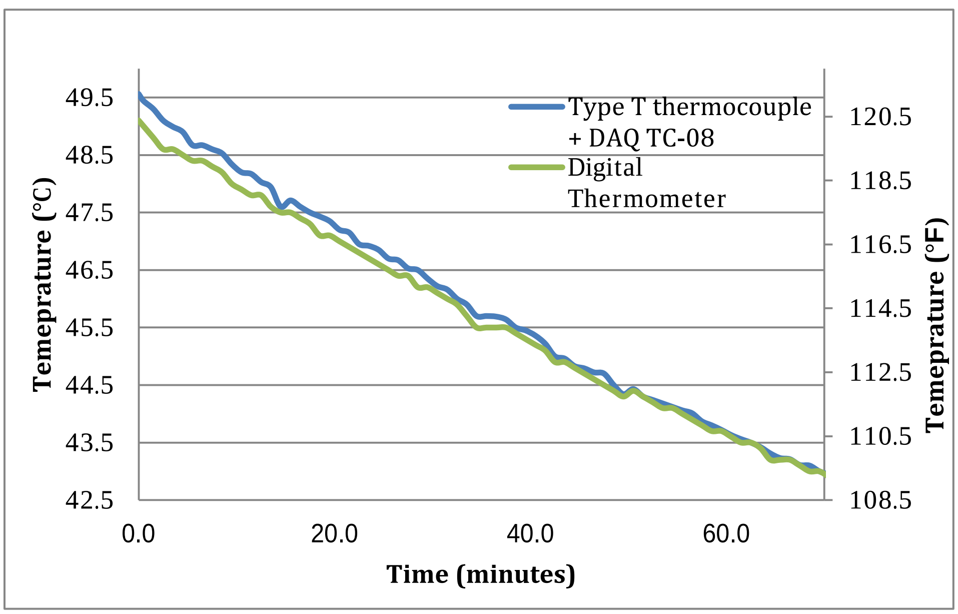


Figure 12. Temperature profile obtained from hot-water test with
two different types of thermocouple sensors.

3.2.2 Test Procedure and Preparation

It was necessary to define a reasonable temperature profile generated by the concrete mixture within a large concrete element. As required, we modified the insulation and environmental curing conditions of the sample to give a temperature profile that simulated that which normally exists during production in the field. To simulate a large volume specimen in an economical and efficient manner, we simulated a large element by exposing a standard cylinder to semi-adiabatic (well-insulated thermally) conditions instead of casting full-sized 2-ft x 2-ft x 8-in (0.61 m x 0.61 m x 0.2 m) concrete block samples. The semi-adiabatic test configuration is shown in Figure 13. It consisted of layers of commercial insulation foam stacked to give a 40 x 40 x 12-in. (1 m x 1 m x 0.3 m) block. A standard 6 x 12-in. cylinder mold was fit into a hole bored into the center of the foam block. In the first test (Figure 13), the top of cylinder mold was exposed to the laboratory environment, simulating the top surface of a thick concrete slab.

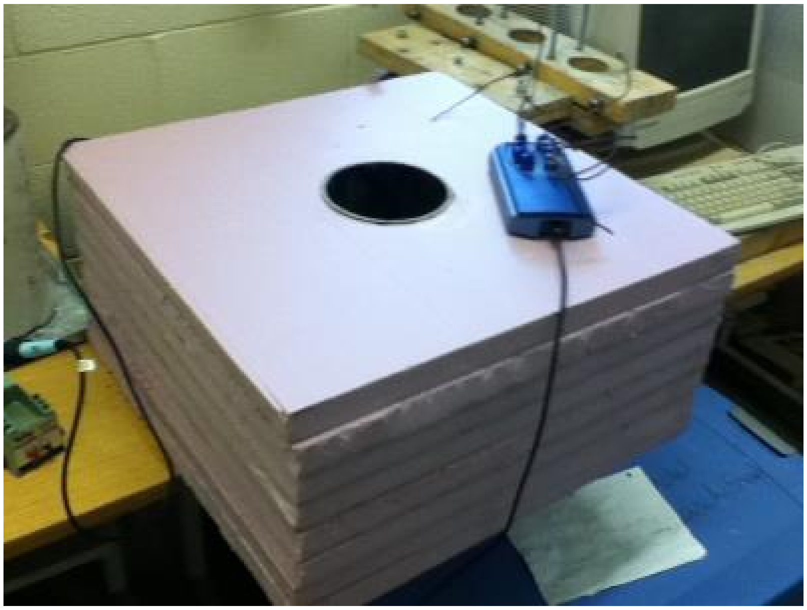


Figure 13. Semi-adiabatic testing setup used to simulate internal temperature of large 6-in.deep slab. A standard 6 x 12-in. cylinder mold is embedded in foam insulation.

After fresh concrete (mixture 1) was placed and consolidated into the embedded mold, the temperature was continuously monitored at three different depths within the cylinder using pre-placed thermocouples. Figure 14 shows the thermocouple locations within the 6 x 12-in. (150 x 300 mm) cylinder mold. Sensors 1, 2, and 3 are located at the bottom, the middle, and near the top surface, respectively. Sensor 4 measures the ambient temperature in the laboratory.

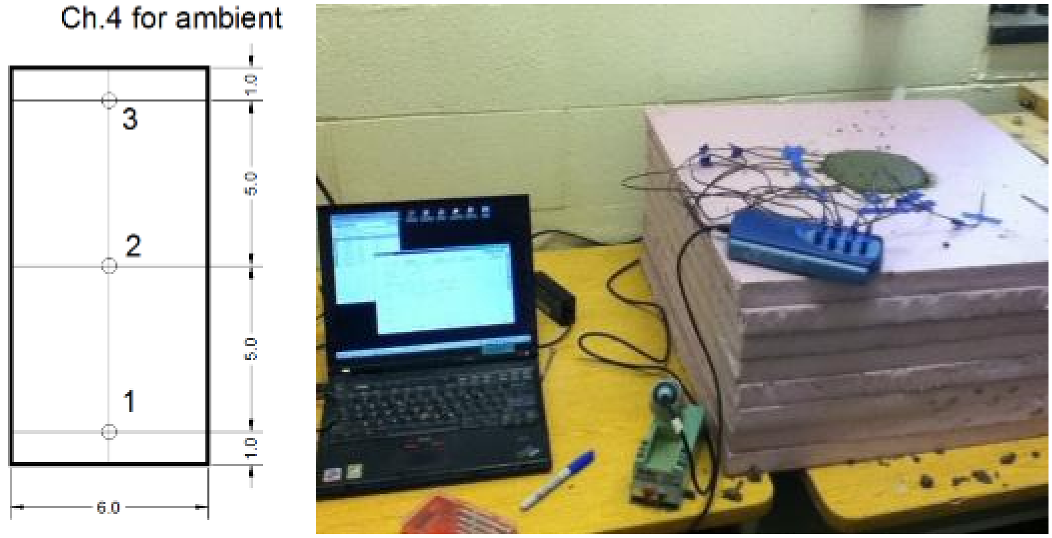


Figure 14. Temperature profile test using semi-adiabatic test configuration: Thermocouple location within cylinder, with dimensions in inches (left) and photo of testing equipment (right). Note: 1 in. = 25.4 mm.

3.2.3 Preliminary Temperature Control and Measurement Results

The temperature profile data obtained from the first test of the semi-adiabatic test configuration (Figures 13 and 14) are shown in Figure 15; again, we propose that this configuration reasonably simulated the temperature profile within a large, 12-in. (30.5 cm) thick slab. The room ambient temperature varied between 68 and 77°F (20 and 25°C), with an average of 72°F (22°C). This variation in temperature (channel 4) was rather large and was caused by the reduced air-temperature control in the laboratory at nighttime. The temperature of the concrete immediately after mixing was approximately 73°F (23°C). All three embedded sensors showed a rise in temperature after the concrete was placed, reaching a maximum value between 11 and 12 hours after casting. Afterward, all three embedded sensors showed a gradual decrease in temperature, approaching the ambient value approximately 40 hours after casting. The maximum temperature obtained depended on the position of the thermocouple. The bottom and middle sensors (channels 1 and 2) showed similar responses and reached a peak value of approximately 97°F (36°C) and appeared to be largely unaffected by the variation in ambient room temperature. The near-surface sensor (channel 3) showed a notably lower temperature peak at 88°F (31°C); furthermore, the temperature at this location appeared to be affected by the variation in ambient room temperature. The obtained peak value was notably lower than that ordinarily obtained in the field during production, which is normally 113 to 122°F (45 to 50°C). Thus, the semi-adiabatic test configuration was modified with a top cover to increase internal temperatures.

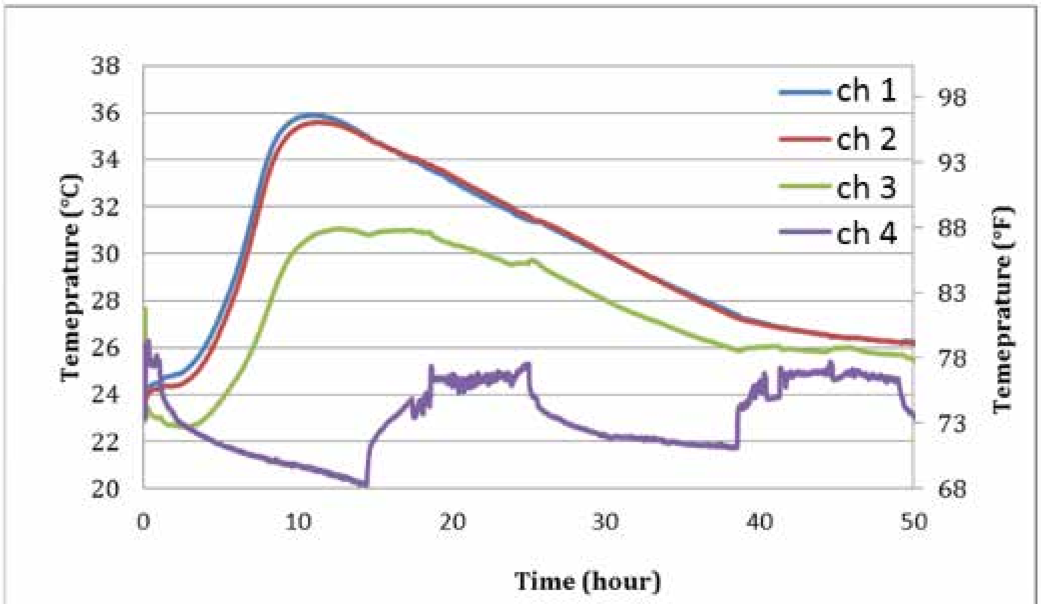


Figure 15. Typical temperature profile result from semi-adiabatic configuration shown in Figure 14. Data collected for mixture 1 for a period of 48 hours after casting.

The temperature profile tests were repeated with concrete mixture 2, using the same locations of the thermocouple sensors. The adiabatic test setup was modified by adding a thermally insulating layer (a piece of insulating foam) over the top of the embedded cylinder, as shown in Figure 16.

Figure 16. Temperature profile test using top covered, semi-adiabatic test configuration.

The resulting temperature profiles are shown in Figure 17. The room ambient temperature varied between 74 and 78°F (24 and 26°C), with an average of 76°F (25°C). The ambient-temperature profile was fairly consistent, although the signal did contain some disruption events. These were likely caused by electrical noise and did not represent actual temperature changes. The temperature of the concrete immediately after mixing was approximately 77°F (25°C). In a trend similar to the previous testing result, all three embedded sensors then showed a rise in temperature, reaching a maximum value between 11 and 12 hours after casting. All three embedded sensors then exhibited a gradual decrease in temperature but did not approach the ambient value even at 48 hours after casting. In this test, the maximum temperature obtained depended on the position of the thermocouple. However, unlike the previous test, the top and middle sensors (channels 2 and 3) showed similar responses and reached a peak value of approximately 122°F (50°C), which is 25°F (14°C) higher than in the previous test. The bottom sensor (channel 1) showed a lower temperature peak at 115.8°F (46.6°C), which was still higher than the maximum temperature from the previous test and represents the acceptable range of internal temperature. The higher overall values of the temperature profiles were caused by the extra insulating layer on top of the concrete sample. Thus, the top surface of the placed concrete was insulated in subsequent tests to reach this desired temperature range. In addition, ambient temperatures 3.5°F (2°C) higher may have also contributed to the increase in the maximum temperature, although the effect of ambient temperature was mitigated by the extra layer of insulation. We chose the temperature profile from channel 1, shown in Figure 17, to represent our standard temperature command profile for subsequent work on the effect of temperature control on match-cured strength.

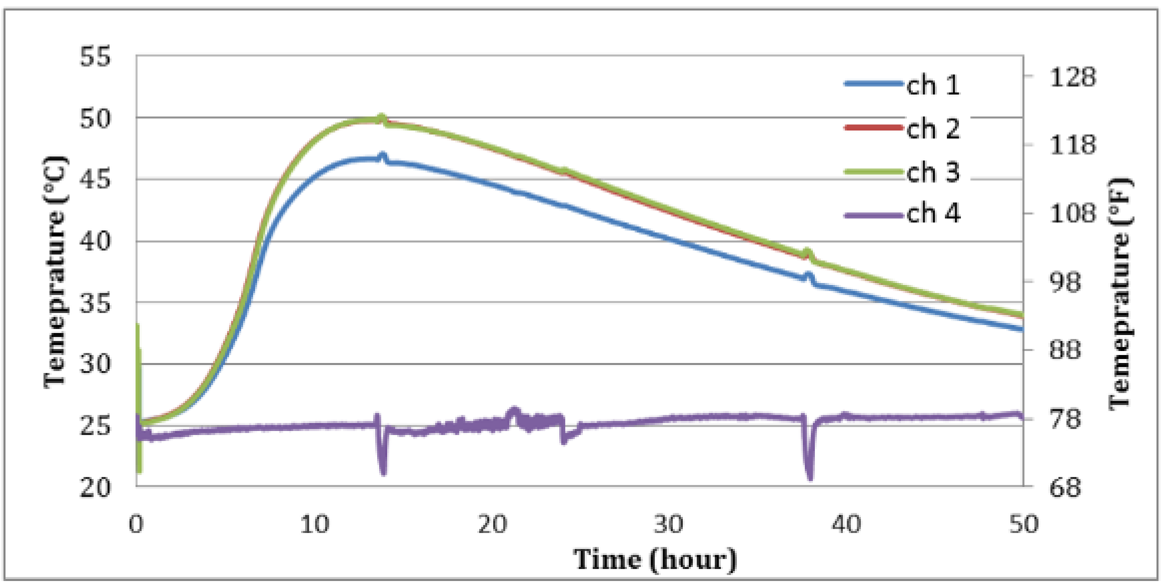


Figure 17. Typical temperature profile result from semi-adiabatic configuration shown in Figure 16. Data collected for mixture 2 over a period of 48 hours after casting.

3.3 WATER BATH

The water bath match-cure system was used for two different functions: (1) to expose immersed concrete cylinders to a controlled-temperature profile with different levels of control "error" (described in more detail in Section 4.1.1), and (2) to expose immersed concrete cylinders to a constant-temperature environment. The water bath system consists of a 36 x 30 x 24-in. (0.9 m x 0.76 m x 0.6 m),112-gal. (423.9 L) water tank made of polypropylene (US Plastic, model number TAMCO PP#91881). This material normally withstands temperatures up to the boiling point of water. Furthermore, polypropylene is a rather inexpensive polymer whose glass transition temperature is 14°F(-10°C) and melting point is 212°F (100°C); thus, this product can be operated at temperatures between 32 and 200°F (0 and 93°C). The tank size is big enough to contain ten 6 x 12-in. cylinders at one time. Two 9-amp water heater units hang on the inside of the container, and a water circulator ensures consistent water temperature throughout the tank. The maximum heating rate of the heating system in a full tank of water was determined to be 0.18°F/minute (0.1°C/minute). The heaters are controlled by a control module (Red Lion model number: CSPID) that controls a solid state relay electric switch system that provides power to the heater units. This control module also receives temperature command signals, either from a preset command signal or from the thermocouple receiver module (model number: CSTC8). The control module is based on a CPU (Red Lion model number: CSMSTRSX). Figure 18 shows the entire water bath match-cure system used in this work, and Figure 19 shows a detail of the control network and electric wiring diagram for the control box. The system uses standard 110V AC electric supplies, one for the control system and another for the heater units. All control-system connections and programming were done in our lab. The water bath control software code, written in Crimson 2 control software, is provided in Appendix B.

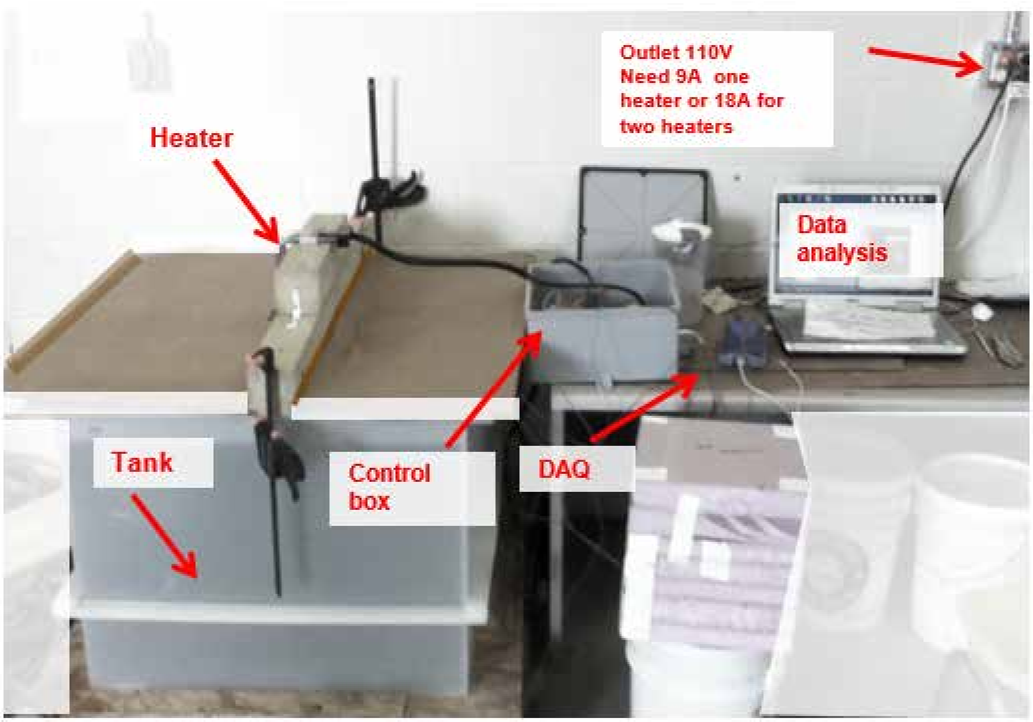


Figure 18. Water bath testing setup.

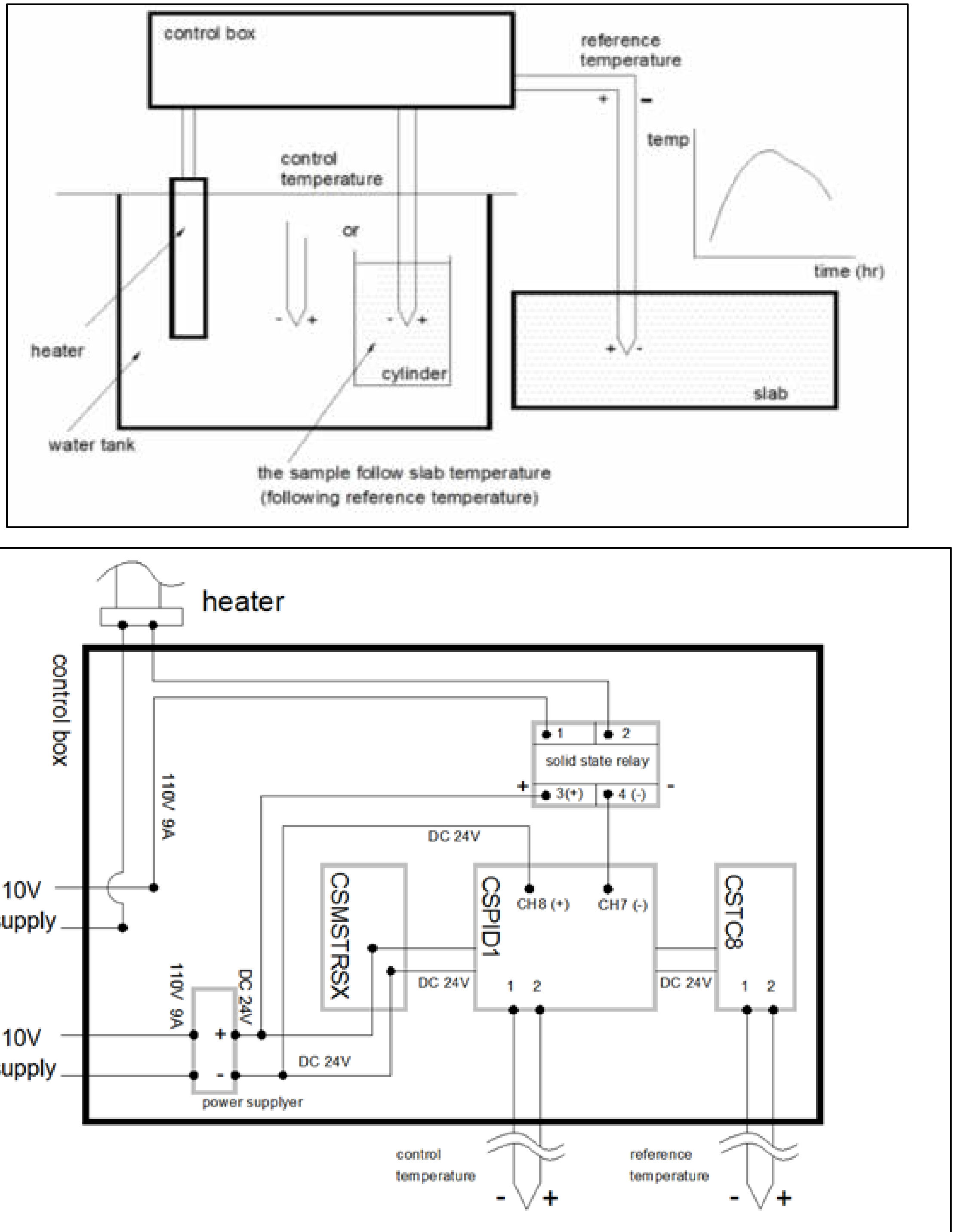


Figure 19. Water bath control configurations: overall configuration (top) and detail of control box electronic modules (bottom).

Preliminary verification tests demonstrated that the water bath system provides excellent [average temperature error was ±0.36°F (± 0.2 °C)] control of temperature of the water in the tank and the cylinders immersed in the water, within the heating rate limit of 0.18°F/minute (0.1°C/minute). However, the water bath system provides only heating and relies on ambient cooling to reduce the temperature. Thus, the ambient air temperature of the laboratory should be considerably lower [at least 9°F or (5°C)] than the desired temperature-control range to ensure that ambient cooling processes can sufficiently reduce temperature.

When water bath tests were run, the water in the tank was preheated to a starting temperature. For the case of the temperature-control error tests, the temperature was preset to a starting value to reasonably match the starting temperature of the fresh concrete; this starting value depended on the type of error and daily environmental conditions and ranged from 77 to 88°F (25 to 31°C). Then, multiple filled concrete cylinder molds were placed in the water bath, such that the water level approached but never exceeded the top of the cylinders. The entire water bath tank was covered with a PVC plate to maintain water level and an insulating sheet to isolate the temperature inside the water tank from the laboratory air temperature. The temperature command profile was then executed. The concrete cylinders themselves were not covered or sealed.

3.4 AIR CHAMBER

The function of the air chamber match-curing systems was evaluated through a series of tests. All of the tests were performed with samples of water or mortar mixture. The mixture proportions of the mortar by mass were 1:0.57:3.04 (c:w:fa).

Electrical potential data from the thermocouples were monitored with an Omega TC-08 data acquisition (DAQ) unit, where the electrical potential data were converted to a temperature. This DAQ allowed measurement of the temperature in eight different locations.

To evaluate the performance of the system, we placed a small cylinder in an enclosed box (air chamber) that contained a heating element. The temperature of the air in the chamber is synchronized with the temperature curve of a reference temperature (e.g., from a concrete slab or beam element) curing concurrently. The temperature inside the chamber is measured either directly in the air within the chamber, or by a separate sensor embedded in the cylinder inside the chamber. In this report, both the air and cylinder temperatures are referred to as the “control” temperature, while the temperature of the element under study (e.g., concrete slab or beam element) is referred to as the “reference” temperature, as shown in Figure 20.

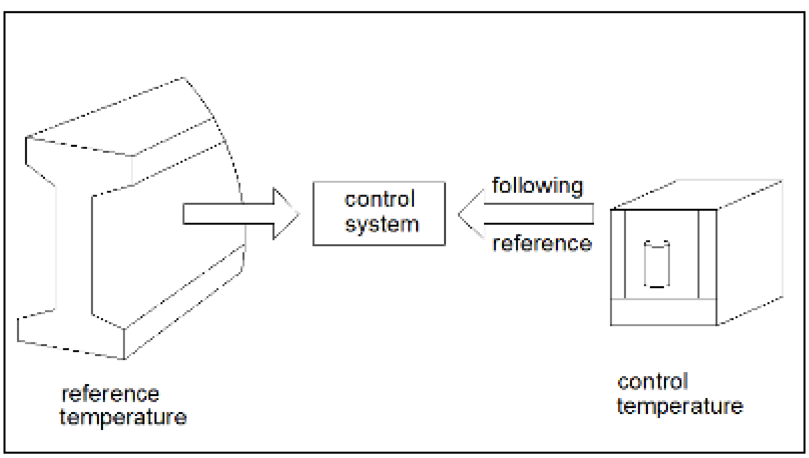


Figure 20. Schematic illustration of air chamber match-curing system.

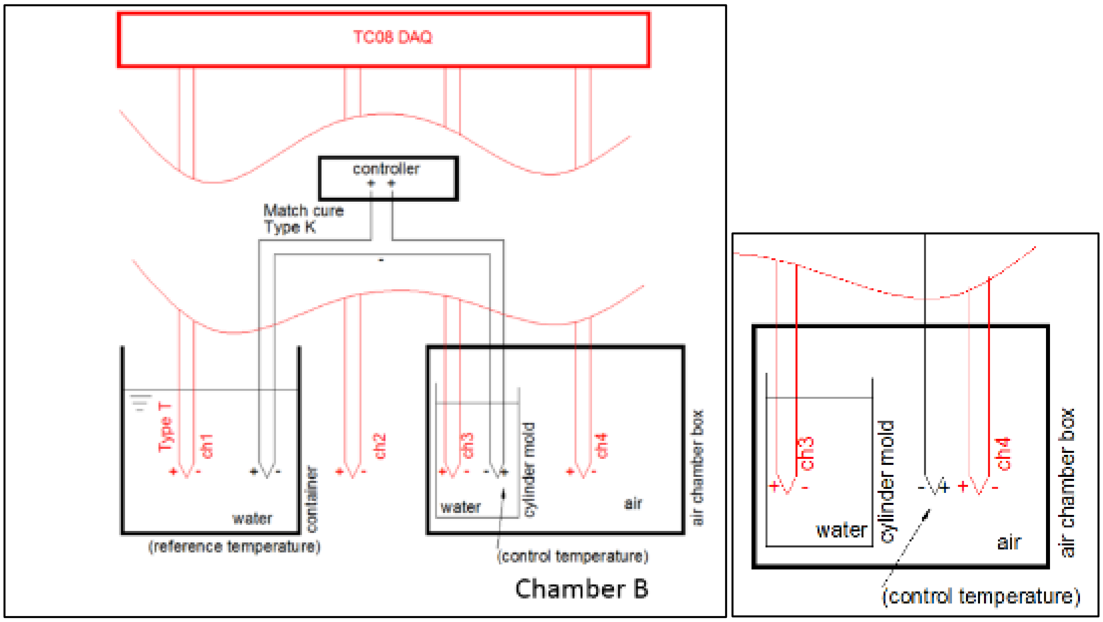
3.4.1 Water-Filled Cylinder as Reference

The air chamber equipment operates using the temperature differential measurement theory. Figure 21 shows the air chambers and the temperature-control mechanism. When the reference temperature in a specimen is higher than the control temperature, the panel shows a negative value. The control system then activates the heaters in the chamber to match the control temperature with the reference temperature. When the control temperature is close to the reference temperature, the value will approach zero and the heater will be turned off.

Figure 21. Two air chamber match-cure systems, B on the left and A on the right (left photo); and control panel on chamber (right photo), where a negative value indicates that the reference temperature is higher than the control temperature.

For the test, the two air chamber match-curing systems were fitted with an 8-channel Omega DAQ and a cylinder mold filled with water. The container used as a reference temperature was filled with 122°F (50°C) water, while a 4 x 8-in. cylinder mold in the air chamber was filled with water at 77°F (25°C), as seen in Figure 22. Figure 23(a) shows a thermocouple sensor in the water in the cylinder mold at control temperature (near the water surface of the cylinder mold), called case 1. Figure 23(b) shows the thermocouple sensor configuration the air box to measure control temperature, called case 2.

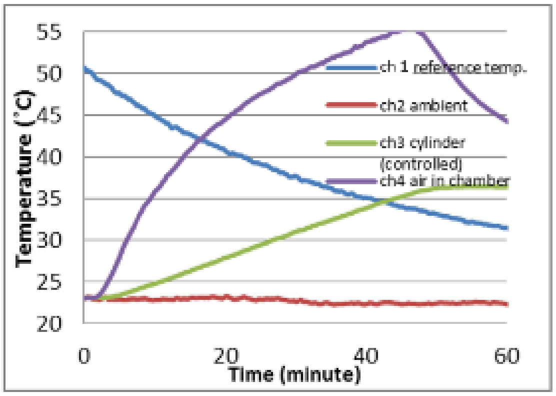
Figure 22. Location of thermocouple in the water-filled 4 x 8-in. cylinder mold.

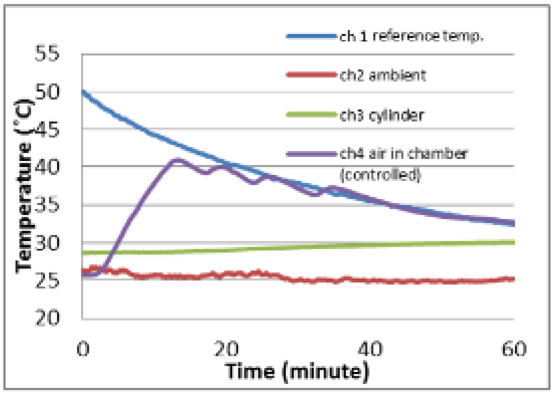


(a) ***(b)***

Figure 23. Illustration of thermocouple locations within the match-curing chamber: (a) case 1, control-temperature sensor located in the water in the cylinder mold; (b) case 2, control-temperature sensor located within the air chamber. Chamber B was used for both tests.

The total measuring time was 60 minutes, and the reference temperature in the container decreased naturally from 122°F to around 89°F (50°C to around 32°C), eventually approaching the ambient temperature. The control temperature in case 1, Figure 24(a), was the temperature of the water in the cylinder mold. The temperature of the air in the chamber exceeded the reference temperature at 41.5 minutes. Because the control-temperature sensor position in case 2, Figure 24(b), was in air in the chamber, the temperature profile rapidly followed the reference temperature (in the container). However, the temperature of the water in the cylinder never reached the reference temperature during the testing time (60 minutes). Usually, water has higher thermal inertia than air. Therefore, based on the result of case 2 (setting the sensor in the water in the cylinder mold), when the heater turned off at 41.5 minutes, channel 3 (i.e., water temperature in the cylinder) leveled off. Given this result of the higher volumetric heat capacity of water, it was expected that mortar mixtures would show similar trends.





(a) ***(b)***

Figure 24. Temperature profiles obtained for (a) case 1, (b) case 2.

3.4.2 Semi-Adiabatic Mortar as Reference

Volumetric heat capacity and thermal inertia were explored using a mortar mixture for the reference temperatures and control temperatures. All mortar mixture portions were as previously described in Section 3.4: the mixture proportions of the mortar by mass were 1:0.57:3.04 (c:w:fa). For the test, the mortar mixture was used to obtain the reference temperature, which is in a semi-adiabatic condition. A 4 x 4-in. (100 x 100-mm) cubic mold, shown in Figure 25, was used for casting mortar.

(a)

(b)

(c)

Figure 25. Testing configuration for semi-adiabatic test: (a) cubic concrete mold (100 x 100-mm) in semi-adiabatic jacket, (b) after casting, (c) closing cover to achieve adiabatic conditions.

Unlike the first test, the temperature of the mortar mixture was used for the reference temperature instead of the water, as demonstrated in Figures 26(a) and (b). Two tests were carried out: one was the control temperature at the water surface in the cylinder mold, called case 1; the other was that of the control temperature in the air in the chamber box, called case 2.

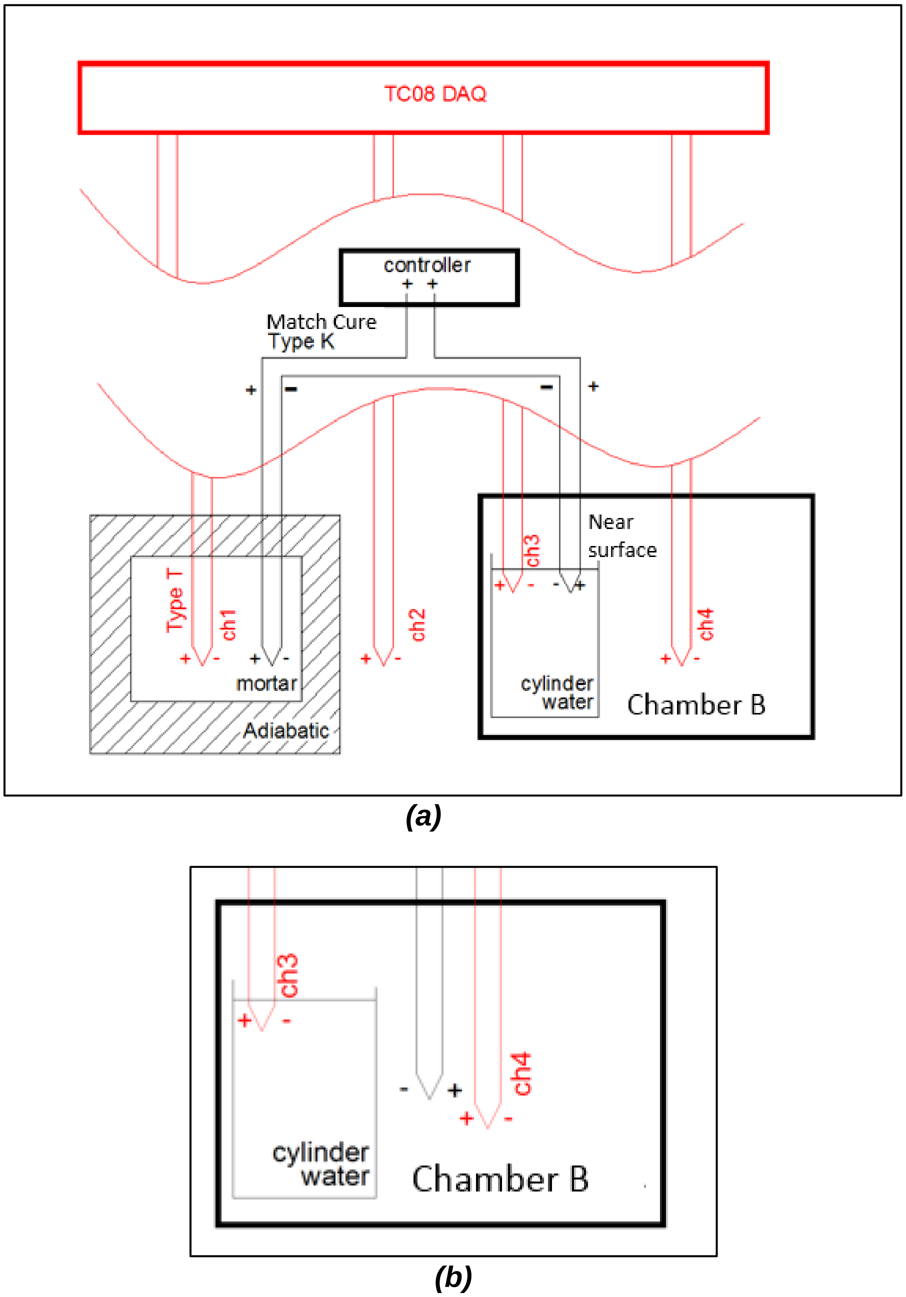
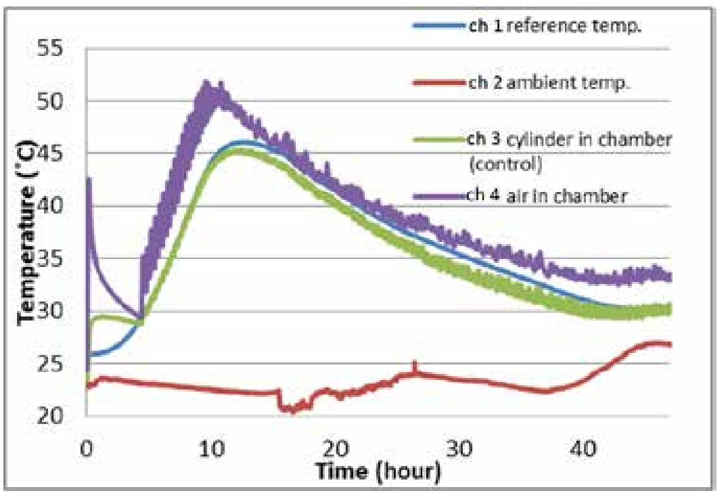
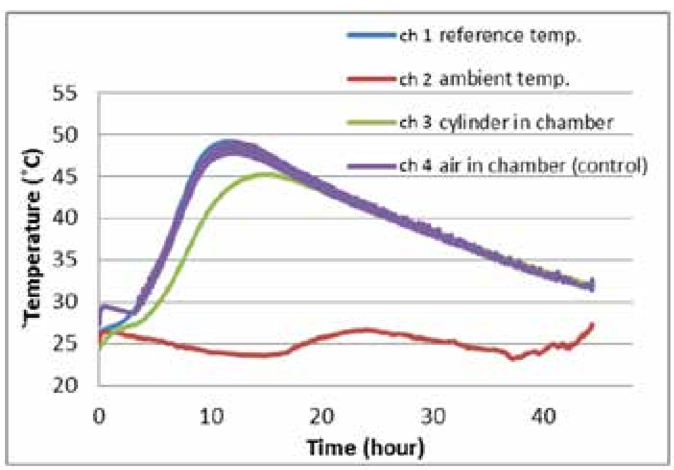


Figure 26. Testing configuration where semi-adiabatic mortar sample serves as reference temperature: (a) case 1, controlling water in cylinder; (b) case 2, controlling air in chamber. Chamber B was used for both tests.

The total measuring time was 48 hours, and the reference-temperature profile was similar to the profile of the concrete mixture with adiabatic condition in Section 3.4.1 Based on the result of case 1 in Figure 27(a) (i.e., control temperature in the water in the cylinder mold), although the air-temperature profile in the chamber was always higher than the reference temperature, the water temperature profile in the cylinder mold was close to reference-temperature profile until 10 hours. However, the water temperature profile was slightly lower than the reference-temperature profile after 10 hours, probably because of surface evaporation effects. A general trend of the case 2 result of the test, shown in in Figure 27(b), was that the air-temperature profile in the chamber box was close to the reference-temperature profile because the thermal inertia of the air was smaller than water. However, the temperature in the water in the cylinder mold did not reach the reference temperature until around 20 hours, after the maximum temperature was achieved. The average reference-temperature profile of case 1 was higher than that of case 2 because the average ambient temperature of case 1 was higher than case 2.



(a)



(b)

Figure 27. Obtained temperature profile for semi-adiabatic test: (a) case1, control in the water in cylinder; (b) case 2, control in the air in the chamber.

3.4.3 Adiabatic Mortar as Reference and Control

The total temperature measuring time was also 48 hours, and the reference-temperature profile was created with the mortar mixture in the adiabatic condition. In the test, the mortar mixture was also used in the cylinder mold in the chamber box. Also, in the test, the control temperature was in the cylinder mold, as shown in the Figure 28.

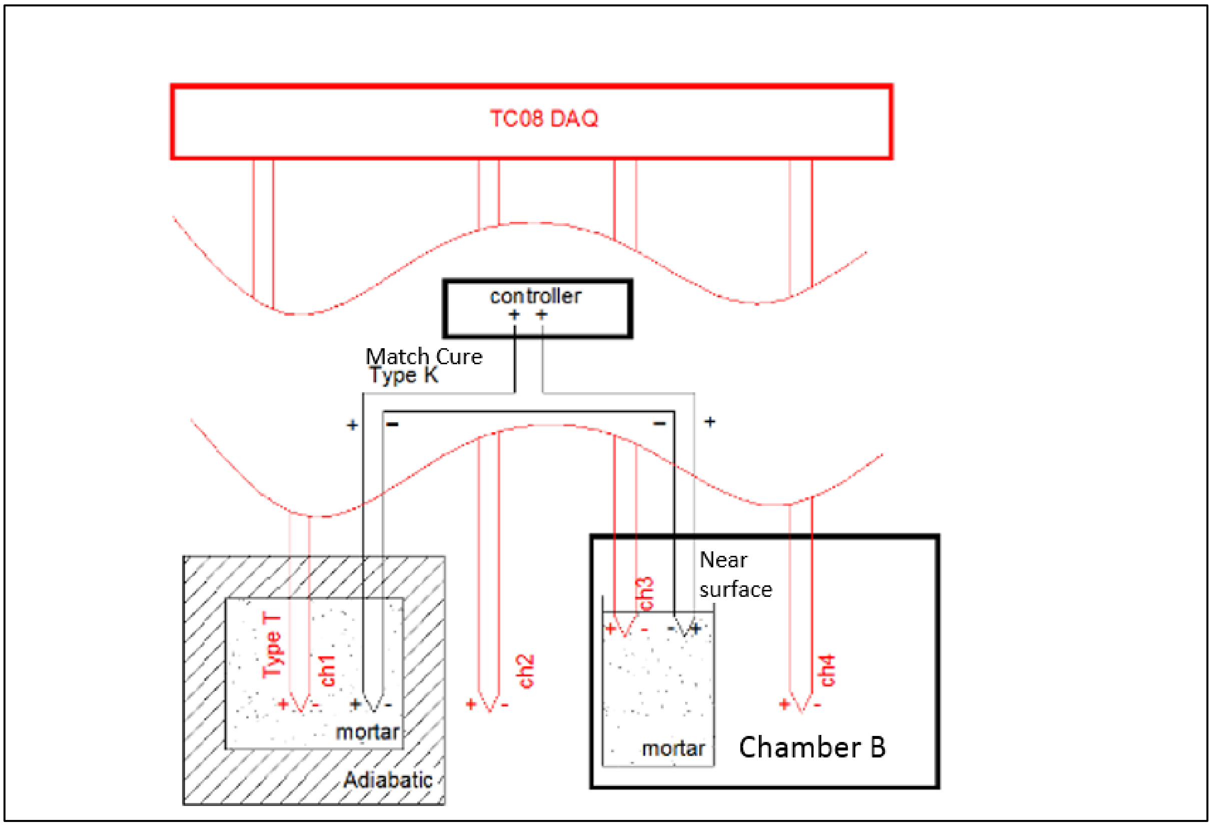
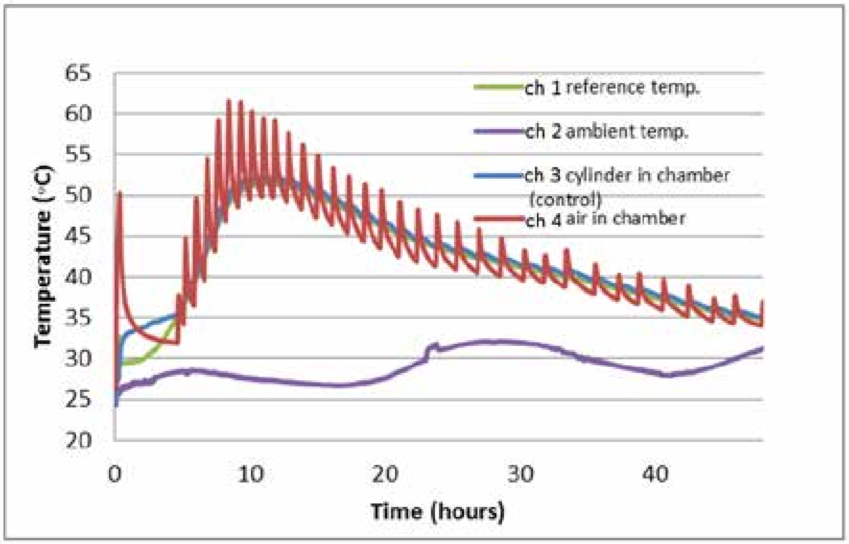
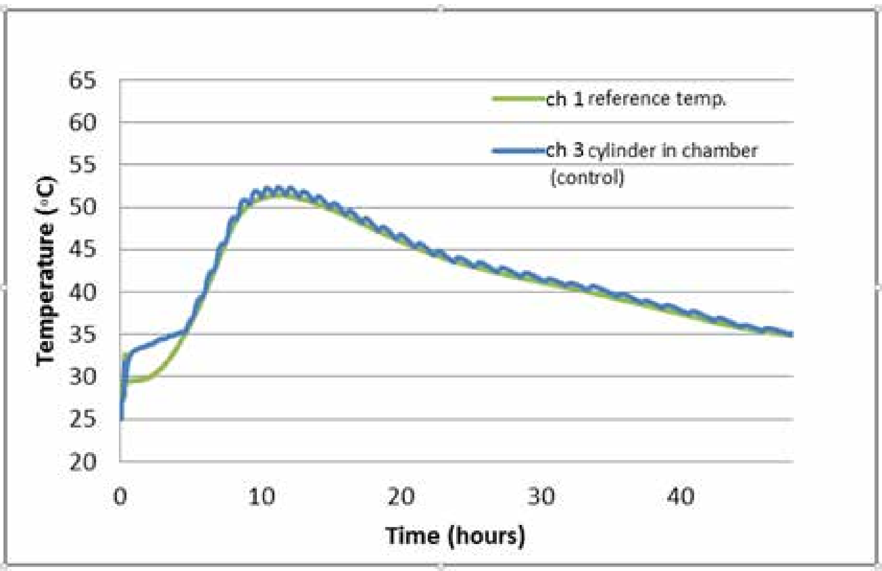


Figure 28. Test configuration where the mortar mixture serves as both reference and control. Chamber B was used.

In Figure 29, because the control temperature was in the cylinder inside the chamber box, the air-temperature profile (channel 4) in the chamber box had large oscillation. In addition, the control-temperature profile (a mortar mixture in the cylinder mold) always showed higher than the reference temperature. It was expected that the compressive strength of the cylinder in the chamber would usually be higher than a specimen (slab) as reference temperature. For the next verification, there was a test of both chambers (left-side chamber, called B; right-side chamber, called A) with the same reference temperature (same mixture and same reference points). If the control-temperature profiles were similar, these qualities of the chambers were considered satisfactory.



(a)



(b)

Figure 29. Obtained temperature profiles for adiabatic test: (a) all temperature profile data, (b) same plot without chamber air temperature and the ambient temperature.

3.4.4 Two Chambers with One Mortar Control

For verification, a test of both chambers was conducted (left-side chamber, called B; right-side chamber, called A) with the same reference temperature (same mixture and reference points for both chamber), as described in Figure 30. The control temperature was at air temperature in each chamber.

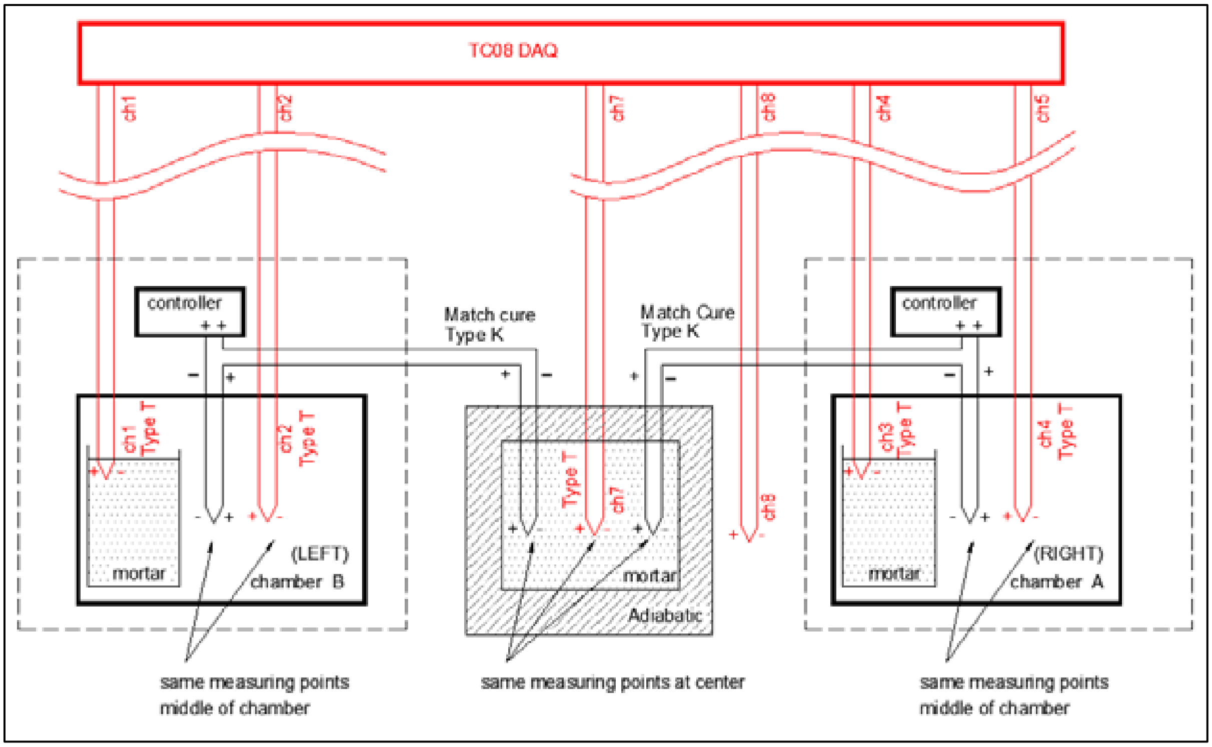
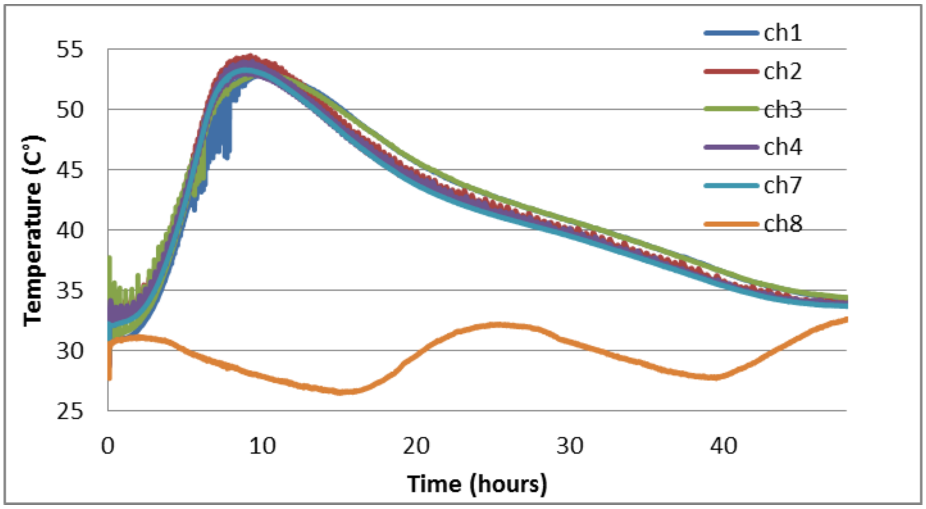
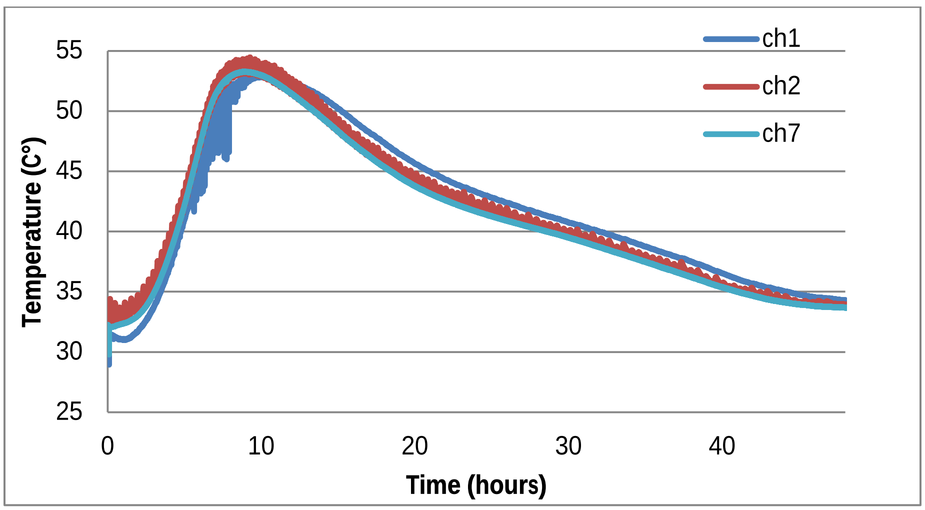
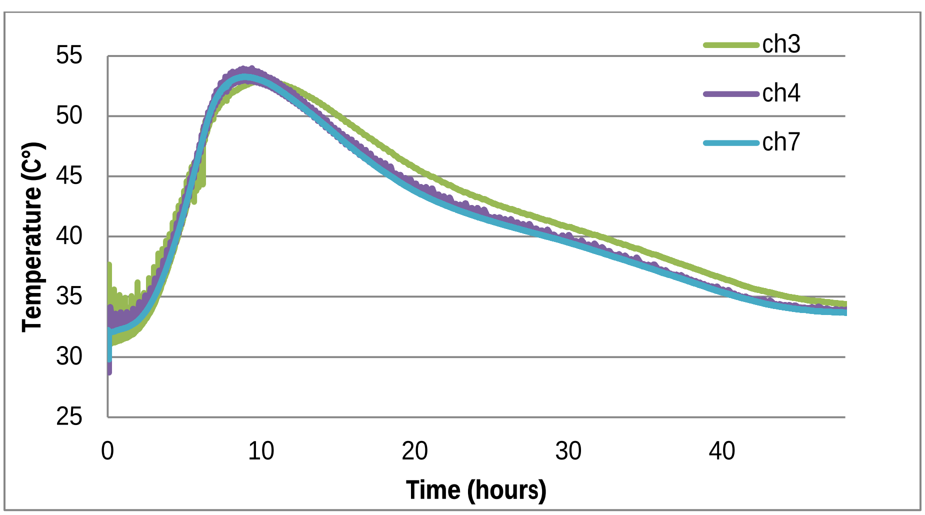


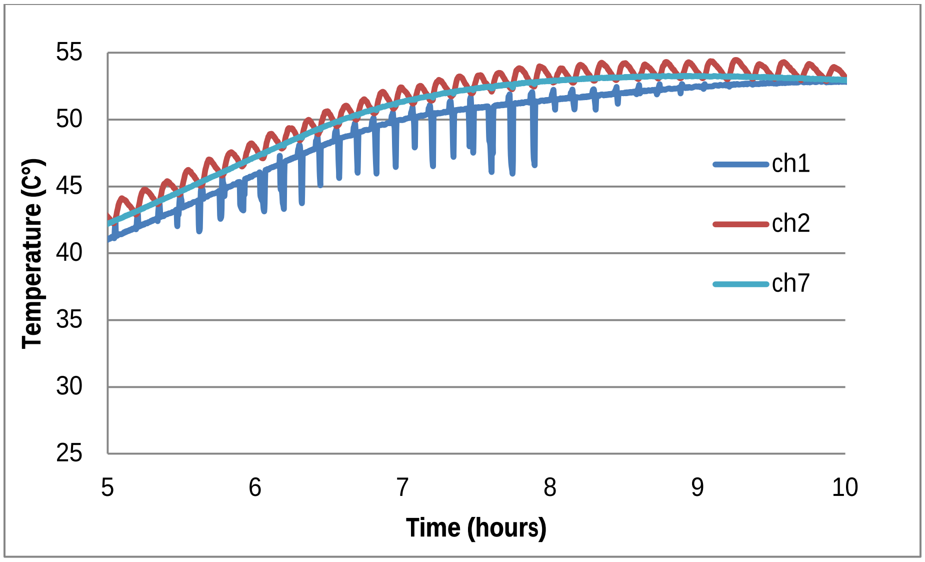
Figure 30. Testing configuration where semi-adiabatic mortar reference drives both chambers simultaneously. The reference temperature is taken as air temperature in the chamber.

Channel 7 represents the semi-adiabatic reference-temperature profile, and channel 8, the ambient temperature. Overall, there existed a trend in that the air-temperature profiles in both chambers were well matched with the reference-temperature profile shown in Figures 31(a), (b), and (c). However, the cylinder temperature of Chamber B (channel 1 in Figure 31(d)) showed oscillations and fluctuation between 5 and 10 hours not observed in the cylinder temperature in chamber A (channel 3 in Figure 31(e)). Even so, they were similar.

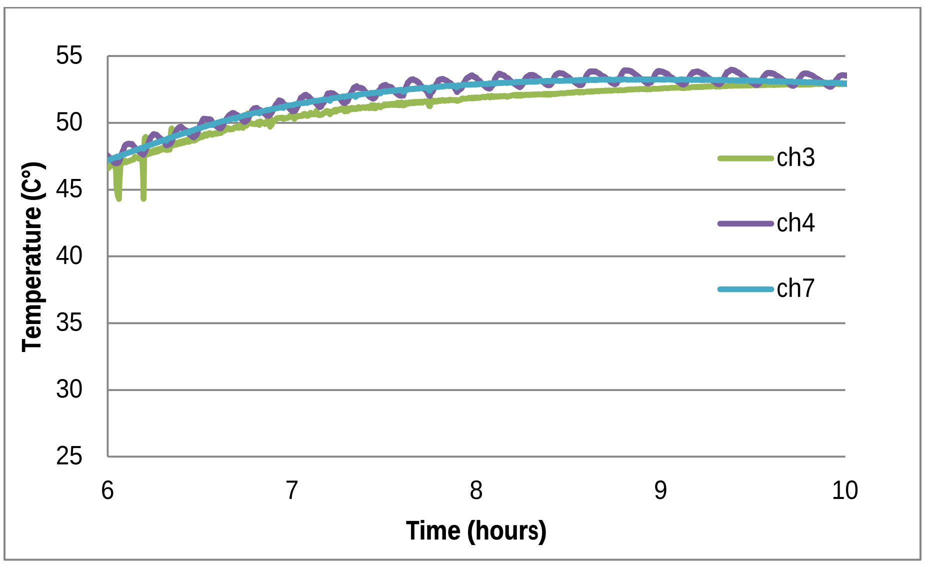

ch1
ch2
ch3
ch4
ch7
ch8
Temperature (C°)
55
50
45
40
35
30
25
0
10
20
30
40
Time (hours)
(a)


ch1
ch2
ch7
Temperature (C°)
55
50
45
40
35
30
25
0
10
20
30
40
Time (hours)
(b)


ch3
ch4
ch7
Temperature (C°)
55
50
45
40
35
30
25
0
10
20
30
40
Time (hours)
(c)



(d)



(e)

Figure 31. Temperature profiles obtained for two-chamber test: (a) all temperature profile data; (b) reference and chamber B sensors only; (c) reference and chamber A sensors only; (d) zoomed-in detail of plot (b); (e) zoomed-in detail of plot (c).

3.4.5 Heat Distribution in Chamber

This test explored the heat distribution in the air chamber box. As with other verification tests, a semi-adiabatic condition as reference temperatures and cylinder mold were used. Controller temperatures were at air temperature in the box, especially channel 2, which was used as the control temperature to match with the reference temperature, as shown in Figure 32. Channels 2, 4, and 6 had different *x* and *y* positions but the same *z* (height); and channels 5 and 7 also had the same *z* position (height), 12 in. Channels 6 and 7 were located near the door of the air chamber box. Channel 1 was the reference temperature in the adiabatic condition. Channel 8 was the ambient-temperature profile.

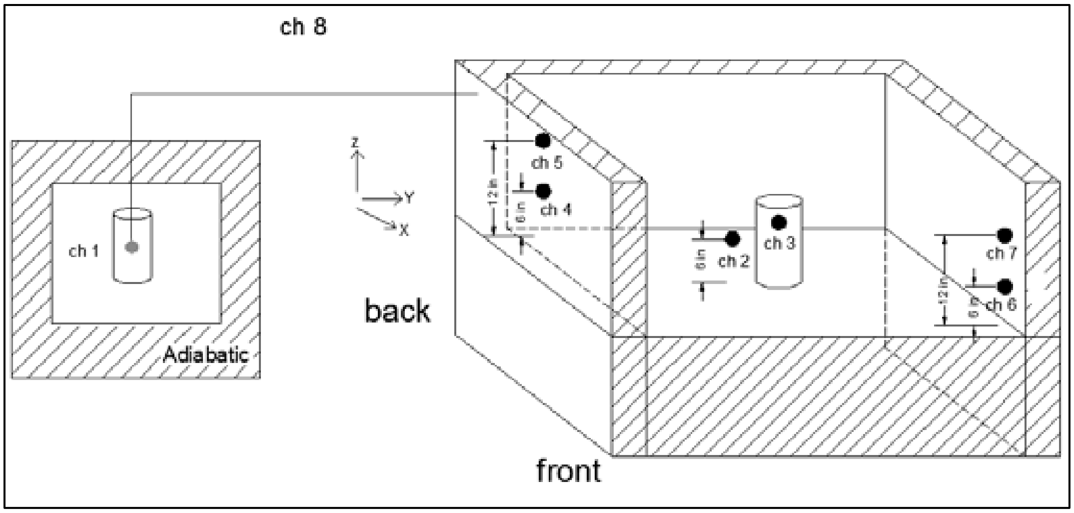
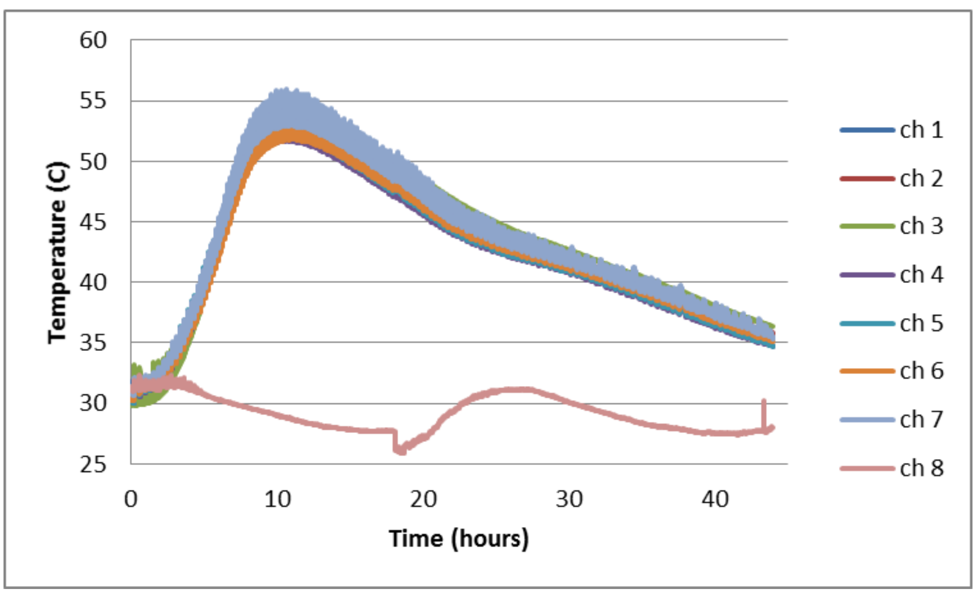
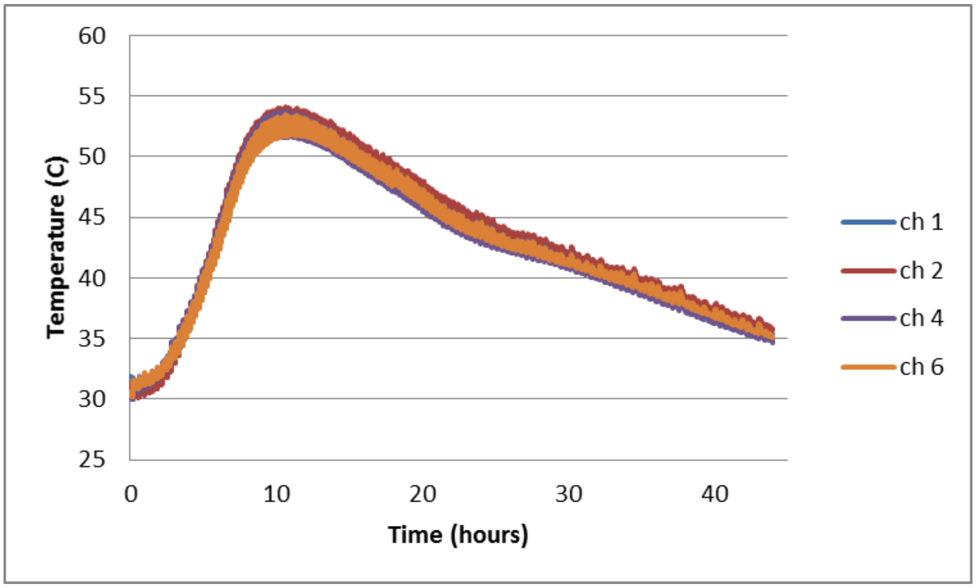


Figure 32. Illustration of thermocouple locations within the air chamber.

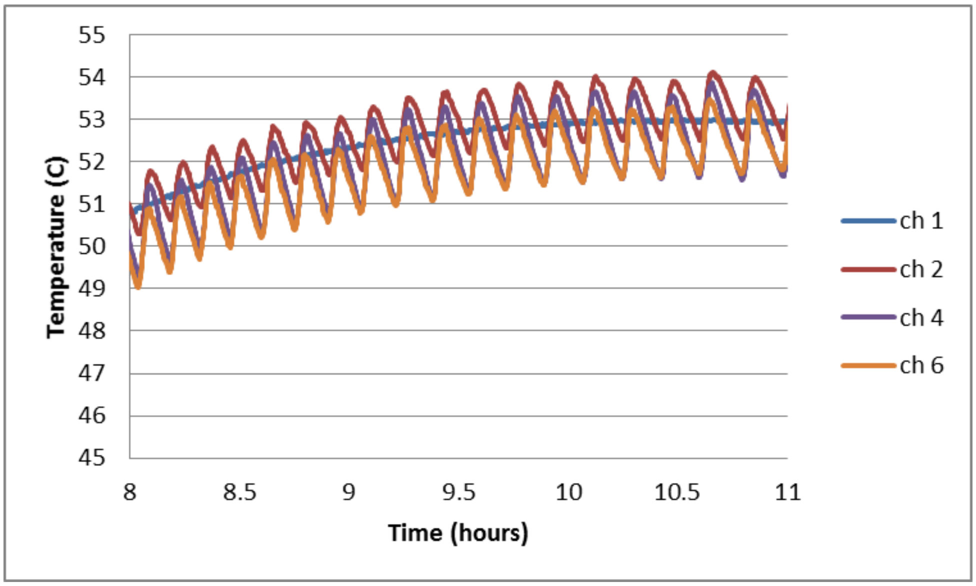
Channels 2 through 7 temperature profiles showed a very similar trend in Figure 33(a). Figures 33(b) and (c) illustrate the temperature profiles at the 6-in. height (same *z* position). In this figure, all the temperature profiles show similar results. Channel 2 (control temperature) gave the most similar result to the reference temperatures. Channels 4 and 6 had slightly larger oscillation than channel 2 at the center. Given this finding, it was expected that the reason was because the heating element was closer at the channel 4 and 6 locations. In conclusion, the air chamber match-curing equipment had acceptable heat distribution when it was running.



(a)



(b)



(c)

Figure 33. Obtained temperature profiles for heat-distribution test:
(a) all temperature profile data, (b) data from only sensors at 6-in. height
(c) blowup detail for plot (b) between 8 and 11 hours.

3.5 CAST-IN-PLACE CYLINDER MOLDS

3.5.1 In-Place Casting of Slab Form and Cylindrical Mold Design

The ASTM standard (ASTM C 873) for in-place cylinder molds is shown in Figure 34. This test method is limited to use in slabs where the depth of the concrete ranges from 5 to 12 in. (12.5 to 30 cm). The special mold consists of an outer cylindrical, adjustable sleeve with fixed supports (= brace) and an inner cylindrical mold that is watertight and of an appropriate size.

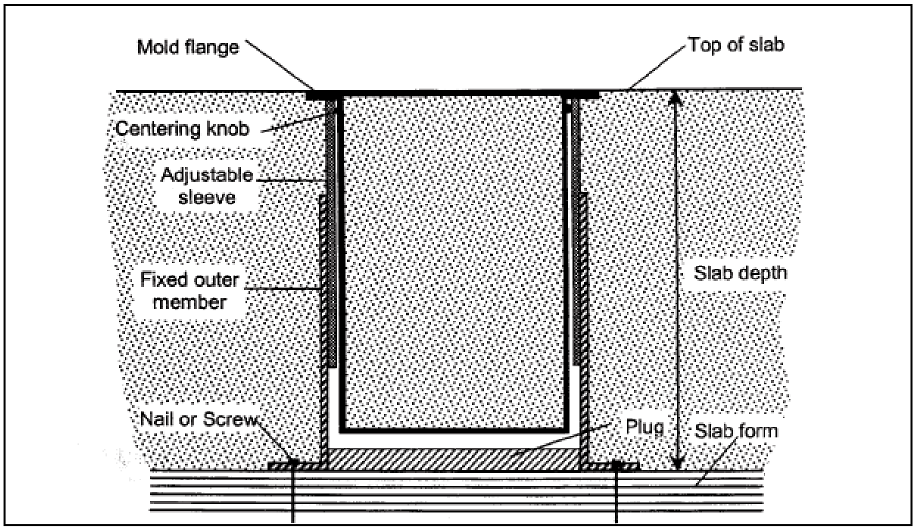


Figure 34. Schematic of cast-in-place cylinder mold assembly (ASTM C 873).

However, we found that the ASTM standard procedure was somewhat limiting (ambiguous description and inefficient design) and expensive. Thus, we designed our own in-place cylinder mold system, which is similar to that in the ASTM standard. To choose an appropriate outer (support) member and inner member (polymer cylinder mold), two main factors - cost effectiveness and thermal conductivity - were considered. Figures 35 and 36 show the basic design and dimensions of our system.

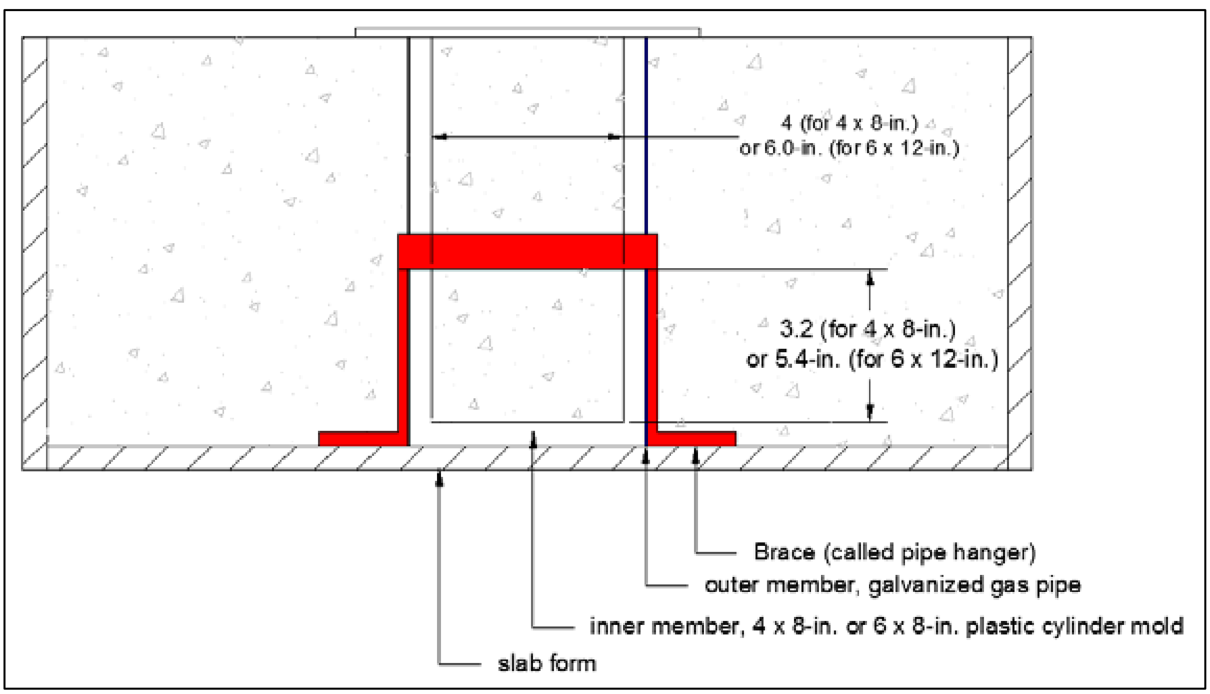


Figure 35. Dimensions of plan of the support member and mold used in this work.

(a) *(b)*

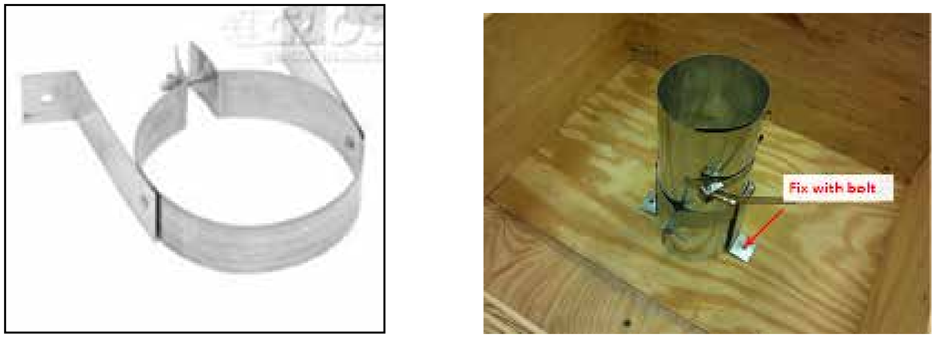
Figure 36. (a) Galvanized pipe sheet outer element in place; (b) regular 4 x 8-in. (100 x 200 mm) mold with outer element for in-place strength.

The detailed construction and casting procedure for the in-place mold is as follows. First, the outer member was assembled, using a 5-in. (127-mm) diameter galvanized gas pipe sheet (for 4-in. cylinder) or 7-in. (177.8-mm) diameter galvanized gas pipe sheet (for 6-in. cylinder). The material (metal) has higher thermal conductivity than plastics such as PVC pipe. The free ends of the pipe sheet were joined using rivets at a 5-in. (127-mm) spacing. First, rivet holes had to be drilled along one end, indicated by A in Figure 37(a). The final diameter of the formed mold had to be between 0.08 and 0.12 in. (2 and 3 mm) larger than the outer diameter of the plastic cylinder. An assembled pipe is shown in Figure 37(b).

(a) *(b)*

Figure 37. Illustration of in-place cylinder mold construction: (a) galvanized sheeting material with rivet point indicated and (b) fastened sheet.

Next, the outer element was fixed with a brace, using a 4- or 6-in. pipe hanger, as shown in Figure 38, and then mounted onto the floor of the form and fixed with bolts to prevent movement of the cylinder mold during casting.



(a) ***(b)***

Figure 38. Illustration of in-place cylinder-fastening system:
(a) cylinder clamp and (b) form-mounting detail.

Standard polymer cylinder molds were then inserted into the formed outer element. The outer element and cylinder mold should fit snugly, and a thin layer of form oil was painted on the outer surface of the cylinder mold to facilitate removal after casting. The components of this forming system were selected to have a low cost. All items can be found in basic hardware stores and are reasonably priced, as shown in Table 8.

Table 8. The Price of Cast-In-Place Mold Components

Name	Price
Outer member (sleeve and support member)	$5.00
4-in. galvanized gas pipe	$3.00
Brace	$2.50
Bolt	$3.00

3.5.2 Test Setup and Preliminary Confirmation

In this test, heat distribution was checked to verify materials and design. Tests were carried out using a basic slab, shown in Figure 39. The result had to show efficient distribution of heat throughout the slab regardless of location, especially between the cylinder interior and the slab outside the cylinder. If the temperature in the cylinder was very different from that in the slab outside the cylinder, it was necessary to improve the material of the outer and inner members. An Omega thermocouple DAQ system was used to monitor temperature at various locations in the slab, as shown in Figure 40. Four thermocouple sensors (Type T) were used to measure all temperatures for temperature profile recording. Channels 1 and 2 were located outside cylinder mold in the slab, while channels 3 and 4 were located within the cylinder mold. To compare the temperature profiles at equal distances from the interface, channels 1 and 2 were installed at distance x, and channels 3 and 4 were installed at distance y (x = 0.75 in., and y = 2 in.).

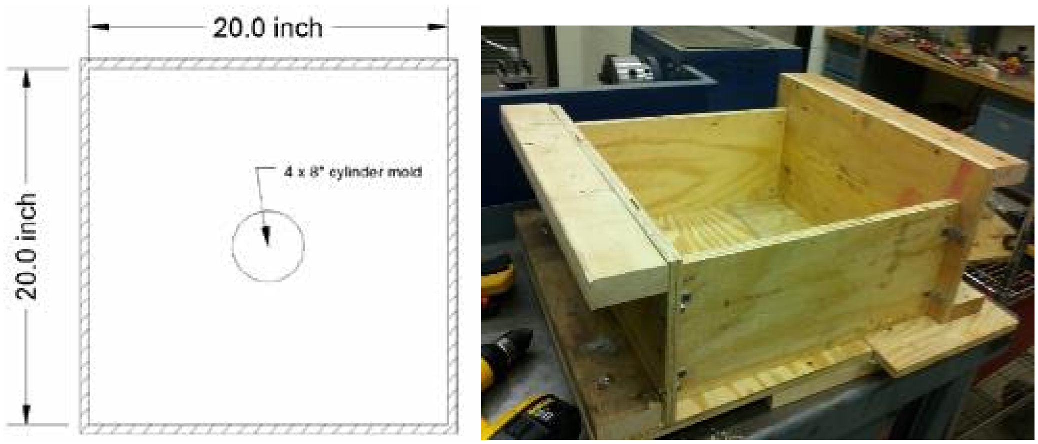


Figure 39. Plan for concrete slab form. Note: 1 in. = 25.4 mm.

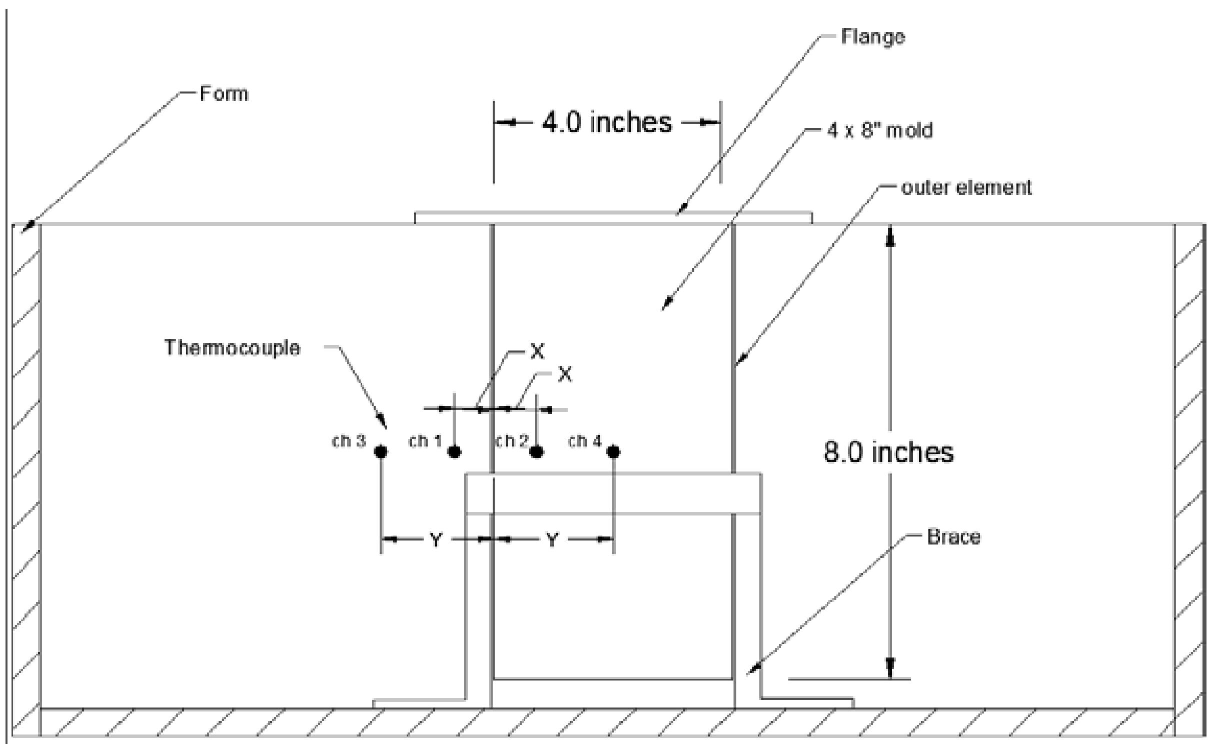


Figure 40. Location of thermocouple; X = 0.75 in. (19 mm), Y= 2 in. (50 mm)

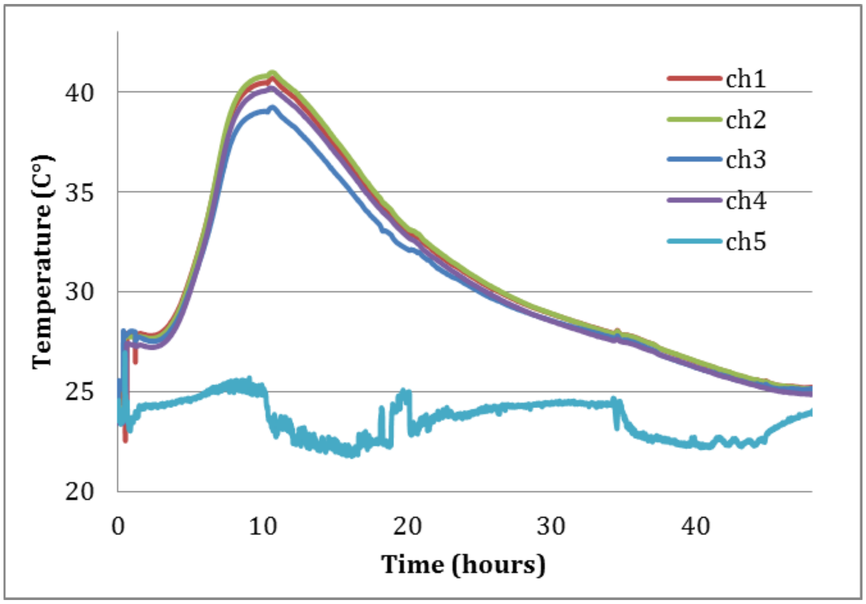
As shown in Figure 41, a concrete mixture was poured into the slab. The outer member was fixed to protect it during casting. After the temperature profile was recorded for 48 hours, at four different locations, the 4 x 8-in. (100 x 200-mm) cylinder mold (inner element) was demolded. The inner cylinder mold was easily removed, and the 4 x 8-in. (100 x 200-mm) concrete cylinder showed a perfect cylindrical shape.

(a)

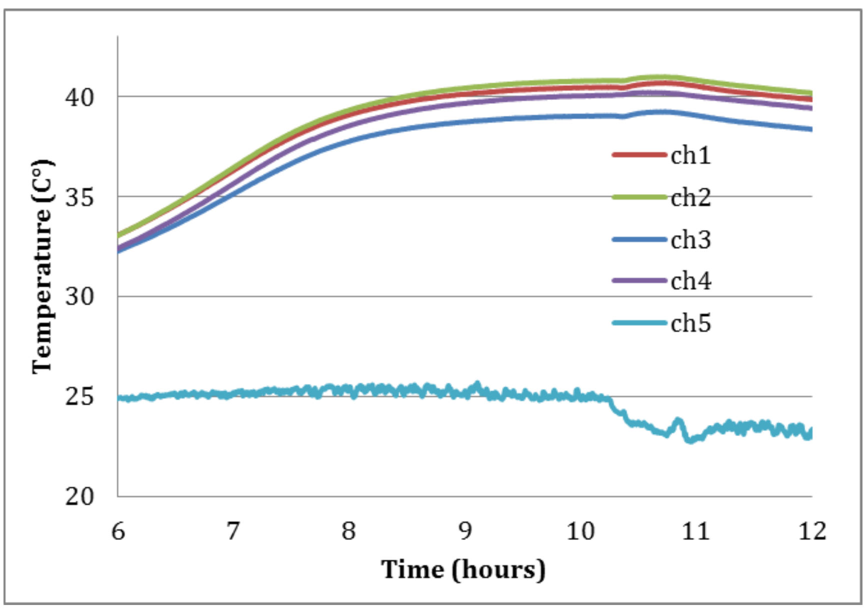
(b)

Figure 41. Cast-in-place testing: (a) right after casting concrete, and (b) after demolding 4 x 8-in. (100 x 200 mm) cylinder.

The results showed that all temperature profiles were similar and within a reasonable range, as shown in Figure 42. Channel 5 shows the ambient temperature in the lab during the test. In a large structure like this slab, one would expect that because of the heat transfer, the temperature at the center would be the highest, while the locations that are far from the center would be the lowest. In this test, the temperature of the center in the cylinder (channel 4) was the third-highest temperature peak. However, very small differences in temperatures were seen among channels 1, 2, and 4. The peak temperatures at 7 hours from channels 1, 2 and 4 are very similar, within the precision of Type T thermocouples. As a result, we concluded that the mold design allows excellent heat transfer between the outside mold in the slab and the inner mold (in the 4 x 8-in. cylinder mold). Furthermore, we concluded that this in-place cylinder design effectively represents the larger slab material.



(a)



(b)

Figure 42. Temperature profile of in-place strength: (a) testing over 48 hours; (b) detailed temperature profile between 6 and 12 hours.

3.6 INSULATED JACKET MOLD SYSTEM

We employed a commercially available insulated jacket mold match-cure system, for both 4- and 6-in.-diameter cylinders. The system consists of a temperature-control system, data acquisition system (DAQ), and 12 insulated jacket match-curing molds. The total cost was approximately $10,000. The control system drives the cylinders' temperature using a profile measured with an external input signal. The basic operation and functionality of the equipment was verified after it was received from the vendor. Several adjustments were made to the system. First, upon delivery of equipment, several wires became disconnected to the main CPU, which resulted in very poor temperature control. We quickly identified and fixed this problem. In addition, an extra electronic register for wireless control connected to the 485 interface box caused disruption to our tests. We removed the extra register, and subsequent test data were stable and reliable. After these adjustments to the control system were made, it was determined that the system functioned properly

3.6.1 Control System and DAQ

The control system comprises a 485 interface box, mini curing controller connected with a 10 ft. (3-m) long data cable, and 6.5 ft. (2-m) long serial cable to connect to a computer's serial port for data transfer and storage. The DAQ system accepts six Type T thermocouple inputs. Six 120V outputs drive the insulated jacket molds. The system is powered with conventional 120V straight-blade inlet and operates between 14 and 150°F (-10 and 65°C) ambient temperature. The system includes software to collect, store, print, and display data, which can be run on a personal computer with Windows XP or other operating system.

3.6.2 4 x 8-in. Cylinders

The 4 x 8-in. cylinders were a cast-in-place concrete system, where concrete is cast directly into the two-part cylinder mold. The jacket mold configuration is shown in Figure 43. Each cylinder contains a built-in heating system on the inner surface of the mold. Internal thermocouples monitor the mold surface temperature for use as feedback in the control system. In our tests, we also used Type T thermocouples to monitor the internal temperature of the concrete in one of the cylinder for each batch cast.

Figure 43. 4 x 8-in. insulated jacket mold system.

3.6.3 6 x 12-in. Cylinders

The design of the 6 x 12-in. insulted jacket mold system differs from that of the 4 x 8-in. system. The larger cylinder system uses a controlled thermal jacket that fits around a standard polymer cylinder mold. The thermal jacket is flexible and pliable, and consists of aluminum and polyurethane foam layers. The jacket layer wraps around the full height of the cylinder, and then must be fastened in place using an elastic band, as illustrated in Figure 44. This external jacket system requires a clean exterior surface of the polymer cylinder mold. The external layer contains a built-in thermocouple temperature sensor and electric heating system, which connects to the insulated jacket mold control module. In our tests, we also used Type T thermocouples to monitor the internal temperature of the concrete in one of the cylinders for each batch cast.

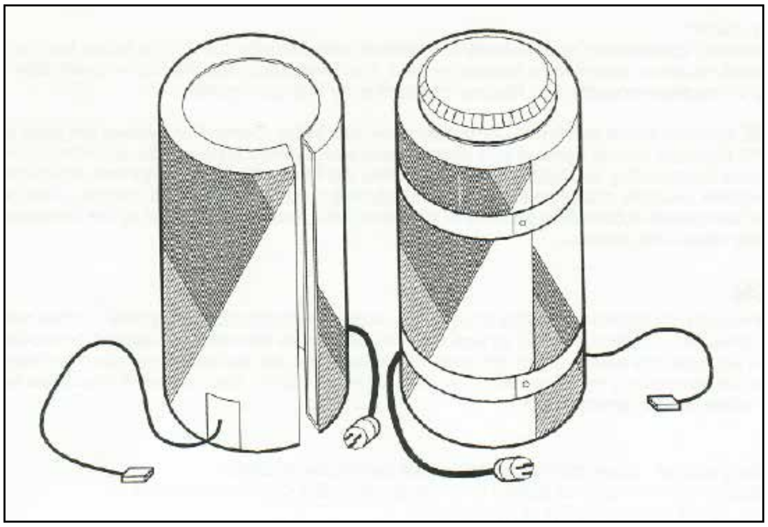


Figure 44. 6 x 12-in. insulated jacket mold system.

CHAPTER 4 RESEARCH GOALS AND TESTING PLAN

Here we provide an overview of the two principal tasks in the experimental program carried out in this project: (1) a study of temperature control on match-curing results, and (2) in-place strength estimation using two different match-cure technologies and taking into consideration the effect of sample size on match-cure cylinder strength estimates.

4.1 STUDY OF TEMPERATURE CONTROL ON MATCH-CURING RESULTS

The goal of this effort was to discover the effects of temperature-control precision in match-cure systems on the 1-day strength estimates of the match-cured samples. Statistical analyses were carried out to discern the effects of control error on the measured 1-day compressive strength. The AASHTO PP 54-06 standard practice recommendation for match-curing requires that match-cure systems maintain the temperature of the matched cylinders within ±4°F (±2°C) of the tested element. In this study, we imposed different types and magnitudes of temperature-control error to a constant, standard temperature profile. That standard temperature profile was determined by semi-adiabatic tests, described in Section 3.2.3 of this report, carried out on a sample of concrete that satisfied the IDOT Class PS concrete specifications assumed in this study. The assumed standard temperature profile is shown as channel 1 in Figure 17. Some of the imposed modified temperature profiles satisfied AASHTO PP 54-06, while others intentionally violated it. Because of the excellent temperature control afforded by our water bath match-cure system, the temperature-control tests were carried out using that system.

Only 4-in. diameter cylinders were studied in this test series. Concrete mixtures that satisfied IDOT Class PS concrete specifications were produced at the Advanced Transportation Research and Engineering Laboratory (ATREL) test facility; the components and proportions of the mixture were described in Section 3.1.1 of this report. Each batch of concrete was mixed using a drum mixer, as described in Section 3.1.2. Each drum mixer batch produced nine to ten cylinders. Repeated batches were mixed until each population of error type contained at least 30 cylinder samples, following the procedure described in Section 3.1.3.4 of this report. Each concrete batch was tested for slump, unit weight and air content, as described in Sections 3.1.3.1, 3.1.3.2, and 3.1.3.3, respectively. Each cylinder sample was tested for density and 1-day compressive strength, as described in Section 3.1.3.5.

4.1.1 Error Type and Magnitude

Here we considered two types of error that may occur with temperature control of match-cure systems. The first is transient error, which we called Type I. This error type represents the situation where loss of temperature control occurs over only a portion of the entire match-cure duration with control is later regained. The second is continuous error, which we called Type II. This type of error represents the situation where a constant level of temperature-control error occurs during the entire match-cure duration. In this study, we considered only positive temperature errors, meaning that the loss of temperature control resulting from the error caused temperatures in the match-cured samples to be greater than the tested element.

Several different levels of error magnitude were also considered. For Type II error, three levels of error were considered: +2°F, +5°F, and +10°F. Only the Type II +2°F profile satisfied the AASHTO PP 54-06 standard recommendation. For each error type, we also defined the amount of the error, which we called “error maturity.” Error maturity was represented as the area of the difference between the standard profile and the error profile throughout the match-cure duration. The Type II error profiles had error maturities of 48, 120, and 240 °F-hour (26.6, 66.7, and 133.3 °C-hour). For Type I error, we considered a 5-hour period of transient control loss that occurred either at the beginning, in the middle, or toward the end of the match-cure duration. In all three cases, the error maturity area was 48 °F-hour (26.6°C-hour), to match that of Type II +2°F (+1.11°C) profile. All of the Type I profiles violated the AASHTO PP 54-06 standard practice, even though the maturity area was the same as the Type II profile that did satisfy that standard.

4.1.2 Imposed Temperature Profiles

The six prescribed error profiles are shown in Figures 45 through 51. In those figures, the assumed standard profile is shown as a dashed line, the error profile as a solid line. The error maturity area is indicated with gray shading. The temperature profiles never exceeded a heating rate of 0.18°F/minute (0.1°C/minute), which is the capacity of the water bath heating system.`

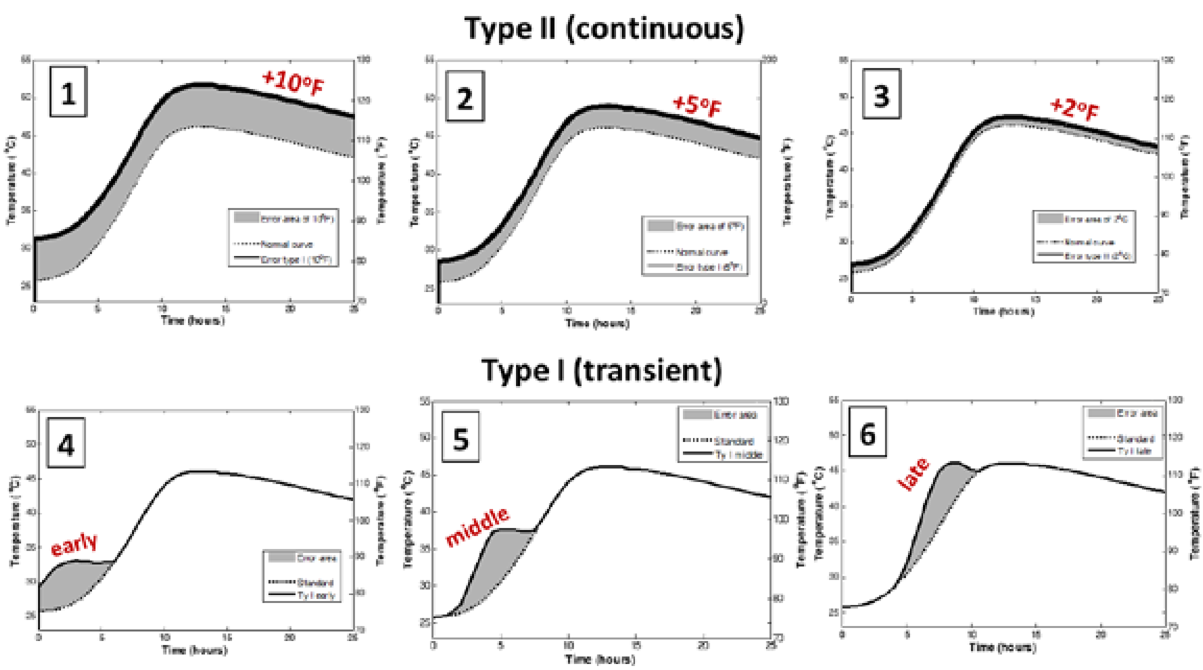


Figure 45. Overview of prescribed adiabatic temperature profile owing to hydration, and the presumed temperature-control error types.

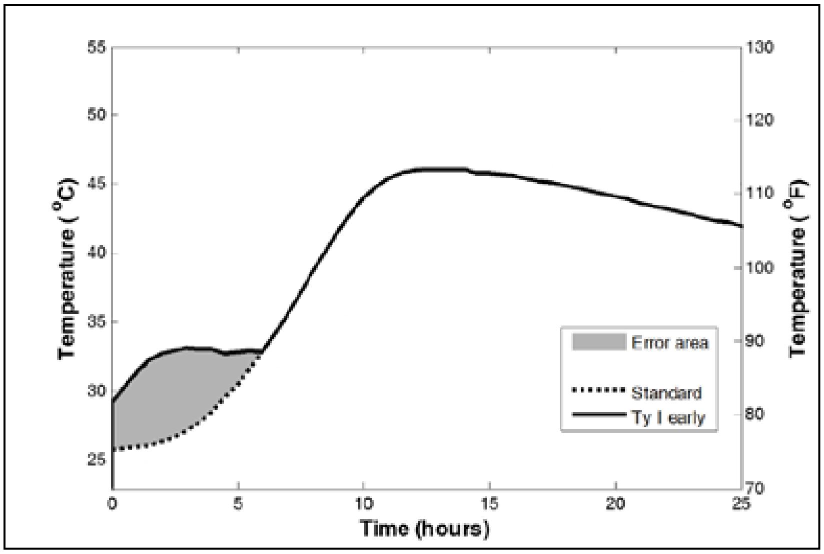


Figure 46. Detail of prescribed Type I early temperature-control error.
The error maturity indicated by the gray area is 48°F-hour.

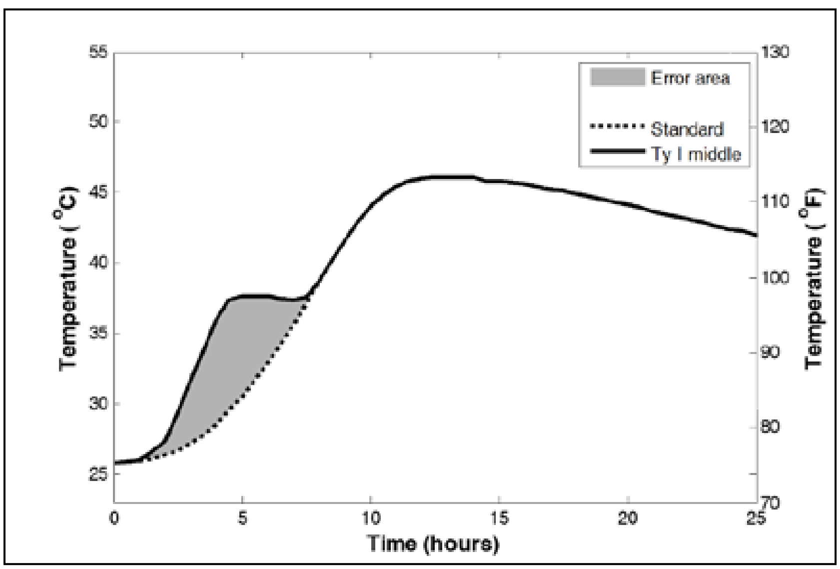


Figure 47. Detail of prescribed Type I middle temperature-control error.
The error maturity indicated by the gray area is 48°F-hour.

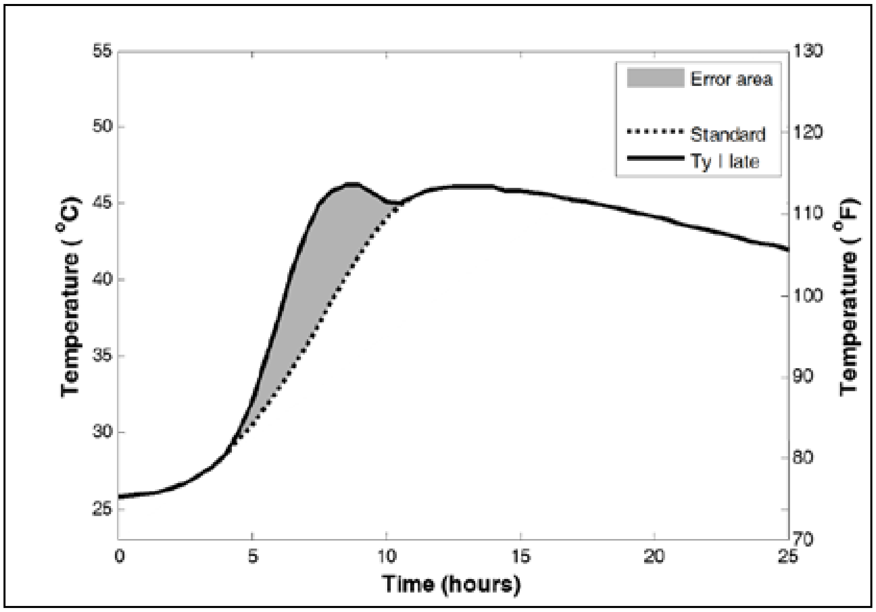


Figure 48. Detail of prescribed Type I late temperature-control error.
The error maturity indicated by the gray area is 48°F-hour.

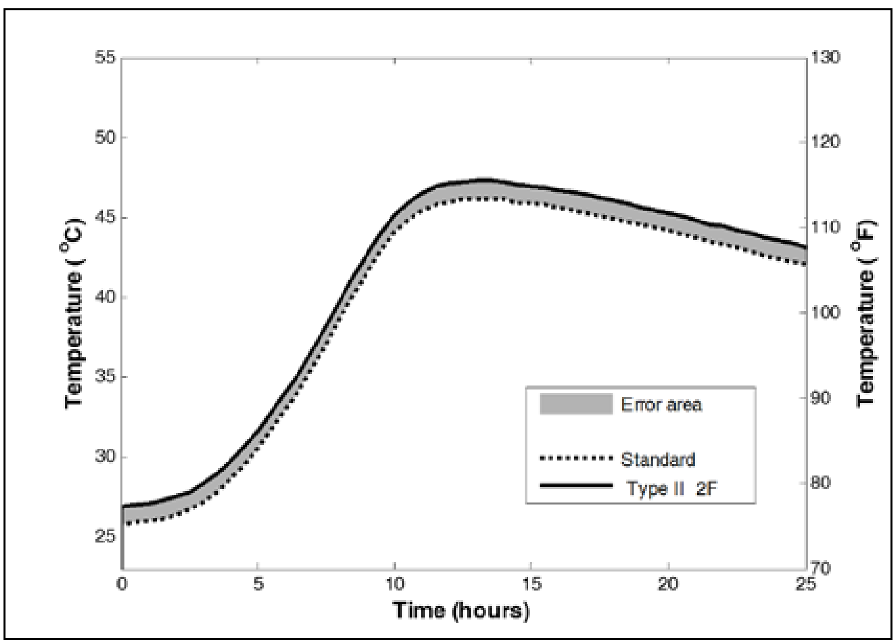


Figure 49. Detail of prescribed Type II 2°F temperature-control error.
The error maturity indicated by the gray area is 48°F-hour.

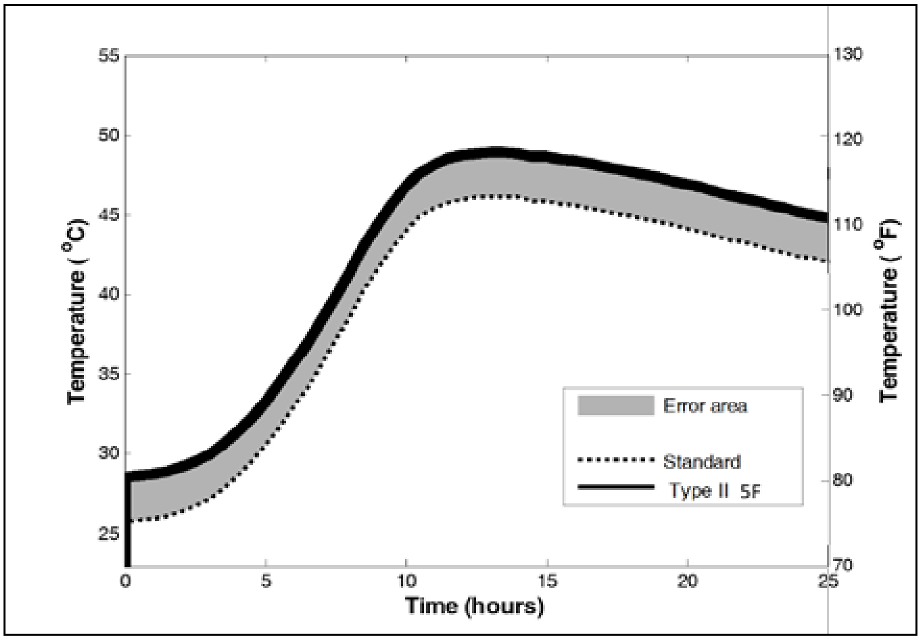


Figure 50. Detail of prescribed Type II 5°F temperature-control error. The error maturity indicated by the gray area is 120°F-hour.

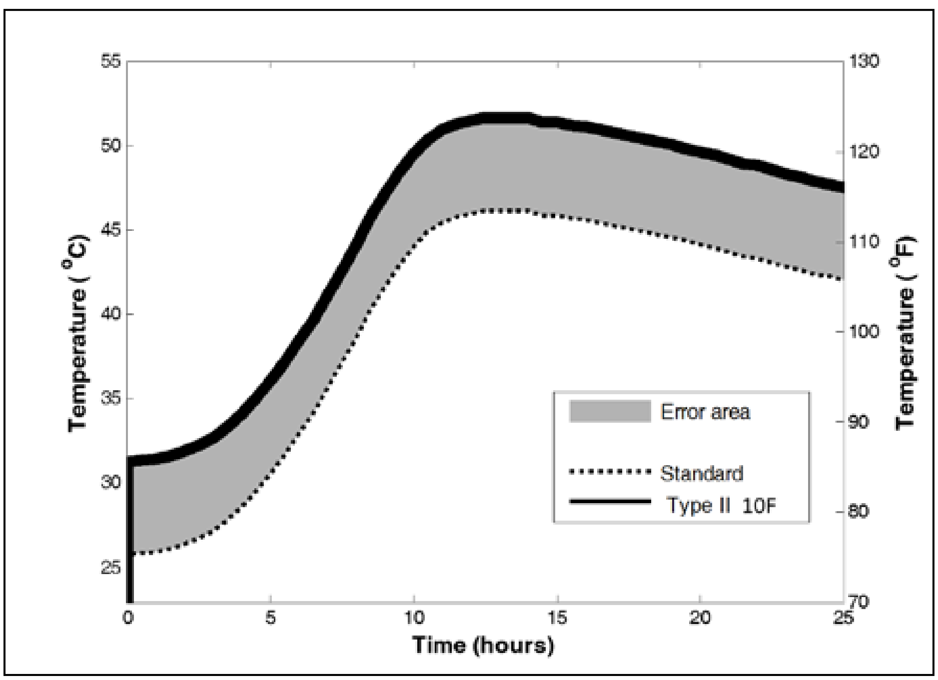


Figure 51. Detail of prescribed Type II 10°F temperature-control error. The error maturity indicated by the gray area is 240°F-hour*.

* Fahrenheit to Celsius conversion : °C = (°F-32)/1.8

4.2 IN-PLACE STRENGTH ESTIMATION

The goal of this effort was to determine the effectiveness of two different match-cure systems to predict in-place compressive strength of concrete. Air chamber and insulated jacket mold systems were studied, using both 4- and 6 in.(100 and 150 mm) diameter cylinders. A statistical analysis was carried out to discern the effectiveness of two different match-cure systems to predict in-place compressive strength. In this study, we cast large concrete slabs that contained in-place concrete cylinders, described in Section 3.5 of this report. A photo of a typical test slab with in-place cylinders is shown in Figure 52. To ensure better (i.e., less gradient) heat distribution within the cast-in-place cylinder slab, we placed an insulating layer over the top of the slab throughout the tests, as shown in Figure 53. We assumed that the concrete strength measured by the in-place cylinders was the actual in-place strength of the element.

Ready-mix concrete mixtures that satisfy IDOT Class PS concrete specifications were used to cast the slabs at the ATREL test facility; the components and proportions of the mixture were described in Section 3.1.1 of this report. Each batch of ready-mix concrete was used to cast two slabs (one slab with 4-in. (100 mm) cylinders and another with 6-in. (150 mm) cylinders), each with four in-place cylinders. Associated match-cure and air chamber cylinders were also cast from this batch. Within each type of cylinder, only three of the four were tested for strength as the fourth cylinder contained an embedded thermocouple which was used as the control signal in the match-cure process. Thus each ready-mix batch generated 18 cylinders that needed to be strength tested within a 2-hour period one day after casting (3 cylinders x 2 slabs + 6 Insulated jacket mold cylinders + 6 air chamber cylinders). Six ready-mix batches were used to obtain at least 18 test cylinders within each population sample. Each concrete batch was tested for slump, unit weight, and air content, as described in Sections 3.1.3.1, 3.1.3.2, and 3.1.3.3, respectively, of this report. Each cylinder sample was tested for density and 1-day compressive strength, as described in Section 3.1.3.5.

Figure 52. Slab form casting process.

Figure 53. Slab form curing process.

4.2.1 Quality Control

To ensure consistent mixture properties across the six ready-mix batches, a separate set of companion test cylinders was analyzed. For each batch, three 4-in. (100-mm) cylinders were exposed to a constant-temperature (at 73.4°F; 23°C) water bath; the compressive strength of three of these cylinders was tested 25 hours after casting, while the fourth was used only to house the thermocouple. This is illustrated in Figure 54. Another three 4-in. (100- mm) cylinders were exposed to an ambient laboratory air environment; the compressive strength of these cylinders was tested 28 days after casting.

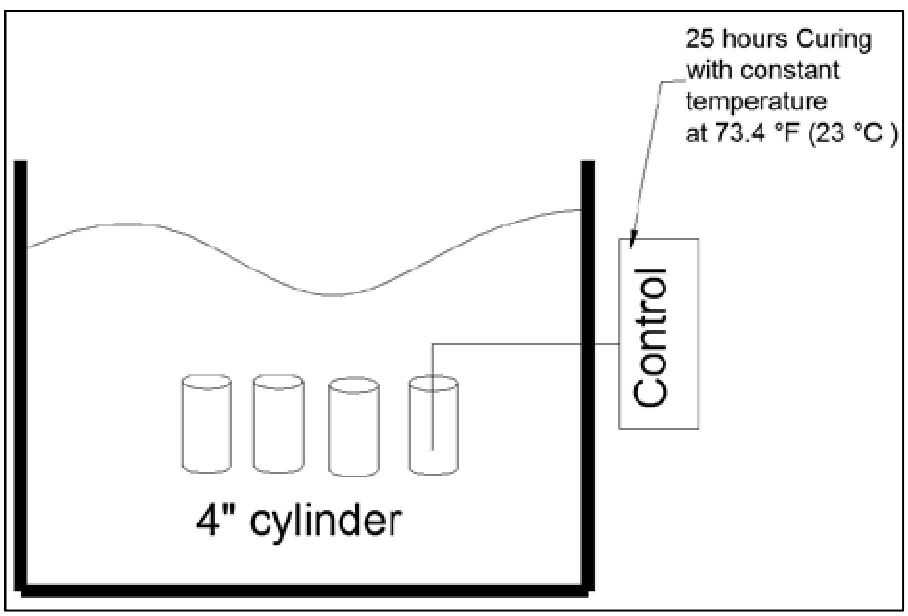


Figure 54. Illustration of water bath curing employed for reference cylinders of ready-mix concrete. Note: 1 in. = 25.4 mm.

The results of the strength tests on the companion cylinders across the six ready-mix batches are shown in Figures 55 and 56. The results illustrated reasonably consistent strength values at 25 hours across the mixtures, with an average strength of about 2,400 psi (16.6 MPa) and nearly all specimens between 2,300 and 2,500 psi (15.9 and 17.2 MPa). Thus, we were confident that the ready-mix batches were consistent enough to serve as a basis of comparison across all mixtures. The strengths at 28 days showed more variability between batches, but these samples were exposed to different temperature environments in the uncontrolled lab space during their 28-day curing period. Nevertheless, the strength values were reasonably consistent, and all strengths were greater than 5,000 psi (34.5 MPa), which is the specified minimum 28-day strength for IDOT Class PS concrete.

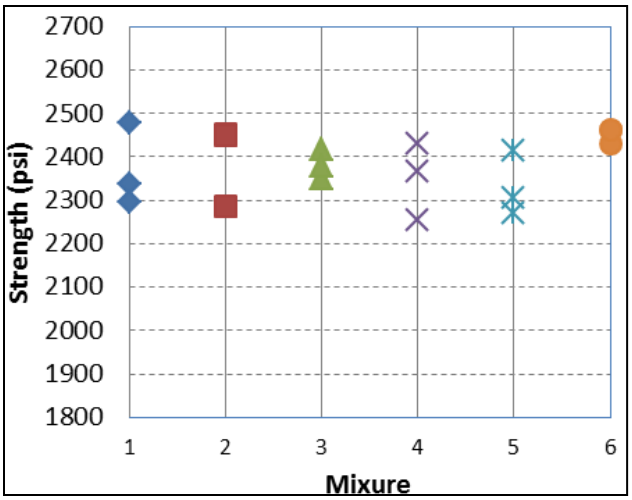


Figure 55. Strength of constant-cure companion cylinders of ready-mix concrete mixtures measured 25 hours after casting.

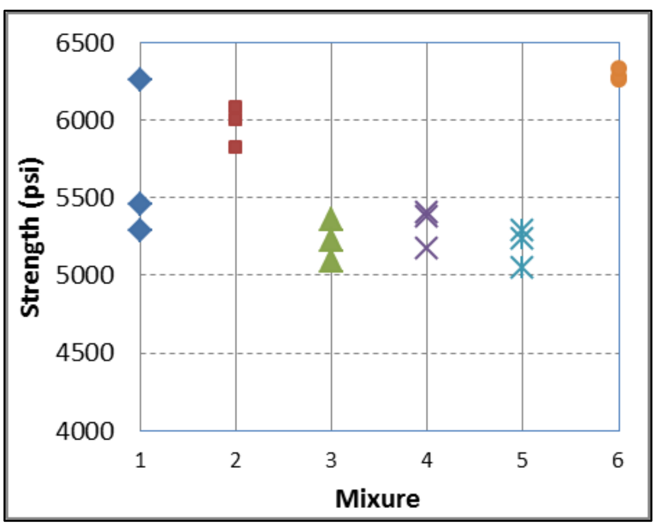


Figure 56. Strength of ambient-cure companion cylinders of ready-mix concrete mixtures measured 28 days after casting.

4.2.2 Testing Configuration

A schematic of the testing setup is shown in Figure 57. Each slab contained four cast-in-place cylinders; three of the cylinders were drawn out and tested for compressive strength 24 hours after casting. The fourth cylinder contained a thermocouple that was used to monitor the internal temperature and provide a common signal for the match-cure systems. Each slab (associated with 4- and 6-in. cylinders, respectively) separately drove two match-cure systems using the temperature measured in the slab as the control; the two sets of slabs and match-cure systems had separate control systems housed in the control box. Within each match-cure system, three cylinders were cured and tested for compressive strength 24 hours after casting, while a fourth cylinder contained a thermocouple used to monitor concrete temperatures within each respective environment.

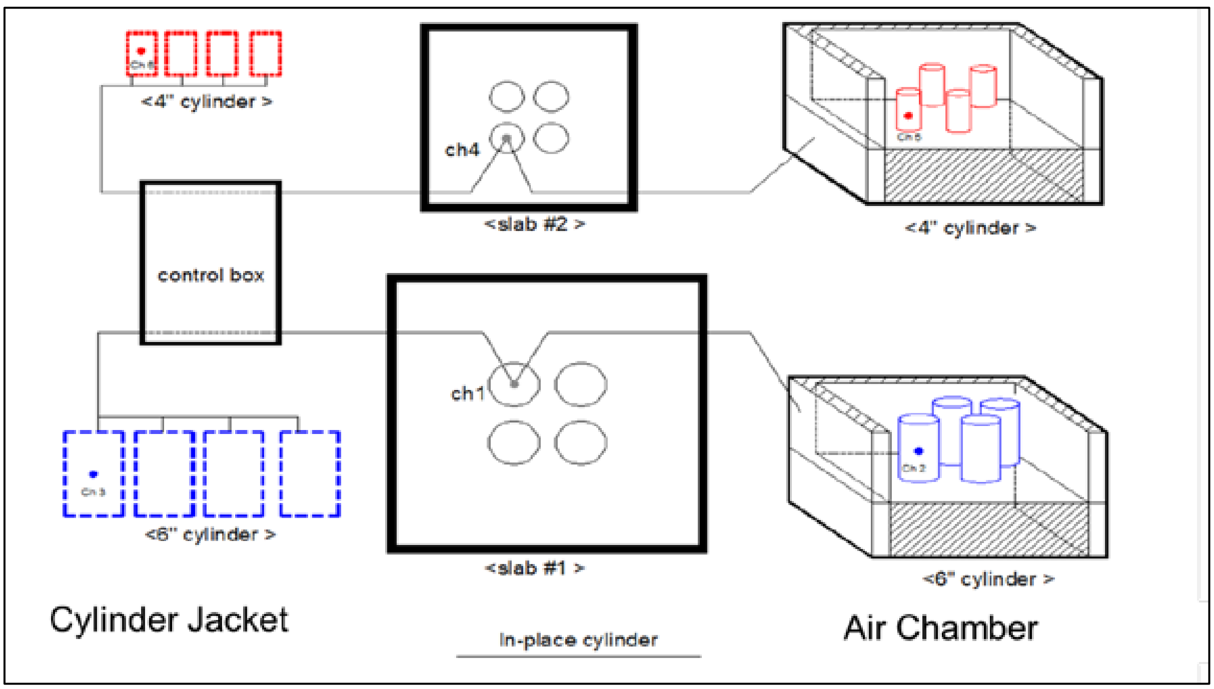


Figure 57. Illustration of match-cure test configuration. Note: 1 in. = 25.4 mm.

4.3 Statistical Analysis

The experimental data were analyzed using a robust statistical basis: Welch's ANOVA analysis. This approach is an extension of the two-sample *t*-test for means, assuming normally distributed data sets but unequal variance among the compared populations and is implemented through the Tukey and least significant difference (LSD) tests. LSD shows the confidence interval and the level of the comparison. The analysis is implemented through SAS (Statistical Analysis System software). Hypotheses are often employed in statistical analysis to express results. In this study, we assumed the following null hypothesis, "population samples have the same mean value." The alternative hypothesis then becomes "population samples have different mean values." In this study, the hypothesis analysis was carried out at a 95% confidence level, meaning that only a 5% chance of a false positive reading is likely. If the null hypothesis is rejected, then the alternative hypothesis is accepted, and we can state, with a 95% confidence level, that the population sets have different mean values. If the null hypothesis is not rejected, then we can state that the mean values of the population sets are not significantly different, with a 95% confidence level.

In statistical analyses, it is important to identify extreme outlying data within a population because these data points usually are not representative of the larger population. These outliers can be identified using the leverage diagnostics criterion (LDC), which assesses how far away a value of the independent variable is from the mean value. We employed LDC through the SAS software to ensure that our sample sets had equivalent means with regard to sample density; this was carried out before the strength data were statistically analyzed. An example SAS output of LDC is shown in Figure 58, where extreme outlying data are indicated with cross points and acceptable data with circles.

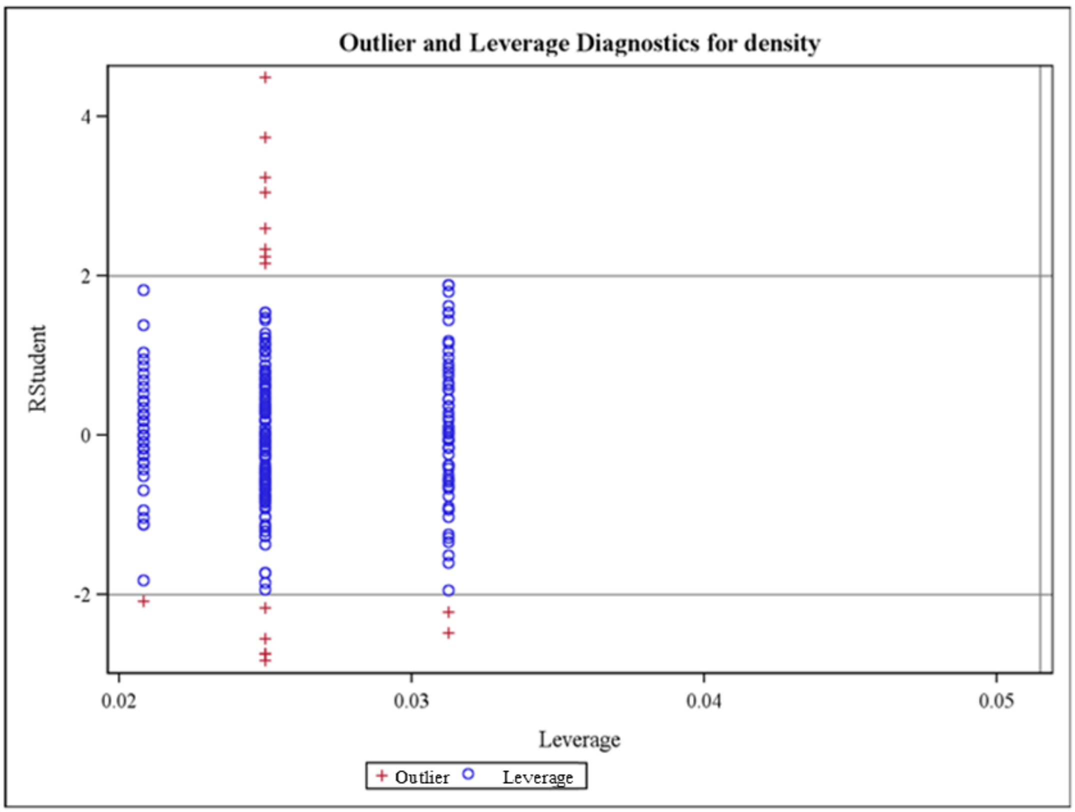


Figure 58. Example SAS output of leverage diagnostic criterion analysis of a sample set.

We employed the following procedure to statistically analyze the data. First, we compared density data from sample populations to determine whether our null hypothesis was rejected for that sample set at the 95% confidence level. If the null hypothesis was rejected (that is, the samples had different mean values), then the most extreme outlying data point, identified using the LDC criterion, was removed and the analysis was run again. This process was repeated until the null hypothesis was not rejected. Once a data set with density means that were not significantly different was established, then the population was statistically analyzed with regard to strength, using our hypothesis through the Welch's ANOVA criterion.

Statistical data are often expressed through "box plots," which is an efficient way to convey much statistical information in one format. In a box plot, an entire sample population set (for example, a set of strength values) is expressed graphically in terms of mean, median, maxima and minima, and upper and lower quartile values. Typically, the data within the upper and lower quartile values are indicated with a shaded box that also contains the sample mean and median values. An illustration of a box plot is shown in Figure 59. Using this format, several sample sets can be easily compared visually. In this study, we employed box plots to express strength and density data.

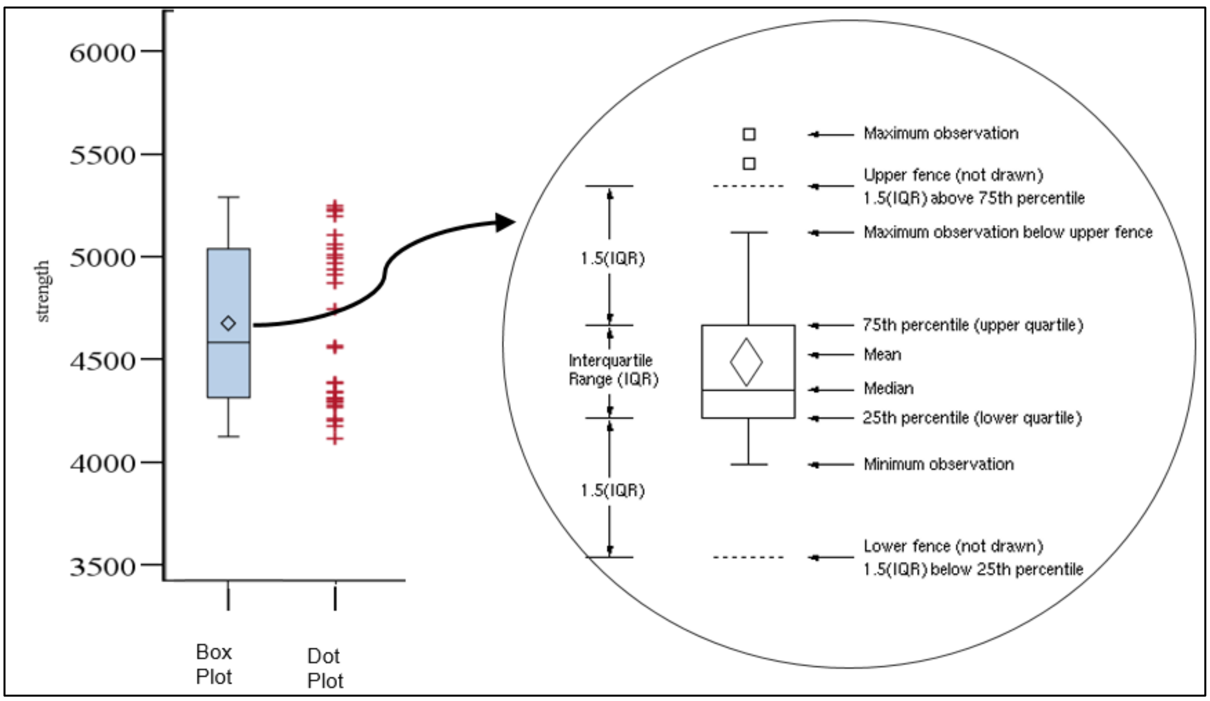


Figure 59. Illustration of statistical box plot format. On the left, a box plot is compared with dot plot of a sample set.

CHAPTER 5 RESULTS AND DISCUSSIONS

In this section, the match-cured concrete sample results are presented and discussed. The data from two separate sub-studies are reported: the study of temperature control on match-cure strength results, and in-place strength estimation using match-cure technology. A study of the effect of sample size is included in the second sub-study.

5.1 STUDY OF TEMPERATURE CONTROL ON MATCH CURING RESULTS

The sample set described in Section 3.1.1 of this report was analyzed using the statistical approach described in Section 4.3. As described in Section 3.1.1: concrete (both ready-mix and in-house mixes) were accepted and cast if air content fell between 5.5 and 7.5% by volume, and slump between 6 and 8 inches (150 and 200 mm). To further ensure that the concrete samples among the six error types and the standard temperature profile (semi-adiabatic profile shown in Figure 17) populations were equivalent (curing exposure, described in Section 4.1.2), we first analyzed the sample density. The box-plot representations of those data are shown in Figure 60. The box plot shows that the sample densities among the populations appear to be similar. A statistical evaluation carried out at a 95% confidence level confirmed that the mean density values of all seven samples were not significantly different from each other. Thus, we were confident that the concrete mixtures among the populations were equivalent in terms of consolidation level and porosity; therefore, any differences seen in strength were attributed to the error type (curing conditions).

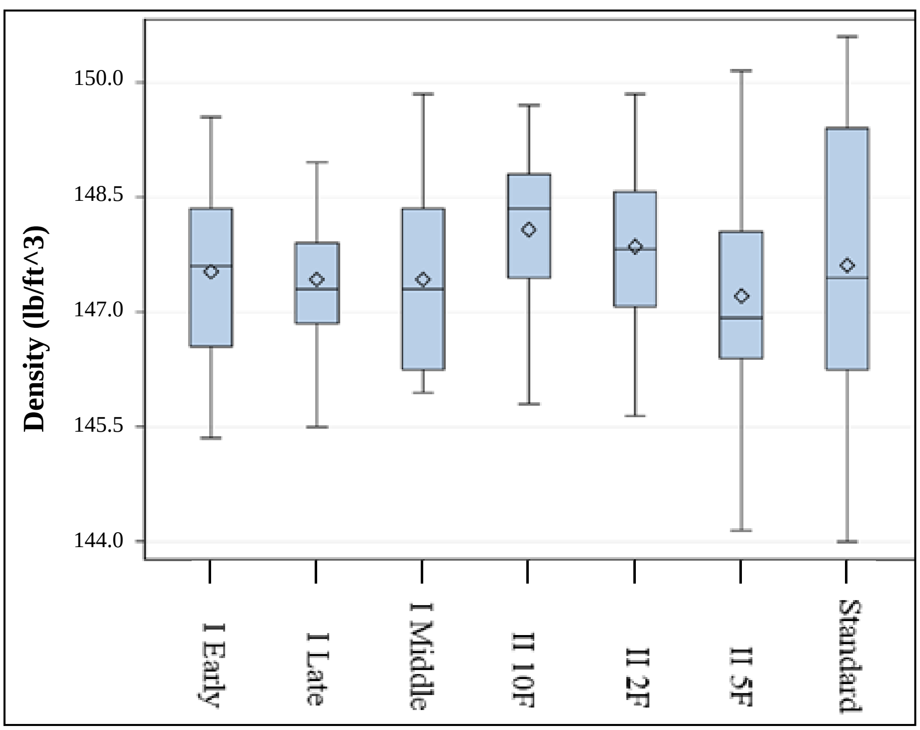


Figure 60. Box-plot presentation of sample density results for 4 x 8-in. (100 x 200-mm) cylinders as a function of error type. The temperature profiles are described in Section 4.1.

The 1-day compressive strength results were then analyzed. The box-plot representation of the strength data is shown in Figure 61. Here, clear differences among the populations appeared. The standard temperature profile produces the lowest average strength. This is expected because that profile experiences the lowest overall temperature exposure. Considering the standard and Type II error (constant-temperature offset) populations, we found that the mean strength increases progressively with increasing temperature offset; this behavior is expected. However, the 2°F Type II error appeared similar to the standard. A statistical analysis carried out at the 95% confidence level confirmed that the mean strength values of the standard and 2°F Type II error populations were not significantly different. We found that the 2°F Type II error profile was the only one that satisfied the AASHTO PP 54-06 standard practice for match curing. The statistical analysis revealed that the mean strengths of other Type II error profiles (5°F and 10°F) were significantly different from the standard-cure profile. Further, we found that the mean strengths of the 5°F and 10°F Type II profiles were significantly different from each other, as revealed by statistical analysis.

The box plot indicates that the Type I error profiles (early, middle, and late) were similar to each other; a statistical analysis carried out at the 95% confidence level confirmed that the mean strengths were not significantly different from each other. We also found that the mean strengths of the three Type I profiles were not significantly different from the Type II 10°F profile, even though the error maturity of the Type I profiles (48°F-hour) were significantly less than that of the Type II °F profile (240 °F-hour). Thus, it appears that the absolute value of the temperature error is a more direct indicator of the compressive strength than the error maturity.

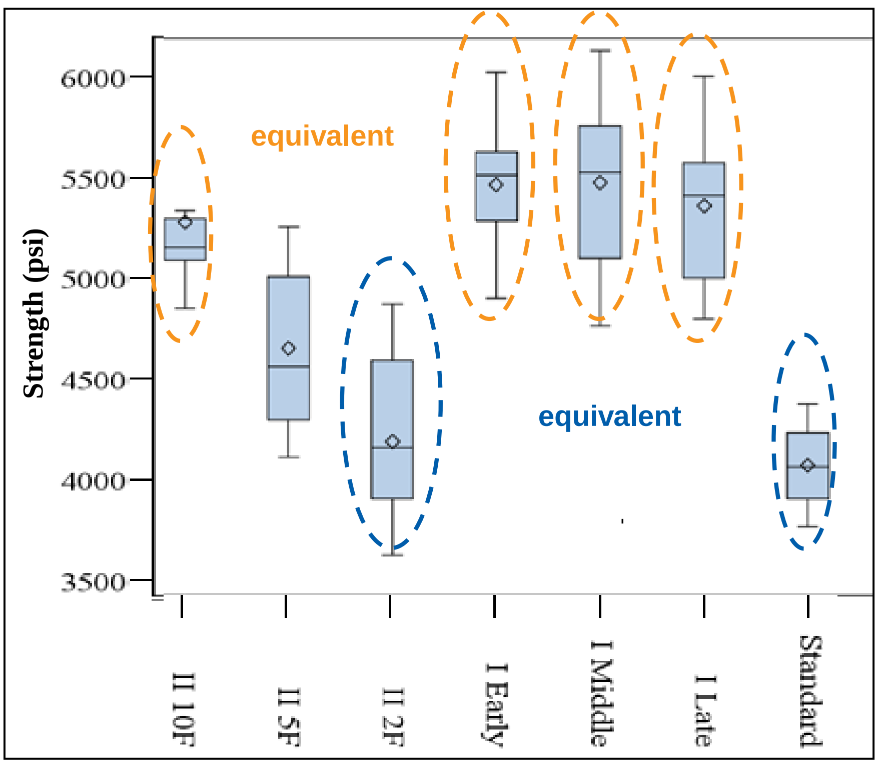


Figure 61. Box-plot presentation of strength results for 4 x 8-in. (100 x 200-mm) cylinders as a function of error type. The temperature profiles are described in Section 4.1.

5.2 IN-PLACE STRENGTH ESTIMATION

The concrete mixture described in Section 3.1.1 of this report was cast into test slabs and companion cylinders, as described in Section 4.2. The actual strength of the slabs was represented by the strengths measured from cast-in-place cylinders in the test slabs. The data from the samples from various match-cure conditions were analyzed statistically, following the procedure described in Section 4.3. The temperature data reported here are from the thermocouple embedded in one cylinder and not from the sensor within the SureCure system itself.

The temperature profiles experienced by the six different slab sets and match-cure companion samples are shown in Figures 62 through 67. The profiles exhibit expected behavior, with the peak temperature reached between 10 and 12 hours after casting. In each case, the deeper slabs that accommodate the 6-in.diameter cylinders consistently exhibited higher temperatures, with the peak temperature values consistently above 120°F (50°C). This situation was expected because the larger elements were expected to generate more internal heat from the hydration reactions of the portland cement. The peak temperatures of the smaller slabs were normally between 113°F and 120°F (45°C and 50°C). These profiles were reasonably similar to the standard profile, shown in Figure 17, used in the temperature-control error study described in the previous section. The temperature profile plots show that both the air chamber and insulated jacket mold samples reasonably followed the reference temperature obtained from the slab. However, the insulated jacket mold temperature responses were smooth, while those from the air chamber samples fluctuated about the reference temperature. These fluctuations were caused by the inherent low thermal inertia of air; this is a natural and expected response from air chambers. This type of fluctuation can be viewed as a series of Type I temperature-control errors. On occasion, these fluctuations momentarily exceeded the 4°F (2°C) error control limit established by AASHTO standard practice PP 54-06; such relatively large fluctuations can be seen in the 4-in. air chamber profiles from slabs 2, 3, 4, and 5, as shown in Figures 63 through 66, respectively. Although these fluctuations were seen throughout the duration of the temperature profile, consistent high deviations were also seen at the early stages (within the first 3 hours) of the 4-in. (100 mm) air chamber tests of slabs 2 through 5. On the other hand, the insulated jacket samples tended to show constant offset error, similar to the Type II error described in the previous section. In some cases, this constant offset error was greater than 2°F (1°C), as seen in the 6-in.diameter insulated jacket mold profiles for slabs 4 and 5, shown in Figures 65 and 66, respectively. As a result of these two types of error, only slabs 1 and 6, shown in Figures 62 and 67, respectively, met the requirements described in AASHTO standard practice PP 54-06 throughout the 24-hour profile and for both sample sizes.

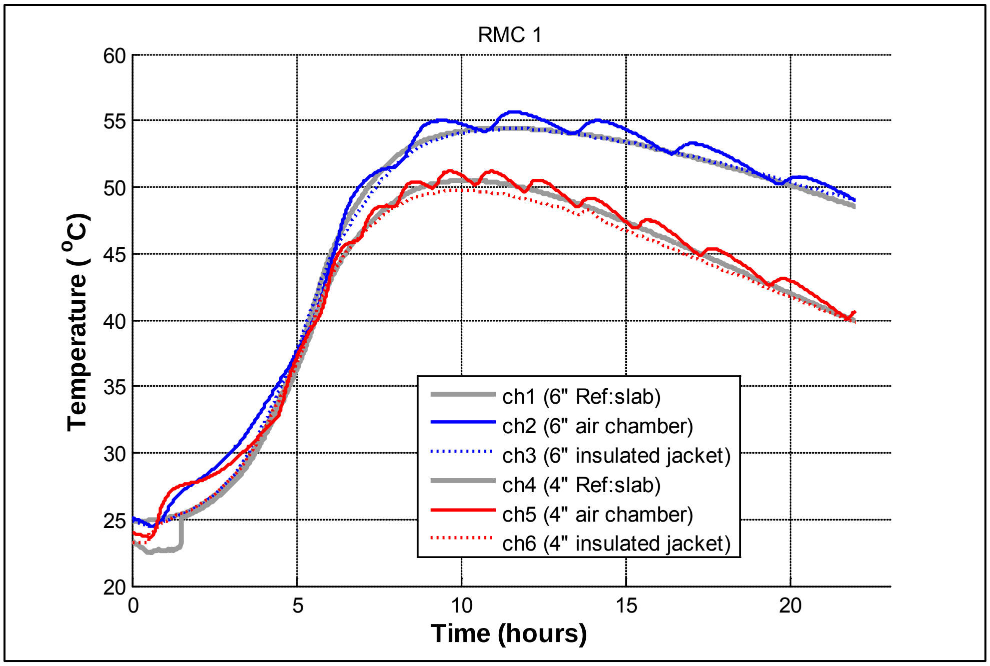


Figure 62. Measured temperature profiles for slab number 1. Note: °C = (°F-32)/1.8.

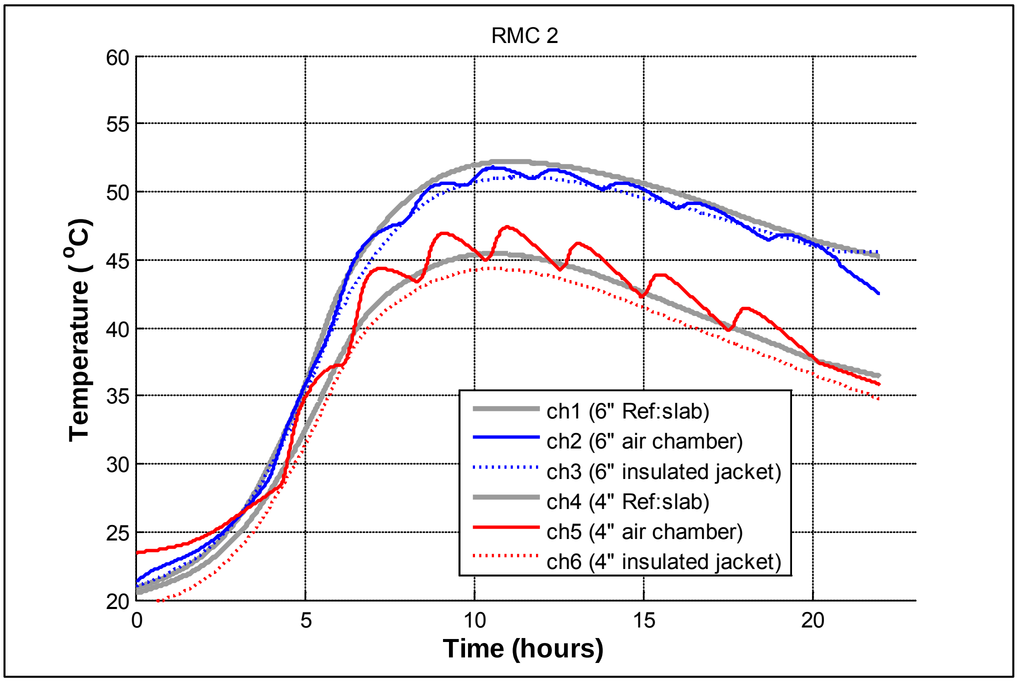


Figure 63. Measured temperature profiles for slab number 2. Note: °C = (°F-32)/1.8..

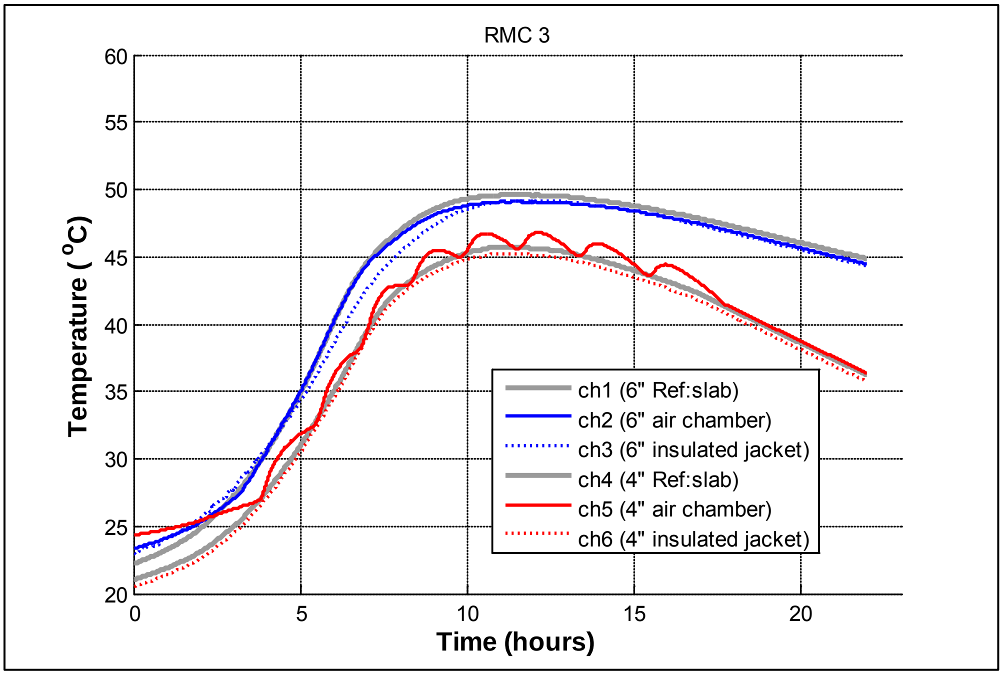


Figure 64. Measured temperature profiles for slab number 3. Note: °C = (°F-32)/1.8.

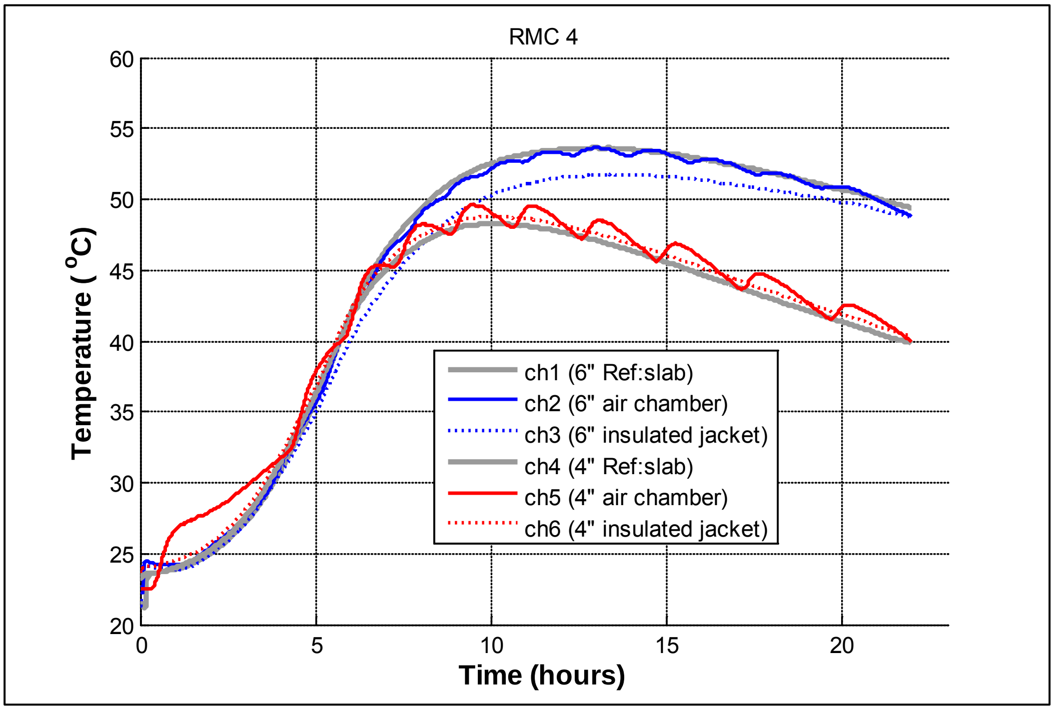


Figure 65. Measured temperature profiles for slab number 4. Note: °C = (°F-32)/1.8.

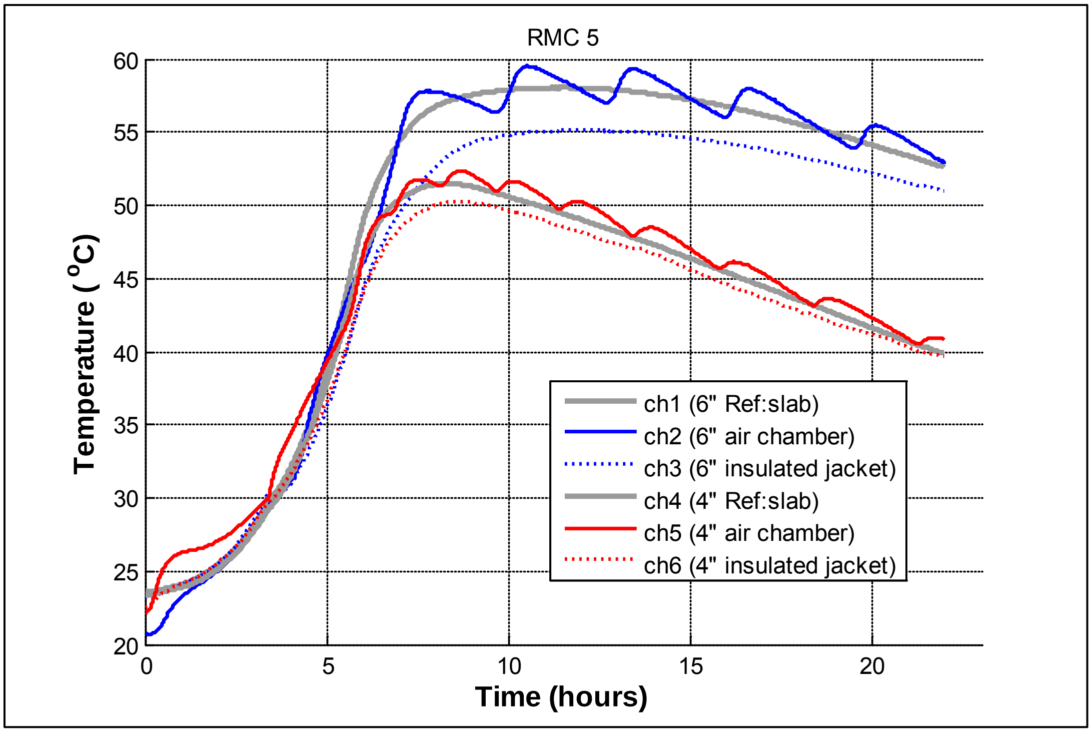


Figure 66. Measured temperature profiles for slab number 5. Note: °C = (°F-32)/1.8.

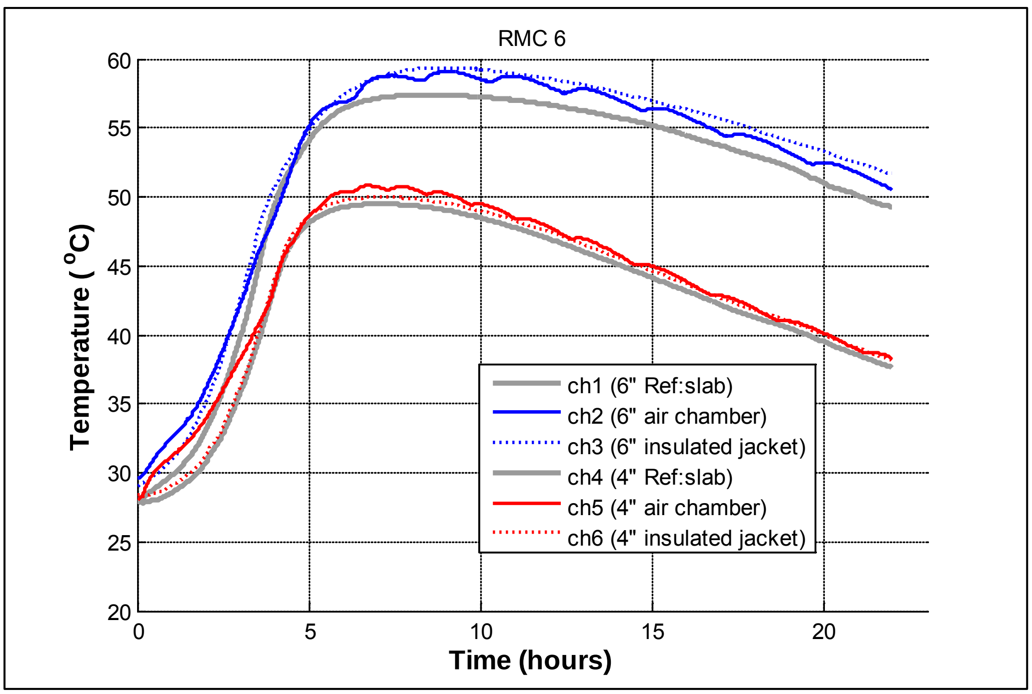


Figure 67. Measured temperature profiles for slab number 6. Note: °C = (°F-32)/1.8.

5.2.1 Density Distribution

The concrete mixture described in Section 3.1.1 of this report was cast into test slabs and companion cylinders, as described in Section 4.2. The density of the match-cured companion cylinders were first analyzed statistically, following the procedure described in Section 4.3. This analysis was done to ensure that the concrete samples among the various match-cure exposure types (in-place cylinders, insulated jacket mold, and air chamber) and cylinder-size populations were equivalent in terms of compaction level and air content. The box-plot representations of those data are shown in Figure 68. The circle points in the plot represent outlier data, below the 25% percentile or above the 75% percentile within a given population set. The box plot shows that the sample densities among the populations appeared to be similar. A statistical evaluation carried out at a 95% confidence level confirmed that the mean density values of all six samples were not significantly different from each other. Thus, we were confident that the concrete mixtures among the populations were equivalent in terms of compaction level and porosity, so any differences seen in strength were attributed to the curing conditions and/or cylinder size.

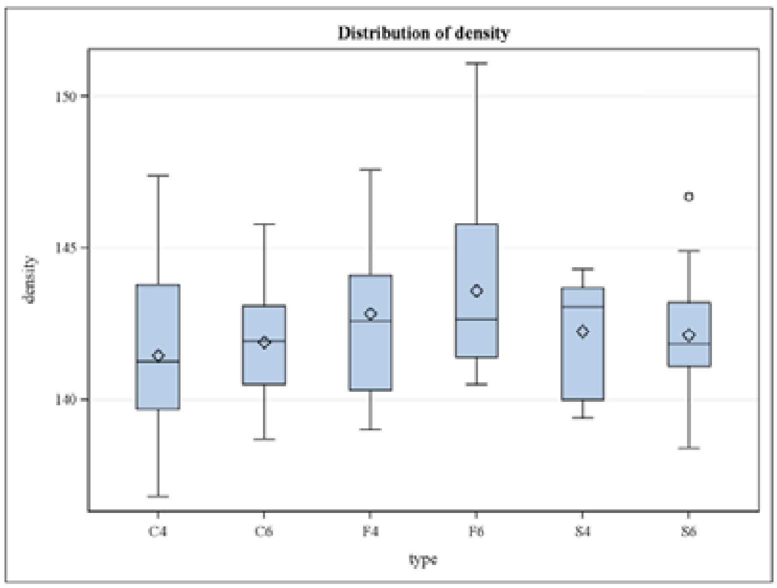


Figure 68. Box-plot presentation of density data as a function of match-curing method. C = air chamber, F = in-place cylinder, S = insulated jacket mold.

5.2.2 Match-Curing Versus In-Place-Strength

The 1-day compressive strength results across the sample populations were analyzed next. Box-plot representations of the data are shown in Figures 69 and 70, where two different data groupings associated with 4- and 6-in. (100 mm and 150 mm) diameter samples, respectively, are indicated. The circle points in the plot represent outlier data, below the 25% percentile or above the 75% percentile within a given population set. As shown in Figure 69, the strengths from 4-in. in-place cylinders appeared to be equivalent to those from 4-in. (100 mm) insulated jacket and 4-in. (100 mm) air chamber samples. A statistical analysis carried out at the 95% confidence level confirmed that the mean strengths for all 4-in. (100 mm) cylinder populations were not significantly different from each other. The mean strengths of 4- and 6-in. (100mm and 150 mm) in-place cylinder populations were not significantly different from each other, although the mean and median strength values for the 6-in. sample set were slightly lower, as expected, based on the known size effect of strength tests. These populations showed statistical equivalence, even though the air chamber temperature profiles for slabs 2, 3, 4 and 5 did not meet the requirements in AASHTO standard practice PP 54-06 because individual fluctuations occasionally exceed 4°F (2°C) above the temperature of the in-place cylinders in the slab.

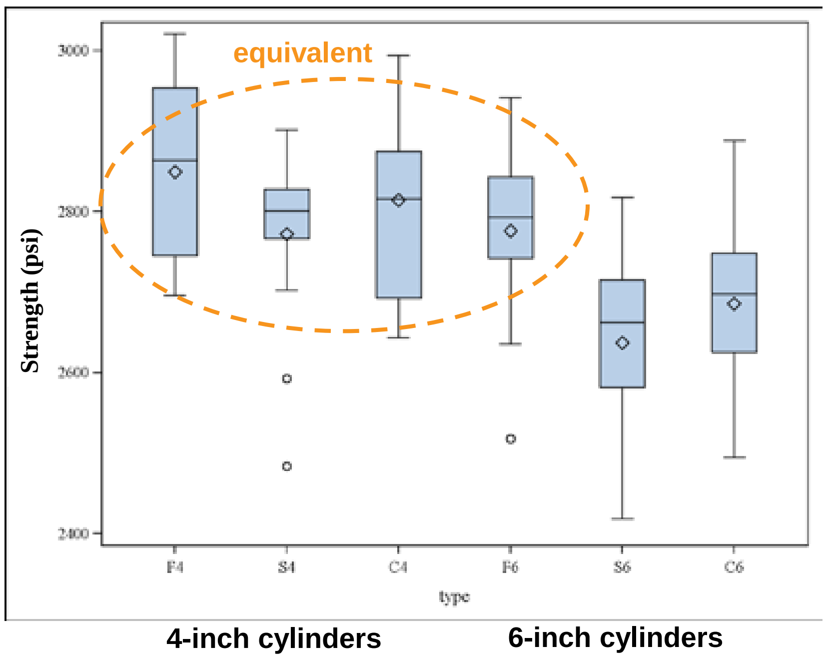


Figure 69. Box-plot presentation of 1-day strength data as a function of match-curing method. Comparison of 4-in. (100 mm) cylinders shown. C = air chamber, F = in-place cylinder, S = insulated jacket mold. Note: 1 MPa = 145 psi.

Figure 70 shows that the strengths from the three populations of 6-in. (150 mm) cylinders appear less similar to each other compared with the 4-in. (100 mm) populations. The in-place cylinder strength values have the highest mean and median values, and the insulated jacket mold samples have the lowest mean and median values. However, a statistical analysis carried out at the 95% confidence level indicated that the mean strengths for the 6-in. in-place and air chamber populations were actually not significantly different from each other. The average strength of the 6-in. (150 mm) insulated jacket mold samples, however, was significantly different than the average strength of the 6-in. (150 mm) in-place sample set. The average strengths from 6-in. match-cure populations with temperature profiles that met the requirements in AASHTO standard practice PP 54-06 showed statistical equivalence to strengths from in-place cylinders, while those that did not meet the AASHTO requirements were statistically distinct. For the 6-in. (150 mm) cylinders, the profiles that violated the AASHTO requirements showed consistent offset, similar to Type II error described in the previous section. This situation differed from that seen with the 4-in. (100 mm) cylinders, which showed fluctuating Type I error that violated the AASHTO requirements yet showed statistical equivalence with regard to average strength.

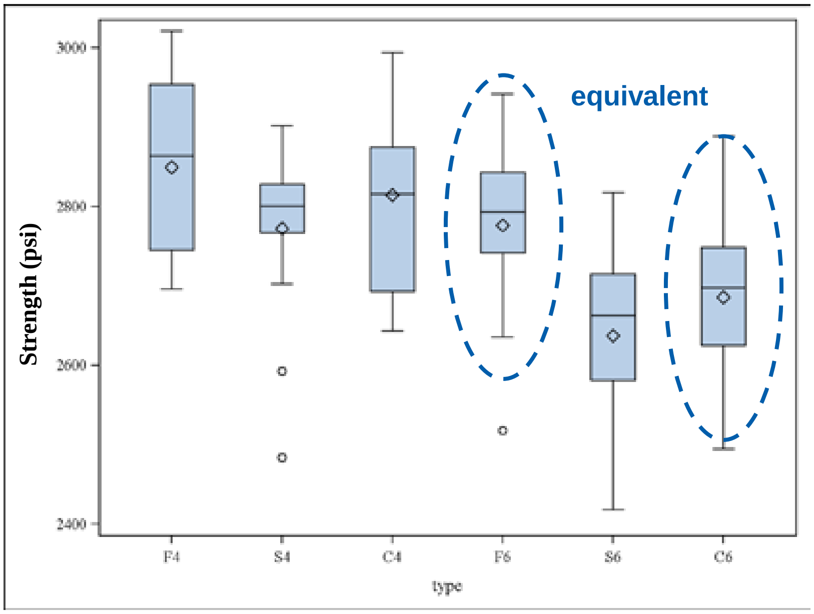


Figure 70. Box-plot presentation of 1-day strength data as a function of match-curing method. Comparison of 6-in. cylinders shown. C = air chamber, F = in-place cylinder, S = insulated jacket mold. Note: 1 MPa = 145 psi.

Additional analyses of the data were carried out to reveal, in more detail, the reasons for the strength differences between match-cure and in-place cylinders. First, the differences between temperature profiles for the various match-cure systems were analyzed. Figure 71 shows the average of temperature difference between match-cure and in-place cylinders, shown using the box-plot presentation. In this plot, a *y*-axis value of zero indicates perfect agreement between in-place and match-cure temperatures. The results showed that both the 4-in. (100 mm) insulated jacket mold and 6-in. (150 mm) air chamber matched the temperature of the test slab (in-place cylinders) reasonably well; this is indicated by the fact that the box representing most of the population data intersects the zero line of the axis. It follows that these two profiles meet the requirements in AASHTO standard practice PP 54-06 in all cases. On the other hand, the 4-in. (100 mm) air chamber temperatures were consistently higher than in-place, while the 6-in. (150 mm) insulated jacket mold temperatures were consistently lower. The discrepancy in the 4-in. (100 mm) air chamber results arose from the Type I error temperature fluctuations in the profiles that already have been noted; most of these fluctuations are above the reference temperature. On the other hand, the discrepancy in the 6-in. (150 mm) insulated jacket mold results arose from the Type II error in the profiles that already have been noted; most of the errors in this case lay below the reference temperature.

When we compared these temperature results to the strength results shown in Figures 69 and 70, interesting trends were seen. The lowest average strength was associated with the 6-in. (150 mm) insulated jacket samples, which also showed the lowest average temperature with respect to the slab reference temperature. However, the 4-in. (100 mm) air chamber samples were not associated with the highest average strength, although their average strength was the highest of the match-cure populations. The relative strengths of the various match-cure systems, with respect to that of the in-place cylinders, is further explored in Figure 72, which shows that the 4-in. (100 mm) air chamber samples exhibited the highest average strength and the 6-in. (150 mm) insulated cylinders had the lowest average strength. Thus, the strength ratio results (Figure 72) generally follow that of temperature difference (Figure 71) although the strength results appear to be shifted lower.

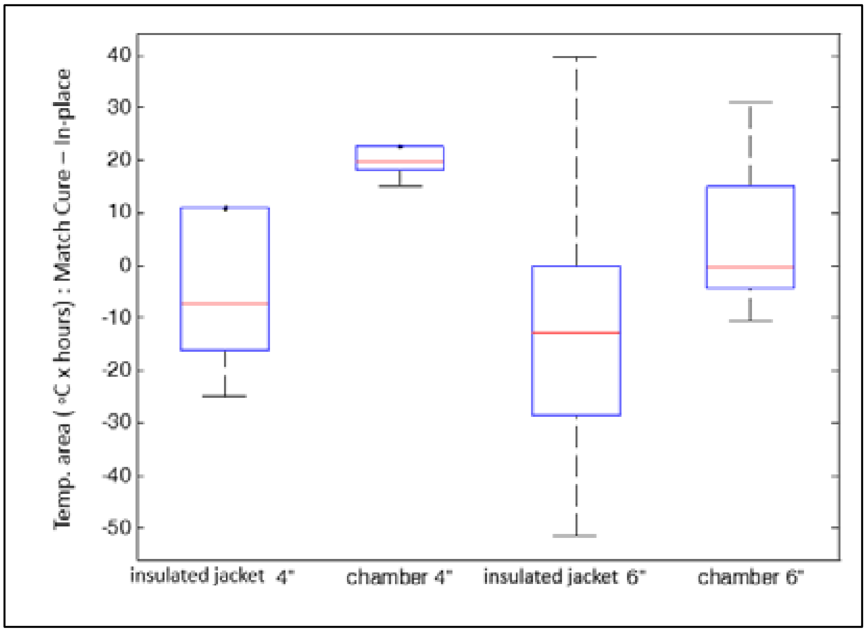


Figure 71. Box-plot presentation of temperature difference (match-cured minus in-place) as a function of match-curing method.
Note: 1 inch = 25.4 mm and °C = (°F-32)/1.8.

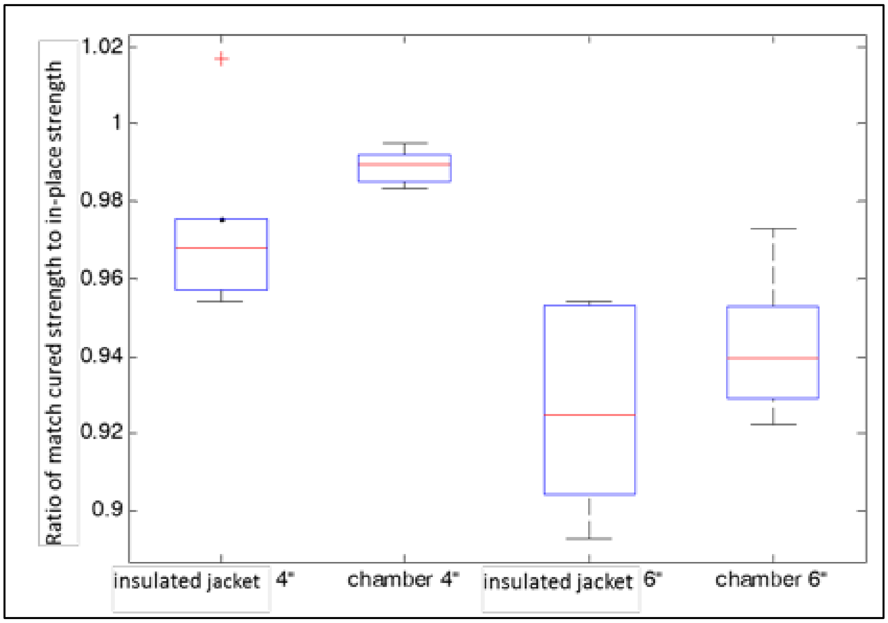


Figure 72. Box-plot presentation of temperature ratio (match-cured to in-place) as a function of match-curing method. Note: 1 inch = 25.4 mm and °C = (°F-32)/1.8.

Figures 73–79 show 6 data points for each test method, where each data point represents the average values for one batch of ready-mix concrete. Figure 73 shows that the match-cured cylinder strengths were almost always lower than in-place cylinders strengths; this occurred even when temperature profiles of the two were equivalent. So, although there was some connection between average cure temperature and average strength, which was expected, this relationship was somewhat complicated by the nature of the temperature fluctuations and type of match-curing system. This behavior was explored further, as shown in the "target plot" in Figure 74, which plots the relative strength (ratio) of match-cured samples with respect to the in-place samples against the respective relative temperature profile area average. Perfect agreement between match-cured and in-place samples, for both strength and temperature profiles, is represented by the plot origin at coordinates (1,1). The data in the plot confirm that the strengths of the match-cured samples were consistently lower than those of the in-place samples, even though several of the temperature profiles from the match-cured samples were actually higher than those from the in-place samples. This behavior is further quantified by computing the global error for each data point in Figure 74; the method by which global error is computed is illustrated in Figure 75. This global error accounts for both relative strength and relative temperature profile differences between match-cured and in-place samples, where a larger global error value indicates a larger distance between the origin and each data point in Figure 74. The box-plot representation of the global error data for each match-cure population is shown in Figure 76. In Figure 76, the vertical axis shows the global error, which is represented by the magnitude of the radial distance from the plot center to any point. The box plot results reveal that the 4-in. match-cured samples showed lower average global error, with the 4-in. air chamber samples having the lowest average global error overall. This finding is especially interesting, considering that the 4-in. air chamber showed the poorest temperature agreement with the reference in-place cylinders.

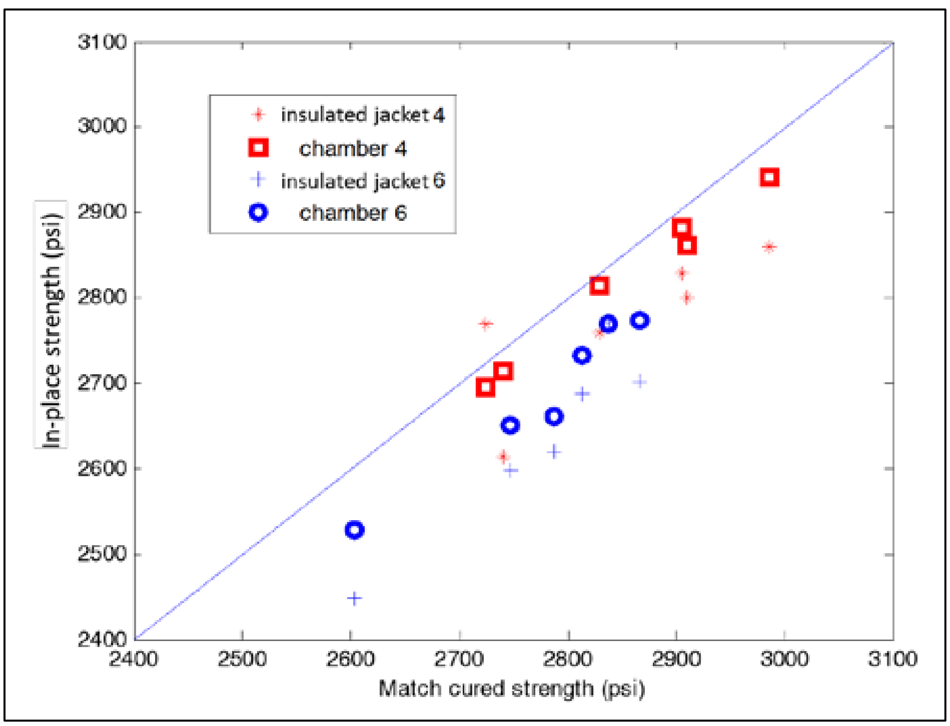


Figure 73. Comparison of in-place strength to match-cured cylinder strength for both match-cure environments and cylinder sizes. The line of equality is indicated in blue. Note: 1 MPa = 145 psi.

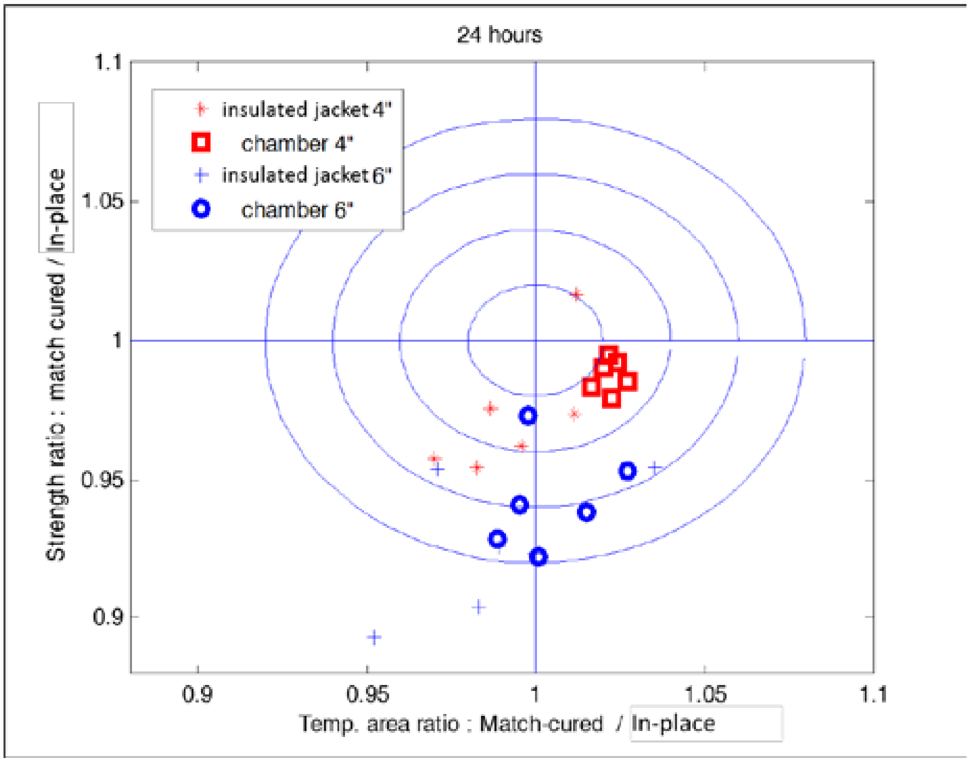


Figure 74. Presentation of strength and temperature-control ratios (match-cured to in-place) for both match-cure environments and cylinder sizes. The plot center (1,1) indicated perfect temperature and strength match to in-place cylinders. Note: 1 inch = 25.4 mm.

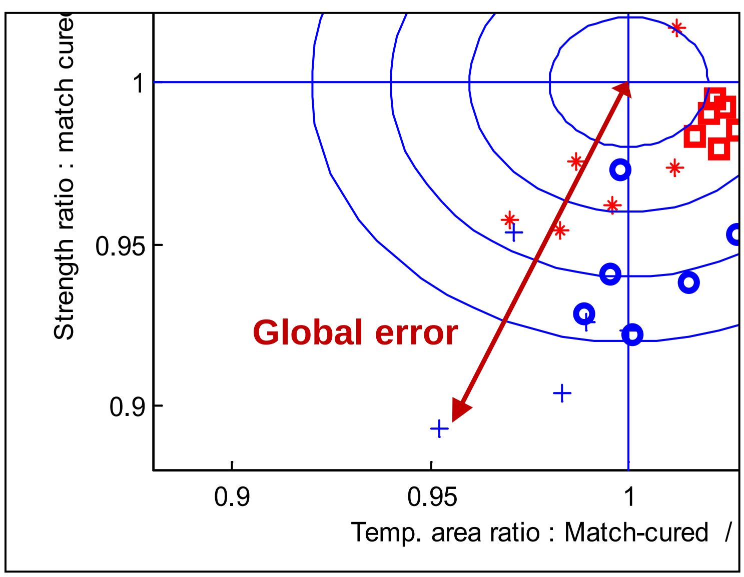


Figure 75. A closer view of Figure 74. Illustration of global error of a given data point, defined as the radial distance from the plot center to any point.

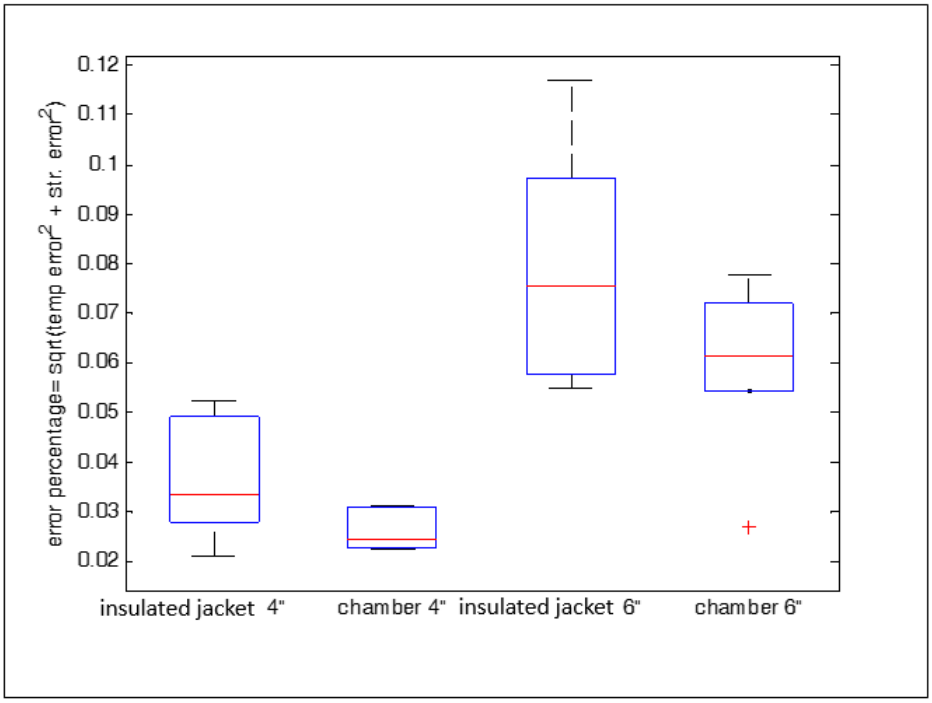


Figure 76. Box-plot presentation of global error (radial distance from the plot center to any point) of data in Figure 74. Note: 1 inch = 25.4 mm.

5.2.3 Size Effect

Because the 4- and 6-in. cylinder sets, for both match-cured and in-place samples, experienced significantly distinct temperature profiles, our ability to compare strengths directly to evaluate sample-size effect was somewhat limited. However, we can point to general trends, keeping this restriction in mind. For example, the strength results shown in Figure 69 demonstrate that the basic, expected effect of cylinder size on the measured strength was observed. When we compared the 1-day strengths of 4- and 6-in. in-place cylinders, we found that the 6-in. cylinders had slightly lower average strength but also lower data variance. However, the difference in average strength was quite small; in fact, the statistical analysis revealed that the average strengths in the two populations were not significantly different, even though the temperature profiles experienced by the 6-in. cylinders were known to be higher.

Despite the analytical restriction to direct comparison, described above, we investigated whether cylinder size has some general influence on match-cure strength results. The results showed that the cylinder size appeared to have some effect on match-cure results. The ratios of 6-in. match-cure to in-place strength and temperature were plotted against associated values for 4-in. cylinders, for both insulated jacket and air chamber samples; these results are shown in Figures 77 and 78, respectively. In both figures, the star indicates the coordinates associated with perfect agreement with in-place values, and the line of equality indicates agreement in behavior between the two cylinder sizes. As shown in those figures, most of the strength data had values lower (below and to the left) than the star on both axes. This confirmed that match-cured strength values tended to be lower than in-place strengths, even when the associated temperature profiles were not necessarily lower; this behavior was discussed in Section 5.2.2. Beyond this behavior, we saw an interesting trend: The strength data consistently lay below the line of equality, even though the temperature values lay on both sides of this line. These results indicated that there was a general size effect for match-cured samples: 6-in. match-cured cylinders showed lower strength relative to in-place cylinders than 4-in. ones did. This distinction in behavior appeared to be consistent for both types of match curing employed: insulated jacket mold in Figure 77 and air chamber in Figure 78.

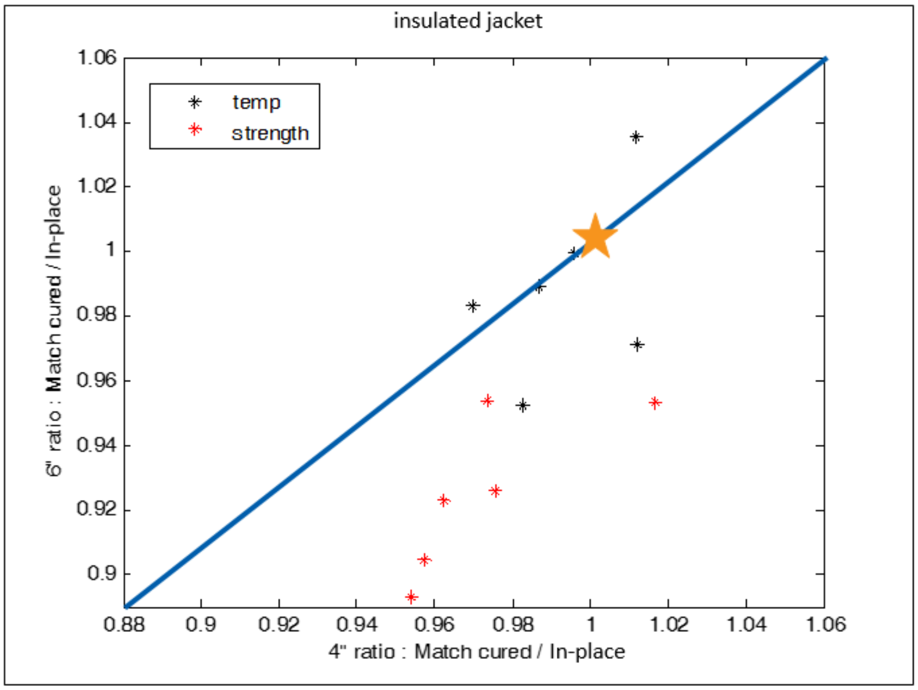


Figure 77. Comparison of 1-day strength and temperature ratios (match-cured to in-place) of 6- and 4-in. (150 mm and 100 mm) cylinders for insulated jacket match-cure samples. The line of equality is indicated in blue, and the star indicates the position of perfect match between cylinder sizes.

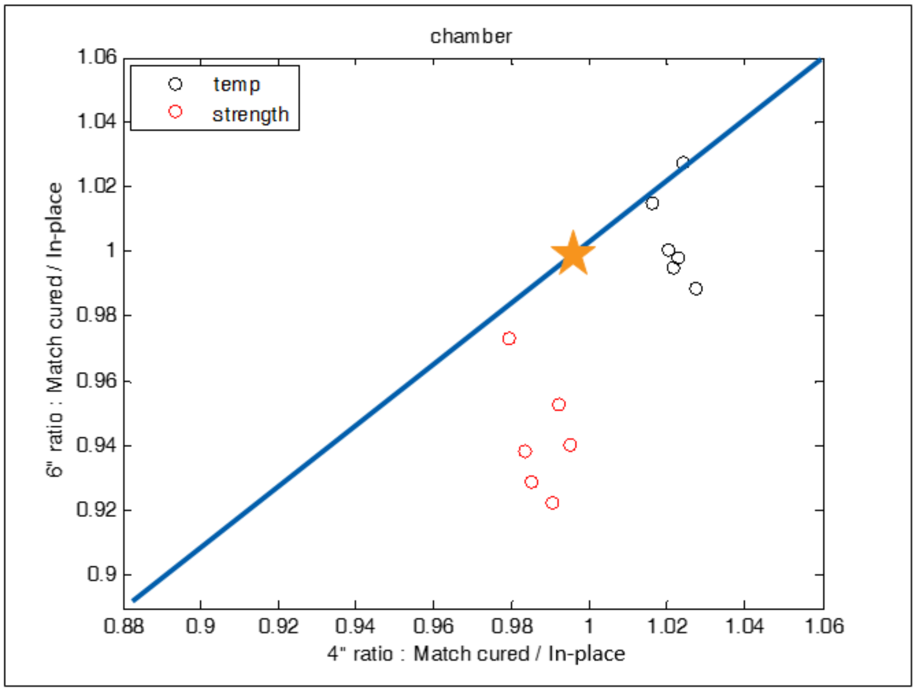


Figure 78. Comparison of 1-day strength and temperature ratios (match-cured to in-place) of 6- and 4-in. (150 mm and 100 mm) cylinders for air chamber match-cure samples. The line of equality is indicated in blue, and the star indicates the position of perfect match between cylinder sizes.

When we compared the 6- and 4-in. 1-day strengths directly, as shown in Figure 79, we found that the larger samples were generally between 5% and 10% lower than the smaller samples. Again, it was difficult to compare these strength values directly, but we did find that the 4-in. cylinders showed higher average strength despite experiencing lower average temperature profiles. Furthermore, the data in Figure 79 indicate that match-cured cylinders appeared to experience more of a size effect than in-place cylinders.

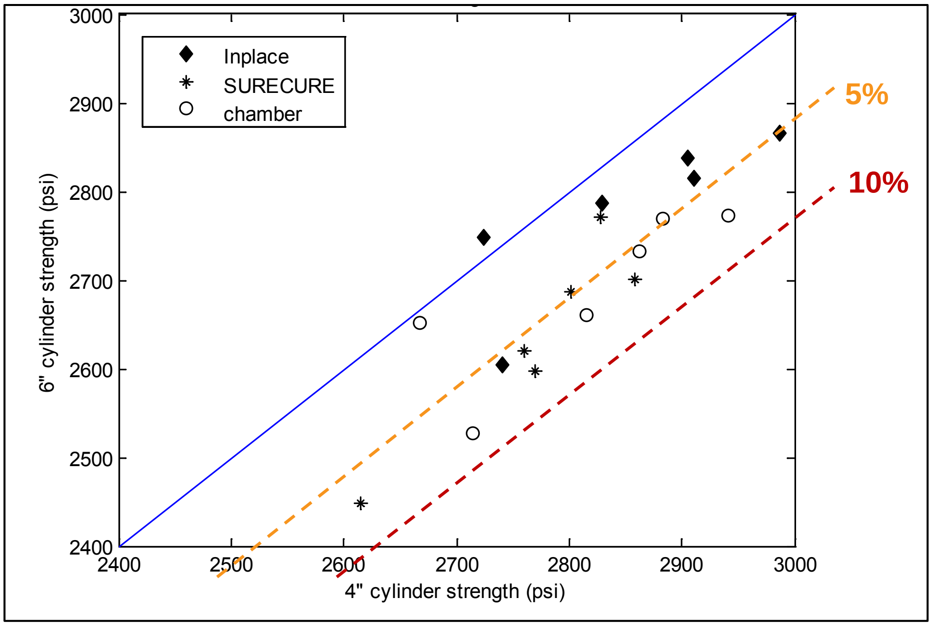


Figure 79. Comparison of 1-day strengths of 6- and 4-in. (150 mm and 100 mm) cylinders for both match-cure environments and in-place cylinders. The line of equality is indicated in blue; and 5% and 10% offset lines are indicated in yellow and red, respectively. Note: 1 MPa = 145 psi.

CHAPTER 6 CONCLUSIONS AND FUTURE WORK

Based on the literature review, experimental findings, and conclusions obtained in this project, the following conclusions are drawn.

6.1 CURRENT STATE OF UNDERSTANDING AND PRACTICE

- Smaller test samples tend to exhibit higher average strength and also tend to show more variation in the results. Both of these behaviors are affected by the compressive strength of the concrete, with high-strength concrete showing larger differences in strength and, possibly, more variable data.
- Although many design codes and state transportation agencies neglect the difference in strength values between 4 x 8-in. (100 x 200-mm) samples and 6 x 12-in. (150 x 300-mm) samples, some agencies do require a higher number (usually three) of 4 x 8-in. (100 x 200-mm) samples to be tested to establish a strength value.

6.2 EXPERIMENTAL PROCEDURES

- Three principal temperature match-curing systems were used: water bath, air chamber, and insulated jacket molds. All three types of match curing were shown to provide test samples that more accurately represent the strength of in-place concrete in an element, compared with conventionally cured samples.
- The employed thermocouple and DAQ system is an effective and practical way to measure internal concrete temperature. The accuracy of the thermocouple system is reasonable, within 0.55°C (1°F).
- The proposed concrete mixtures meet IDOT Class PS concrete specifications. The ready-mix concrete batches exhibit consistent properties, based on strength values of companion samples exposed to constant-temperature water bath curing.
- The temperature profile obtained from the semi-adiabatic test configuration is a reasonable representation of that obtained from a thick concrete slab, as long as the top of the concrete sample is thermally insulated. This temperature profile, shown in Figure 6, was used as the representative profile to drive the water bath experiments.
- Thermocouples embedded within a properly thermally insulated concrete sample provide internal concrete temperatures that are largely unaffected by the external ambient environment and represent the heat evolved by hydration of the cement.
- The water bath match-cure system is very controllable and reliable in cases where rapid cooling profiles are not required, unless a cooling system is included as part of the water bath system.

6.3 RESULTS

6.3.1 Temperature-Control Error

- Type I error (transient disruption) has much larger influence on 24-hour strength than Type II error (constant offset), when error area (error maturity) is compared. Absolute temperature error is likely a better standard of comparison across these two error types.
- The time of occurrence of Type I error disruption (early, middle, and late) has negligible effect when a constant area error is considered.
- The temperature-control criteria in AASHTO standard procedure PP 54-06 are appropriate for obtaining accurate representation of in-place strength for both 4- and 6-in. (100 and 150-mm) cylinders using insulated jacket mold systems.
- The temperature-control criteria in AASHTO standard procedure PP 54-06 are appropriate for obtaining accurate representation of in-place strength for both 4- and 6-in. (100 and 150-mm) cylinders using air chamber systems assuming the match-cured sample temperature is controlled using a sensor embedded in a concrete sample within the chamber.

6.3.2 In-Place Strength Estimation Within 24 hours of Casting

- Ready-mix concrete mixtures are reasonably consistent batch to batch and can be compared with each other.
- Air chambers are more likely to exhibit Type I (transient disruption) error and, insulated jackets are more likely to exhibit Type II (constant offset) error.
- Although 4- and 6-in. (100 and 150-mm) match-cure cylinders exhibit lower average concrete strength for air chamber and insulated jacket mold systems when compared to in-place concrete strength, they are statistically equivalent at the 95% confidence level as long as temperature-control errors are maintained within reason (i.e., AASHTO PP 54-06). Note: match-cure cylinders were not covered as required by AASHTO PP 54-06
- 4-in. (100-mm) match-cure samples appear to show a closer match to in-place strength, although reasonable results can be obtained with 6-in. (150-mm) samples.
- The 6-in. (150-mm) insulated jacket mold system used in this study shows less accurate temperature control than the commercially available 4-in. (100-mm) system.

6.3.3 Effects of Cylinder Size

- In general, 4-in. (100-mm) cylinders show higher average strength regardless of the curing type.
- There appears to be a cylinder-size effect for match-cure performance: generally, 6-in. (150-mm) cylinders shows less accurate estimation of in-place strength. This effect appears to be consistent for both air chamber and insulated jacket mold systems.
- Despite this apparent size effect, both 4- and 6-in. (100 and 150-mm) cylinders show a lower test result but reasonable match to in-place strength for both air chamber and insulated jacket mold systems.

- The observed strength differences between 4- and 6-in. (100 and 150-mm) cylinders match expectations.

6.4 FUTURE WORK

- Evaluate water bath system for in-place strength prediction.
- Directly evaluate match-cure cylinder-size effect with water bath system and preset temperature profile.
- Study critical levels of Type I error for in-place strength assessment—both in terms of temperature and temperature area error.
- Study the effects of a test specimen temperature being lower than the product to verify that the minimum temperature proposed in Chapter 7 is correct.

CHAPTER 7 RECOMMENDATIONS

Based on the literature review, experimental findings, and conclusions obtained in this project, we recommend that properly controlled match-curing procedures be deployed with confidence for insulated jacket mold, air chamber, and water bath systems; and for both 4- and 6-in. (100 and 150-mm) cylinders, when the data are used to determine materials strength development within 24 hours after casting. In particular, we suggest that the AASHTO PP 54-06 standard practice for match curing be deployed but with the following recommended revisions:

- In Section 5.1 of the standard practice document, modify the wording to list more possible types of match-cure systems: insulated jacket molds, air chambers, and water baths.
- In Section 5.1 of the standard practice document, modify the wording to state that the temperatures of concrete *inside of* the match-cured cylinders be within the temperature specification.
- In Section 5.1 of the standard practice document, change the temperature-control limit from "… within ±4°F (±2°C) of…" to "… as close as possible but not greater than 4°F (2°C) above …." More research is needed to define a lower temperature threshold limit, our preliminary observations suggest that -6°F (-3°C) would be a conservative value to consider. This recommendation is based on the observation that some match curing systems (e.g. air chambers) exhibit natural temperature fluctuation during the course of operation, and so the temperature limits should be widened in order to accommodate such systems while at the same time ensuring that the Type I (transient) temperature-control error does not exceed 4°F (2°C) of in-place concrete temperature.

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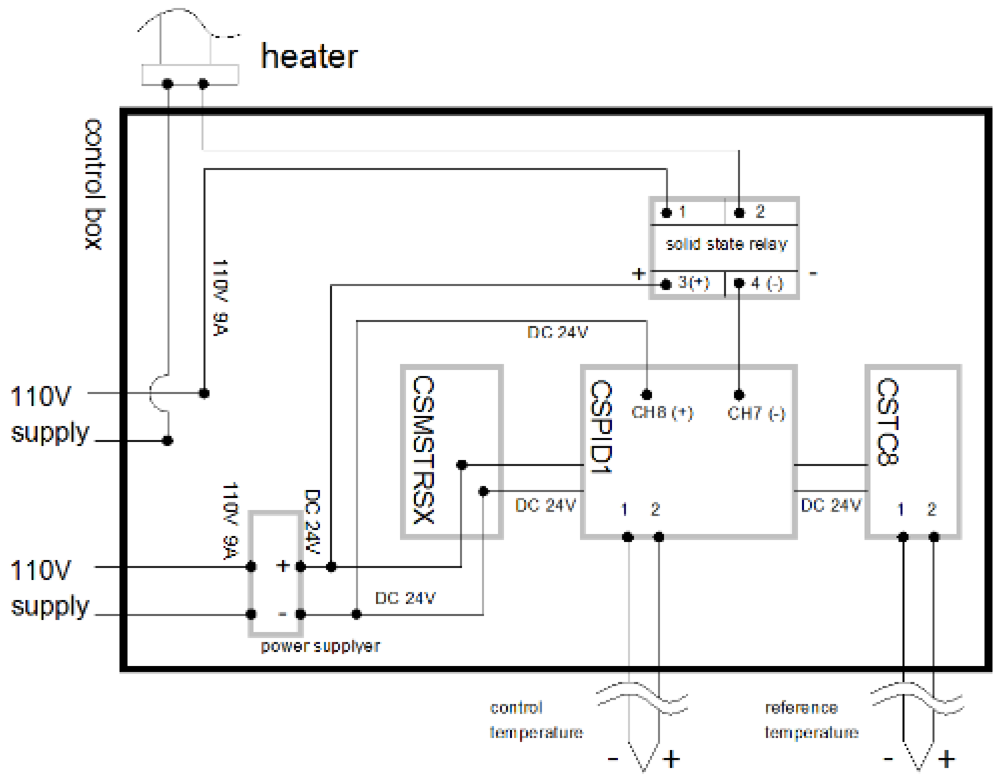
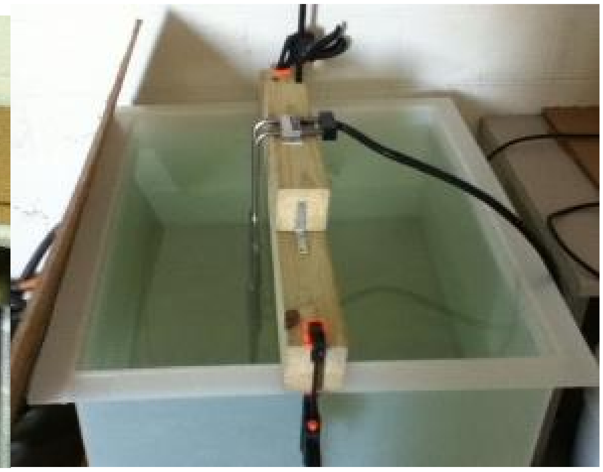
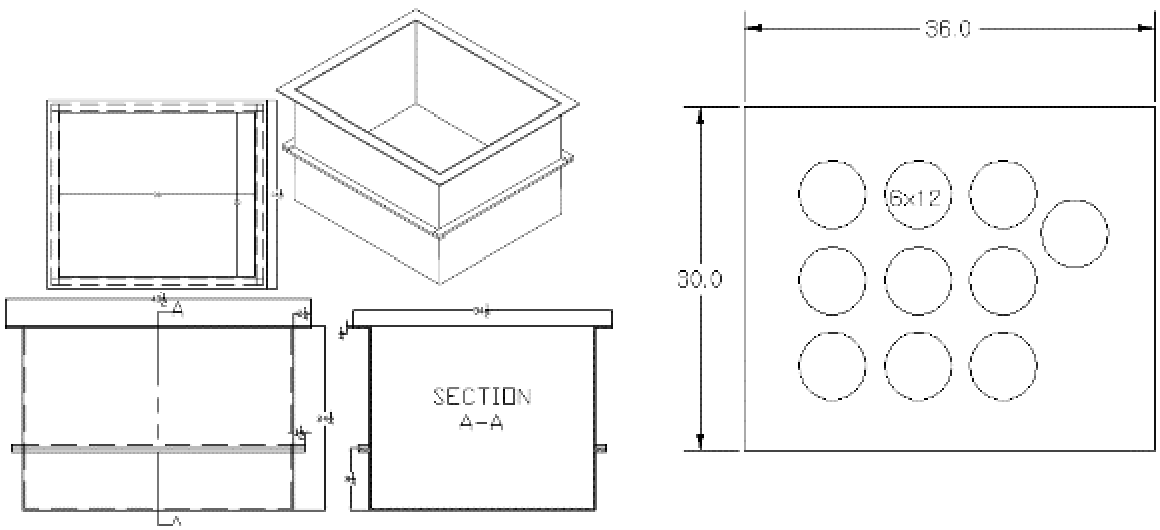
APPENDIX A WATER BATH SETUP



Complete water bath system



Heating element



Capacity and dimensions in inches. Note: 1 inch = 25.4 mm

APPENDIX B WATER BATH CONTROL-SYSTEM SOFTWARE

Water bath system code

Control system : Redlion / Program name : Crimson 2.0

```
STARTUP
      ReqProfile:=0;
      ProfileTracker:=0;
      ReqSegment:=0;
WRITE_SP
      REQ_SP:=TC1;
LOAD_INIT
      ProfDone:=0;

      if (SegmentAmount>=30) {
         EndSegment:=30;
         ProfileTracker:=1;
      }
      else {
         EndSegment:=SegmentAmount;
      }

      [Module1.Loop.Seg00Time]:=Seg00Time1;
      [Module1.Loop.Seg00SP]:=Seg00SP1;
      [Module1.Loop.Seg00Mode]:=Seg00Mode1;

      [Module1.Loop.Seg01Time]:=Seg00Time2;
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      [Module1.Loop.Seg04Time]:=Seg00Time5;
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      [Module1.Loop.Seg04Mode]:=Seg00Mode5;

      [Module1.Loop.Seg05Time]:=Seg00Time6;
      [Module1.Loop.Seg05SP]:=Seg00SP6;
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```

```
[Module1.Loop.Seg06Time]:=Seg00Time7;
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```

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[Module1.Loop.Seg18SP]:=Seg00SP19;
[Module1.Loop.Seg18Mode]:=Seg00Mode19;

[Module1.Loop.Seg19Time]:=Seg00Time20;
[Module1.Loop.Seg19SP]:=Seg00SP20;
[Module1.Loop.Seg19Mode]:=Seg00Mode20;

[Module1.Loop.Seg20Time]:=Seg00Time21;
[Module1.Loop.Seg20SP]:=Seg00SP21;
[Module1.Loop.Seg20Mode]:=Seg00Mode21;

[Module1.Loop.Seg21Time]:=Seg00Time22;
[Module1.Loop.Seg21SP]:=Seg00SP22;
[Module1.Loop.Seg21Mode]:=Seg00Mode22;

[Module1.Loop.Seg22Time]:=Seg00Time23;
[Module1.Loop.Seg22SP]:=Seg00SP23;
[Module1.Loop.Seg22Mode]:=Seg00Mode23;

[Module1.Loop.Seg23Time]:=Seg00Time24;
[Module1.Loop.Seg23SP]:=Seg00SP24;
[Module1.Loop.Seg23Mode]:=Seg00Mode24;

[Module1.Loop.Seg24Time]:=Seg00Time25;
[Module1.Loop.Seg24SP]:=Seg00SP25;
[Module1.Loop.Seg24Mode]:=Seg00Mode25;

[Module1.Loop.Seg25Time]:=Seg00Time26;
[Module1.Loop.Seg25SP]:=Seg00SP26;
[Module1.Loop.Seg25Mode]:=Seg00Mode26;

[Module1.Loop.Seg26Time]:=Seg00Time27;
[Module1.Loop.Seg26SP]:=Seg00SP27;
[Module1.Loop.Seg26Mode]:=Seg00Mode27;

[Module1.Loop.Seg27Time]:=Seg00Time28;
[Module1.Loop.Seg27SP]:=Seg00SP28;
[Module1.Loop.Seg27Mode]:=Seg00Mode28;

[Module1.Loop.Seg28Time]:=Seg00Time29;
[Module1.Loop.Seg28SP]:=Seg00SP29;
[Module1.Loop.Seg28Mode]:=Seg00Mode29;
```

```
    [Module1.Loop.Seg29Time]:=Seg00Time30;
    [Module1.Loop.Seg29SP]:=Seg00SP30;
    [Module1.Loop.Seg29Mode]:=Seg00Mode30;


    //after all data is loaded...

    ReqProfile:=1;


LOAD_2
    //Only runs if SegmentAmount is larger than 30
    ReqProfile:=0;
    ProfDone:=0;
    Delay:=GetNow();
    while (GetNow()< (Delay + 2))        {
    }
    // two second delay

    EndSegment:=(SegmentAmount-30);

    [Module1.Loop.Seg00Time]:=Seg00Time31;
    [Module1.Loop.Seg00SP]:=Seg00SP31;
    [Module1.Loop.Seg00Mode]:=Seg00Mode31;

    [Module1.Loop.Seg01Time]:=Seg00Time32;
    [Module1.Loop.Seg01SP]:=Seg00SP32;
    [Module1.Loop.Seg01Mode]:=Seg00Mode32;

    [Module1.Loop.Seg02Time]:=Seg00Time33;
    [Module1.Loop.Seg02SP]:=Seg00SP33;
    [Module1.Loop.Seg02Mode]:=Seg00Mode33;

    [Module1.Loop.Seg03Time]:=Seg00Time34;
    [Module1.Loop.Seg03SP]:=Seg00SP34;
    [Module1.Loop.Seg03Mode]:=Seg00Mode34;

    [Module1.Loop.Seg04Time]:=Seg00Time35;
    [Module1.Loop.Seg04SP]:=Seg00SP35;
    [Module1.Loop.Seg04Mode]:=Seg00Mode35;

    [Module1.Loop.Seg05Time]:=Seg00Time36;
    [Module1.Loop.Seg05SP]:=Seg00SP36;
    [Module1.Loop.Seg05Mode]:=Seg00Mode36;

    [Module1.Loop.Seg06Time]:=Seg00Time37;
```

```
[Module1.Loop.Seg06SP]:=Seg00SP37;
[Module1.Loop.Seg06Mode]:=Seg00Mode37;

[Module1.Loop.Seg07Time]:=Seg00Time38;
[Module1.Loop.Seg07SP]:=Seg00SP38;
[Module1.Loop.Seg07Mode]:=Seg00Mode38;

[Module1.Loop.Seg08Time]:=Seg00Time39;
[Module1.Loop.Seg08SP]:=Seg00SP39;
[Module1.Loop.Seg08Mode]:=Seg00Mode39;

[Module1.Loop.Seg09Time]:=Seg00Time40;
[Module1.Loop.Seg09SP]:=Seg00SP40;
[Module1.Loop.Seg09Mode]:=Seg00Mode40;

[Module1.Loop.Seg10Time]:=Seg00Time41;
[Module1.Loop.Seg10SP]:=Seg00SP41;
[Module1.Loop.Seg10Mode]:=Seg00Mode41;

[Module1.Loop.Seg11Time]:=Seg00Time42;
[Module1.Loop.Seg11SP]:=Seg00SP42;
[Module1.Loop.Seg11Mode]:=Seg00Mode42;

[Module1.Loop.Seg12Time]:=Seg00Time43;
[Module1.Loop.Seg12SP]:=Seg00SP43;
[Module1.Loop.Seg12Mode]:=Seg00Mode43;

[Module1.Loop.Seg13Time]:=Seg00Time44;
[Module1.Loop.Seg13SP]:=Seg00SP44;
[Module1.Loop.Seg13Mode]:=Seg00Mode44;

[Module1.Loop.Seg14Time]:=Seg00Time45;
[Module1.Loop.Seg14SP]:=Seg00SP45;
[Module1.Loop.Seg14Mode]:=Seg00Mode45;

[Module1.Loop.Seg15Time]:=Seg00Time46;
[Module1.Loop.Seg15SP]:=Seg00SP46;
[Module1.Loop.Seg15Mode]:=Seg00Mode46;

[Module1.Loop.Seg16Time]:=Seg00Time47;
[Module1.Loop.Seg16SP]:=Seg00SP47;
[Module1.Loop.Seg16Mode]:=Seg00Mode47;

[Module1.Loop.Seg17Time]:=Seg00Time48;
[Module1.Loop.Seg17SP]:=Seg00SP48;
[Module1.Loop.Seg17Mode]:=Seg00Mode48;
```

```
[Module1.Loop.Seg18Time]:=Seg00Time49;
[Module1.Loop.Seg18SP]:=Seg00SP49;
[Module1.Loop.Seg18Mode]:=Seg00Mode49;

[Module1.Loop.Seg19Time]:=Seg00Time50;
[Module1.Loop.Seg19SP]:=Seg00SP50;
[Module1.Loop.Seg19Mode]:=Seg00Mode50;

[Module1.Loop.Seg20Time]:=Seg00Time51;
[Module1.Loop.Seg20SP]:=Seg00SP51;
[Module1.Loop.Seg20Mode]:=Seg00Mode51;

[Module1.Loop.Seg21Time]:=Seg00Time52;
[Module1.Loop.Seg21SP]:=Seg00SP52;
[Module1.Loop.Seg21Mode]:=Seg00Mode52;

[Module1.Loop.Seg22Time]:=Seg00Time53;
[Module1.Loop.Seg22SP]:=Seg00SP53;
[Module1.Loop.Seg22Mode]:=Seg00Mode53;

[Module1.Loop.Seg23Time]:=Seg00Time54;
[Module1.Loop.Seg23SP]:=Seg00SP54;
[Module1.Loop.Seg23Mode]:=Seg00Mode54;

[Module1.Loop.Seg24Time]:=Seg00Time55;
[Module1.Loop.Seg24SP]:=Seg00SP55;
[Module1.Loop.Seg24Mode]:=Seg00Mode55;

[Module1.Loop.Seg25Time]:=Seg00Time56;
[Module1.Loop.Seg25SP]:=Seg00SP56;
[Module1.Loop.Seg25Mode]:=Seg00Mode56;

[Module1.Loop.Seg26Time]:=Seg00Time57;
[Module1.Loop.Seg26SP]:=Seg00SP57;
[Module1.Loop.Seg26Mode]:=Seg00Mode57;

[Module1.Loop.Seg27Time]:=Seg00Time58;
[Module1.Loop.Seg27SP]:=Seg00SP58;
[Module1.Loop.Seg27Mode]:=Seg00Mode58;

[Module1.Loop.Seg28Time]:=Seg00Time59;
[Module1.Loop.Seg28SP]:=Seg00SP59;
[Module1.Loop.Seg28Mode]:=Seg00Mode59;

[Module1.Loop.Seg29Time]:=Seg00Time60;
```

```
[Module1.Loop.Seg29SP]:=Seg00SP60;
[Module1.Loop.Seg29Mode]:=Seg00Mode60;


//after all data is loaded...


ProfileTracker:=0;
ReqProfile:=1;
```

APPENDIX C STATISTICAL ANALYSIS SOFTWARE (SAS)

[SAS Code]

```
libname st 'D:\Stat 427';

/*/*** Part 1 Select equivalent density samples ***/*/ ;

*format type;
proc format;
  value type 1="II 10F"
            2 ="II 5F"
            3 ="II 2F"
            4 ="I Early"
            5 ="I Middle"
            6 ="I Late"
            7 ="Standard";
run;
*conduct anova to compare the mean density for 7 types;
ods graphics on;
ods rtf file = "C:\Stat 427\anova_density_prelim.rtf";
proc glm data=st.nonoutlier;
 class type;
 model density = type;
 means type / hovtest welch;
 means type / tukey;
 format type type.;
run;
*list out extreme observations;
proc univariate data=st.nonoutlier NEXTROBS=10;
  where type=1 or type=3 or type=5 or type=6;
  by type;
  var density;
  format type type.;
run;
ods rtf close;

/*/*** Part 2 Compare strength of each profile ***/*/ ;

ods graphics on;
ods rtf file = "C:\Stat 427\anova_strength.rtf";
proc means data=st.final_data n mean median std range kurt skew maxdec=5;
 class type;
 var strength;
 format type type.;
run;
proc sgplot data=st.final_data;
```

```
 vbox strength / category=type; *one box plot for each type;
 format type type.;
run;
proc sgscatter data=st.final_data;
matrix strength type / group=type;
format type type.;
run;
*conduct anova to compare the mean density - density equivalent groups;
proc glm data=st.final_data plot=diagnostics(unpack);
 class type;
 model strength = type;
 means type / hovest welch;
 means type / tukey;
 format type type.;
output out=check r=resid;
run;
proc univariate data=check normal;
 var resid;
run;
ods rtf close;

/*/*** Part 3 Regression model: strength ~ density + group ***/*/

*recode interaction terms;
data st.final_data;
  set st.final_data;
  IEarly=0;
  if type=4 then IEarly=1;
  ILate=0;
  if type=6 then ILate=1;
  IMiddle=0;
  if type=5 then IMiddle=1;
  II10F=0;
  if type=1 then II10F=1;
  II5F=0;
  if type=2 then II5F=1;
  II2F=0;
  if type=3 then II2F=1;
  DenIEarly=density*IEarly;
  DenIMiddle=density*IMiddle;
  DenILate=density*ILate;
  DenII10F=density*II10F;
  DenII5F=density*II5F;
  DenII2F=density*II2F;
run;
```

```
ods graphics on;
ods rtf file='C:\Stat 427\regression model final.rtf';
*do regression assumption checks;
proc reg data=st.final_data plot=diagnostics(unpack);
  model strength=density IEarly IMiddle ILate II2F II5F II10F /spec;
  output out=strength2 rstudent=r h=lev cookd=cd dffits=dffit;
run;
proc print data=strength2 (keep=type batch num_cyl air density strength r);
  where abs(r)>2;
  format type type.;
run;
proc print data=strength2 (keep=type batch num_cyl air density strength lev);
  where lev > 0.0606 /*(2k+2)/n*/;
  format type type.;
run;
*final model and backward selection;
proc reg data=st.final_data;
  model strength=density IEarly IMiddle ILate II2F II5F II10F DenIEarly DenIMiddle
DenILate DenII2F DenII5F DenII10F
  /selection=backward include=7;
run;
proc reg data=st.final_data;
  model strength=density IEarly IMiddle ILate II2F II5F II10F
  /acov;
run;
ods rtf close;

/*/*** Part 4 Reveal the relationship between the
      percentage increase of mean strength
      from standard group and error & type ***/*/

*Mean strength of standard is 4071.69;
data st.final_data_2(drop=resid pred rstudent); *st.final_data_2 rename type as
group, add type and error;
 set st.final_data(rename=(type=group));
 if group in (1,2,3) then type=2;
 else if group in (4,5,6) then type=1;
 else if group=7 then type=0;
 if group in (3,4,5,6) then error=48;
 else if group=2 then error=120;
 else if group=1 then error=240;
 else if group=7 then error=0;
 ratio=(strength-4071.69)/4071.69*100; *Percentage increase of strength compared
with standard;
run;
*Scatter Plot for Error and Ratio Grouped by Type;
```

```
proc sgscatter data=st.final_data_2;
 plot ratio*error / group=type join;
run;
*Scatter Plot for Error and Avgrat Grouped;
proc means data=st.final_data_2 nway;
 class error type group;
 var ratio;
 output out=profile mean=avgrat;
run;
proc format;
  value group 1="II 10F"
             2 ="II 5F"
             3 ="II 2F"
             4 ="I Early"
             5 ="I Middle"
             6 ="I Late"
             7 ="Standard";
run;
proc sgscatter data=profile;
 plot avgrat*group / group=group join;
 format group group.;
run;
*Scatter Plot for Error and Avgrat Grouped by Group;
proc sgscatter data=profile;
 plot avgrat*error / group=type join;
run;
*Scatter Plot for Error and Avgrat Grouped by Type;
proc means data=st.final_data_2 nway;
 class type;
 var ratio;
 output out=profile2 mean=avgrat2;
run;
proc sgscatter data=profile2;
 plot avgrat2*type / group=type join;
run;
*Scatter Plot for Error and Avgrat Grouped by Error;
proc means data=st.final_data_2 nway;
 class error;
 var ratio;
 output out=profile mean=avgrat;
run;
proc sgscatter data=profile;
 plot avgrat*error / group=error join;
run;
*Fit regression model;
*Treat error as continuous variable;
```

```
data st.final_data_glm;
 set st.final_data_2;
 where type ^= 0;
 if type=1 then type=0;
 else if type=2 then type=1;
run;
proc reg data=st.final_data_glm;
 model ratio=type error;
run;


/*/*** Part 5 Cluster Analysis Based on strength ***/*/
*Before doing the cluster, check the distribution of vaiable strength
 and if necessary, do transformation on strength to obtain low skewness and
kurtosis;

proc univariate data=st.final_data;
 var strength;
 histogram;
run;
*Skewness=-0.3907    Kurtosis=-0.8695;
data final_data;
 set st.final_data;
 logstrength = log(strength);
run;
proc univariate data=final_data;
 var logstrength;
 histogram;
run;
* Skewness=-0.5773    Kurtosis=-0.7231;
data final_data;
 set st.final_data;
 sqstrength = sqrt(strength);
run;
proc univariate data=final_data;
 var sqstrength;
 histogram;
run;
*Skewness=-0.4845    Kurtosis=-0.8078;

*The transformation doesn't improve the skewness or kurtosis much, hence stick on
untansformed variable. Use fastclus procedure to do the cluster;

proc fastclus data=st.final_data out=clusters maxclusters=3 maxiter=100;
 var strength;
run;
```

```
ods graphics on;
ods rtf file='C:\Stat 427\clusters.rtf';
proc sgscatter data=clusters;
 plot density*type / group=cluster;
 format type type.;
run;
proc sgscatter data=clusters;
 plot strength*type / group=cluster;
 format type type.;
run;
ods rtf close;
```

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