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Research Report

EVALUATION OF JOBSITE CYLINDER CURING PRACTICES FOR THE ALABAMA CONCRETE INDUSTRY

Submitted to

The Alabama Department of Transportation

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16. Abstract
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Nine jobsites were visited to review and evaluate the current practices used by jobsite technicians and contractors to sample and cure concrete test cylinders. The effects of non-standard curing on the 28-day compressive strength when exposed to summer construction conditions were also evaluated. The results indicate that a significant decrease in 28-day compressive strength occurs when cylinders are cured in conditions different than 60 to 80 ºF. The maximum measured reduction in 28-day compressive strength was 22%. Recommended changes to ALDOT 501 are provided in this report to improve the jobsite initial curing practices of cylinders used for quality assurance strength testing.

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ABSTRACT

The effect of initial curing temperature and duration on the 28-day compressive strength of concrete was experimentally evaluated. Concrete cylinders were cured at six initial curing temperatures (60, 68, 78, 84, 90, and 100 ºF) for three different initial curing durations (24, 48, and 72 hours). After the initial curing duration was complete, the cylinders were moved to final curing in a moist cure room that maintained a temperature of 73.5 ± 3.5 °F until compressive strength testing at 28 days. Eight different concretes were produced at elevated temperatures to simulate summer placement conditions. The results confirm that as the initial curing temperature increases, the 28-day concrete compressive strength decreases. When cured at an initial curing temperature of 100 ºF, a maximum reduction of 23% in the 28-day compressive strength occurred. It is critical to maintain initial curing temperatures ranging from 60 to 80 ºF because then the change in 28-day strength remains within the acceptable ranges. When the initial curing temperature ranges from 60 to 80 ºF, then increasing the initial curing duration from 48 hour to 72 hour does not significantly affect the 28-day concrete compressive strength. The maximum initial curing duration can thus be increased from 48 to 72 hours, which will permit cylinders made on Fridays to be transported to their final curing location on Mondays.

Nine jobsites were visited to review and evaluate the current practices used by jobsite technicians and contractors to sample and cure concrete test cylinders. The effects of non-standard curing on the 28-day compressive strength when exposed to summer construction conditions were also evaluated. The results indicate that a significant decrease in 28-day compressive strength occurs when cylinders are cured in conditions different than 60 to 80 ºF. The maximum measured reduction in 28-day compressive strength was 22%. Recommended changes to ALDOT 501 are provided in this report to improve the jobsite initial curing practices of cylinders used for quality assurance strength testing.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Concrete cylinders made and cured on the jobsite, transported to the testing facility, cured under controlled conditions, and tested in compression at 28 days in accordance with relevant AASHTO standards are meant to provide an indication of the quality of the concrete produced by the concrete supplier as delivered to the jobsite. An important aspect at the jobsite is to keep all quality assurance cylinders in an initial curing environment for no more than 48 hours where they are in a temperate range from 60 to 80 ºF in an environment that prevents any moisture loss AASHTO T23 (2018) and ALDOT 501 (2022). ALDOT 501 (2022) requires the use of cylinder curing boxes on all jobsites to cure quality assurance strength cylinders to meet AASHTO T23 (2018) initial curing requirements. Some example cylinder curing boxes are shown in Figure 1-1.

Figure 1-1: Examples of commercially available heating and cooling cylinder curing boxes (Source: Humboldt Manufacturing Company, Illinois)

After initial curing, cylinders are transported to their final curing location where they are demolded and placed in a final curing environment. The final curing method must maintain a temperature of 73.5 ± 3.5 ºF and provide free water on all cylinder surfaces for the remainder of the curing duration. At the specified design age, cylinders are broken to determine the compressive strength which is then compared to the specified design strength (f'_c) to determine if the concrete provided has adequate strength. Because of the controlled curing conditions and other parameters (consolidation, load rate, etc.) that are standardized, strengths from standard cured cylinders do not represent the in-place strength. By following the procedures set forth in AASHTO T23 (2018), the same concrete cured and tested in two different parts of the country should have similar strengths, while the two locations will have very different in-place concrete strengths due to temperature and humidity differences. If technicians, producers, and contractors do not follow the proper specifications when testing concrete cylinders, the determined strength will not be accurate and can be below the required strength in some instances.

Due to hydration, concrete age is one of the most significant factors that impact concrete strength. The development of strength with time for specimens cured at different constant temperatures is shown in Figure 1-2. Although age is an important variable that affects strength, the rate of strength development is also clearly significantly affected by the curing temperature of the concrete. Figure 1-2 shows that early-age strengths are the greatest when cured at elevated temperatures; however, the long-term compressive strength is significantly reduced when cured at elevated temperatures when compared to curing at room temperature (68 °F) or lower temperatures (55 °F). The origin of the research that supports the use of 60 to 80 °F as the initial curing temperature in current specifications is unknown, and this temperature range might have been establish many decades ago by committee decision. Considering the example data shown in Figure 1-2, it seems reasonable that some initial curing temperature range is required if the objective is to ensure minimal impact on the 28-day strength when curing cylinders for quality assurance purposes.

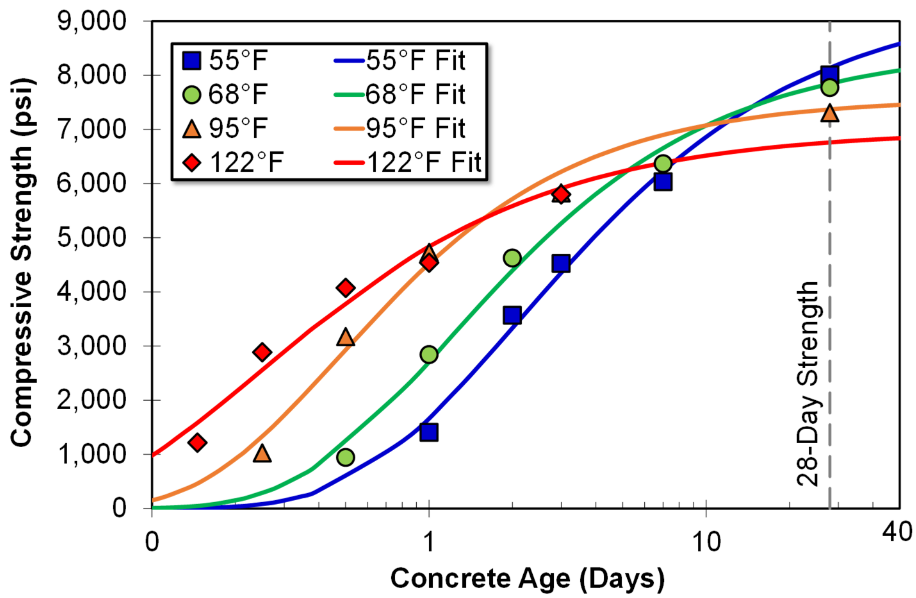

Figure 1-2: Compressive strength development for specimens cured at different constant temperatures (data from Kjellsen and Detwiler 1993)

In recent years, numerous low 28-day concrete cylinder strengths have occurred on Alabama Department of Transportation (ALDOT) projects, which has led to questions being asked about the quality of the concrete delivered to site, and the practices used to make, cure, transport, and test concrete cylinders on ALDOT projects. When low 28-day cylinder results occur, all stakeholders are forced to investigate the potential causes of the low cylinder strengths, project delays occur, and the contactor and concrete supplier have to get ready to deal with the consequences of the potentially substandard concrete. In response to recent low 28-day concrete cylinder strength results, ALDOT has adopted in ALDOT Article 501.05 (2018) new methods and procedures to evaluate the in-place strength of potentially substandard concrete by core investigation. ALDOT's Materials and Tests Bureau personnel has also participated in delivering training session on how to make, cure, transport, and test concrete cylinders on ALDOT projects. The Alabama concrete industry has been monitoring on-site practices used to make and cure cylinders and have found numerous cases where ALDOT requirements are not met. The most notably of the requirements not being met is associated with the initial curing period where the concrete cylinders are not kept within a temperature range of 60 to 80 ºF. Problems have been discovered with cylinder curing boxes not functioning property for the whole duration of the initial curing period or the cylinder curing boxes used are not adequate to maintain temperatures of 60 to 80 ºF considering the high temperatures conditions experienced during Alabama summer months. Figures 1-3 and 1-4 show some examples of improper initial curing practices used on some jobsites.

Figure 1-3: Improper jobsite cylinder curing boxes that do not meet ALDOT requirements: (*Left*) Coolers without temperature control and (*Right*) Plywood box without temperature control (Source: NRMCA)

Figure 1-4: Improper jobsite curing of cylinders that neither meet ALDOT 501 nor AASHTO T23 requirements (Source: NRMCA)

AASHTO T23 (2018) and ALDOT 501 (2022) limit the initial curing duration to no more than 48 hours. When cylinders are made on Fridays, this creates the situation where project personnel need to come in over the weekend to transport the cylinders to their final curing location on either Saturdays or Sundays. In the work covered herein, the effect of increasing the initial curing duration from 48 to 72 hours is evaluated, as this additional 24 hours will allow concrete specimens made on a Friday to be transported to the laboratory on Monday and remain in accordance with specification requirements. Also, time and money could be saved because of additional flexibility regarding when to transport the cylinders to their final curing location. Cylinders made two days apart could potentially be transported together instead of having to make separate trips to the final curing location.

1.2 Research Objectives

The objectives of this study are as follows:

1. Determine how different initial curing temperatures affects the 28-day compressive strength of moist-cured concrete.
2. Determine the effect of initial curing duration on the compressive strength of moist-cured concrete.
3. Review all current practices used to make, cure, transport, and test concrete cylinders for ALDOT projects.
4. Assess the effects of non-standard curing practices on the 28-day cylinder strength
5. Evaluate new and improved practices used to make, cure, transport, and test concrete cylinders.
6. Improve and clarify ALDOT 501.02 section (d) “Sampling and Inspection”, if necessary.

1.3 RESEARCH APPROACH

The work was conducted in two phases, where Phase 1 consisted of laboratory work and Phase 2 consisted of field work. In the laboratory, batches of eight different concretes were produced to test the influence of initial curing temperature and duration on the 28-day compressive strength of concrete cylinders. For each batch, six different initial curing temperatures were used. These temperatures were 60, 68, 78, 84, 90, and 100 ºF. Using a reference of 68 ºF, the relative strength differences were determined for each initial curing temperature. At each temperature, three concrete cylinders were tested to determine an average 28-day compressive strength, and a fourth cylinder was used to measure temperature development in the concrete specimen. Concretes representative of ALDOT bridge applications were proportioned with varying types of cementitious materials. A total of 24 batches were produced consisting of eight different mixture proportions. Fresh properties of concrete were tested in accordance with AASHTO T119 (2018), T152 (2019), and T309 (2020). Each concrete mixture was batched and tested at least twice. Concrete cylinders were allowed to initially cure for approximately 24 hours one time and 48 hours the other. Upon completion of all 24- and 48-hour batches, four concrete mixtures were chosen based off the results of the previous batches. The mixtures that had the most significant 28-day strength reductions were chosen for the 72-hour initial curing duration. An initial curing duration of 72 hours will permit the testing agency to move cylinders that are made on a Friday to their final curing location on Monday. This will prevent the need to move cylinders to their final curing location on either Saturday or Sunday. After all the 72-hour batches were completed, four verification batches were randomly chosen and tested. The 28-day strength of the concrete obtained due to different initial curing conditions was only compared to itself so the variations between compressive strengths of different batches is negligible.

The goal of the field work phase was to get a more accurate representation of the current practices used to make and cure concrete test cylinders in the field and to determine how such practices affect the 28-day compressive strength. For the field work phase, multiple jobsite visits in and around east and central Alabama were performed during summer months where extreme temperatures were experienced. At these jobsite visits, concrete was sampled, and test cylinders were made and cured during summer months where temperatures were high. It was also important for the research team to evaluate the sampling, molding, and curing practices of jobsite technicians on different project types and to evaluate the effect of these on the 28-day compressive strength. Therefore, the research team aimed to sample concretes from various project types and specified 28-day compressive strengths.

1.4 REPORT OUTLINE

Chapter 2 includes a literature review on concrete curing, materials and production of concrete, compressive strength testing and various initial curing research projects. Chapter 2 has an emphasis on previous work that reviewed the effect of elevated curing temperature on the compressive strength of concrete. This chapter also includes a discussion on the consequences of improper curing as well as an examination of state departments of transportation specifications from across the country and how they compare to ALDOT 501. The experimental plan used for the laboratory work of Phase 1 is covered in Chapter 3. The raw materials used, and mixture proportions are also covered in Chapter 3. Chapter 4 includes the presentation and discussion of all Phase 1 test results. Chapter 5 discusses the experimental plan developed for the field work conducted as part of Phase 2 of this project. Chapter 6 presents the Phase 2 results, which include the temperature data, compressive strength results, and recorded observations of jobsite technician testing practices for each jobsite. Chapter 7 discusses the recommendations and proposed alterations to ALDOT 501, section (d) “Sampling and Inspection” based on the results collected for this project. A summary, conclusions, and recommendations of the study are covered in Chapter 8. Various appendices are included to present the data collected over the course of this project.

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

This chapter covers some background needed to understand concrete production, concrete curing, and concrete strength testing. More details are provided regarding the effect of elevated curing temperatures on the compressive strength of concrete.

2.1.1 WHAT IS CONCRETE CURING

Curing is defined as “the action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and (if applicable) pozzolanic reactions to occur so that the potential properties of the mixture may develop” (ACI CT 2021). The strength of concrete is a complex relationship of factors that is directly impacted by its age. As concrete ages, its microstructure develops and the overall strength of the concrete increases. There are many factors that can affect concrete strength and therefore controlling these factors, especially during the acceleration and deceleration phases of the hydration process, is essential for developing the specified concrete properties. Proper curing measures also promote cement hydration by providing continuous moisture which allows the formation of more hydration products and is beneficial for the development of long-term strength. As relative humidity decreases during curing, the compressive strength of cementitious materials within concrete will decrease (Sun et al. 2020). Concretes cured at higher temperatures have an increased maturity and higher initial strengths but will have lower long-term strengths than those cured in lower temperatures (Carino and Lew 2001). Concrete cylinders used for quality assurance testing have specific conditions because the results from their strengths are used for acceptance (NRMCA 2014). When curing concrete cylinders, it is important to remember that the cylinders do not represent the in-place strength of concrete, but the quality of the concrete delivered to the jobsite (Obla et al. 2018).

2.1.2 HYDRATION PROCESS

Immediately after cement comes in contact with water a chemical reaction known as hydration begins (Bullard et al. 2010). This hydration process produces a cement paste that stiffens and eventually becomes a solid material (Darwin et al. 2016). During the hydration process substances such as C_3S and C_3A react with water to form hydration products (Bullard et al. 2010). Cement hydration is an exothermic process, releasing heat (Samarai et al. 1983). As the heat of hydration is increased, the rate of hydration in increased and vice versa. Figure 2-1 shows the relationship between curing temperature and the heat of hydration for cement.

The data in Figure 2-1 shows how as the heat of hydration increases, the total time for the hydration process to finish decreases. As the temperature is increased during hydration the initial compressive strengths will be higher, but the long-term strengths will decrease (Dejeto and Kurumisawa 2015). While increased short-term strengths can speed up the construction process, loss in long-term strength might lead to potential problems in the future.

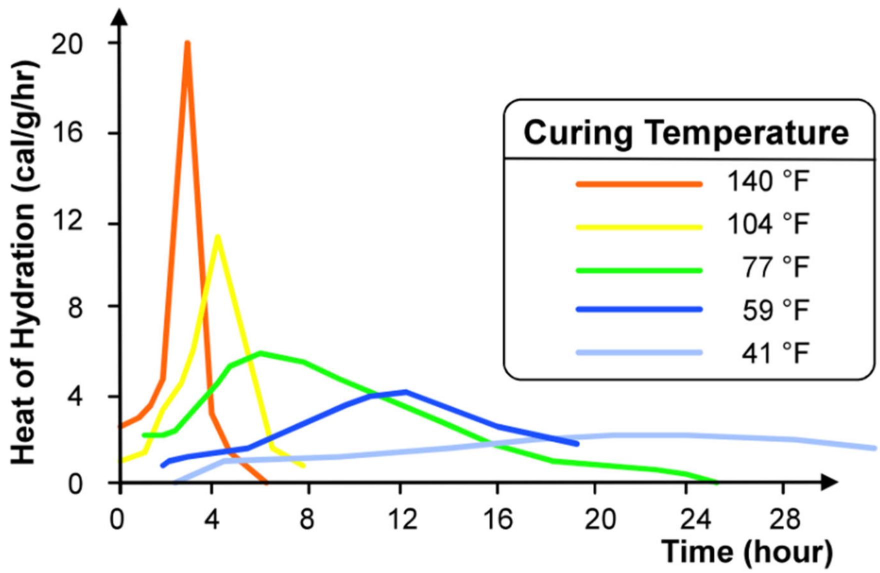

Figure 2-1: Cement heat of hydration (adapted from Samarai et al. 1975)

2.2 Making and Curing Concrete Specimens

2.2.1 Sampling of Concrete

Section 1.2 of AASHTO T 23 (2018) states that the concrete used to make and mold specimens shall be sampled after all on-site adjustments to the concrete have been made. For the molded test specimen to be an accurate representation of the strength of the concrete placed, it is extremely important to sample the concrete after the addition of all water and admixtures. AASHTO T 23 (2018) also states “the samples used to fabricate test specimens under this standard shall be obtained in accordance with AASHTO R60, Sampling Freshly Mixed Concrete.” Section 5.2.2 of AASHTO R60 (2020) states that no sample should be taken before 10 percent, or after 90 percent, of the batch has been discharged. The purpose of this requirement is to avoid sampling from the beginning and the end of a load because these portions are not necessarily representative of the concrete in the truck as these portions are potentially rocky and segregated.

2.2.2 MOLDING OF CONCRETE CYLINDERS

Molding standards are described in AASHTO T 23 (2018) Section 9. While each subsection in Section 9 is important, it is necessary to highlight Section 9.1 that is titled “Place of Molding”. This section states that specimens must be molded on a level, rigid, horizontal surface free from vibration and other disturbances while ideally at a place as close as possible to the place where they are to be stored. The purpose of this standard is to ensure that the specimens have a flat rigid top and bottom for testing as well as uniform consolidation in order to maintain the specimens as representative of the concrete load as possible.

2.2.3 CURING OF CONCRETE CYLINDERS

To avoid the many negative consequences of improper curing, standard curing practices have been developed. These practices are intended for use when the resulting compressive strength data of the specimens made are to be used for the following purposes (AASHTO T 23 2018):

- Acceptance testing for specified strength,
- Checking the adequacy of mixture proportions for strength, and
- Quality assurance.

There are two types of cylinder curing methods that can be used on jobsites covered in AASHTO T23 (2018). The two types of cylinder curing methods are standard curing and field curing and these are discussed in detail in the following two subsections.

2.2.3.1 STANDARD CURING

The curing of concrete cylinders for quality assurance purposes on ALDOT projects is regulated by AASHTO T23 (2018) and ALDOT 501 (2022). Standard curing according to AASHTO T23 (2018) consists of initial curing and final curing.

Initial curing occurs on the jobsite for a duration of up to 48 hours (AASHTO T23 2018). Regarding initial curing, AASHTO T23 (2018) states “Immediately after molding and finishing, the specimens shall be stored for a period up to 48 h in a temperature range from 16 to 27 °C (60 to 80 °F) in an environment preventing moisture loss from the specimens” (AASHTO T23 2018). For ALDOT projects, the moist environment must be maintained using a “cylinder curing box with a minimum capacity of 22 test cylinders 6” × 12” {150 mm × 300 mm} in size, equipped with heating/cooling capabilities, automatic temperature control, and a maximum/minimum (high/low) temperature readout” (ALDOT 501 2022). High-strength concrete, specified as concrete that has a design strength greater than 6000 psi has the same duration requirements and has stricter initial curing temperature requirements from 68 °F to 78 °F.

For final curing, AASHTO T23 (2018) states that “On completion of initial curing and within 30 min after removing the molds, cure specimens with free water maintained on their surfaces at all times at a temperature of 23 ± 2°C (73.5 ± 3.5°F) using water storage tanks or moist rooms”. The final curing conditions of AASHTO T23 (2018) are the same for normal- and high-strength concrete. Moist rooms are chambers that are temperature regulated and have a fog machine that keeps the chamber at 100% relative humidity in accordance with AASHTO M201 (2015). Water storage tanks are temperature-controlled tanks in which cylinders are completely submerged in accordance with AASHTO M201 (2015). After demolding, cylinders are placed in the moist cure room or are completely submerged within their respective water bath. Final curing takes place until the desired age of the concrete is met. Common standard curing durations are 3, 7, 28, and 56 days, with an age of 28 days the often used for acceptance testing.

In ALDOT 501 (2022), the standard curing of concrete cylinders is similar to AASHTO T23 (2018); however, it includes a minimum initial curing duration while AASHTO T23 (2018) does not. It specifies that cylinders must remain in an "initial curing period of not less than 24 hours or more than 48 hours. During the initial curing period, the specimens shall be stored in a moist environment at a temperature range between 60 ºF to 80 ºF {16 ºC to 27 ºC}, preventing any loss of moisture for up to 48 hours" (ALDOT 501 2022). ALDOT 501 (2022) has included stricter specifications regarding the initial curing duration for concrete cylinders used for acceptance criteria.

2.2.3.2 FIELD CURING

While standard curing is used to verify the quality of the concrete delivered to the project, field curing is used to help estimate the strength of in-place concrete. When field curing is done, specimens are molded and allowed to cure as close to the actual structure as possible. (AASHTO T23 2018). By replicating the curing environment of in-place concrete, cylinders will be subject to similar temperature and humidity values (Obla et al. 2005). Field curing should never be used for the acceptance of concrete as "Field-cured specimens are used to determine if a structure may be put into service, evaluate the adequacy of curing and protection of the concrete in the structure, and to help determine form and shoring removal times" (Obla et al. 2018).

2.3 CONCRETE COMPRESSIVE STRENGTH

The compressive strength of concrete is the leading test to assess the acceptability of concrete. Many factors affect the compressive strength of concrete such as water-to-cementitious materials ratio, air content, concrete age, material composition, curing conditions, and testing conditions (Ozyildirim and Carino 2006). When determining the compressive strength of concrete, the use of concrete cylinders is most often used in the United States. A compression machine is used to apply a vertical load on the cylinder. The load is increased at a controlled rate until the cylinder fails. Using the failure load and surface area of the cylinder, the strength of concrete can then be determined in psi.

2.3.1 STANDARD TEST SPECIFICATIONS FOR COMPRESSIVE STRENGTH

The standard specification for determining the compressive strength of concrete cylinders either molded or taken as drilled cores is AASHTO T22 (2020). Using this standard specification, concrete strengths can be accurately tested and evaluated to determine for acceptability of the concrete. Like all other specifications, it is crucial to follow AASHTO T22 (2020) to accurately assess the compressive strength of the concrete provided by the producer.

2.3.2 CONCRETE AGE AND MATURITY

The age of concrete is one of the most significant factors for the strength of concrete. Figure 2-2 illustrates the strength development of concrete with time using a concrete that consists of 100% Type I cement. Figure 2-2 shows that during the first 3 days, the strength gain is rapid and as the age reaches 28 days the strength has stabilized. Also, the initial strengths are largest when cured at 100 °F, but the long-term compressive strength is greatest when cured at 46 °F.

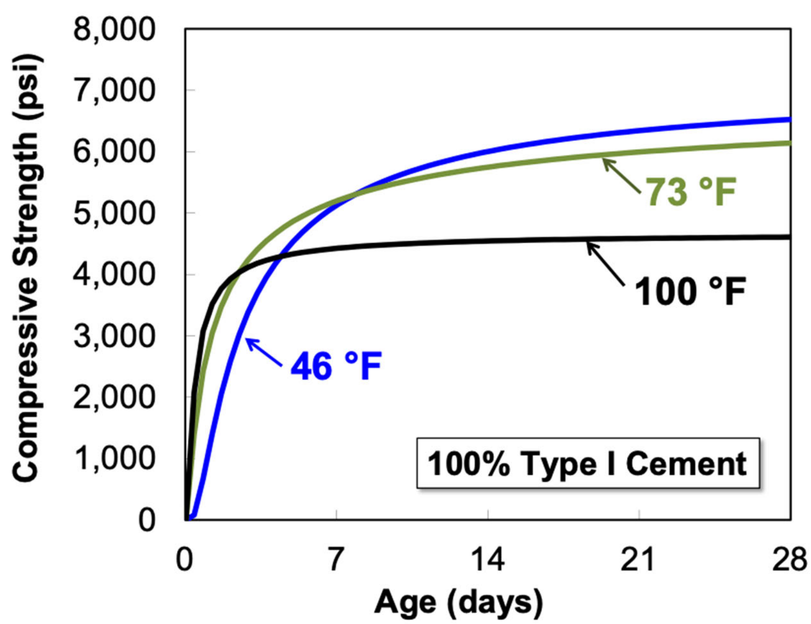

Figure 2-2: Compressive strength development for specimens made with 100% Type I cement cured at different constant temperatures (adapted from Brooks et al. 2007)

Although age is an important variable that affects the strength development of concrete, the rate of strength is also affected by the temperature of the concrete and surrounding environment (Carino and Lew 2001). A method known as the maturity method can be used to account for the effects of temperature and time on the compressive strength of concrete (Carino and Lew 2001). According to Saul (1951) “Concrete of the same mix at the same maturity (reckoned in temperature-time) has approximately the same strength whatever combination of temperature and time go to make up that maturity.” Initially, when exposed to higher temperatures, the maturity of concrete is much more than if exposed to lower temperatures and results in increased early-age compressive strengths (Carino and Lew 2001). At a certain age, there is a cross-over and the concrete exposed to warmer temperatures begin to have lower compressive strengths when compared to concrete with cooler temperature development (Carino and Lew 2001). Carino and Lew (2001), coined this change in strength between warm and cold concrete temperatures as the "cross-over effect" and it shows how the classical maturity method is insufficient in accounting for temperature effects on the long-term compressive strength of concrete. Tests results for the maturity method show that "For equal values of the maturity index, specimens with higher early-age temperatures resulted in higher initial strengths and lower long-term strength" (Carino and Lew 2001).

2.4 Effect of Initial Curing on Concrete Strength

Special care must be taken when concreting in hot weather. Hot weather concreting occurs mostly due to hot air temperatures but can result from various other issues as well. The ACI CT (2021) defines hot weather concreting as "one or a combination of the following conditions that tends to impair the quality of freshly mixed or hardened concrete by accelerating the rate of moisture loss and rate of cement hydration, or otherwise causing detrimental results: high ambient temperature; high concrete temperature; low relative humidity; and high wind speed." As shown in Figure 2-2, when the hydration of cement is accelerated, the long-term compressive strength may decrease.

Some research projects have looked at the effect of initial curing temperature on the compressive strength of cylinders. A comprehensive study on the effect of mixing temperature on the strength of concrete was performed in 1958 by Klieger. The study consisted of the evaluation of curing temperatures ranging from 40 °F to 120 °F. In the study, concrete cubes were exposed to various curing conditions and durations. Klieger (1958) found that cylinders cured at 105 °F for 7 days and then moved to normal curing of 73 °F had approximately 1000 psi less strength than when compared to cylinders that remained at 73 °F for the entire 28 days. It was concluded that "Increasing the initial and curing temperatures results in considerably lower strengths at 3 months and one year" (Klieger 1958). This research shows how important initial curing temperature is to the compressive strength of concrete specimens.

Bloem (1969) studied the effect of high initial curing temperature for various durations. Cylinders were initially cured at 100 °F for 1, 3, and 7 days and then moved to final curing until testing at 28 days. This study revealed that as the initial curing duration is increased, the compressive strength of cylinders cured at 100 °F will reduce when compared to concrete cured under standard conditions. The longer the concrete was subjected to the elevated initial curing temperature, the more 28-day compressive strength is lost when compared to the cylinders that remained in standard curing.

Meininger (1983) reviewed the effects of initial curing temperature and duration on the compressive strength of concrete cylinders. This work was performed in response to changes in ASTM C31 and the study consisted of four different initial curing conditions and two initial curing durations. The four different initial curing conditions evaluated were 60 °F in water, 60 °F in air, 80 °F in water, and 80 °F in air. The temperature range consisted of the current AASHTO T23 (2018) range from 60 to 80 °F. Cylinders that were cured in the air were left within a controlled laboratory space while covered with plastic to prevent moisture loss. The cylinders cured in water were submersed in a water tank. After the desired initial curing duration, cylinders were demolded and moved to standard curing in a moist room for the remainder of the 28 days. The compressive strength results from this study are summarized in a Table 2-1.

Table 2-1: Summary of average strength for each condition and time of curing (adapted from Meininger 1983)

Condition[b]	Average Strength at 28-Days, psi (%)[a]	
	Cement A	Cement B
INITIAL ONE-DAY FIELD CURE		
60°F water	6078 (100)	6094 (100)
60°F air	5611 (92)	5926 (97)
80°F water	5424 (89)	5692 (93)
80°F air	4896 (81)	5373 (88)
INITIAL TWO-DAY FIELD CURE		
60°F water	6069 (100)	6078 (100)
60°F air	5399 (89)	5810 (95)
80°F water	5353 (88)	5629 (92)
80°F air	4842 (80)	5290 (87)

[a]Percent of one-day 16°C (60°F) water field cure; and 1 psi = 0.006895 MPa.
[b]t°C = (t°F − 32)/1.8.

These results show that for both mixtures, the water-cured cylinders have a higher compressive strength than the air-cured cylinders for both initial curing temperatures and durations. Additionally, the average strengths are greater for the cylinders initially cured at 60 °F when compared to the cylinders cured at 80 °F. Meininger (1983) concluded that "Increasing the initial curing period from one to two days only reduced compressive strength by about 1%." The results further suggest that a lower initial curing temperature will result in stronger concrete at 28 days and that initial curing duration is not as significant as the temperature in affecting 28-day concrete compressive strength. Meininger's finding regarding the impact of initial curing duration does not contradict the findings of Bloem (1969) because in Bloem's study the initial curing temperatures where above the range from 60 to 80 °F when longer initial curing durations where evaluated.

Research was performed by Obla et al. (2005) at the NRMCA Laboratory to determine the effect of non-standard curing on compressive strength of concrete. In this study, four different curing environments were tested. The curing environments consisted of 1) standard curing of 73 °F and 100% relative humidity for the control, 2) laboratory air-drying at 73 °F for the entire curing duration, 3) curing outside for 48 hours and then moist curing for the remainder, and 4) outside curing for the entire curing duration. Initially, the tests were performed to simulate cold weather concreting with an average air temperature of 32 °F. Compressive strengths were tested at 1, 3, 7, 28 and 90 days and the results showed the effect of different curing environments on compressive strength. Table 2-2 shows the strength reductions based off the standard curing control cylinders. Figure 2-3 includes a plot of the compressive strength versus concrete age, as well as the average daily air temperature.

Table 2-2: Strength results for cold weather (adapted from Obla et al. 2005)

Age, days	Control Strength, psi (1)	Percent of control strength at same age		
		Lab Air-dry (2)	Out 48 h, moist (3)	Outside (4)
1	1508	-	-	-
3	2828	-	46%	14%
7	3852	95%	68%	40%
28	4745	88%	78%	66%
90	5374	74%	90%	82%

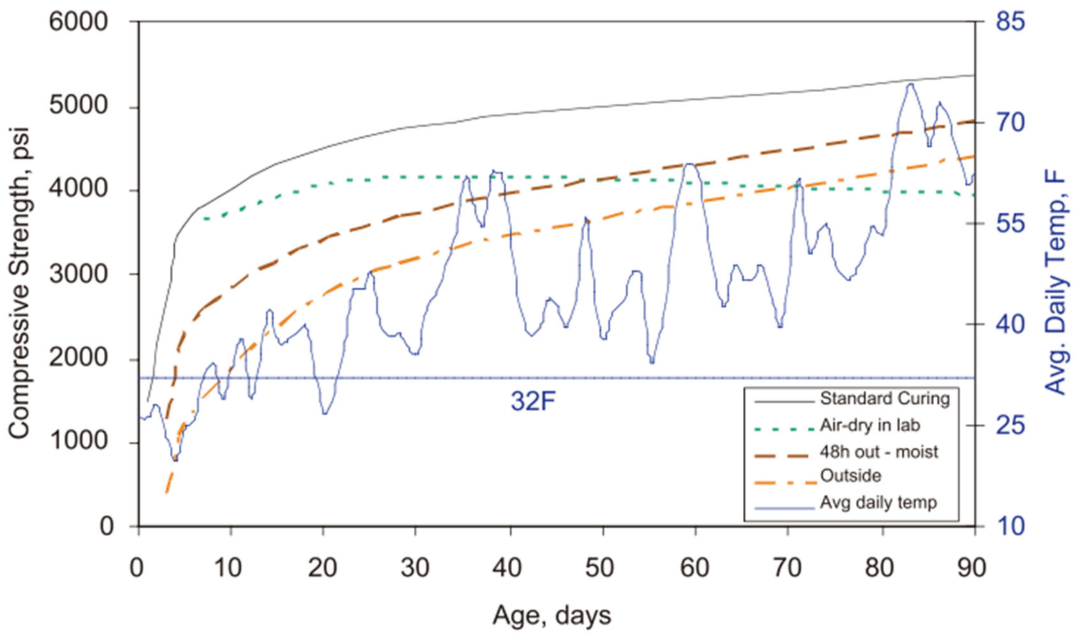

Figure 2-3: Plot of concrete strength for cold weather exposure (adapted from Obla et al. 2005)

At each age tested, all three non-standard curing environments had compressive strengths less than the standard cured cylinders. The concrete cured in the outside (4) environment, had the lowest percent of the control compressive strength at ages of 3, 7, and 28 days. At a concrete age of 7 and 28 days, the concrete cured in the lab, air-dry (2) environment had the largest percent of the control compressive strength. However, at 90 days the compressive strength for the concrete cured in the lab, air-dry (2) environment had the lowest percent of the control compressive strength. The concrete cured outside for 48 hours and then moist curing for the remainder had the largest percentage of the control compressive strength at an age of 90 days. Table 2-2 shows that at 7 and 28 days, both of the outdoor curing environments, had larger compressive strength reductions than the lab, air-dried concrete. As the curing duration increases the low curing temperatures begin to be advantageous when comparing the compressive strengths of the concrete cured outside to the strengths of the lab, air-dried specimens. Figure 2-3 shows a cross-over effect between the 48 out-moist and the air-dry lab cylinders at approximately 52 days. In addition to simulating cold weather concreting, this study was repeated during warm weather conditions.

For the warm weather study, the lab, air-dry cylinders were not tested. The results for the warm weather study are summarized in Table 2-3. Figure 2-4 includes a plot of the compressive strength versus concrete age, as well as the average daily air temperature for the warm weather conditions. As expected, the one-day compressive strengths are larger than the control. This is due to the heat increasing the rate of hydration and accelerating the strength development. For the outside (3) environment, an increase in the percent of control compressive strength occurred when the curing duration was increased from three to seven days and decreased as the curing duration was extended to 28 and 90 days. The concrete cured outside for 48 hours and then moist cured for the remainder had a decreasing percent of the control strength as the curing duration increased. For both curing environments, a cross-over effect occurred within the first ten days. Figure 2-4 shows the cross-over effect and illustrates how much more effective standard curing was for the compressive strength of concrete during the warm weather exposure conditions.

Although the warm and cold weather studies have different results, they lead to the same conclusions. When concrete cylinders are not cured properly, the compressive strengths can be reduced and that initial curing temperatures play a major role in the strength development of concrete.

Table 2-3: Strength results for warm weather (adapted from Obla et al. 2005)

Age, days	Control Strength, psi (1)	Percent of control strength at same age	
		Out 48 h, moist (2)	Outside (3)
1	784	180%	180%
3	2370	89%	86%
7	3176	81%	90%
28	4384	78%	84%
90	5659	84%	80%

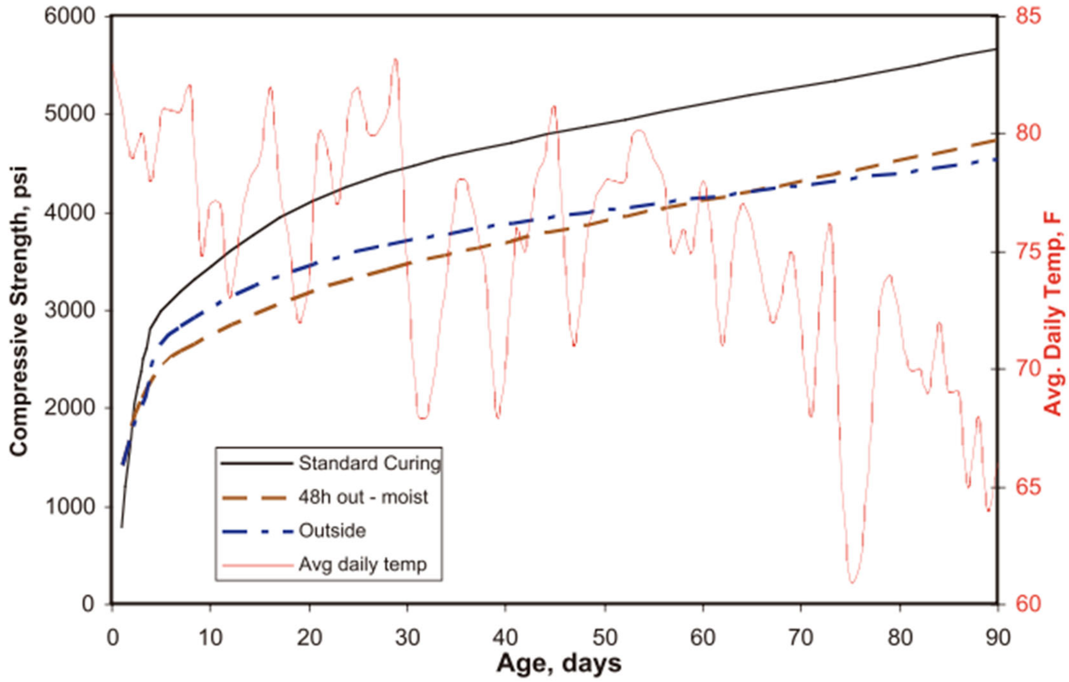

Figure 2-4: Plot of concrete strength for warm weather exposure (adapted from Obla et al. 2005)

From the various research studies reviewed it can be concluded that the curing temperature of concrete plays a vital role in developing the compressive strength of concrete specimens. From the extensive amounts of tests performed, it can be concluded that if the curing temperature of concrete specimens is not adequately controlled, the 28-day compressive strength could be significantly reduced. Initial curing temperatures thus play a major role in the measured 28-day compressive strength of quality assurance cylinders.

2.5 Review of U.S. State Specifications

A review of initial curing specifications was performed for each U.S. State DOT. The purpose of this review was to compare ALDOT 501 (2022) to the specifications of other U.S States regarding the making and curing of concrete test specimens in the field. Before reviewing and comparing the specifications from each state DOT, ALDOT 501 (2022) was compared with AASHTO T23 (2018) and ASTM C31 (2021). This comparison is shown in Table 2-5.

As shown the Table 2-5 above, there are a couple of major differences between AASHTO T23 (2023), ASTM C31 (2022), and ALDOT 501 (2022). ALDOT 501 (2022) does not contain a separate initial curing temperature requirement for high-strength concrete (f'_c > 6000 psi). In addition, ALDOT 501 (2022) requires a temperature record of the concrete specimen using a minimum-maximum thermometer unlike AASHTO T23 (2018) and ASTM C31 (2021) which require a temperature record of the curing environment using a minimum-maximum thermometer. ALDOT 501 (2022) also does not have any requirements for transporting cylinders in cases where large doses of retarding chemical admixtures are employed. This is in contrast with AASHTO T23 (2018) and ASTM C31 (2021), which both require that transportation of concrete cylinders cannot occur until at least 8 hours after final set.

Table 2-4: ALDOT 501 (2022) versus AASHTO T23 (2018) and ASTM C31 (2021)

Initial Curing Requirements		**Specification**		
		ALDOT 501 (2022)	**AASHTO T23 (2018)**	**ASTM C31 (2021)**
Duration:	"Up to 48 hrs"		YES	YES
	"24-48 hrs"	YES		
Temperature range:	60-80°F	YES	YES	YES
	if >6000 psi: 68-78°F		YES	YES
A temperature record of the **specimens** using a maximum/minimum thermometer.		YES		
A temperature record of the **curing environment** using a maximum-minimum thermometer.			YES	YES
Minimum curing tank size		YES (22 cylinders)		
Transportation :Not Allowed "Until at least 8 hours after final set"			YES	YES

Note: YES = covered in the specification

After comparing ALDOT 501 (2022) to AASHTO T23 (2018) and ASTM C31 (2021), other state DOT specifications were reviewed to see whether they followed AASHTO T23 (2018), ASTM C31 (2021), or had their own custom set of specifications. Table 2-6 lists these results, while Figure 2-5 presents them as a color-coded map.

Table 2-5: Standard Specification used for Initial Curing of Concrete Test Specimen

State DOT Specification for making and curing concrete test specimen in the field				
AASHTO T23 (2018)		**ASTM C31 (2019)**	**Custom**	**Not available**
Arizona	Mississippi	California	Alabama	Iowa
Arkansas	Missouri	Florida	Alaska	Michigan
Colorado	New Hampshire	Nebraska	Kentucky	Montana
Connecticut	New Jersey	New York	Louisiana	South Carolina
Delaware	New Mexico	Virginia	Minnesota	
Georgia	North Carolina		Nevada	
Hawaii	Ohio		North Dakota	
Idaho	Oregon		Oklahoma	
Illinois	Rhode Island		Pennsylvania	
Indiana	Tennessee		South Dakota	
Kansas	Texas		Utah	
Maine	Washington		West Virginia	
Maryland	Wisconsin		Wyoming	
Massachusetts				

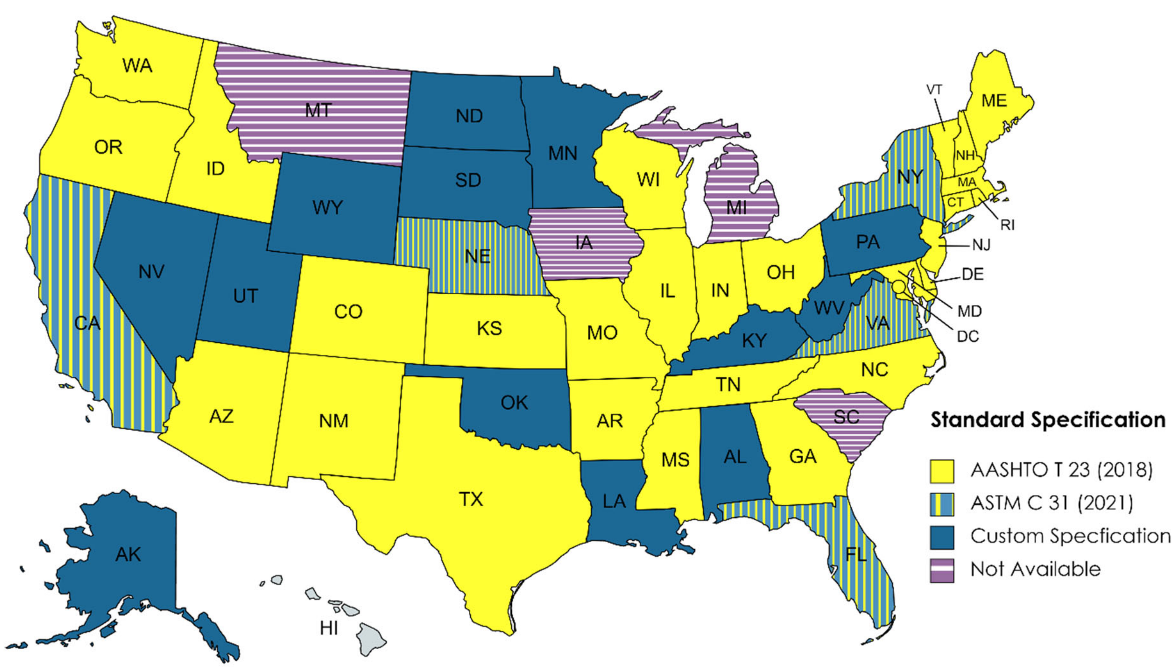

Figure 2-5: Standard Specification Used for Initial Curing of Concrete Test Specimens

Custom specification refers to states that write their own requirements for making and curing concrete test specimens in the field. These custom specifications often follow AASHTO T23 (2018) for most of their requirements, however they differ from AASHTO T23 (2018) on a few certain specific requirements which therefore require them to be placed in a separate category.

While AASHTO T23 (2018) and ASTM C31 (2021) are technically different standards, the specific specifications within them with respect to initial curing temperature, initial curing duration, high-strength concrete initial curing temperatures, and temperature monitoring during the initial curing period are identical. Therefore, the rest of this section will not distinguish between the two but rather the specific initial curing requirements themselves.

After reviewing whether each state followed a national standard or custom wrote their own, each main requirement within Section 10.1.2 of AASHTO T23 (2018) was compared from state to state. Table 2-7 shows which states specify a temperature range of 60-80°F for the initial curing period of normal-strength concrete and which states do not.

Table 2-6: Review of State Specifications of Initial Curing Temperatures for Normal-Strength Concrete

State DOT Specifications of Initial Curing Temperature				
60-80°F			**Other**	**Not available**
Alabama	Louisiana	Ohio	Kentucky (60-90°F)	Iowa
Alaska	Maine	Oklahoma		Michigan
Arizona	Maryland	Oregon		Montana
Arkansas	Massachusetts	Pennsylvania		South Carolina
California	Minnesota	Rhode Island		
Colorado	Missouri	South Dakota		
Connecticut	Mississippi	Tennessee		
Delaware	Nebraska	Texas		
Florida	Nevada	Utah		
Georgia	New Hampshire	Virginia		
Hawaii	New Jersey	Washington		
Idaho	New Mexico	West Virginia		
Illinois	New York	Wisconsin		
Indiana	North Carolina	Wyoming		
Kansas	North Dakota			

Table 2-7 shows that Kentucky is the only state that does not specify the initial curing temperature for normal-strength concrete be between 60°F and 80°F. Instead, the Kentucky DOT requires the initial curing temperature to be between 60°F and 90°F.

The next specification requirement reviewed was which states required a separate initial curing temperature range for high strength concrete (f'_c > 6000 psi). Both AASHTO T23 (2018) and ASTM C31 (2021) specify the initial curing temperature range for high strength concrete as 68-78°F. After reviewing each state DOT, Figure 2-6 was created to show which states had an initial curing temperature range for high-strength concrete of 68-78°F and which had no unique requirement for high-strength concrete at all. The review concluded that 20% of states do not have a unique specification for high strength concrete.

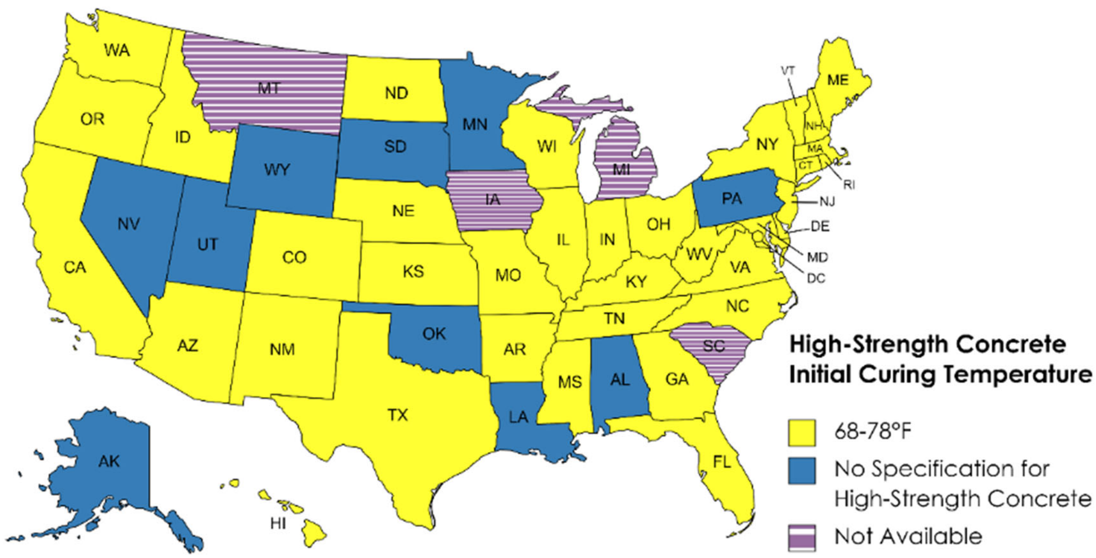

Figure 2-6: Initial Curing Temperature Range for High Strength Concrete

Next, the specification requirement regarding the duration of the initial curing period was investigated for each state. While most states follow AASHTO T23 (2018) and ASTM C31 (2021) with an initial curing period of "up to 48 hours", other states have differing specified initial curing durations. These states, along with their specified initial curing duration, are shown in Table 2-8. While the states that followed AASHTO T23 (2018) or ASTM C31 (2021) had an initial curing duration of "up to 48 hours", the majority of the states with custom specifications had similar initial curing duration requirements somewhere between 20 and 52 hours. Only Minnesota had a vastly different custom initial curing duration requirement of 12 to 14 days.

Table 2-7: Initial Curing Durations

State DOT Specification for Duration of Initial Curing Period				
Up to 48 hrs		**Other**		**Not available**
Arizona	Missouri	Alabama	24-48 hrs	Iowa
Arkansas	Nebraska	Alaska	none	Michigan
California	New Hampshire	Kentucky	24±4 hrs	Montana
Colorado	New Jersey	Louisiana	48±4 hrs	South Carolina
Connecticut	New Mexico	Minnesota	12-14 days	
Delaware	New York	Nevada	48 hrs	
Florida	North Carolina	Oklahoma	> 16 hrs	
Georgia	North Dakota	Pennsylvania	24±2 hrs	
Hawaii	Ohio	South Dakota	24 hrs	
Idaho	Oregon	Utah	16 hrs	
Illinois	Rhode Island	West Virginia	24±8 hrs	
Indiana	Tennessee			
Kansas	Texas			
Maine	Virginia			
Maryland	Washington			
Massachusetts	Wisconsin			
Mississippi	Wyoming			

One difference between ALDOT 501 (2022) and AASHTO T23 (2018) is that ALDOT 501 (2022) requires a minimum/maximum temperature recording of the concrete specimen temperature while AASHTO T23 (2018) requires a minimum/maximum temperature record of the curing environment. After reviewing other state specifications, Nevada is the only state other than Alabama that requires a minimum/maximum temperature record of the specimen.

The last specification requirement reviewed was the minimum specimen curing box size. ALDOT 501 (2022) states that the contractor must provide “a cylinder curing box with a minimum capacity of 22 test cylinders (6" × 12" in.). Only four states had a specified minimum initial curing box size, as shown in Table 2-9.

Table 2-8: Minimum Curing Box Size

Minimum Curing Box Size					
No Specification		22 Cylinders	6 Cylinders	54" x 18" x 17"	Not available
Arizona	Nevada	Alabama	Alaska	Rhode Island	Iowa
Arkansas	New Hampshire	Georgia			Michigan
California	New Jersey				Montana
Colorado	New Mexico				South Carolina
Connecticut	New York				
Delaware	North Carolina				
Florida	North Dakota				
Hawaii	Ohio				
Idaho	Oklahoma				
Illinois	Oregon				
Indiana	Pennsylvania				
Kansas	South Dakota				
Kentucky	Tennessee				
Louisiana	Texas				
Maine	Utah				
Maryland	Virginia				
Massachusetts	Washington				
Minnesota	West Virginia				
Missouri	Wisconsin				
Mississippi	Wyoming				
Nebraska					

CHAPTER 3
PHASE 1–EXPERIMENTAL PLAN FOR LABORATORY WORK

This chapter provides the experimental plan used to determine the effect of initial curing temperature and duration on the 28-day compressive strength of concrete. Details on the raw materials used, mixture proportions, batching and molding of concrete cylinders, initial and final curing methods, and compressive strength testing are included. Also, the method of analysis used to compare compressive strength results is covered in this chapter.

3.1 Introduction

The main objectives of the laboratory testing phase of this study were to determine the effect of initial curing temperature and duration on the 28-day compressive strength of concrete cylinders. Using the Auburn University Advanced Structural Engineering Laboratory, tests were performed to determine how varying initial curing temperatures and initial curing durations will affect the 28-day compressive strengths of concrete. When performing laboratory tests, there was an emphasis on using elevated initial curing temperatures which are typically experienced during summer months in Alabama. Various concrete mixtures containing different supplementary cementitious SCMs were tested to best understand the effects of initial curing temperature and initial curing duration on the 28-day compressive strength.

3.3 Methods

3.3.1 Overview of Laboratory Approach

Laboratory batches of eight different concretes were produced to determine the influence of initial curing temperature and duration on the 28-day compressive strength of moist-cured, 6×12 in. concrete cylinders. Initial curing durations of just greater than 24 hours and just below 48 hours were first tested for all eight mixtures. The decision to use 24- and 48-hour initial curing durations was to stay within the requirements of AASHTO T23 (2018) and ALDOT 501 (2022). After reviewing the data from the 24- and 48-hour batches, it was decided to also evaluate how much an initial curing duration of 72 hours would affect the 28-day concrete strength. If an initial curing duration of 72 hours is allowed, project personnel would be able to transport cylinders from a Friday placement on the following Monday, removing the need to send an employee to demold and transport cylinders to final curing on the weekend. Also, time and money could be saved because of additional flexibility on when to transport the cylinders to their final curing location. Cylinders made two days apart could potentially be transported together instead of having to make separate trips to the final curing location. The four batches that had the greatest strength difference with 24- and 48-hours of initial curing were chosen, and testing was repeated with a 72-hour initial curing duration. All batches were mixed at elevated temperatures targeting fresh concrete temperatures between 90 and 100

°F to mimic hot weather concreting. For each batch, cylinders were initially cured in water baths set at constant temperatures of 60, 68, 78, 84, 90, and 100 °F. After the specified initial curing duration, specimens were then demolded and transferred to the moist-curing room which maintained a temperature of 73.5 ± 3.5 °F and provided a relative humidity of 100%. Specimens remained in the final curing moist room until their 28-day strengths were determined using a compression testing machine. Using the average strength of the concrete cylinders cured at 68°F, the relative strength differences for the cylinders cured at the other initial curing temperatures were calculated. These relative strength differences were then compared to determine the effect of initial curing practices on the 28-day compressive strength.

3.3.2 Mixture Proportions

A total of eight concrete mixtures, each with proportions commonly used in ALDOT bridge applications, were used to evaluate the effect of initial curing temperature on 28-day compressive strength. A summary of the concrete mixture proportions can be found in Table 3-1. All mixtures were proportioned to have a fixed water-to-cementitious material ratio of 0.44 with a total cementitious materials content of 620 pcy. When supplementary cementitious materials were used, they were substituted by percentage of mass of portland cement. After calculating the volume of material produced, the increase or decrease in total volume, due to the addition of SCMs, was adjusted to yield one cubic yard (27 cubic feet) by adjusting the amount of fine aggregate used.

Table 3-1: Concrete Mixture Proportions Evaluated

Concrete ID	Material Composition (lb/yd^3)							
	Water	Cement	CA*	FA*	Class F Fly Ash	Class C Fly Ash	Slag Cement	Silica Fume
100% T1	273	620	1800	1216	-	-	-	-
30% FFA	273	434	1800	1214	186	-	-	-
30% CFA	273	434	1885	1096	-	186	-	-
50% SC	273	310	1800	1190	-	-	310	-
10% SF	273	558	1800	1190	-	-	-	62
20% CFA & 30% SC	273	310	1800	1203	124	-	186	-
20% CFA & 10% SF	273	434	1800	1189	124	-	-	62
100% T3	273	620	1800	1216	-	-	-	-

*Coarse aggregate (CA) and fine aggregate (FA) in saturated-surface dry state (SSD)

This method was used in all batches except for all batches containing 30% Class C fly ash. When changing the quantity of fine aggregate for the 30% Class C fly ash batches, both the fine aggregate and coarse aggregate amount was adjusted. This inconsistency was not noticed until after all the batches of 30% Class C fly ash were completed. Although this difference occurred, the total combined volume of fine and coarse aggregate did not change, which will not have a significant impact on strength or the effect of initial curing conditions on the measured relative strength.

3.3.3 Raw Materials Used

3.3.3.1 Portland Cement

To ensure the most accurate results, the same portland cement source was used throughout the entirety of the laboratory batches. Type I/II and Type III cement was supplied by Argos Cement. The only times Type I/II cement was not used was when concrete was batched with 100% Type III cement. Both the Type I/II and Type III cements had a specific gravity of 3.15.

3.3.3.2 Supplementary Cementing Materials

The Class F fly ash was obtained from TVA's Cumberland Plant via the SEFA Group and had a calcium oxide content of 6.7% and a specific gravity of 2.60. The Class C fly ash was obtained from Alabama Power's Miller Plant via Boral Resources and had a calcium oxide content of 21.5% and a specific gravity of 2.61. The slag cement used was from the Cape Canaveral Slag Plant of Lehigh Cement and had a specific gravity of 2.86. The silica fume used was sourced from Elkem Materials and had a specific gravity of 2.20.

3.3.3.3 Coarse and Fine Aggregate

Coarse aggregate consisted of #57 Crushed Granite. The aggregate was provided by Vulcan Materials from their Loachapoka quarry. The coarse aggregate had a bulk specific gravity of 2.628 and an absorption capacity of 0.51 percent. Fine aggregate consisted of 1773 Sand from Wiregrass's Ariton pit. The fine aggregate had a bulk specific gravity of 2.629 and an absorption capacity of 0.4 percent.

3.3.3.4 Chemical Admixtures

3.3.3.4.1 Water-reducing Admixture

Two water-reducing admixtures were used for the laboratory concrete batches. For all batches not including silica fume MasterPozzolith 322 was used. Batches with silica fume used a high-range water-reducing admixture called MasterGlenium 7920.

3.3.3.3.2 Air-entraining Admixture

A target air content of 4% ± 2% was desirable, therefore, an air-entraining admixture was added to each batch. MasterAir AE 90 was used as air-entraining admixture in all concretes.

3.3.4 BATCHING AND MIXING

Batching took place in the Structural Concrete Materials laboratory of AU’s Advanced Structural Engineering Laboratory. A 9 ft^3 revolving steel drum mixer was used for all batches. Figure 3-1 shows the drum mixer used for this project. The first step of batching was to weigh out all the material the day before using 5-gallon buckets. It was necessary to provide an excess amount of coarse and fine aggregate to accommodate for moisture corrections that were performed just prior to mixing the concrete. Upon completion of weighing out the materials, they were placed in an environmental chamber set at an elevated temperature. The aggregate was then allowed to heat over night to simulate the excessive temperatures of hot weather concreting. Before leaving the materials in the environmental chamber, all buckets were adequately sealed with lids. It was crucial to ensure a proper seal to prevent loss of moisture while in the environmental chamber. Figure 3-2 includes all materials prepared for a batch and was taken just before placing the buckets in the environmental chamber which is shown to the right of the image.

Figure 3-1: Concrete mixer used

Figure 3-2: Concrete materials before entering environmental chamber

Initially, a temperature setpoint of 95 °F was used for the environmental chamber. Later a temperature of 105 °F was used because the initial batches did not have the desired fresh concrete temperature of between 90 °F and 100 °F. After the first two batches it was determined that the time it took to remove the materials from the environmental chamber and then begin batching, allowed for the materials to cool to below 90 °F. For this reason, the temperature of the environmental chamber was increased for all remaining batches. Not all the fresh concrete temperatures were within the desired temperature range, some were just below 90°F and one exceeded 100 °F. Before batching could begin, moisture corrections were performed in accordance with ASTM C566 (2019), and the aggregate batch weights were corrected. This was done by first determining the weight of the moist aggregate. After determining the moist aggregate weight, the aggregate was heated to remove all moisture and then reweighed. By comparing the moist and dry weight of aggregate, the moisture content was calculated and the correct amount of water and aggregate to be used during the batching process could be determined.

3.3.4.1 Standard Mixing Procedure

Mixing consisted of two different procedures. For all mixtures that did not include silica fume, the standardized mixing procedure found in Appendix C was used. After all material was added in accordance with the standardized mixing procedure, fresh concrete property tests were performed. These consisted of slump, air content, concrete temperature, and unit weight tests. A target concrete unit weight from 140 to 150 pcf was used for this study. A target air content of 2 to 6% was used. The slump of concretes batched was used to determine the workability of concrete. A target range of 2.5 inches to 5.0 inches was used. Table 4-1 includes the fresh concrete properties measured for each batch. When the desired slump was not achieved, additional water-reducing admixture was added in accordance with the standardized mixing procedure. Once the workability test results were satisfactory, the mixing process was complete, and molding of cylinders could begin.

3.3.4.2 Mixing with Silica Fume

For batches with silica fume, a different mixing procedure was required. Silica fume is extremely fine and in densified form needs to be violently broken apart to react with water. To accommodate this, all the silica fume and coarse aggregate were added first and allowed to mix. This violent procedure facilitates the breakup of silica fume particles and prepares the material for the addition of water. The specific procedure used to mix all concretes with silica fume can be found in Appendix C. A high-range water-reducing admixture, MasterGlenium 7920, was used to increase workability while maintaining the water-to-cementitious ratio of the concrete for all batches that used silica fume. Normal water-reducing admixture, MasterPozzolith 322, which was used for all other batches could not be used because it did not provide sufficient water reduction needed when using fine silica fume. If the desired workability was not achieved, more water-reducing admixture was added in accordance with the standardized mixing procedure. Like the normal mixing process, once the desired fresh concrete properties were achieved, molding of cylinders proceeded.

3.3.5 Molding of Cylinders

Concrete cylinders were made using 6 × 12 in. plastic cylinder molds. For each batch a total of 24 cylinders were made. Four cylinders were made for each initial curing temperature. Three cylinders were used to determine the 28-day compressive strength, while the fourth was used for measuring the concrete temperature development. All cylinders were made in accordance with AASHTO T23 (2018). After capping, cylinders were left in their initial curing temperature-controlled water baths. To measure the temperature development of one concrete cylinder in each initial curing bath, straws were inserted through a hole in the cap allowing a temperature probe to be inserted near the middle of the specimen. The straws allowed for removal and reuse of the probes once the concrete hardened and temperature testing on a cylinder was complete.

3.3.5.1 Initial Curing and Final Curing

3.3.5.1.1 Initial Curing

Initial curing of concrete cylinders was completed in six curing tanks that were constructed to maintain initial curing temperatures of 60, 68, 78, 84, 90, and 100 °F. Initial curing temperatures were chosen to assess AASHTO T23 (2018) and ALDOT 501 (2022) initial curing limits. AASHTO T23 (2018) requires all cylinders of normal-strength concrete to be cured from 60 to 80 °F. In AASHTO T23 (2018), concrete with a design strength greater than 6,000 psi has even stricter temperature limit from 68 to 78 °F; however, this is not used by ALDOT 501 (2022). Therefore, 68 °F was chosen as the control because it was close to the middle of 60 to 80 °F and also represented the minimum for the high-strength concrete temperature range. The 60 °F curing tank was used because this is the lower limit allowed by AASHTO T23 (2018). Since the focus in the State of Alabama is on hot weather concreting and cement hydration tends to elevate temperatures, the other four temperatures were chosen to be above the control temperature of 68 °F. The first temperature, 78 °F, is close to the upper limit of 80 °F of AASHTO T23 (2018) and ALDOT 501 (2022) and was the maximum temperature of the high-strength concrete limit. Finally, the last three temperatures of 84, 90, and 100 °F were selected to cover summer-time conditions in Alabama.

Initial curing tanks were constructed by using insulated coolers that were each retrofitted with an internal cooling and heating system. The laboratory setup of all six curing tanks is shown in Figure 3-3. The temperature-control systems for the curing tanks were constructed using copper piping that was connected to a water circulator. Each circulator pumped hot or cold water through the pipes and ensured that the water temperature in the cooler maintained the desired initial curing temperature. Temperature probes were inserted from the circulator into the water to determine whether to heat or cool the circulated water. The initial curing temperature that was maintained was the water in the curing tank, and not the water in the circulator and piping. This is important to note because AASHTO T23 (2018) and ALDOT 501 (2022) require that the curing environment and not the concrete must maintain the desired temperature. The circulated water had to either heat or cool the entire curing tank; therefore, it had to output water at different temperatures, so the water temperature in the circulator and copper piping may have been hotter or colder than the actual curing tank water temperature. Figures 3-4 and 3-5 show pictures of a typical curing tank and circulator setup.

Figure 3-3: Laboratory initial curing setup

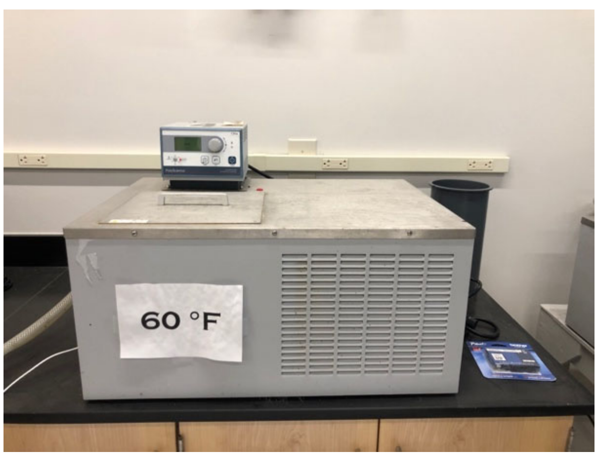

Figure 3-4: Water Circulator **Figure 3-5: Initial Curing Tank**

Each initial curing tank also had a small submersible circulation pump that contributed to a uniform water temperature throughout the entire initial curing tank. Without a submersible circulation pump, the top and bottom of the cooler water temperatures would vary. Figure 3-5 shows a picture of the inside of a typical initial curing tank with copper pipes and small submersible circulation pump. A close-up of the submersible circulation pump can be seen in Figure 3-6.

Figure 3-6: Submersible Circulation Pump

To verify and record the water and concrete temperatures during initial curing, temperature probes were used that logged temperatures every 15 minutes. For each batch, the temperature of the concrete cylinder and water surrounding the cylinder was recorded using a HOBO Thermocouple. The cylinder with a temperature probe was not used for any strength testing. A typical curing tank with cylinders in their initial curing location can be seen in Figure 3-7; however, during the initial curing period the lid of each cooler was kept closed.

Figure 3-7: Cylinders in Initial Curing Tank

As shown in Figure 3-7, temperature probes were inserted into the center of one cylinder that remained capped to retain moisture like all other cylinders. Readings from both the concrete and water temperature were evaluated to ensure the desired initial curing temperatures was maintained. As an example, the temperature versus time plot for concrete with 10% silica fume is shown in Figure 3-8.

Although the fresh concrete temperature for this test was 94 °F, the first measurement is around 86 °F because of the heat lost over the time (approximately 20 to 25 minutes) it took to mold the samples and place them in the initial curing tank. It can be seen in this figure that the temperature of the water in the curing tank was accurately controlled to the target curing temperature. Just like on a jobsite, due to hydration the temperature of the concrete cylinder briefly deviated from the water temperature; however, after a concrete age of approximately 20 hours the temperature of the concrete and the water is very similar. Depending on the desired initial curing duration, cylinders were left in their initial curing environment a little over 24, a little under 48, or a little under 72 hours.

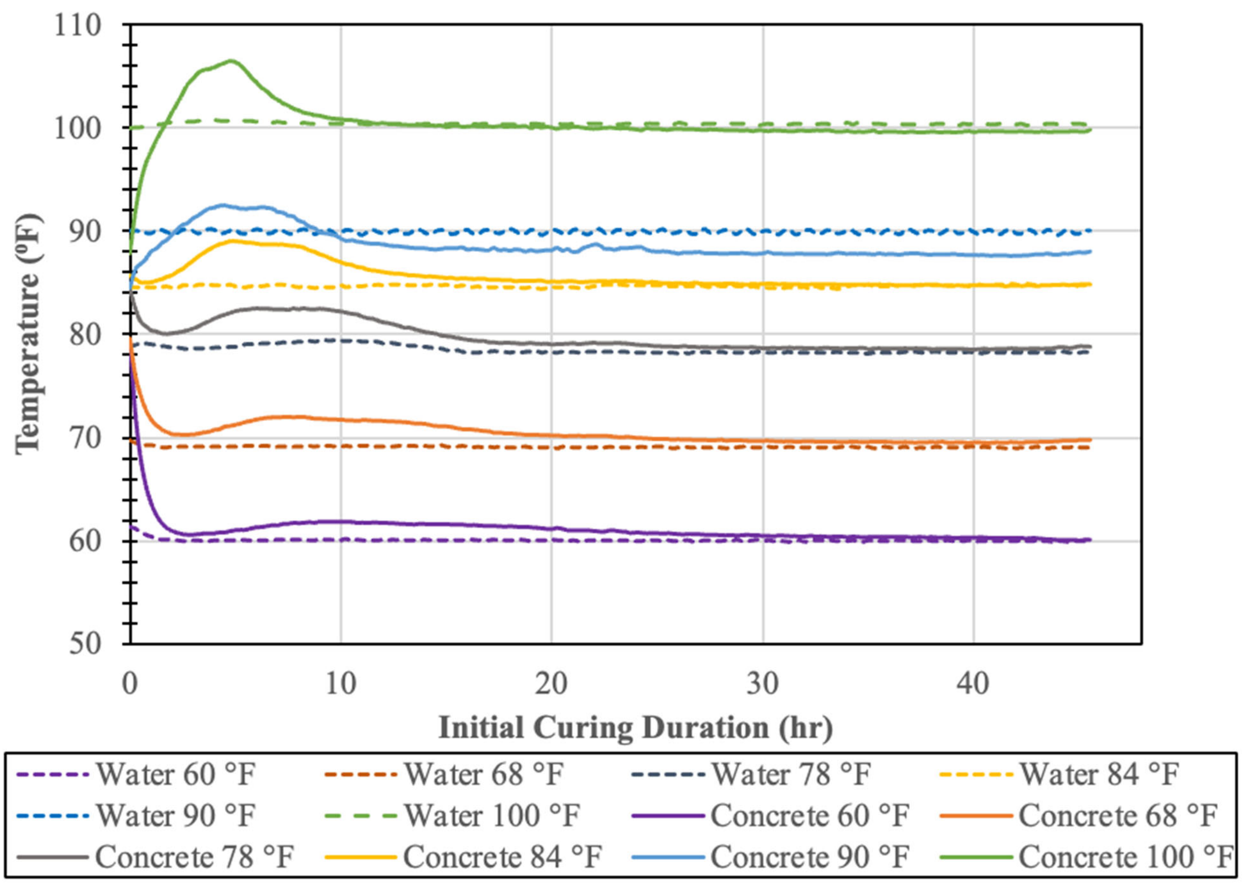

Figure 3-8: Example of measured initial curing temperatures

All temperature plots can be found in Appendix A. Depending on the desired initial curing duration, cylinders were left in their initial curing environment for 24, 48, or 72 hours. After the desired curing duration was met, the cylinders were then removed from their molds and moved to their final curing location.

3.3.5.1.2 Final Curing

After the desired initial curing duration was reached, the cylinders were demolded and moved to their final curing location. All final curing practices followed AASHTO T23 (2018) and ALDOT 501 (2022). First, the cylinders were removed from their initial curing environment and then demolded and labelled. Once demolded, the cylinders were moved to the final curing room as it was critical to transfer the cylinders in under 30 minutes, per specification. This room was constructed by Darwin Chambers and maintained a temperature of 73.5 ± 3.5 °F and provided a 100% relative humidity. Figure 3-9 shows the final curing room with cylinders from three concrete batches in their final curing location. As shown in Figure 3-9, cylinders undergoing final curing were placed on wire shelves. Using wire shelves helped to prevent any water ponding. Cylinders remained in the final curing room until an age of 28 days and were then tested to determine their 28-day compressive strength.

Figure 3-9: Cylinders in Final Curing Room

3.3.6 Strength Testing

Concrete cylinder compressive tests followed the standard set forth by ASTM C1231 (2015) and AASHTO T22 (2022). All cylinders were broken using the same machine, a Forney Variable Drive Technology Automatic machine with a capacity of 600 kips. Additionally, within each concrete batch, one operator was used to test the cylinders because this helped to remove variability that could arise between operators. ASTM C1231 (2015) was used for the unbonded capping of cylinders. Using ASTM C1231 (2015) it was determined to use neoprene pads. A durometer value of 70 was used for the neoprene pads, and they were replaced after 50 tests. Three cylinders were tested at each initial curing temperature to determine the average 28-day strength for this set of cylinders. While testing, only three cylinders were removed from the curing room at a time because when cylinders are allowed to dry, they can have a slightly higher strength than cylinders in moist state. By limiting the number of cylinders removed at a time, the exposed cylinders did not have enough time to lose moisture and this practice ensured that moisture loss which could affect the measured 28-day compressive strength did not occur.

After testing three cylinders to determine the result for each initial curing temperature, the three strength results were evaluated for any outliers. An outlier was determined to be any cylinder that had a relative difference greater than ±7.8% (AASHTO T22) when compared to the other two cylinders it was cured with. Over the course of this study only six outliers (i.e., 1.4% of all cylinders tested) were detected, and these were not used in any subsequent calculations.

3.3.6.1 Evaluation of Strength Differences within Each Batch

Strength differences were determined by using the average 28-day compressive strengths measured for the cylinders in the 68 °F initial curing tank as the reference value. Using 68 °F as the reference temperature, the relative strength difference was determined as a percent for each of the other initial curing temperatures. The use of relative strength differences allows the results from different concretes and different batches (initial curing durations) to be directly compared to each other although their 28-day strengths were different. As an example, Figure 3-10(left) shows the 28-day compressive strength of a single batch of 100% Type I cement with respect to each initial curing temperature for an initial curing duration of 24 hours. After the 28-day compressive strengths were determined, the relative strength differences were determined for each initial curing temperature with respect to the concrete initially cured at 68 °F. The equation used to determine the relative strength difference (in percent) is shown in Equation 3-1:

$$\text{Strength Difference} = \frac{f_c\ at\ T - f_c\ at\ 68°F}{f_c\ at\ 68°\mathrm{F}} \times 100 \qquad \textbf{(Equation 3-1)}$$

where: f_c at T = 28-day compressive strength at specific initial curing temperature (psi); and
f_c at 68 °F = 28-day compressive strength at initial curing temperature of 68 °F (psi).

Figure 3-10(right) shows the relative strength differences for the 28-day strengths shown in Figure 3-10(left). Since 68 °F is the reference temperature, no result is visible for this temperature in Figure 3-10 (right). Average strengths of each initial curing duration were used for all strength difference calculations. Note in Figure 3-10(left) that the 28-day strength systematically decreases as the initial curing temperature increases, which is why in Figure 3-10(right) the strength difference decreases from +3% to -19% as the initial curing temperature increases.

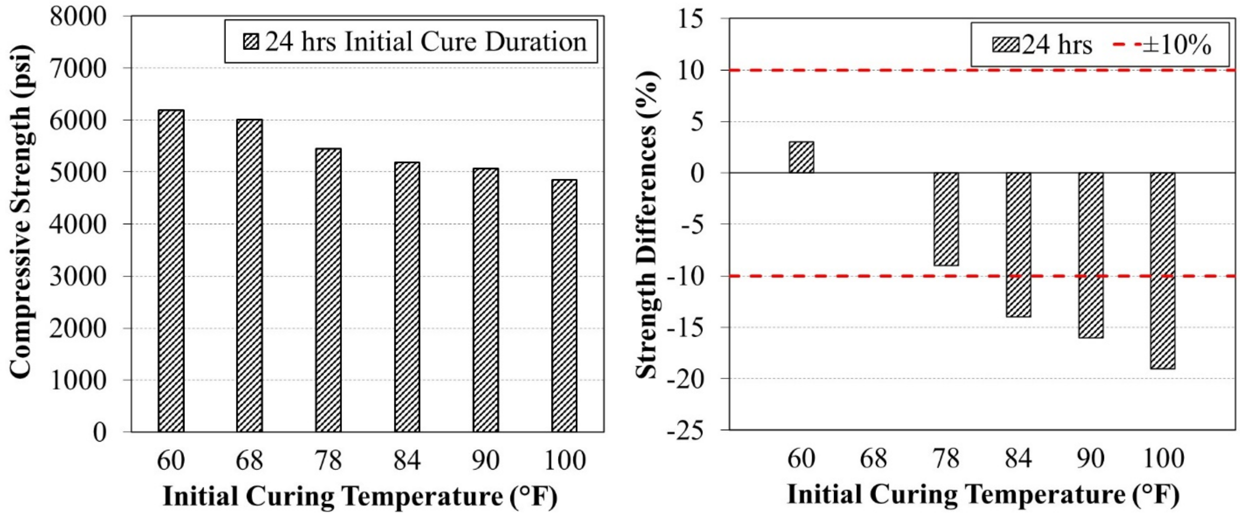

Figure 3-10: (left) Average 28-Day Compressive Strength and (right) Relative Strength Differences Example for 100% Type I Cement with an Initial Curing Duration of 24 hours

To assess the effect of initial curing temperature and duration on compressive strength a limit is needed for what is considered an acceptable strength difference between cylinders cured at various initial curing temperatures. AASHTO T22 (10) lists a single-operator acceptable range of ±7.8% for three 6×12 in. cylinders tested under laboratory conditions. This acceptable range is for “companion cylinders prepared from the same sample of concrete and tested by one laboratory at the same age” (AASHTO T22). Although tested in a laboratory, the compressive strength results at each curing temperature will be compared to results from cylinders that were cured at different temperatures. Slightly more variation is to be expected when initially cured at various temperatures and therefore an acceptable range of ±10% was chosen as the limit to evaluate the results of cylinders cured at different initial curing temperatures. This limit is also shown with the results shown in Figure 3-10 (right).

CHAPTER 4

PHASE 1–PRESENTATION AND DISCUSSION OF RESULTS

This chapter includes the results and discussion of the experimental procedure covered in Chapter 3. The fresh concrete properties and the relative strength differences of each batch are presented and discussed.

4.1 FRESH CONCRETE PROPERTY RESULTS

The fresh concrete properties of each concrete batch are summarized in Table 4-1. All fresh concrete property tests were within the target ranges before molding of cylinders took place. The target range for the slump of fresh concrete, as mentioned in Section 3.3.4.1, was 2.5 to 5.0 inches. All batches, including the four verification batches, had measured slump values within the target range. The target value for the air content of fresh concrete was 2 to 6 percent. All batches, including the four verification batches, had measured air content values within this target range. Although not a reason for rejection, the target temperature range for the fresh concrete was 90 to 100 °F. Three concrete batches had fresh concrete temperatures that fell outside of the ideal temperature range. The three batches that had fresh concrete temperatures outside of the chosen target range were the 100% Type I PCC mixtures when initially cured for a duration of both 24 and 48 hours, and the batch of 100% Type III PCC when initially cured for 72 hours. Although, the three batches had fresh concrete temperatures outside of the chosen target range, the nature of this study allowed the use of the concrete to determine relative strength differences resulting from changes in initial curing temperature and duration.

Table 4-1: Fresh Concrete Properties

Mixture Type	Slump (in.)	Unit Weight (lb/ft^3)	Air Content (%)	Fresh Concrete Temperature (°F)
24-Hour Initial Curing				
100% Type I PCC	2.5	149.0	3.5	77
30% Class F Fly Ash	4.0	145.2	2.9	90
30% Class C Fly Ash	4.0	147.0	3.0	90
50% Slag Cement	2.5	143.2	3.9	95
10% Silica Fume	2.5	142.2	5.0	98
20% Class F Fly Ash 30% Slag Cement	3.0	144.0	4.0	90
20% Class F Fly Ash 10% Silica Fume	3.5	142.5	5.0	97
100% Type III PCC	2.5	144.0	4.5	95
48-Hour Initial Curing				
100% Type I PCC	3.5	145.3	4.5	85
30% Class F Fly Ash	4.5	146.0	2.9	90
30% Class C Fly Ash	2.5	146.0	2.5	91
50% Slag Cement	3.5	143.0	5.0	92
10% Silica Fume	3.5	142.5	5.5	94
20% Class F Fly Ash 30% Slag Cement	4.0	143.4	4.0	95
20% Class F Fly Ash 10% Silica Fume	4.5	141.0	6.0	90
100% Type III PCC	2.5	143.0	5.0	90
72-Hour Initial Curing				
100% PCC	3.5	142.2	5.5	96
50% Slag Cement	3.5	142.8	5.0	95
10% Silica Fume	3.0	143.0	5.0	96
20% Class F Fly Ash 10% Silica Fume	4.0	140.0	6.0	95
Verification Batches				
30% Class C Fly Ash	4.0	146.7	3.0	97
100% Type III PCC	3.0	143.4	5.0	102
50% Slag Cement	4.0	142.0	4.0	95
100% Type I PCC	3.5	143.0	4.0	94

4.2 Individual Concrete Relative Strength Differences

4.2.1 100% Type I PCC Concrete

The 100% Type I PCC mixture was one of the four concrete mixtures that included a batch with an initial curing duration of 72 hours. Although most concrete batches in the industry include at least one supplementary cementitious material, some batches still consist of only portland cement. It was expected that without any supplementary cementitious material the temperature effects would be severe. The results from all three initial curing durations are compared in Table 4-2. Figure 4-1 plots the values found in Table 4-2 against the ±10% relative strength difference limit. All three initial curing durations show relative strength differences that become more extreme with increasing initial curing temperature. Within an initial curing temperature range from 60 °F to 80 °F, the relative strength differences were within the chosen acceptable limits for all three initial curing durations. A clear trend of more relative strength differences with increasing initial curing temperature can be identified in Figure 4-1. At initial curing temperatures of 60 °F and 78 °F the relative strength differences are within the chosen acceptable relative strength difference limits for all three initial curing durations. As the initial curing temperature is increased to 84 ºF and beyond, the relative strength differences begin to fall outside of the acceptable relative strength difference limits. At an initial curing temperature of 100 ºF, all three initial curing durations result in relative strength differences greater than the acceptable limits.

Table 4-2: 100% Type I PCC Concrete relative strength differences

Initial Curing Temperature	Initial Curing Duration		
	24 hrs	48 hrs	72 hrs
60 °F	3	3	4
78 °F	-9	-6	-4
84 °F	-14	-12	-7
90 °F	-16	-11	-7
100 °F	-19	-16	-11

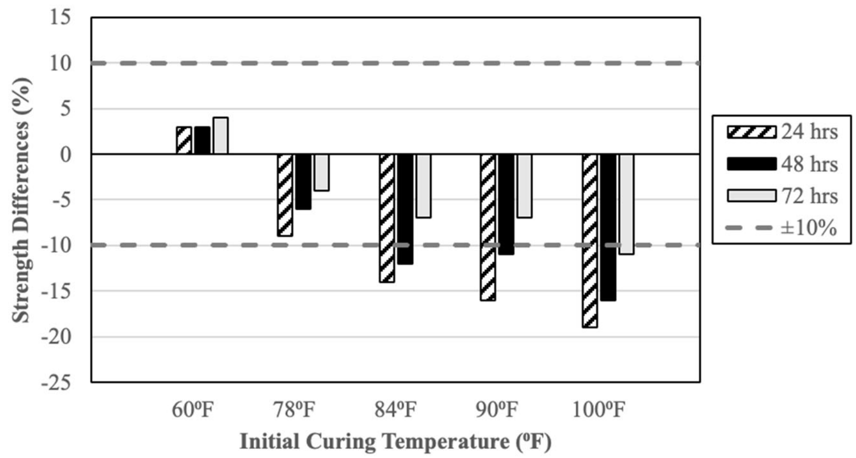

Figure 4-1: Relative 28 strength differences for 100% Type I PCC Concrete

4.2.2 30% Class F Fly Ash Concrete

Table 4-3 includes the values of strength differences for the 30% Class F fly ash batches and Figure 4-2 plots the values shown in Table 4-3 against the ±10% relative strength difference limit. For the 30% Class F fly ash mixture, strength differences from the 24- and 48-hour batches were not as extreme as some other mixtures and therefore a 72-hour batch was not performed. For both initial curing durations, the most extreme relative strength differences occurred when cylinders were cured at 100 °F. At initial curing temperatures of 78 °F, 84 °F, and 90 °F in the 24-hour initial curing duration batch, the strength differences were all similar. These relative strength differences were -6%, -7%, and -7%, respectively. Within an initial curing temperature range from 60 °F to 90 °F all the relative strength differences were within the acceptable limits of ±10%. Upon inspection of Figure 4-2, the relative strength differences are similar for both initial curing durations. Only the cylinders initially cured at 100 °F for 24 hours visually stands out at -12% with the others all being around -7%. When cured at a lower temperature of 60 °F there was a relative strength gain of 4% for an initial curing duration of 48 hours compared to only 1% for 24 hours. Only the relative strength difference for the cylinders cured at 100 °F for a duration of 24 hours was outside the acceptable limit of ±10%.

Table 4-3: 30% Class F Fly Ash Concrete relative strength differences

Initial Curing Temperature	Initial Curing Duration	
	24 hrs	48 hrs
60 °F	1	4
78 °F	-6	-4
84 °F	-7	-8
90 °F	-7	-7
100 °F	-12	-8

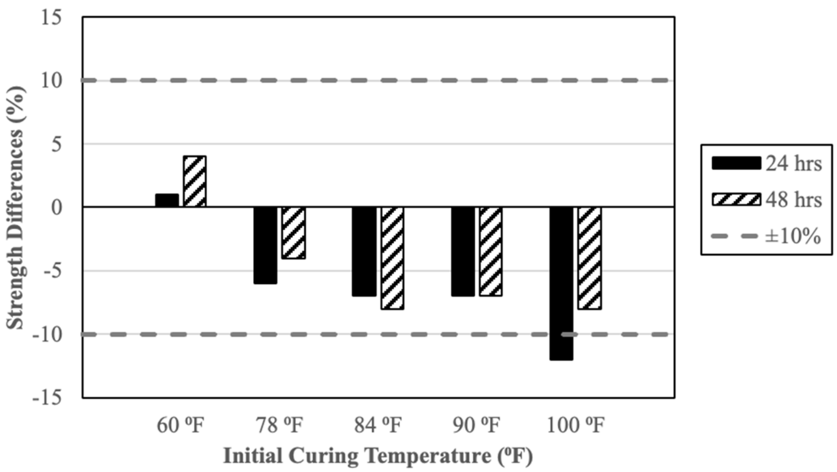

Figure 4-2: Relative strength differences for 30% Class F Fly Ash Concrete

4.2.3 30% Class C Fly Ash Concrete

Table 4-4 includes a summary of the relative strength differences measured for the 30% Class C fly ash mixture. Figure 4-3 consists of a plot of the values from Table 4-4 against the ±10% relative strength difference limit. The relative strength differences from the 24- and 48-hour batches were not as extreme as some other mixtures and therefore a 72-hour batch was not performed for the mixture with 30% Class C fly ash. A maximum difference of -14% occurred when cured an initial curing temperature of 100 °F with an initial curing duration of 48 hours. For both initial curing durations, when cured at temperatures of 90 °F and below, the relative strength differences were within the acceptable test limit of ±10%. Although larger than the relative strength differences from the Class F fly ash, the Class C fly ash had mostly low relative strength differences when compared to some of the other mixtures. The relative strength differences did not exceed the acceptable limit until initially cured at a temperature of 100 °F for both initial curing durations. The differences shown in Figure 4-3 help to demonstrate the effect of initial curing temperature on the relative strength differences in the Class C fly ash mixtures. Also, the results do not show a distinct relationship between initial curing duration and 28-day compressive strength.

Table 4-4: 30% Class C Fly Ash Concrete relative strength differences

Initial Curing Temperature	Initial Curing Duration	
	24 hrs	48 hrs
60 °F	-1	4
78 °F	-3	-5
84 °F	-6	-4
90 °F	-10	-8
100 °F	-12	-14

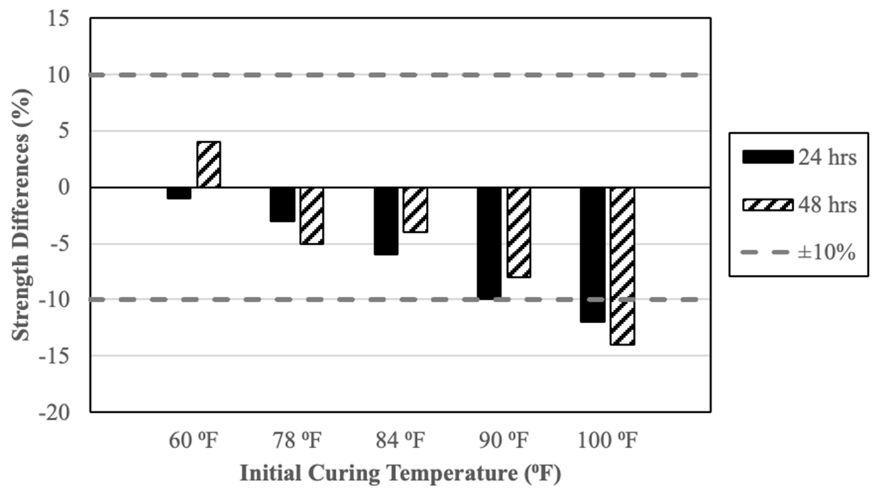

Figure 4-3: Relative strength differences for 30% Class C Fly Ash Concrete

4.2.4 50% Slag Cement Concrete

Table 4-5 includes the values of strength differences for the three 50% Slag cement batches. Figure 4-4 consists of a plot of the values from Table 4-5 against the ±10% relative strength difference limit. The maximum relative strength difference of -15% occurred when initially cured for 24 hours at a temperature of 100 °F. The relative strength difference of -15% was the only value to fall outside the acceptable limit of ±10%. The relative strength difference for cylinders initially cured at 100 °F for 24 hours is the largest relative strength difference measured for this mixture.

Table 4-5: 50% Slag Cement Concrete relative strength differences

Initial Curing Temperature	Initial Curing Duration		
	24 hrs	48 hrs	72 hrs
60 °F	7	3	3
78 °F	-5	-1	-4
84 °F	-5	-1	-5
90 °F	-9	-5	-8
100 °F	-15	-8	-9

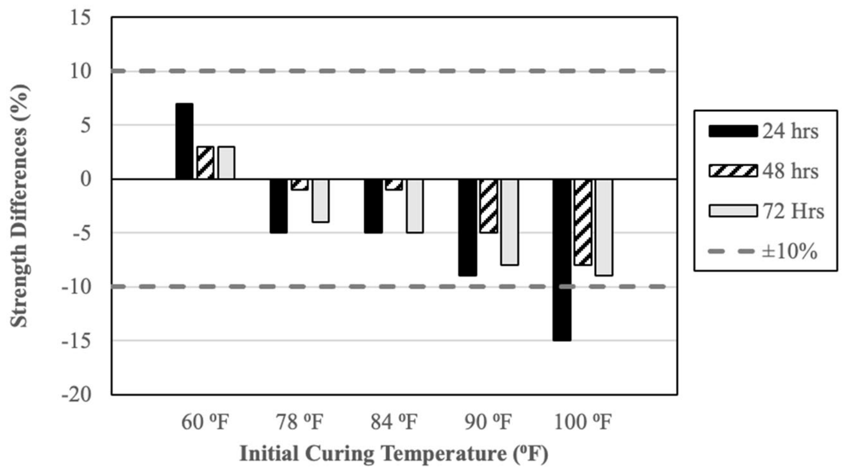

Figure 4-4: Relative strength differences for 50% Slag Cement Concrete

4.2.5 10% SILICA FUME CONCRETE

Table 4-6 includes the values of strength differences for each 10% Silica Fume batch. Figure 4-5 shows the relative strength differences values from Table 4-6 against the ±10% relative strength difference limit. For the 24- and 48-hour initial curing durations, the 100 °F cured cylinders had a relative strength difference of -20%. Like other batches, the colder curing environment of 60 °F helped improve the strength development, but the differences were larger than most batches. Because of the large strength differences in both the positive and negative directions for the two initial curing durations, the use of a 72-hour initial curing duration was also evaluated for the 10% silica fume mixture. The acceptable strength difference of ±10 was exceeded for all three initial curing durations when initially cured at 84 °F, 90 °F and 100 °F, while the cylinders initially cured at 60 °F and 78 °F were all within the acceptable relative strength difference limit. The 10% Silica Fume batches had the largest relative strength differences when initially cured at 100 ºF. The large difference shows how silica fume can be easily affected by initial curing temperature differences. Both cold and hot curing conditions will affect the compressive strength of concrete batched with silica fume, and special care must be taken to control initial curing temperatures of this concrete type.

Table 4-6: 10% Silica Fume Concrete relative strength differences

Initial Curing Temperature	Initial Curing Duration		
	24 hrs	48 hrs	72 hrs
60 °F	8	10	3
78 °F	-9	-6	-5
84 °F	-15	-11	-11
90 °F	-17	-14	-13
100 °F	-20	-20	-18

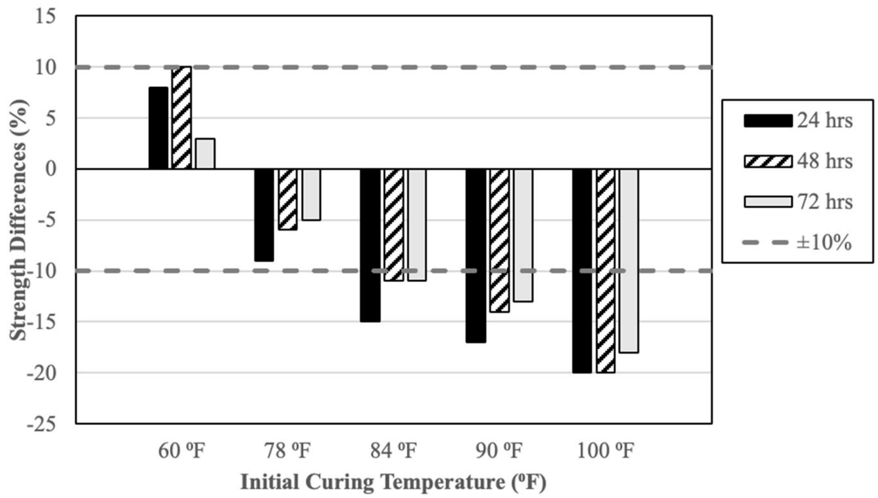

Figure 4-5: Relative strength differences for 10% Silica Fume Concrete

4.2.6 20% Class F Fly Ash with 30% Slag Cement Concrete

Table 4-7 includes the values of relative strength differences for the 20% Class F Fly Ash with 30% Slag Cement concrete batches. Figure 4-6 illustrates the relative strength difference values from Table 4-7 against the ±10% relative strength difference limit. The ternary blend of Type I cement, Class F fly ash, and Slag cement had some of the least extreme relative strength differences. It is interesting that when Class F fly ash and slag cement is combined, the relative strength differences are less significant than their individual batches. All the relative strength differences for the 20% Class F fly ash with 30% Slag cement batches were within the acceptable limit of ±10%. Larger differences, shown in Figure 4-6, were recorded for the extremes of 60 °F and 100 °F, but for initial curing temperatures of 78 °F, 84 °F, and 90 °F the differences were within the acceptable limits. Within initial curing temperatures of 78 °F, 84 °F, and 90 °F there is a maximum relative strength difference of only -5%. The small relative strength differences show how effective this blend is at mitigating initial curing temperature effects, and as a result, no 72-hour initial curing duration batch was performed.

Table 4-7: 20% Class F Fly Ash with 30% Slag Cement Concrete relative strength differences

Initial Curing Temperature	Initial Curing Duration	
	24 hrs	**48 hrs**
60 °F	8	9
78 °F	-2	1
84 °F	-4	-5
90 °F	-3	-3
100 °F	-9	-9

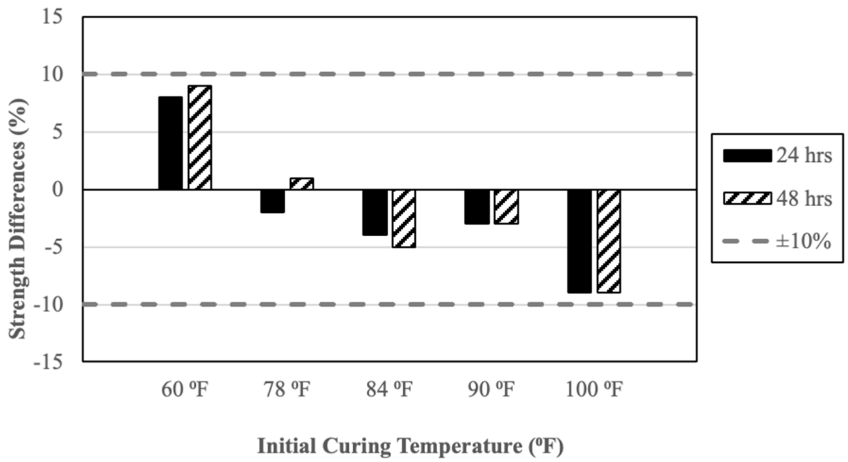

Figure 4-6: Relative strength differences for 20% Class F Fly Ash with 30% Slag Cement Concrete

4.2.7 20% CLASS F FLY ASH WITH 10% SILICA FUME CONCRETE

Table 4-8 includes the values of relative strength differences for the 20% Class F Fly Ash with 10% Silica Fume concrete batches and Figure 4-7 plots the values from Table 4-8 against the ±10% relative strength difference limit. Unlike the fly ash and slag cement blend, this ternary blend had significant relative strength differences. Large differences were expected due to the addition of silica fume in the mixture. The relative strength differences of the 24 and 48-hour batches were large enough to warrant the addition of a 72-hour initial curing duration batch. For initial curing temperatures of 60 °F and 78 °F, the relative strength differences are within the acceptable limits for all three initial curing durations. At an initial curing temperature of 84 °F, two of the initial curing durations had relative strength differences that exceeded the acceptable limits. The concrete initially cured at 84 °F for an initial curing duration of 24 hours did not exceed the acceptable limit. As initial curing temperature increased, the relative strength differences grew until a maximum difference occurred at 100 °F for each initial curing duration.

Table 4-8: 20% Class F Fly Ash with 10% Silica Fume Concrete relative strength differences

Initial Curing Temperature	Initial Curing Duration		
	24 hrs	48 hrs	72 hrs
60 °F	9	9	5
78 °F	-3	-4	-9
84 °F	-6	-11	-13
90 °F	-11	-16	-16
100 °F	-16	-23	-22

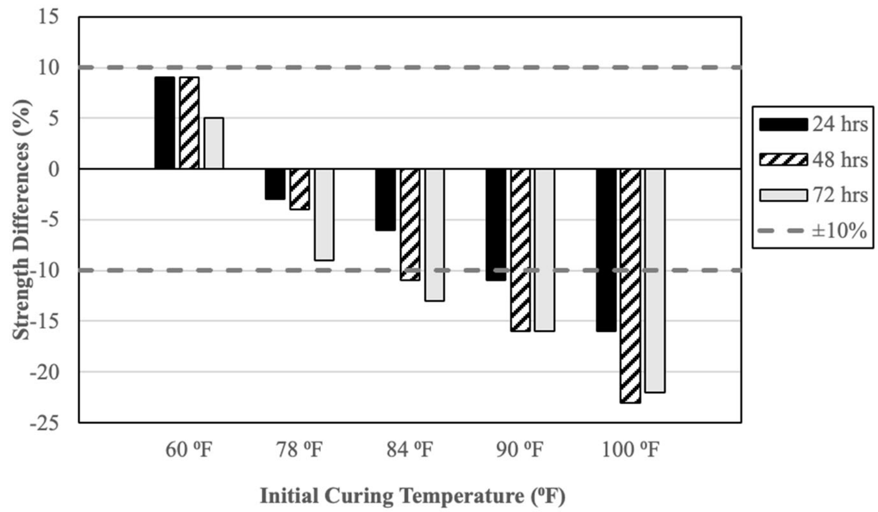

Figure 4-7: Relative strength differences for 20% Class F Fly Ash with 10% Silica Fume Concrete

4.2.8 100% TYPE III PCC CONCRETE

Table 4-9 includes the values of relative strength differences for the 100% Type III concrete batches. Figure 4-8 plots the values of Table 4-9 against the ±10% relative strength difference limit. The Type III cement mixture had small relative strength differences for the first two initial curing durations and therefore no 72-hour batch was evaluated. Only the relative strength differences for the 24-hour batch cured at 100 °F fell outside of the acceptable limit. Minimal relative strength differences are shown in Table 4-9. A maximum relative strength difference of -11% when initially cured for 24-hours occurred while all other differences were within the acceptable limits of ±10%. From the results of the Type III concrete batches, it was concluded that the mixture was less susceptible than some of the other concretes tested to strength differences resulting from temperature effects during initial curing.

Table 4-9: 100% Type III PCC relative strength differences

Initial Curing Temperature	Initial Curing Duration	
	24 hrs	48 hrs
60 °F	5	7
78 °F	-2	1
84 °F	-4	-2
90 °F	-3	-5
100 °F	-11	-7

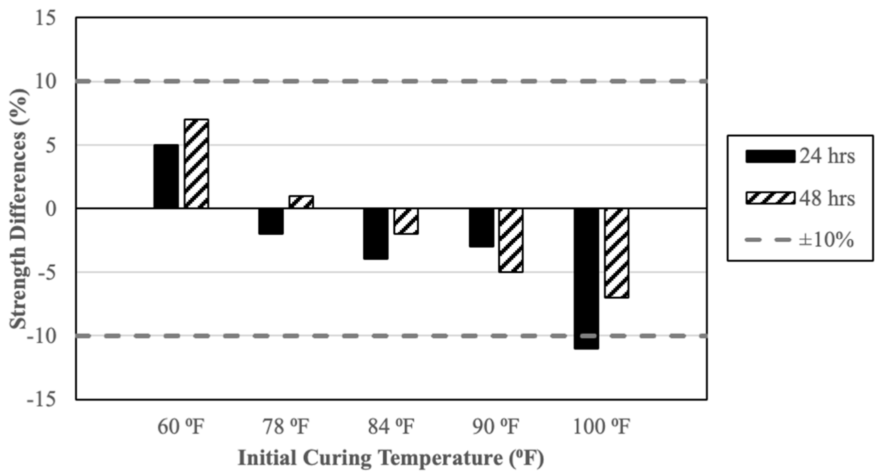

Figure 4-8: Relative strength differences for 100% Type III PCC

4.2.9 ACCEPTABILITY OF 28-DAY CONCRETE COMPRESSIVE STRENGTH RESULTS

The concrete cylinders in each of the six different initial curing environments were identical concrete sampled from each respective batch. Therefore, each batch developed a unique set of relative strength differences. Only the relative strength differences within each individual batch were compared to other batches. By comparing each concrete specimen's compressive strength to identical concrete, it was not necessary to compare the 28-day compressive strengths between different batches of concrete. However, to ensure that all produced concrete was representative of typical concrete used in the industry, the average 28-day compressive strengths of the cylinders initially cured at 68 °F were analyzed. Figure 4-9 illustrates the 28-day compressive strengths for cylinders initially cured at 68 °F. Four mixtures show three data sets as they were the ones chosen for the 72-hour initial curing durations. Differences in strength between the initial curing durations were expected and it was concluded that all 20 concrete batches had adequate 28-day compressive strength.

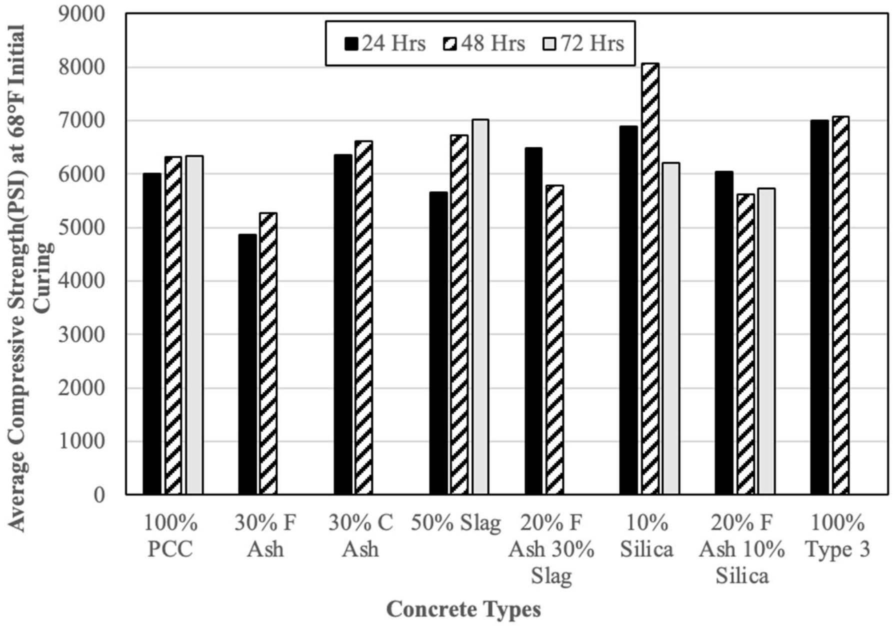

Figure 4-9: Compressive strengths of cylinders initially cured at 68 °F

4.3 Verification Batches

A major aspect for the validity of the study was whether the results were repeatable. To determine the repeatability of the results, four concrete mixtures were chosen and repeated. The goal of repeating the batches was to show that the relative strength differences were similar to those obtained from the initial batches. First the average strengths of the initial and verification batches were compared at an initial curing temperature of 68 °F to ensure the concrete produced was an acceptable representation of typical concrete produced in the industry. These results are shown in Figure 4-10.

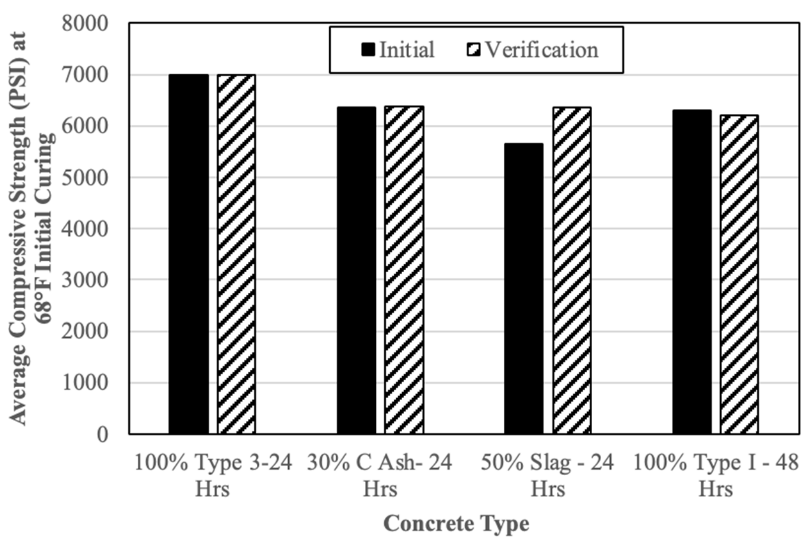

Figure 4-10: Compressive strengths of cylinders initially cured at 68 °F for verification batches

The compressive strengths shown in Figure 4-10 are quite similar. Remarkably, the verification batches for the 100% Type III concrete had an identical compressive strength to its initial batch while the 30% Class C fly ash had only a 10-psi difference. With the variability associated with making and testing concrete test cylinders, it was unexpected that the 28-day compressive strengths would be that close to each other. Overall, after reviewing the results at 68 °F, it was confirmed that the 28-day compressive strengths from the concretes were acceptable for analysis of the relative strength differences.

After completing these verification batches, the results were analyzed, and the repeatability of the experiment was confirmed. Table 4-10 includes the relative strength differences for the verification batches. As shown in Table 4-10, the four mixtures and curing durations chosen were as follows: 100% Type III 24 hours, 100% PCC 48 hours, 30% Class C Fly Ash 24 hours, and 50% Slag cement 24 hours. Each verification batch showed similar trends to their respective initial batches. Table 4-10 shows a maximum difference of 8% between the relative strength differences for the initial and verification batches. Most of the differences in relative strength differences for the verification batches are within ±5% while many are only ±2% different and some are identical when compared to the initial batches. Another important finding is the verification batch relative strength differences are consistent with the overall results of the study. All the relative strength differences were within the acceptable limit of ±10% when initially cured between 60 °F and 80 °F. From the values in Table 4-10, it is clear to see that the test methods and procedures used in this study are repeatable, and the results are valid. For a visual representation, the relative strength differences of one verification batch is plotted against its initial batch in Figure 4-11. In Figure 4-11, the values are similar, with the relative strength differences for the 68 °F, 78 °F, and 100 °F initial curing temperatures being identical. All similar plots for all verification batches can be found in Appendix B.

Table 4-10: Verification Batches relative strength differences

Initial Curing Strength Differences (%)					
Verification Batches	**Initial Curing Temperature**				
	60 °F	**78 °F**	**84 °F**	**90 °F**	**100 °F**
100% T3 24 Hour-Initial	5	-2	-4	-3	-11
100% T3 24 Hour-Verification	2	-5	-6	-8	-15
30% CFA 24 Hour-Initial	-1	-3	-6	-10	-12
30% CFA 24 Hour- Verification	7	-2	-4	-5	-11
50% SC 24 Hour- Initial	7	-5	-7	-9	-15
50% SC 24 Hour- Verification	3	-5	-9	-11	-15
100% T1 48 Hour- Initial	3	-6	-12	-11	-16
100% T1 48 Hour- Verification	5	-7	-6	-7	-14

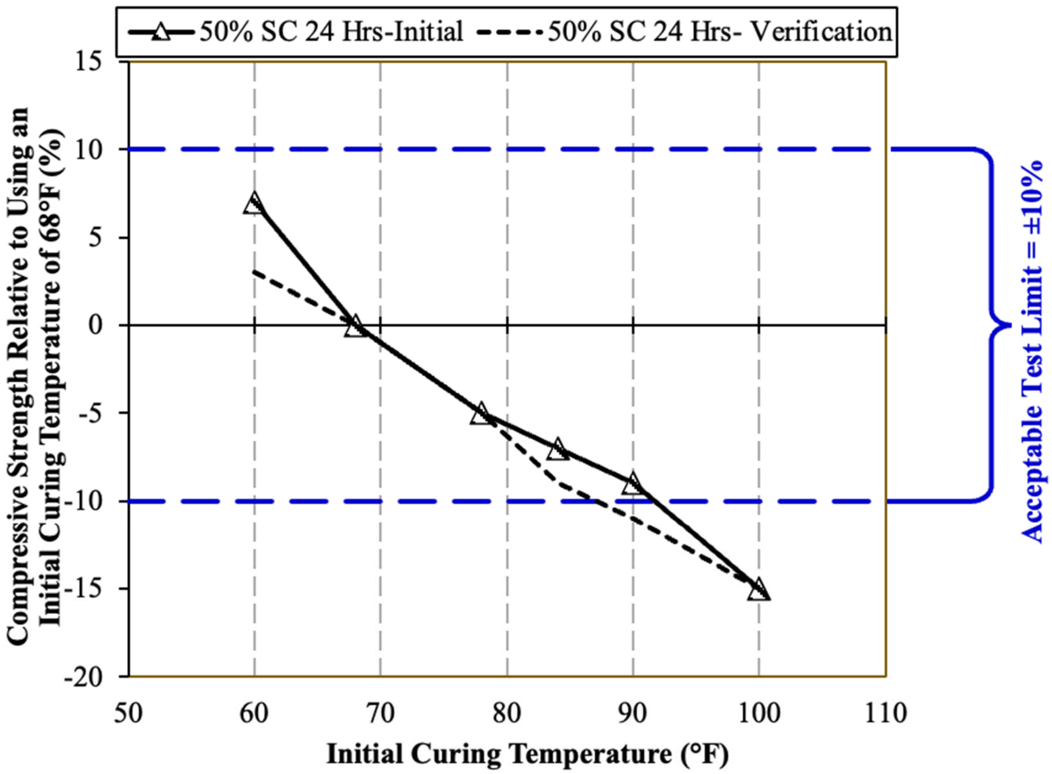

Figure 4-11: 50% Slag Cement Concrete Verification Batch

4.4 24-Hour Initial Curing Duration

According to AASHTO T23 (2018) Section 10.1.2, the initial curing duration has a maximum duration of 48 hours. Although not in AASHTO T23 (2018), the current edition of ALDOT 501 (2022) specifies a minimum of 24 hours of initial curing. It is common practice within the industry to ensure a minimum of 24 hours of initial curing before moving to final curing. To simulate the minimum initial curing period, cylinders were removed after they reached an age just greater than 24 hours and then placed in the final curing environment until testing at 28 days.

After completing 28-day compressive strength tests for each concrete, the relative strength differences of the cylinders with an initial curing duration of 24 hours were determined and are shown in Table 4-11. The 100% Type I cement and 10% Silica Fume mixtures had the most extreme relative strength differences for each initial curing temperature above the reference temperature of 68 °F. The 28-day strength of the ternary-blend mixture made with 20% Class F fly ash and 30% slag cement was the least impacted by initial curing temperature.

In Table 4-11, the values in the shaded cells represent values outside the acceptable range of ±10%. The first two data columns, 60 and 78 °F, are the two initial curing temperatures that fall within the specified temperature range of 60 to 80 °F in ALDOT 501 (2022) and AASHTO T23 (2018). No relative strength differences fell outside of the ±10% acceptable range for cylinders cured at these two temperatures. However, as the initial curing temperature is increased above 80 °F, the relative strength differences begin to fall outside of the acceptable range which indicates a significant loss in 28-day strength. Twelve out of 24 (50%) of the cylinder sets initially cured at 84, 90, and 100 °F, had relative strength differences that exceeded the ±10% acceptable range. The maximum measured 28-day strength loss was 20% and this was measured for the concrete made with 10% silica fume. The data suggests that it is crucial to maintain initial curing temperatures within 60 to 80 °F for quality assurance testing of cylinders.

Table 4-11: 24-Hour initial curing relative strength differences

Concrete ID	24-Hour Initial Curing Temperature				
	60 °F	**78 °F**	**84 °F**	**90 °F**	**100 °F**
100% T1	3	-9	-14	-16	-19
30% FFA	1	-6	-7	-7	-12
30% CFA	-1	-3	-6	-10	-12
50% SC	7	-5	-5	-9	-15
10% SF	8	-9	-15	-17	-20
20% CFA & 30% SC	8	-2	-4	-3	-9
20% CFA & 10% SF	9	-3	-6	-11	-16
100% T3	5	-2	-4	-3	-11

Note: Shaded values are when relative strength differences fall outside the acceptable range

Using the values from Table 4-12, Figure 4-12 was created to illustrate the relative strength differences versus the initial curing temperatures for the batches cured at 24 hours. Observation of Figure 4-12 shows that above an initial curing temperature of 80 °F, the concrete relative strength differences fall outside of the acceptable limit. As initial curing temperatures increased beyond the reference temperature of 68 °F, the relative strength differences continued to become closer to the acceptable limit and once above 80 °F fall outside the limit.

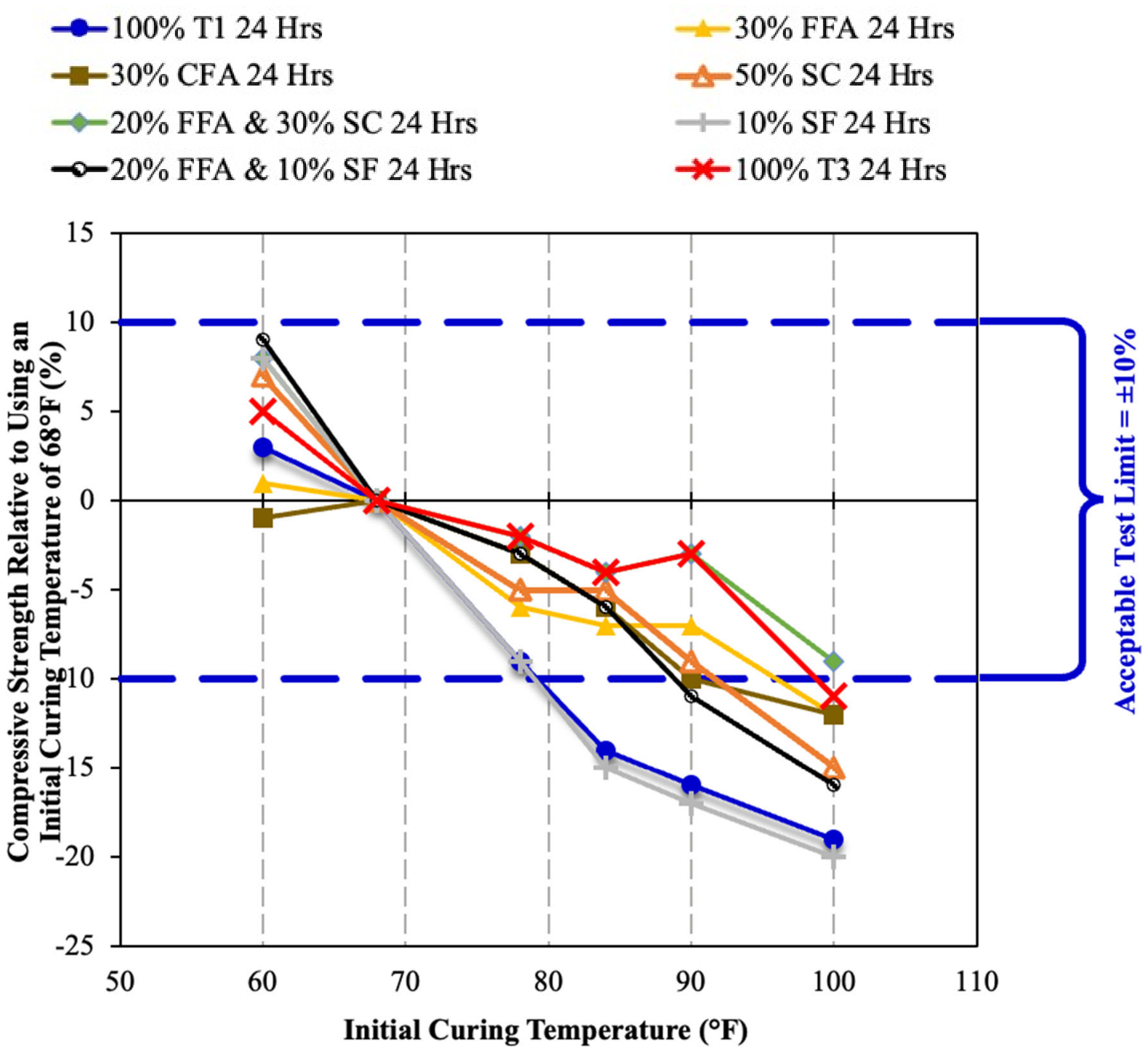

Figure 4-12: 24-Hour Initial Curing relative strength differences

4.5 48-Hour Initial Curing Duration

In addition to testing the minimum initial curing duration of 24 hours, the effect of the maximum allowable curing duration permitted by ALDOT 501 (2022) and AASHTO T23 (2018) was also evaluated. Using AASHTO T23 (2018), cylinders were cured as close as possible, but never over, 48 hours. Each cylinder was demolded and in their final curing room before reaching a concrete age of 48 hours. The strength differences shown in Table 4-12 were determined for an initial curing duration of 48 hours. Similar to what was found for a 24-hour curing duration, as the initial curing temperature increases, the loss in 28-day strength becomes greater for most concretes tested. For the results for initial curing temperatures that fall within 60 and 80 °F shown in Table 4-12, the relative strength differences all remained within the ±10% acceptable range. Ten out of 24 (41%) of the cylinder sets initially cured at 84, 90, and 100 °F, had relative strength differences that exceeded the ±10% acceptable range.

Similar to the results for the 24-hour initial curing duration, the 100% Type I and 10% silica fume batches had significant losses in 28-day strength, but the 20% Class F fly ash with 10% silica fume batch had the greatest loss in strength (23%) when cured at an initial curing temperature of 100 °F.

Table 4-12: 48-Hour Initial Curing relative strength differences

Concrete ID	48-Hour Initial Curing Temperature				
	60 °F	78 °F	84 °F	90 °F	100 °F
100% T1	3	-6	-12	-11	-16
30% FFA	4	-4	-8	-7	-8
30% CFA	4	-5	-4	-8	-14
50% SC	3	-1	-1	-5	-8
10% SF	10	-6	-11	-14	-20
20% CFA & 30% SC	9	1	-5	-3	-9
20% CFA & 10% SF	9	-4	-11	-16	-23
100% T3	7	1	-2	-5	-7

Note: Shaded values are when relative strength differences fall outside the acceptable range

Figure 4-13 illustrates the relative strength differences obtained for the 48-hour initial curing durations. Initial curing durations of 48 hours had significant effects on the relative strength differences of the concrete batches. Between 60 °F and 80 °F, every data point was within the chosen acceptable limit. However, after exceeding the 80 °F curing temperature, the relative strength differences begin to spread out and eventually fell outside of the acceptable limit for many concretes. Like the 24-hour initial curing batch, the 100% Type I and 10% Silica Fume batches had significant relative strength differences, but the 20% Class F fly ash with 10% Silica Fume batch had the largest when the initial curing temperature was increased to 100 °F. The results from the 48-hour batches reaffirm the importance of curing concrete cylinders used for quality assurance purposes at initial curing temperatures ranging from 60 to 80 °F.

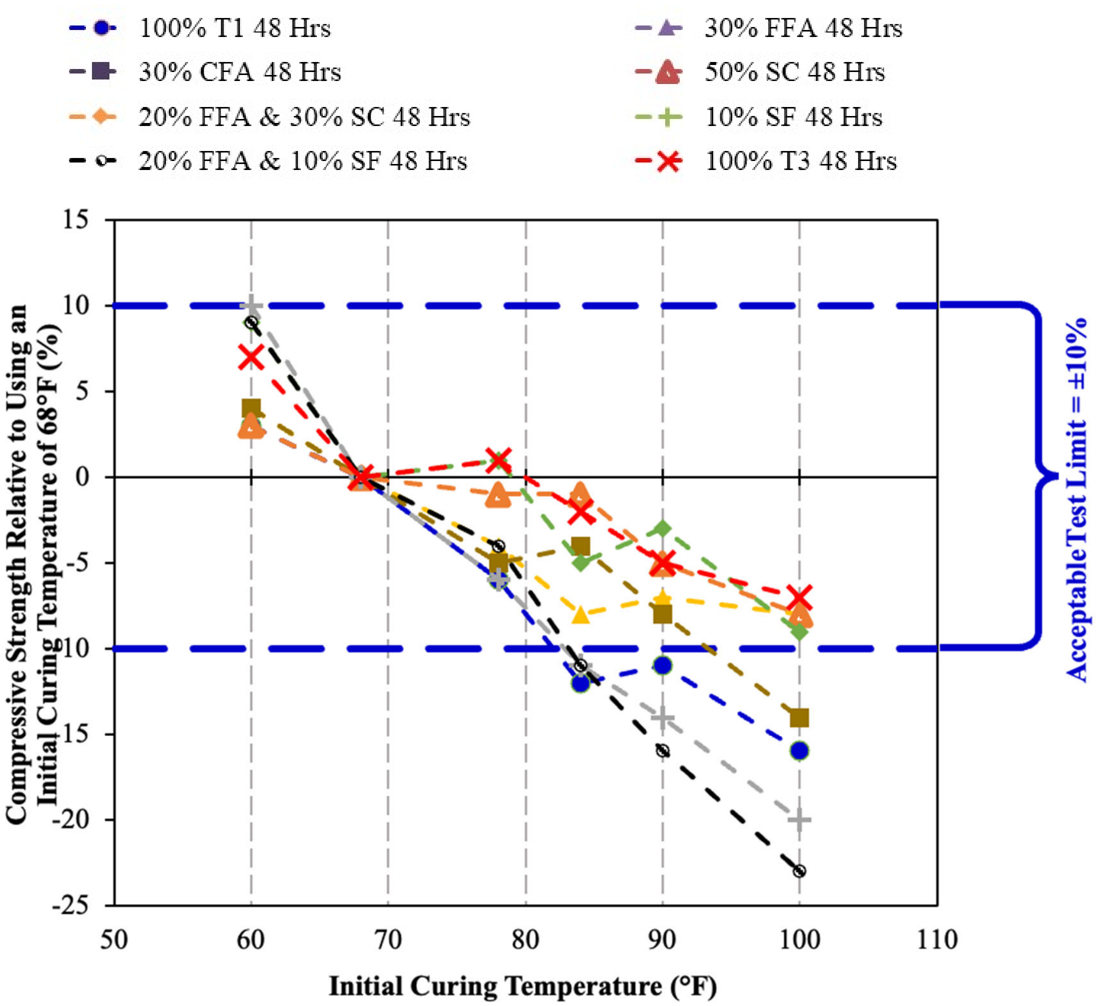

Figure 4-13: 48-Hour Initial Curing relative strength differences

4.6 72-Hour Initial Curing Duration

After analyzing the results of the 48-hour initial curing duration batches, it was decided to also determine the effect of a 72-hour initial curing duration on the 28-day strength. Instead of testing this for every mixture, four mixtures were chosen using the results available for the 24- and 48-hour curing durations. The four concretes selected had the greatest relative strength differences for the 24- and 48-hour curing durations as it was expected that they would also have the most significant strength differences when exposed to an initial curing duration of 72 hours. The following four concretes were selected to evaluate the effect of a 72-hour initial curing duration: 1) 100% Type I PCC, 2) 50% Slag cement, 3) 10% Silica Fume, 4) and 20% Class F fly ash with 10% Silica Fume.

Using the same procedures as used for the 24- and 48-hour initial curing duration batches, these mixtures were mixed and left in their respective initial curing environments for just under 72 hours. After completing 28-day compressive strength tests for each of these four mixtures, the strength differences shown in Table 4-13 were obtained.

Table 4-13: 72-Hour Initial Curing relative strength differences

Concrete ID	72-Hour Initial Curing Temperature				
	60 °F	78 °F	84 °F	90 °F	100 °F
100% T1	4	-4	-7	-7	-11
50% SC	3	-2	-5	-8	-12
10% SF	3	-5	-11	-13	-18
20% CFA & 10% SF	5	-9	-13	-16	-22

Note: Shaded values are when relative strength differences fall outside the acceptable range

Similar to the results for the 24- and 48-hour initial curing durations, the cylinders that remained within the ALDOT 501 (2022) and AASHTO T23 (2018) initial curing temperature range of 60 to 80 °F did not exhibit significant relative strength differences. Although the initial curing duration was increased by an entire day (24 hours), the relative strength differences did not change much when compared to the previous two initial curing durations. The maximum 28-day strength loss occurred in the 20% Class F fly ash with 10% Silica Fume concrete and was 22% when the initial curing temperature was 100 °F. When this concrete was initially cured at the same temperature for 48 hours, the 28-day strength loss was 23%, which is similar. Eight out of 12 (66%) of the test results fall outside of the ±10% acceptable range. It is important to note that a higher percentage of values over the ±10% acceptable range does not mean the 72-hour batches had worse results than the 24- and 48-hour initial curing duration batches. The four concrete mixtures chosen were the ones that had the most significant 28-day strength loss in the previous tests. Therefore, a higher percentage of results falling outside of the acceptable range should be expected. If only the four mixtures tested in the 72-hour batches are evaluated for the 24- and 48-hour initial curing durations, the 72-hour initial curing duration has the lowest percentage (66%) falling outside the acceptable range. Both the 24- and 48-hour initial curing duration concretes have a failure rate of 75% for the four concretes tested during the 72-hour initial curing study when the initial curing temperature exceeds 80 °F which is not too much different to the 72-hour initial curing duration results. These results are similar to the findings of Meininger (1983) who concluded that "that initial curing duration is not as significant as the temperature in affecting 28-day concrete compressive strength".

A visual representation of the four 72-hour initial curing duration batches is shown in Figure 4-14. Like the 24- and 48-hour initial curing duration batches, the cylinders that remained in the ALDOT 501 (2022) and AASHTO T23 (2018) curing environment temperature specification had minimal relative strength differences. In Figure 4-14, the 20% Fly Ash with 10% Silica Fume is the closest to exceeding the acceptable limit while remaining in the initial curing temperature requirements. At 78 °F there is a difference of -9% and although, close to the limit, it is still within ±10% and acceptable for this study. As initial curing temperatures increased past the 80 °F mark, the results were similar to those obtained when testing the previous initial curing durations of 24 and 48 hours. The results begin to fall outside of the acceptable limits as the initial curing temperature is increased past 80 °F. At the initial curing temperature of 100 °F, all relative strength differences were outside the acceptable limits of ±10%.

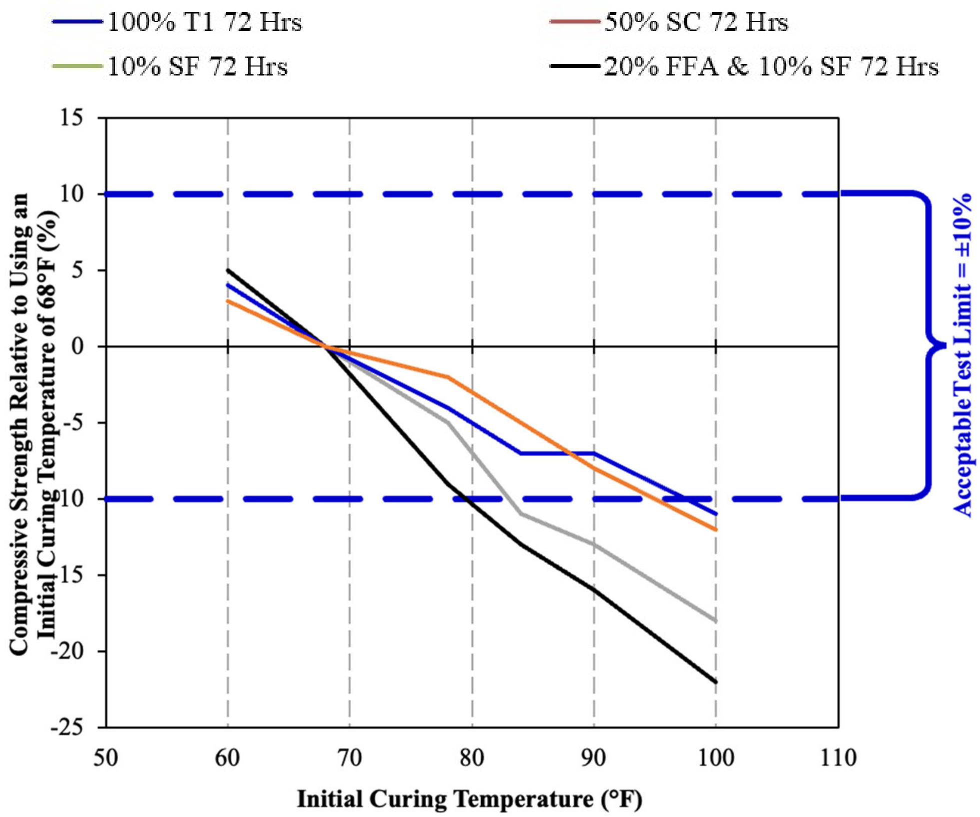

Figure 4-14: 72-Hour Initial Curing relative strength differences

4.7 Graphical Comparison of All Results for Different Initial Curing Durations

The relative strength differences of all 24 concrete batches tested are presented in Figure 4-15. In the results in Figure 4-15 in general show that as initial curing temperature increases, the concrete relative strength differences become more significant. From the data presented in Figure 8, no unique trend of increasing relative strength difference versus increasing initial curing temperature that is valid for all concretes tested can be identified. Additionally, no clear trend of relative strength differences versus initial curing duration can be determined. The data in Figure 8 shows that when the initial curing temperatures range from 60 to 80 °F, the strength differences remain within the ±10% acceptable range. Once initial curing temperatures exceed 80 °F, many (approximately half) of the 28-day concrete strengths are reduced by more than the acceptable range.

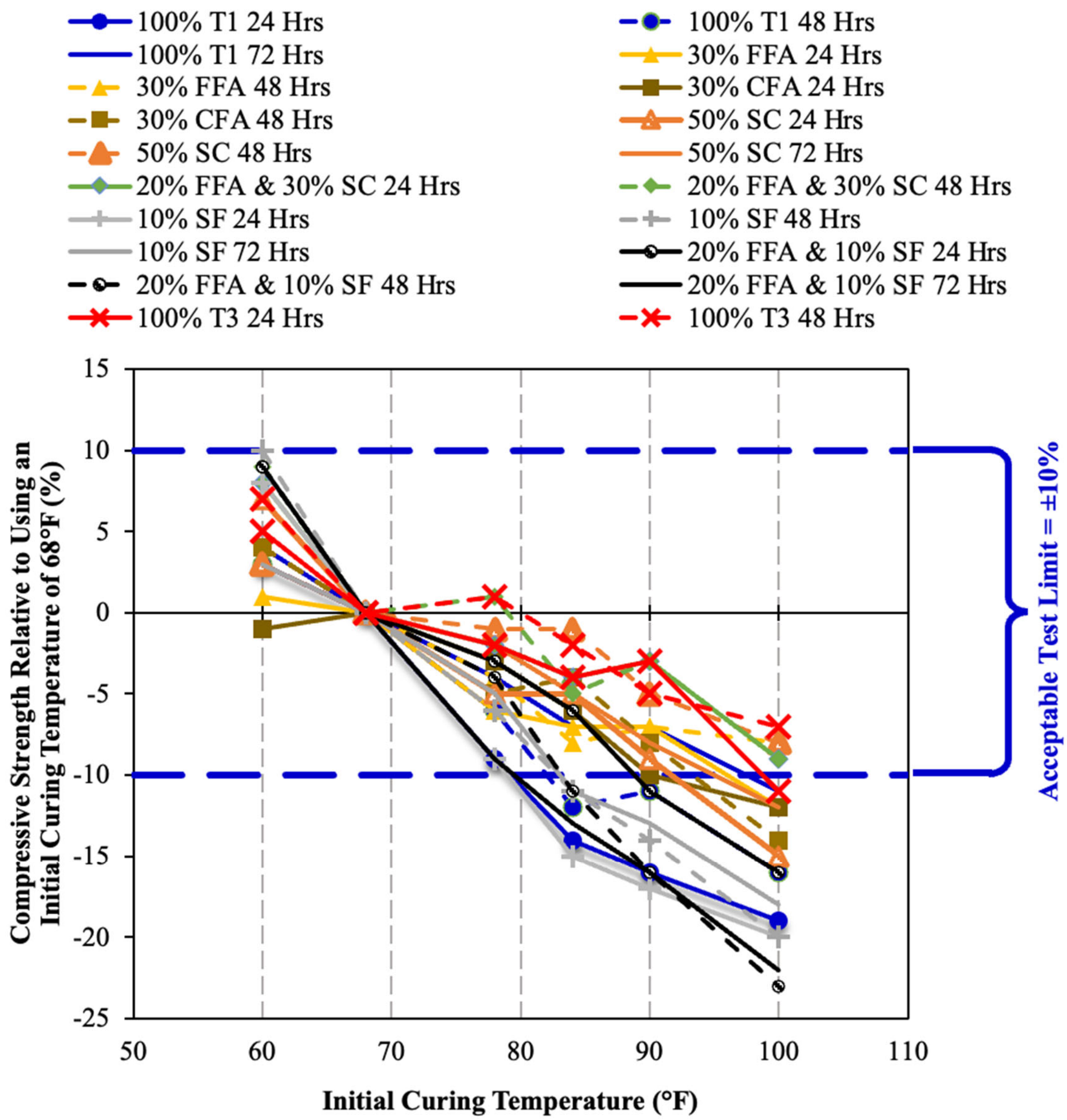

Figure 4-15: Relative strength differences for all concretes and all tested initial curing durations

In addition to initial curing temperatures, the effects of initial curing duration on the 28-day concrete compressive strength were analyzed. The relative strength differences versus initial curing temperature are shown in Figure 4-16 with data markers denoting initial curing durations of 24, 48, and 72 hours. An increase in initial curing duration did not significantly affect the relative strength differences of the concretes tested. In fact, the data supports the conclusion that concrete subjected to an initial curing duration of 72 hours has a similar 28-day strength when compared to concrete exposed to initial curing temperatures for 24 or 48 hours. Figure 4-16 clearly shows that if the initial curing temperature range remains from 60 to 80 °F then the relative strength differences should remain within the ±10% acceptable range when the initial curing duration is 24, 48, or 72 hours.

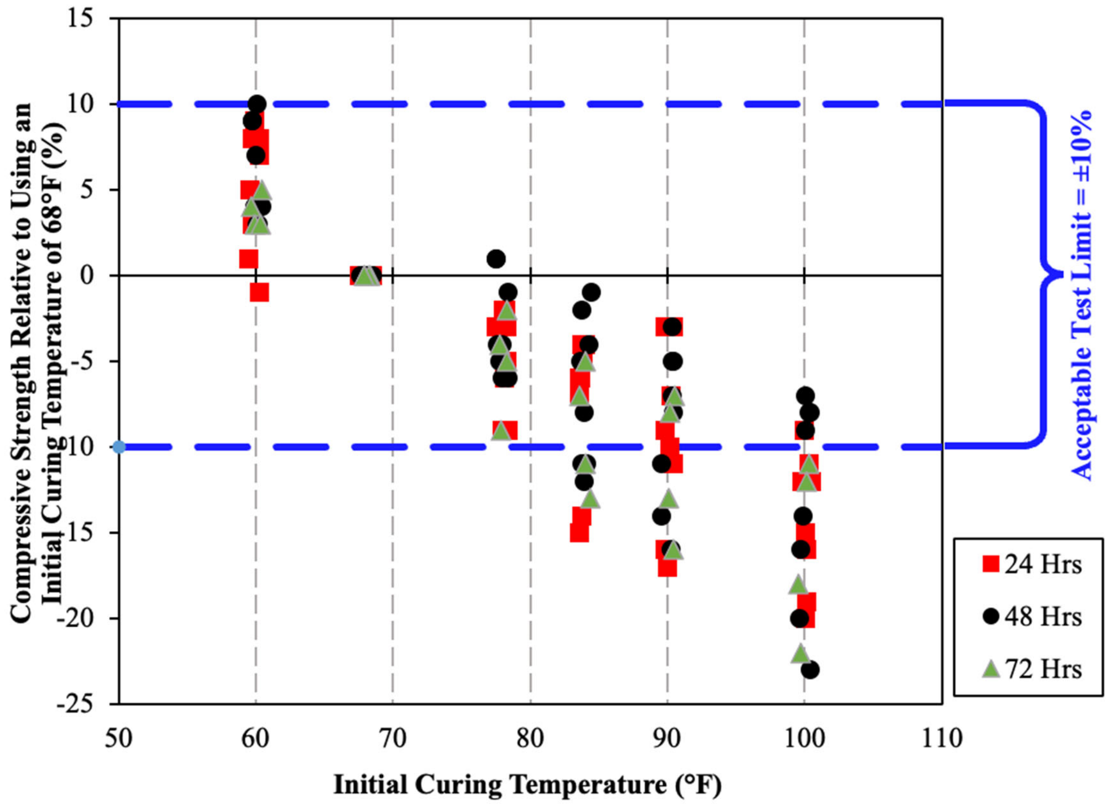

Figure 4-16: Concrete strength differences for different initial curing durations

4.8 Summary of Phase 1 Work

A total of 20 concrete batches and 4 verification batches were produced to determine the impact of concrete initial curing temperature and duration on the 28-day compressive strength of concrete. Using six different initial curing temperatures and three different initial curing durations, the relative strength differences were determined. All strength results were calculated using the average 28-day compressive strength of three cylinders for the respective initial curing environment. The relative strength differences are based on the strengths determine at a reference initial curing temperature of 68 °F. Review of all the acquired data confirms that as initial curing temperature increases the relative strength differences will become larger. The difference in initial curing duration from 24 to 72-hours does not have a significant effect on the compressive strength of concrete. Within initial curing durations from 24 to 72 hours, if the initial curing temperatures range from 60 to 80 °F, the change in 28-day compressive strength remains within acceptable limits. Once initial curing temperatures exceed 80 °F, many (approximately half) of the 28-day strengths are reduced by more than 10 percent. A maximum strength difference of 23% (almost a quarter of the control strength) was measured when the initial curing temperature was 100 °F. When the initial curing temperature remains within 60 to 80 ºF, then increasing the initial curing duration from 48 hour to 72 hour does not significantly affect the 28-day concrete compressive strength.

CHAPTER 5
PHASE 2–EXPERIMENTAL PLAN FOR FIELD WORK

This chapter provides details of the experimental plan developed for Phase 2 to assess the practices used to make, cure, transport, and test concrete cylinders to determine the 28-day compressive strength for quality assurance purposes on ALDOT projects. To evaluate practices used to provide initial curing on ALDOT jobsites, many active jobsites were visited by the research team. This chapter also includes descriptions of the equipment used, as well as the approach used to review the practices of the site personnel.

5.1 EXPERIMENTAL APPROACH

5.1.1 CURING ENVIRONMENTS

To properly review current jobsite practices for curing concrete test cylinders, three different curing environments were evaluated for each jobsite visited. These environments consisted of:

1. Standard initial cure (SIC),
2. Non-standard initial cure (NSIC), and
3. Contractor curing box.

The standard initial cure (SIC) consisted of a cylinder curing box filled with water that met all the criteria put forth in AASHTO T23 (2018) and ALDOT 501 (2022). Since the curing box used did not have the ability to record the minimum and maximum temperature of the water inside, separate temperature probes were used to measure these temperatures. This included temperature probes that could monitor temperature and capture the minimum and maximum temperature of both the curing environment temperatures as well as the cylinder temperatures. More details regarding the temperature probes are discussed in Section 5.2.1. The SIC curing box also had a capacity of 22 6x12 in. cylinders as required by ALDOT 501 (2022) and is shown in Figure 5-1. To provide power to the SIC curing box, a 3500-watt generator was used. This generator, as well as the process used to test and verify its capabilities, is discussed in Section 5.2.2.

Figure 5-1: Example of SIC Environment

The non-standard initial cure (NSIC) consisted of a generic cooler with a capacity of seven 6x12 in. cylinders, with no water inside and no temperature control. The purpose of this curing environment was to create an extreme or “worst-case scenario” curing environment during hot-weather concreting. This curing environment was designed to violate almost every requirement in ALDOT 501 and AASHTO T23 with regard to curing temperature regulation and curing box size. An example of this NSIC environment is shown in Figure 5-2.

Figure 5-2: Example of NSIC Environment

The other curing method examined was that provided by the Contractor on each jobsite visited. The purpose of this curing method was to evaluate current curing practices being used in the field. Therefore, the exact details of the Contractor curing box were different for each jobsite visited. The details of the Contractor curing box for each individual jobsite visit are discussed in Chapter 4. An example of a curing box provided by the Contractor is shown in Figure 5-3.

Figure 5-3: Example of Contractor Curing Environment

5.1.2 PROJECT TYPES

To accurately review and evaluate current practices for making, curing, transporting, and testing of concrete cylinders for ALDOT projects, multiple different project types were to be visited and reviewed. This was done to investigate if there would be a difference in meeting the requirements of ALDOT 501 depending on the type of structure, the specified design strength of the concrete being placed, or the on-site cylinder curing practices used by the Contractor. A summary of the various project types and concrete strengths reviewed is shown in Table 5-1.

Table 5-1: Jobsite types

Jobsite Visits	Project Type			Concrete Strength (psi)		
	Bridge Deck	Box Culvert	Curb and Gutter	3000	4000	5000
1-1		X				X
1-2		X			X	
1-3		X			X	
2-1			X	X		
2-2		X			X	
2-3		X				X
3-1	X					X
3-2	X					X
4-1			X	X		

5.1.3 CYLINDER TRANSPORTATION AND FINAL CURING

Upon completion of initial curing, the cylinders inside the SIC and NSIC environments were removed from their respective curing environments and transported to the Auburn University Advanced Structural Engineering Laboratory (ASEL) for final curing. Cylinders were placed in a transportation apparatus made of wood that kept them upright while protecting them from impact and excessive vibrations. The transportation setup of the cylinders is shown in Figure 5-4. The cylinders initially cured in the Contractor curing box were removed and transported to the closest ALDOT laboratory by jobsite personnel as they normally would for the ongoing project.

After arriving at ASEL, the SIC and NSIC cylinders were demolded and placed in the curing room for final cure. The curing room, produced by Darwin Chambers, was set at 73.5 ± 3.5 °F and maintained a relative humidity of 100% in accordance with ALDOT 501 (2022) and AASHTO T23 (2018).

Figure 5-4: Cylinder Transportation apparatus

5.1.4 COMPRESSIVE STRENGTH TESTING

For both the SIC environment and the NSIC environment, seven cylinders were made. Three cylinders were tested at 7 days and three at 28 days. All cylinders were tested at ASEL using the same 600 kips, Forney Automatic cylinder testing machine used for Phase 1. The testing was conducted in accordance with AASHTO T22 (2018) by a certified Level 1 ACI Concrete Laboratory Testing Technician. The cylinders were removed from the curing room in groups of three to prevent moisture loss. Neoprene pads were used; therefore, no grinding or sulfur capping of the cylinders was employed. The final seventh cylinder in the two curing environments was used solely to monitor the specimen temperature and therefore was not used for strength testing. The test cylinders made by the jobsite technicians and cured in the Contractor curing box were transported and broken by ALDOT as they normally would for the ongoing project and the test results were relayed to the research personnel for use in this report.

5.1.5 APPROACH TO EVALUATE JOBSITE PRACTICES

In addition to comparing strength results obtained for the three initial curing environments, the jobsite staff and setup were evaluated on their practices of sampling concrete, testing fresh concrete properties, and making and curing concrete cylinders. This was done by observing the actions of the technicians in how they performed each task and if it was in accordance with ALDOT 501 (2022) and AASHTO T23 (2018). Table 5-2 shows an example of the summary evaluation checklist used for the major ALDOT 501 (2022) and AASHTO T23 (2018) specification requirements that relate to sampling, fresh property testing, making, and curing of concrete test cylinders that were evaluated during each jobsite visit.

Table 5-2: Sample Evaluation Checklist for an Example Project

Did the procedure meet ALDOT 501 specification?		
Procedure	**Yes/No**	**If no, what did they do wrong?**
Sampling		
All water added before sampling?	No	Added water on site after sampling concrete for testing
Discharge first 10% of load?	No	Sampled from first 10% of the load
Fresh Concrete Testing		
Slump test	Yes	
Air Content Test	Yes	
Making Cylinders		
Mold specimens promptly on a level, rigid, horizontal surface, free from vibration	Yes	
Specimen molded in a shaded area	No	Molded in the direct sun
Initial Curing		
Curing environment within 60-80 range before concrete arrives?	No	Curing water > 80°F
22-cylinder capacity?	No	
Power source?	No	No power source supplied for the Contractor cutting box
A temperature record of the environment and specimens shall be established by means of maximum/minimum thermometers	No	Curing box did not record maximum and minimum temperatures

5.2 EQUIPMENT

5.2.1 TEMPERATURE PROBES

To record the minimum and maximum temperatures of the curing environment, temperature probes from Exact Technologies were used. This equipment consisted of temperature probes plugged into a data logger that would then collect the data and send it to a relay. Each data logger can handle up to four temperature probes. The relay had cellular capabilities that allowed it to upload readings in real-time, allowing research personnel to monitor the temperature development of the curing environment as well as the cylinders. This equipment is shown in Figure 5-5.

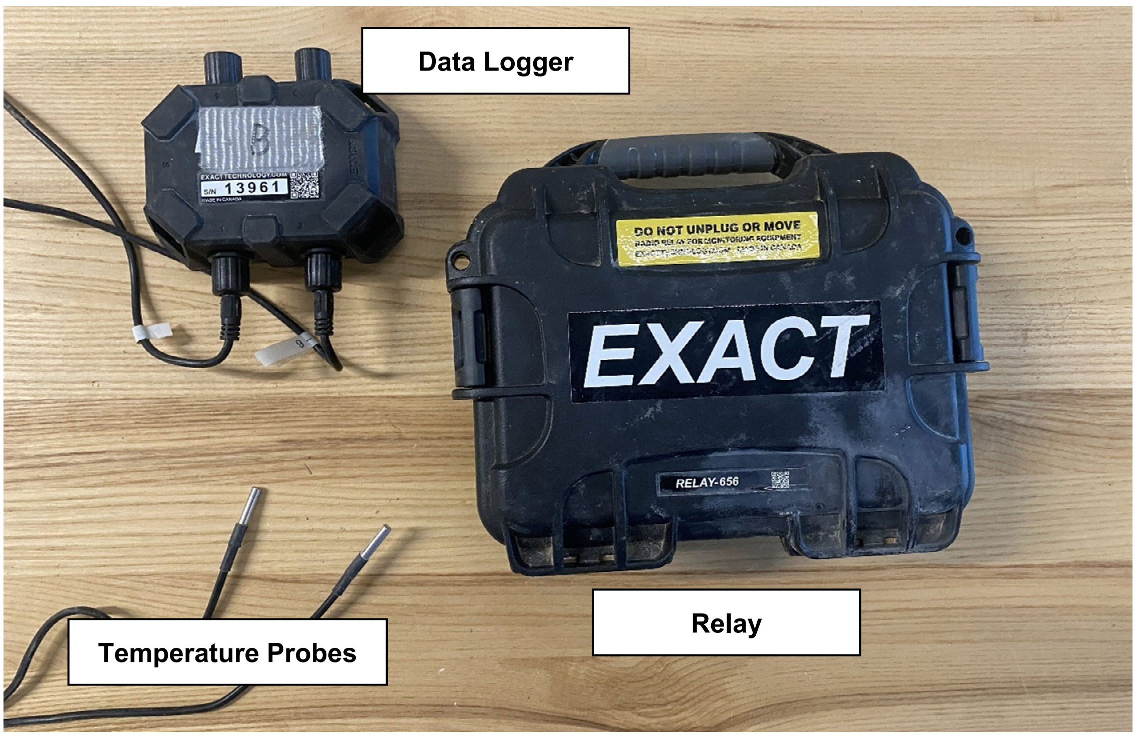

Figure 5-5: Temperature Monitoring Equipment

For each jobsite visit, six temperature probes were used, with two placed in each of the three curing environments. For the SIC environment, one probe was placed in the water to record the curing environment temperature and one probe was placed inside a cylinder to record the actual specimen temperature. For the NSIC environment, one probe was put inside the cooler to record the temperature of the curing environment (air) and one put inside a cylinder to record the specimen temperature. The probe placed to measure the curing environment was hung from the roof of the cooler not in contact with the surface of any of the cylinders inside. For the Contractor curing box, one probe was placed in the water and one in a cylinder to record the specimen temperature. The cylinder in each curing environment that contained a temperature probe was made strictly for that purpose and was not tested for strength.

For the temperature probes intended to record concrete specimen temperatures, each probe was placed within a plastic straw that was taped closed on one end. The straw had an inside diameter of 0.275 in. and the probe fit very tightly inside the straw. This straw was then inserted into the intended temperature cylinder with the probe inside. The purpose of using straws was to be able to reuse the temperature probes for multiple site visits because after the concrete hardens, the straw would be stuck in the concrete, but the temperature probe could still be removed.

5.2.2 GENERATOR

To ensure the SIC environment stayed within the acceptable temperature range specified in ALDOT 501 (2022) and AASHTO T23 (2018), a power source was required for jobsites that did not have electrical power. After researching various generator brands and models, a Craftsman 3500-watt portable generator was selected due to its power output capacity and runtime and is shown in Figure 5-6. This generator has a six-gallon fuel tank which is large for its class. To verify that it could support a SIC environment for at least 24 hours, a controlled test was performed. For the test, the SIC environment was plugged into the generator, filled with freshly made cylinders, and placed in the sun during a hot summer day. During the test, the generator ran for 28 hours before running out of gas.

Figure 5-6: Generator used to provide power to SIC Curing Box

5.3 SETUP AND TESTING AT EACH JOBSITE

Upon arrival to the jobsite, the SIC and NSIC curing boxes were set up on level ground where the NSIC would receive direct sunlight for most of the day. The generator was then turned on and the SIC curing box was plugged into it. After setting up the curing environments, the cylinder molds were laid out on a level area protected from the sun and wind. Then, the temperature probes were set up and the temperatures of both the SIC and Contractor curing boxes were checked and confirmed to be within the 60 to 80°F temperature range. This is important as it states in ALDOT 501 (2022) and AASHTO T23 (2018) that the curing environment must be in the specified range before the concrete arrives.

Upon arrival of the concrete truck, the research team observed the testing technicians and filled out the evaluation checklist described in Section 5.1.5. After the fresh concrete properties passed their respective requirements as tested by jobsite technicians, the research personnel sampled concrete by filling up a full wheelbarrow and began making cylinders in accordance with AASHTO T23 (2018). Note that all research personnel received ACI Concrete Field Testing Technician- Grade 1 certification for this project. Then, the cylinders were capped and placed in their respective initial curing environment. Lastly, the probes to record the concrete specimen temperatures were inserted into straws and then into the cylinders to record temperatures. Figure 5-7 shows the research team making cylinders on a flat shaded area. The initial curing duration of the cylinders cured in SIC and NSIC was between 24 and 48 hours, whereas the duration of the jobsite cylinders was dependent on when the jobsite staff would transport them to their final curing location and thus varied for each jobsite visit.

Figure 5-7: Research Personnel Making Cylinders

CHAPTER 6

PHASE 2–PRESENTATION AND DISCUSSION OF RESULTS

6.1 OVERVIEW OF JOBSITE VISITS

In this chapter, the results are summarized and discussed for the jobsite visits performed under the experimental plan described in Chapter 5. For each jobsite visit, the practices of the jobsite technicians and contractor are reviewed, and the temperature and concrete compressive strength results are provided. The acceptability of these results is assessed relative to the range discussed in Section 6.1.1. The effects of certain jobsite practices on the initial curing temperature and strength results are analyzed when appropriate. The names of the contractors, testing agencies, and concrete providers have intentionally not been provided as they are not relevant to the objectives of this study.

To evaluate the quality of the concrete delivered to each jobsite, the approved batch proportions are also compared to the actual supplied batch proportions. This was done to evaluate the quality of the concrete delivered to the jobsite as well as to evaluate if the amount of water added at the jobsite exceed the approved amount.

6.1.1 ACCEPTABLE RANGE OF STRENGTH RESULTS

To evaluate the initial curing methods and equipment used at each jobsite, acceptable ranges were established for the temperature and strength results obtained from each jobsite visit. Temperature results were evaluated according to the specified temperature range for the initial curing period described in AASHTO T23 (2018). Therefore, when the temperature of an initial curing environment exceeded the 60 to 80 °F range, it was deemed out of specification and thus unacceptable.

Compressive strength results for each curing method were evaluated based on their percent decrease when compared to the average cylinder compressive strength of the test cylinders cured in the SIC Curing Box for the same jobsite visit. Using the value of 9.5% presented in AASHTO T22 (2018) for three 6×12 in. cylinders cured under field conditions as shown in Table 6-1, an acceptable range of ±10% was selected as the acceptable range for compressive strength results. Since there are results from multiple jobsites being evaluated, it is reasonable that this acceptable range is slightly larger than the 9.5% of AASHTO T22 (2018) and this acceptable range also matches the range used in Phase 1 of this project as discussed in Section 3.3.6.1

Table 6-1: Acceptable Range for Cylinder Strengths (AASHTO T22 2018)

Cylinder Size and Condition	Coefficient of Variation[a]	Acceptable Range[a] of Individual Cylinder Strengths	
		2 Cylinders	3 Cylinders
150 x 300 mm (6 x 12 in.)			
Laboratory conditions	2.4%	6.6%	7.8%
Field Conditions	2.9%	8.0%	9.5%
100 x 200 mm (4 x 8 in.)			
Laboratory conditions	3.2%	9.0%	10.6%

[a] These numbers represent respectively the (1s) and (d2s) limits as described in ASTM C670

6.2 JOBSITE 1

Jobsite 1 was located in Opelika, Alabama, and consisted of a narrow construction work zone that had very limited space for concrete testing. As a result, all concrete sampling, testing, and cylinder molding were performed at an off-site field office approximately one mile away. The SIC curing box and NSIC cooler were placed outside in a location that would receive direct sunlight for most of the daylight hours. Since this jobsite testing location was at the field office, the Contractor had access to power as well as a large garage that provided shade to protect the initial curing box from direct sunlight. The Contractor's curing environment for this jobsite consisted of a curing box created with the combination of an Engel cooler and Construction Industries Thermocure II cooling system. Within the curing box, a small circulation pump was installed to help distribute water throughout the curing box. The Contractor initial curing box was placed inside a large garage and plugged into wall power as shown in Figure 6-1.

Figure 6-1: Jobsite 1–Contractor Curing Box

6.2.1 JOBSITE 1, VISIT 1

Jobsite 1, Visit 1 was performed on August 10th, 2021. The Contractor curing box was set at 74.5°F, which is within the 60 to 80 °F temperature range before the concrete was delivered. The Contractor curing box was temperature regulated; however, the Contractor had no means to record the minimum and maximum temperatures of the initial curing environment, as required by ALDOT 501 (2022) and AASHTO T23 (2018).

All testing equipment (slump cone, air meter, thermometer, etc.) was prepared and ready for the arrival of the concrete. Upon arrival of the concrete, the jobsite technicians began sampling from the front of the load. This was also not in accordance with Section 5.2.2 of AASHTO R60 (2020), as one should wait until at least 10% of the load has been discharged. After sampling, the jobsite technicians performed all fresh concrete tests and made cylinders for quality assurance testing. Once the concrete was approved, the research personnel made cylinders with the same concrete as the jobsite technicians. It was determined from the batch ticket that the Contractor added water to the load at the jobsite *after* the concrete had been sampled and tested. This is not in accordance with Section 5.2.4 of AASHTO R60 (2020), which states that samples should not be obtained until after all the water and chemical admixtures have been added.

The data collected from the temperature probes were compiled and are shown in Figure 6-2. It is significant to note that for this first jobsite visit, the research team's SIC curing box did not contain a water circulation pump inside the curing box. This caused the water temperature to vary significantly with depth as the cooling system was located at the bottom of the cooler. This is believed to have caused the SIC cylinder temperatures to be higher than that of the Contractor curing box even with colder water temperature. After learning this lesson, it was decided for future jobsite visits to ensure a water circulation pump was added to the research team's SIC curing box. A water circulation pump test was performed to verify the effectiveness of using a water circulation pump to evenly distribute the water temperature in the cylinder curing box. The results of this test are presented and discussed in Section 6.2.2.

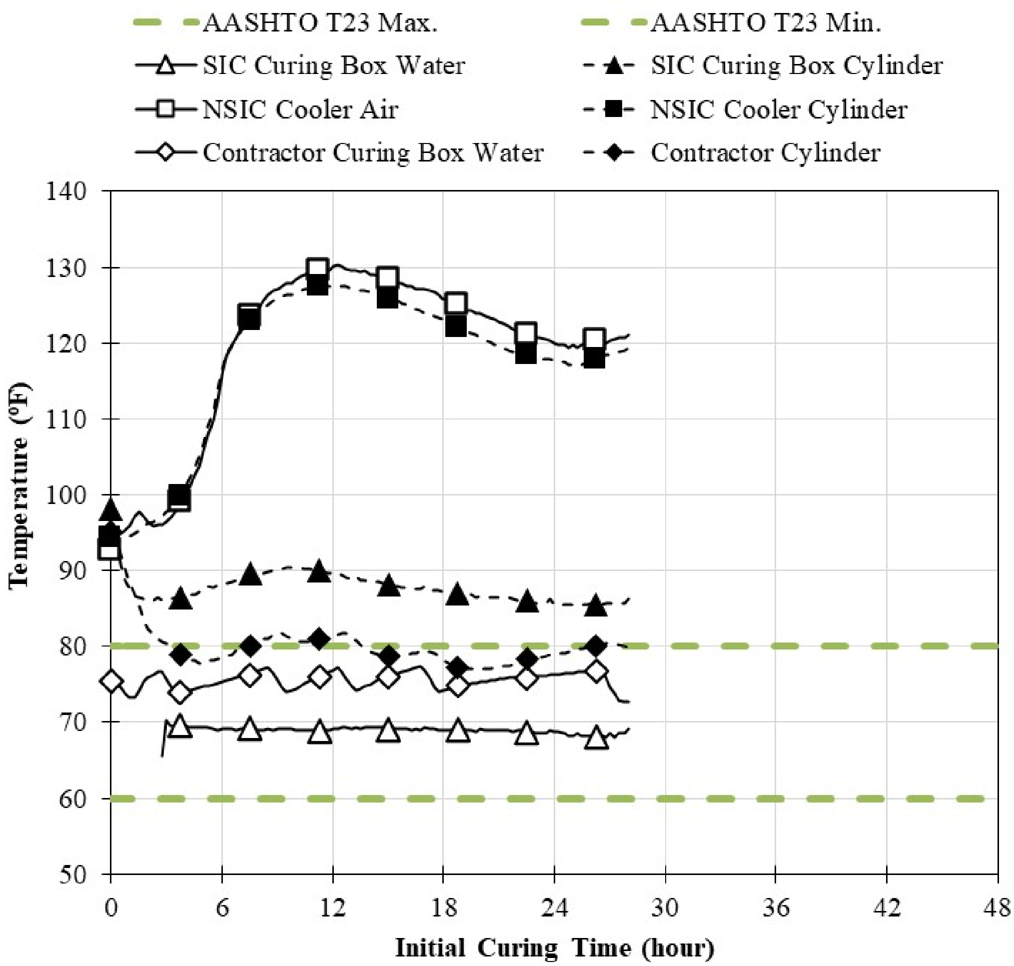

Figure 6-2: Jobsite 1, Visit 1–Temperature Results

The NSIC cooler air had a much higher temperature than that of the SIC Curing Box Water, shown in Figure 6-2, while being exposed to the same amount of ambient temperature and sunlight. This directly contributed to the significant difference in temperature measured in the concrete cylinders during the initial curing period. A pattern of gradual increase followed by a sharp decrease in the Contractor curing box water was also observed, and it was determined that while the Contractor curing box was powered on throughout the entire initial curing period, the cooling system within the curing box switched on and off depending on the water temperature.

The cylinders were retrieved and transported back to the Auburn ASEL where they were demolded and placed in the moist cure room for final curing. Cylinders were then tested at 7 and 28 days where their average cylinder compressive strength (ACCS) was calculated based off Equation 6-1.

$$\mu = \frac{\sum X_i}{n} \quad \text{(Equation 6-1)}$$

Where: X_i = test value,

n = number of test values, and

μ = average.

The average cylinder compressive strength results collected from breaking cylinders at 7 and 28 days are shown in Table 6-2. The individual cylinder compressive strength results can be found in Appendix E. The average initial curing temperature in each curing environment was determined using the temperatures recorded in each curing environment during the initial curing period and was also calculated using Equation 6-1.

Table 6-2: Jobsite 1, Visit 1, Strength Results

Jobsite 1, Visit 1					
Curing Location	**Concrete Age (days)**	**Test Date**	**Average Compressive Strength (psi)**	**Strength Difference (%)**	**Average Initial Curing Temperature (°F)**
Outdoor AU Curing Box (SIC)	7	8/17/2021	4330	0	69
	28	9/7/2021	5790	0	
Outdoor Non-Standard Cooler (NSIC)	7	8/17/2021	3820	-12	118
	28	9/7/2021	5020	-13	
Contractor Curing Box	7	8/17/2021	4470	3	76
	28	9/7/2021	5900	2	

Using the average compressive cylinder strength (ACCS) of each curing type, relative strength difference was determined by using Equation 6-2.

$$Strength\ Difference\ (\%) = \frac{(\,ACCS - SIC\ ACCS)}{SIC\ ACCS} \times 100\% \qquad \text{(Equation 6-2)}$$

These strength differences were based on the average cylinder strength of the cylinders cured in the SIC and are also summarized in Table 6-2. The strength from the SIC cylinders were used as the baseline to compare the other curing methods because they were cured and tested with in accordance with the requirements of AASHTO T23 (2018) and ALDOT 501 (2022). A negative strength difference means there was a decrease in compressive strength relative to the SIC cylinders, while a positive strength difference means there was an increase in compressive strength. The strength differences between the curing methods are illustrated in Figure 6-3.

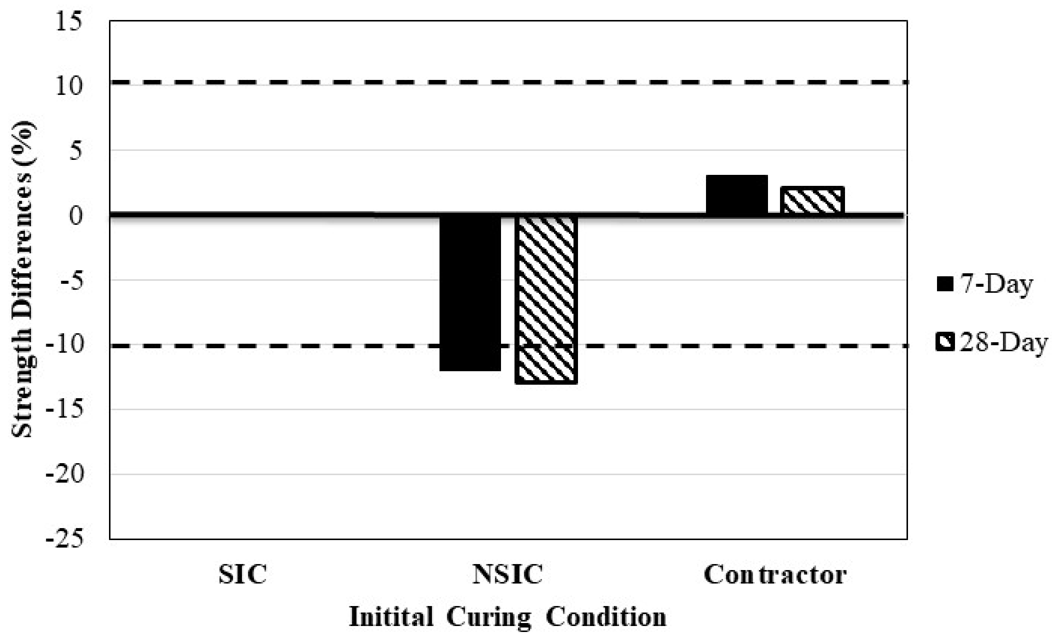

Figure 6-3: Jobsite 1, Visit 1–Strength Difference Results

6.2.2 WATER CIRCULATION PUMP TEST

After analyzing the temperature results from Jobsite 1, Visit 1, the research personnel installed a water circulation pump inside the SIC curing box. The purpose of this circulation pump was to eliminate the difference in curing box water temperature from the top of the water to the bottom as the cooling pipes in the cooler were located at the bottom. To verify the effectiveness of the water circulation pump on evening out the water temperature throughout the curing box, a water circulation pump test was conducted. This test consisted of placing the SIC curing box in an environmental chamber and filling the curing box with water. Four temperature probes were used in total. For each set of two probes, one probe was placed just under the surface of the water while the other was placed at the very bottom of the curing box, 10 in. below the top sensors. The probe set up is shown in Figure 6-4.

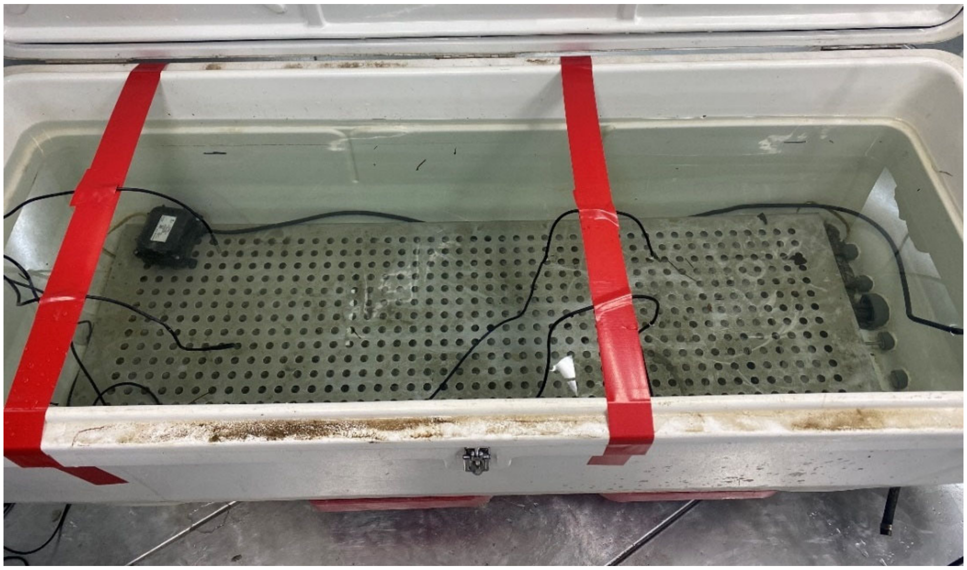

Figure 6-4: Circulation Pump Test Setup

The water circulation pump test was conducted in three phases. Phase A consisted of turning on the environmental chamber and setting it to 100°F. The SIC curing box was then propped open and left unplugged along with the water circulation pump. The purpose of this phase was to allow the chamber to heat up to the desired temperature, as well as to verify that the temperature probes used were all working correctly. Since the curing box was not powered on and the lid was propped open, each probe should have recorded approximately the same temperature. The temperature results from phase one are shown in Figure 6-5.

As expected, all four temperature probes recorded approximately the same temperature for the entire duration of Phase A. It was also expected that there would be a gradual increase in water temperature as the environmental chamber heated up to 100°F.

Phase B immediately followed Phase A and consisted of turning on the cylinder curing box and setting it at 68°F. The water circulation pump remained unplugged for Phase B as the purpose of this phase was to see the difference in water temperature from the bottom to the top of the curing box without the use of a water circulation pump. The temperature results from Phase B are shown in Figure 6-6.

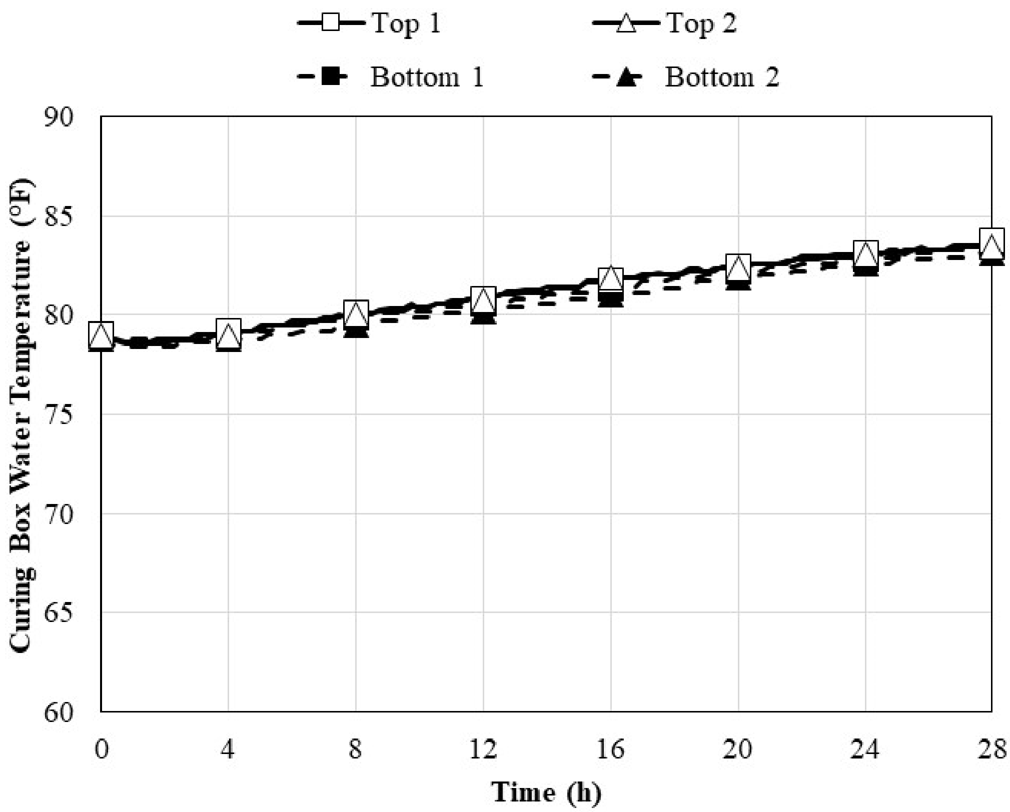

Figure 6-5: Phase A–Water Circulation Pump Test Results

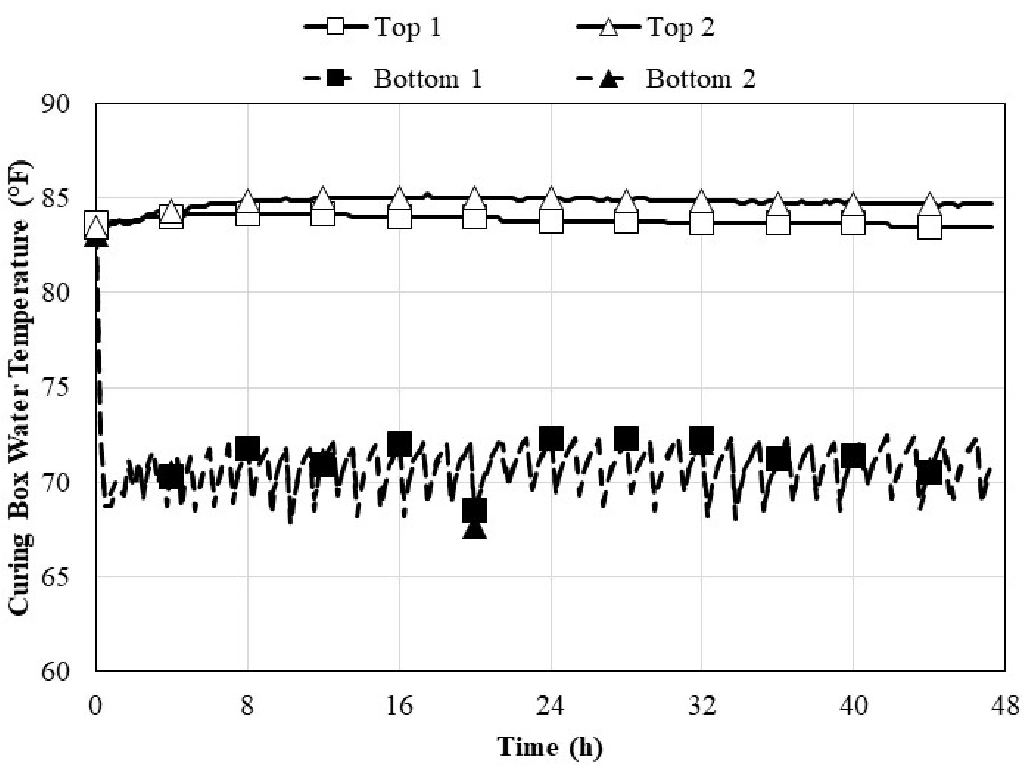

Figure 6-6: Phase B–Water Circulation Pump Test Results

Shortly after the curing box was turned on and set at 68°F, the water temperature at the bottom of the curing box dropped down to within a few degrees of the set temperature. However, the water temperature at the top of the curing box remained at approximately 84°F for the entire duration of Phase B, an approximate 12°F difference from the bottom of the curing box just 10 in. below.

Phase C immediately followed Phase B and consisted of starting the water circulation pump while the cylinder curing box and environmental chamber remained set at 68°F and 100°F, respectively. The purpose of Phase C was to evaluate the effectiveness of using a water circulation pump. The temperature results from Phase C are shown in Figure 6-7.

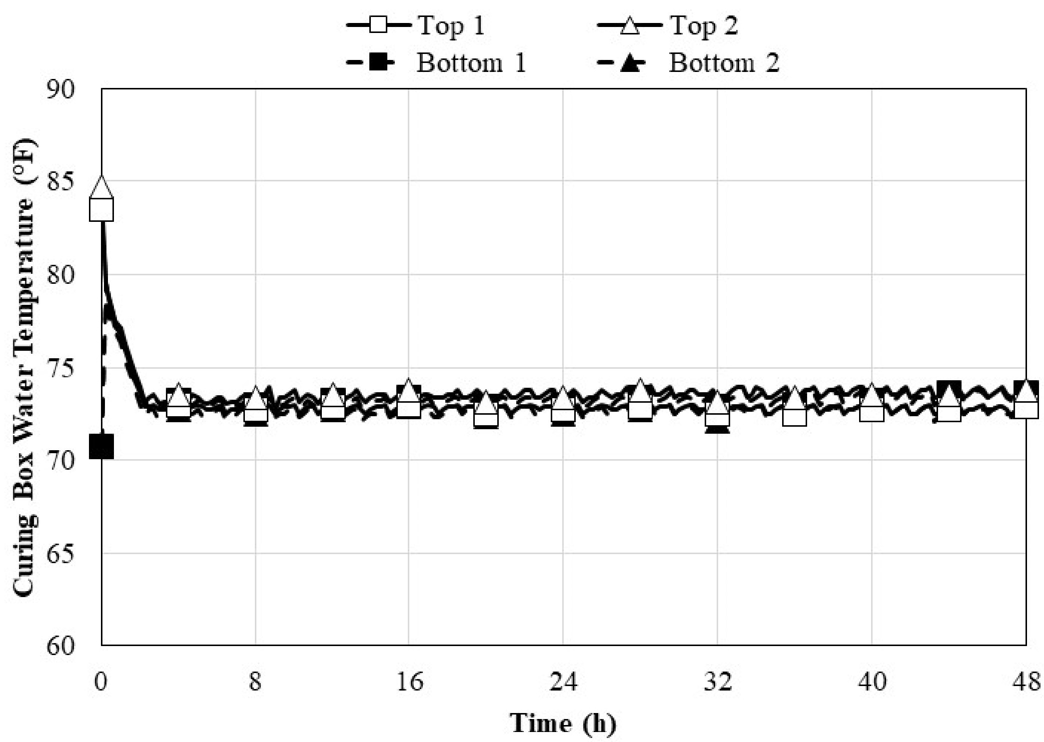

Figure 6-7: Phase C–Water Circulation Pump Test Results

Within a few hours of turning on the water circulation pump, the temperature gradient in the curing box water that caused the top of the water to be 12°F warmer than the water at the bottom of the curing box was eliminated and the water temperature throughout the curing box became consistent. This is extremely important when curing concrete cylinders because higher temperatures can cause concrete test cylinders to have a reduced 28-day compressive strength. Ultimately, it was determined that using a water circulator makes a significant difference in keeping the water temperature consistent through the entire cylinder curing box.

6.2.3 JOBSITE 1, VISIT 2

Visit 2 of Jobsite 1 was performed on August 12th, 2021. The Contractor curing box was turned on and within the 60 to 80°F temperature range before the concrete was delivered. The box was temperature regulated; however, the Contractor had no means to record the maximum and minimum temperature ranges, as required by AASHTO T23 (2018).

Upon arrival of the concrete, jobsite technicians began sampling from the front of the load. This was not in accordance with Section 5.2.2 of AASHTO R60 (2020), as one should wait until at least 10% of the load has been discharged. After sampling, the jobsite technicians performed all required concrete tests as shown in Figure 6-8, and the provided concrete failed the air content test multiple times (AASHTO T152-19). As a result, the concrete was rejected by ALDOT and therefore only the research personnel made cylinders with the concrete provided by the concrete supplier.

Figure 6-8: ALDOT Technicians Performing Fresh Concrete Property Tests

Since the batch was rejected due to high air, the research personnel were unable to acquire the mixture proportions and resulting batch ticket. Additionally, the research personnel were unable to compare the approved batch proportions with the provided batch proportions as the concrete provided and used by the research personnel to make cylinders was never placed. However, the research personnel were able to compare the temperature and strength results of the SIC and NSIC cylinders.

The data collected from the temperature probes was compiled and is shown in Figures 6-9. The AU curing box did contain a water circulation pump for the water inside the SIC curing box, unlike Visit 1, which kept the water temperature constant throughout the entire curing box. The water circulation pump was used for all following jobsite visits.

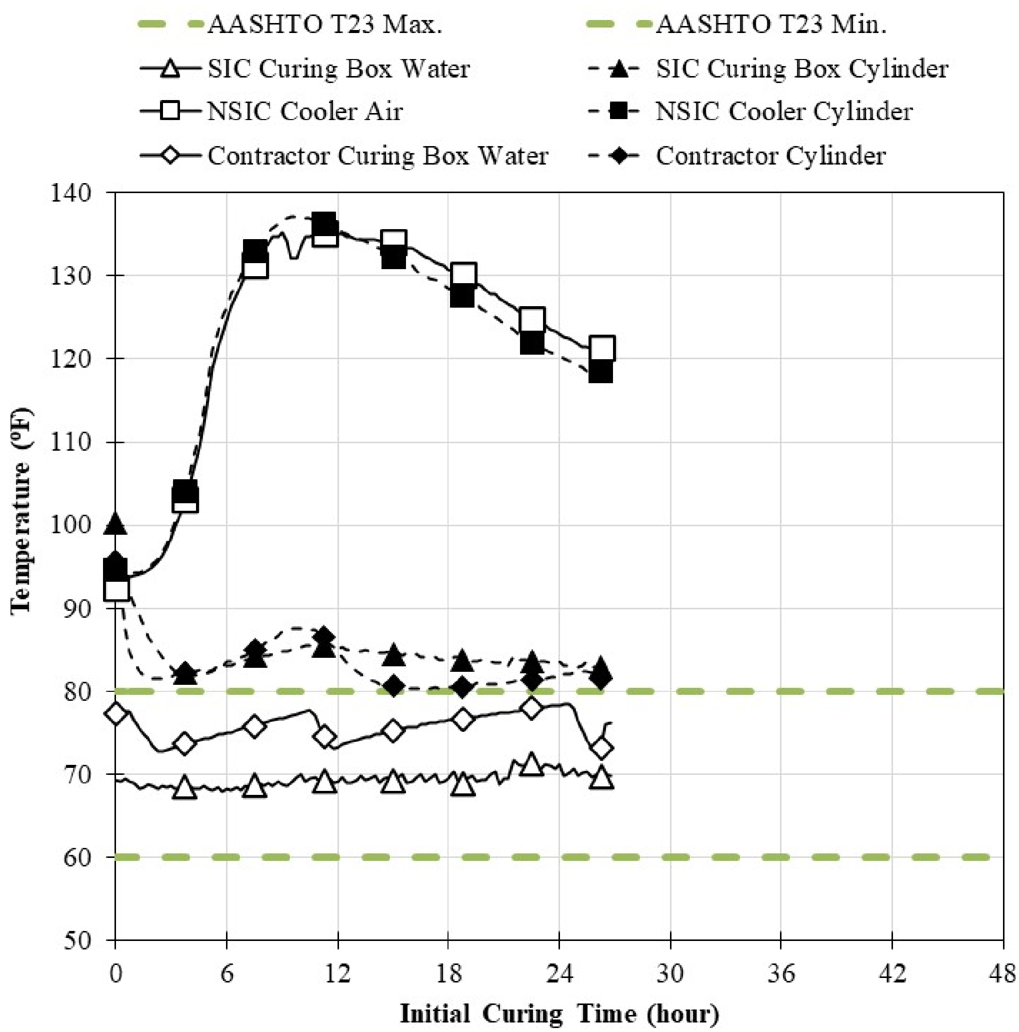

Figure 6-9: Jobsite 1, Visit 2–Temperature Results

The temperature of the NSIC cooler air was much higher than that of the SIC Curing Box water, shown in Figure 6-9, while being exposed to the same amount of ambient temperature and sunlight. This directly contributed to the significant difference in temperature measured in the respective concrete cylinders during the initial curing period. Even though the Contractor did not make any cylinders because the batch was rejected, the research personnel still put a cylinder with a temperature probe in the Contractor curing box to monitor its temperature. As it was during visit 1, a pattern of gradual increase followed by a sharp decrease in the Contractor curing box water was observed. It was determined that while the Contractor curing box remained on throughout the entire initial curing period, this was a result of the cooling system within the curing box being switched on and off depending on the water temperature. The compressive strength results for the SIC and NSIC cylinders are shown in Table 6-3.

Table 6-3: Jobsite 1, Visit 2 Strength Results

Jobsite 1, Visit 2					
Curing Location	**Concrete Age (days)**	**Test Date**	**Average Compressive Strength (psi)**	**Strength Difference (%)**	**Average Initial Curing Temperature (°F)**
Outdoor AU Curing Box (SIC)	7	8/19/2021	3800	0	69
	28	9/9/2021	5040	0	
Outdoor Non-Standard Cooler (NSIC)	7	8/19/2021	3180	-16	124
	28	9/9/2021	4350	-14	

The average cylinder compressive strength and percent strength differences were calculated using Equations 6-1 and 6-2, respectively. The Contractor did not make any cylinders because ALDOT rejected the batch due to too high air content. As a result, the only comparisons that could be made were between the AU SIC cylinders and the NSIC cylinders. The NSIC cylinders had a 16% and 14% decrease in strength at 7 and 28 days, respectively. The percent difference is based on the average cylinder compressive strength for the SIC cylinders with a negative sign representing a decrease in strength. The individual cylinder compressive strengths can be found in Appendix E. The percent differences are graphed in Figure 6-10.

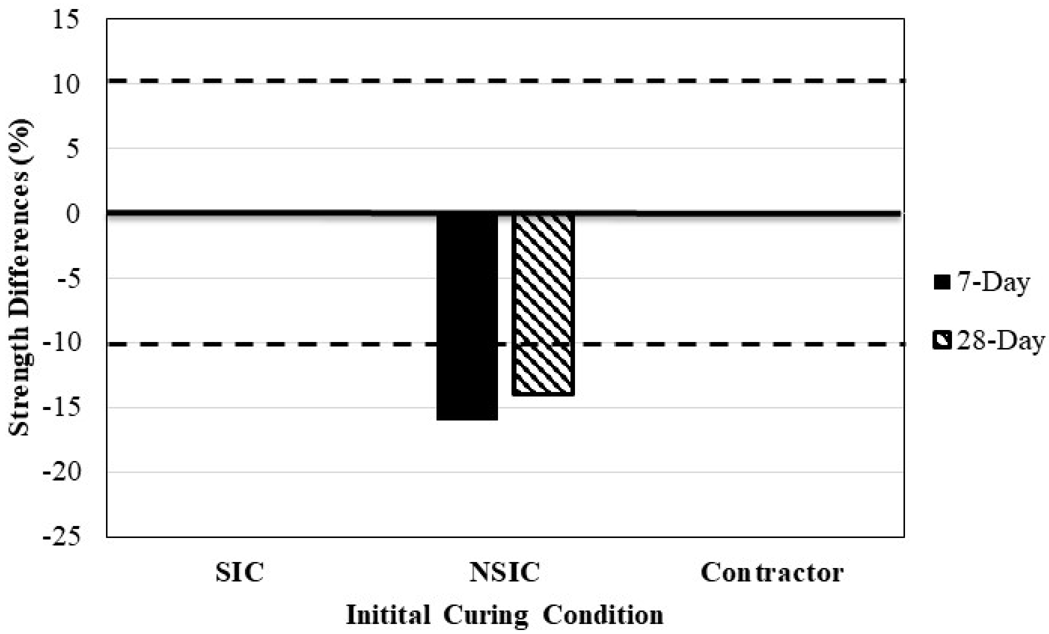

Figure 6-10: Jobsite 1, Visit 2–Strength Difference Results

6.2.4 JOBSITE 1, VISIT 3

Jobsite 1, Visit 3 was performed on August 19th, 2021. The Contractor curing box was on and within the 60-80ºF temperature range before the concrete was delivered. The Contractor curing box was temperature regulated; however, the Contractor had no means to record the maximum and minimum temperatures, as required by AASHTO T23 (2018).

Upon arrival of the concrete, jobsite technicians began sampling from the front of the load. This was not in accordance with Section 5.2.2 of AASHTO R60 (2020), as one should wait until at least 10% of the load has been discharged. After sampling, the jobsite technicians performed all fresh concrete tests and made cylinders for quality assurance testing. The research team made cylinders with the concrete approved by the jobsite technicians. The data collected from the temperature probes was compiled and is shown in Figure 6-11.

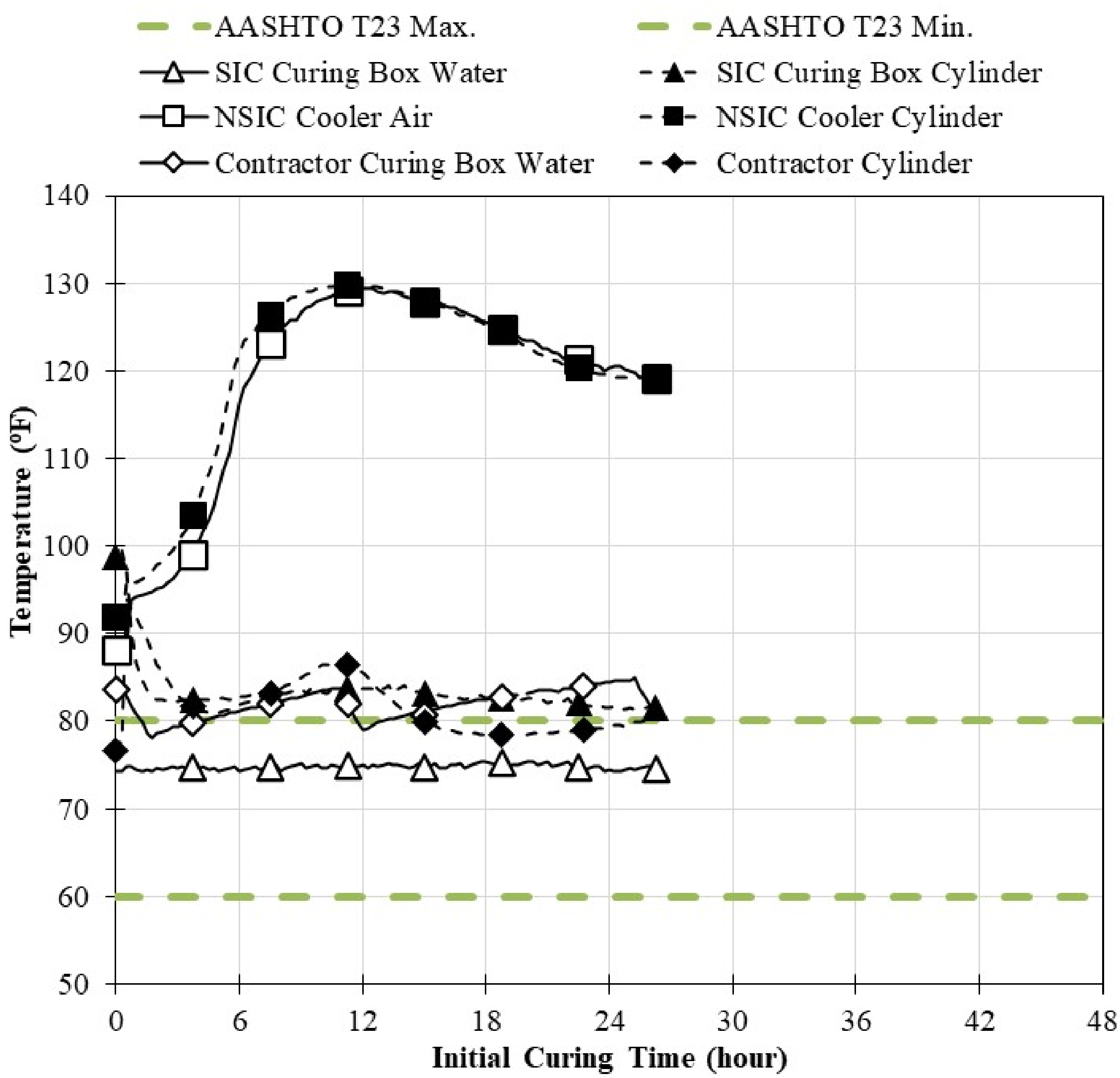

Figure 6-11: Jobsite 1, Visit 3–Temperature Results

The temperature of the NSIC cooler air was much higher than that of the SIC Curing Box water as shown in Figure 6-11, while being exposed to the same amount of ambient temperature and sunlight. This directly contributed to the significant difference in concrete temperature measured in the concrete cylinders during the initial curing period. The temperature recorded in the Contractor curing box also exceeded the 80 °F upper limit during the initial curing period. The corresponding strength results from the SIC, NSIC, and Contractor cylinders are shown in Table 6-4.

Table 6-4: Jobsite 1, Visit 3 Strength Results

Jobsite 1, Visit 3					
Curing Location	**Concrete Age (days)**	**Test Date**	**Average Compressive Strength (psi)**	**Strength Difference (%)**	**Average Initial Curing Temperature (°F)**
Outdoor AU Curing Box (SIC)	7	8/26/2021	3970	0	75
	28	9/16/2021	5450	0	
Outdoor Nonstandard Cooler (NSIC)	7	8/26/2021	3430	-14	119
	28	9/16/2021	4720	-13	
Results from Contractor	7	8/26/2021	3910	-2	82
	28	9/16/2021	5100	-6	

The average cylinder compressive strength and percent strength differences were calculated using Equations 6-1 and 6-2, respectively. The individual cylinder compressive strengths can be found in Appendix E. The percent differences are graphed in Figure 6-12.

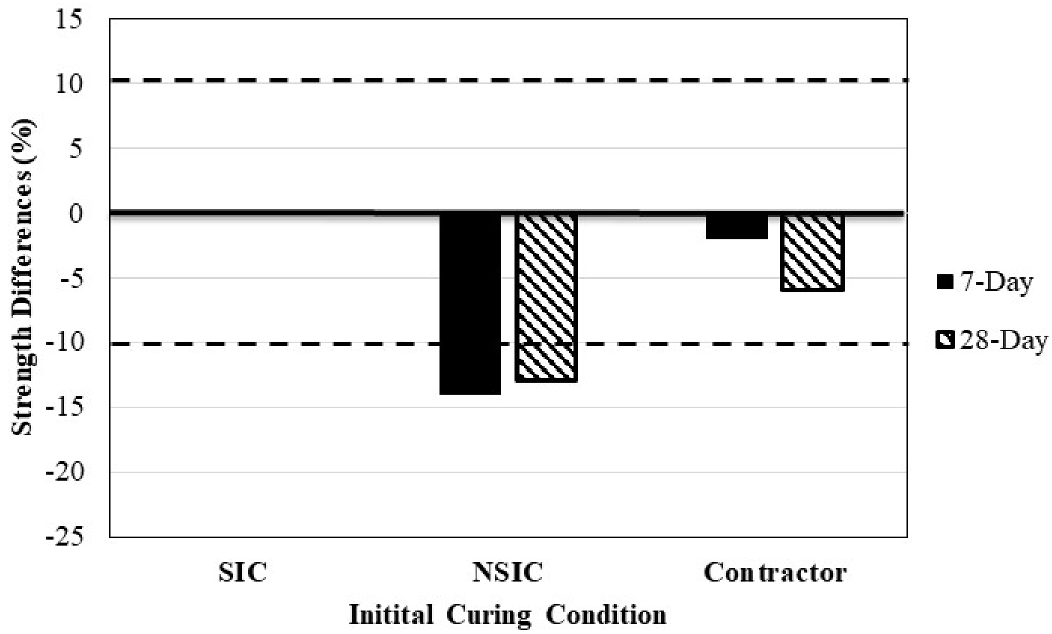

Figure 6-12: Jobsite 1, Visit 3–Strength Difference Results

6.3 JOBSITE 2

Jobsite 2 was located in Auburn, Alabama and the sampling, field testing, and initial curing were all conducted at a location very near where the concrete was placed. The Contractor curing box consisted of a curing box very similar to the Auburn University SIC Curing Box and is shown in Figure 6-13. The Contractor curing box was not hooked up to any source of power for each visit to Jobsite 2 and as a result, the Contractor was unable to regulate the temperature of the water inside. In addition, the Contractor had no means to record the minimum and maximum temperatures of the initial curing environment and therefore could not monitor whether their curing box kept the water within the 60 to 80°F temperature range. This did not meet ALDOT 501 (2022) or AASHTO T23 (2018), as one must ensure the initial curing environment is within the specified temperature range both before the concrete is delivered as well as while the cylinders remain inside the initial curing box using a minimum and maximum thermometer.

Figure 6-13: Jobsite 2–Contractor Curing Box

6.3.1 JOBSITE 2, VISIT 1

Jobsite 2, Visit 1 was conducted on June 23rd, 2022. Upon arrival to the Jobsite, members of the research team placed the AU SIC box next to the Contractor curing box to achieve similar environmental exposure conditions for comparison. The NSIC box was placed next to the SIC box where it would not be shaded from the tree but in a similar location to that of the SIC box. Both curing boxes were set up out of the way of construction equipment and wood pieces were used to ensure the curing boxes were level. The SIC and NSIC boxes are shown in Figure 6-14.

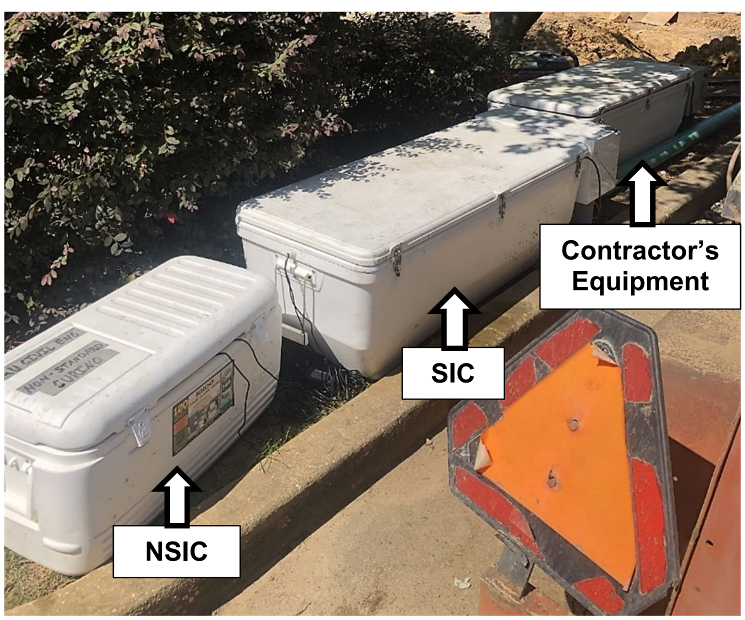

Figure 6-14: Jobsite 2, Visit 1–Cylinder Curing Box Equipment

Upon arrival of the concrete, the jobsite technicians began sampling from the front of the load. This was not in accordance with Section 5.2.2 of AASHTO R60 (2020), as one should wait until at least 10% of the load has been discharged. After sampling, the jobsite technicians performed all fresh concrete tests and made cylinders for quality assurance testing. The research personnel then made cylinders with the concrete approved by the jobsite technicians. The data collected from the temperature probes was compiled and is shown in Figure 6-15.

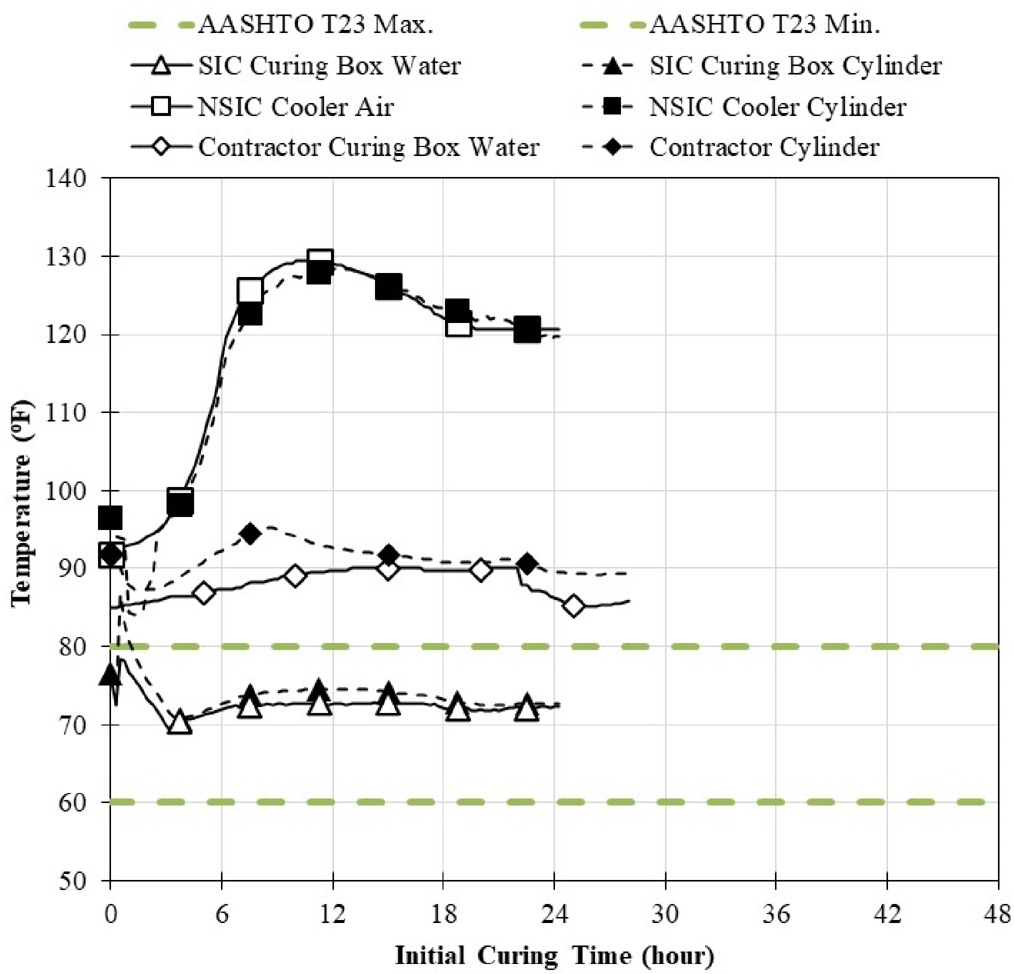

Figure 6-15: Jobsite 2, Visit 1–Temperature Results

As shown in Figure 6-15, the temperature in the NSIC cooler air was much higher than that of the SIC Curing Box water while being exposed to the same amount of ambient temperature and sunlight. This directly contributed to the significant difference in concrete temperature measured in the concrete cylinders during the initial curing period. The Contractor curing box also exceeded the 80 °F upper limit for the entire initial curing period. This led to the temperatures in the Contractor's cylinders also being high and is a result of the Contractor providing no source of power for their cylinder curing box. Without power, the Contractor curing box was unable to turn on and therefore to regulate the water temperature inside. The corresponding strength results from the SIC, NSIC, and Contractor cylinders are shown in Table 6-5. The 7-day strength results for the SIC and NSIC cylinders were unavailable as these additional cylinders were not made by the research personnel.

Table 6-5: Jobsite 2, Visit 1 Strength Results

Jobsite 2, Visit 1					
Curing Location	**Concrete Age (days)**	**Test Date**	**Average Compressive Strength (psi)**	**Strength Difference (%)**	**Average Initial Curing Temperature (°F)**
Outdoor AU Curing Box (SIC)	7	6/30/2022	N.A.	N.A.	73
	28	7/21/2022	3940	0	
Outdoor Nonstandard Cooler (NSIC)	7	6/30/2022	N.A.	N.A.	118
	28	7/21/2022	3470	-12	
Contractor Curing Box	7	6/30/2022	2920	N.A.	88
	28	7/21/2022	3780	-4	

Note: N.A. = Not Available

The average cylinder compressive strength and percent strength differences were calculated using Equations 6-1 and 6-2, respectively. The individual cylinder compressive strengths can be found in Appendix E. The percent differences are plotted in Figure 6-16.

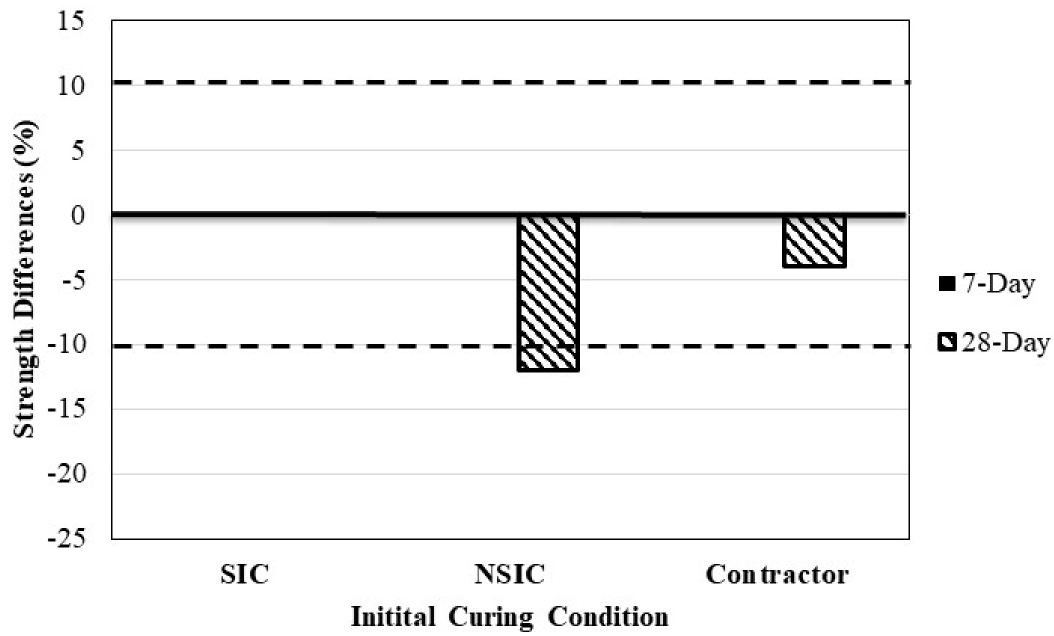

Figure 6-16: Jobsite 2, Visit 1–Strength Difference Results

6.3.2 JOBSITE 2, VISIT 2

Jobsite 2, Visit 2 was conducted on July 7th, 2022. Upon arrival to the jobsite, members of the research team placed the AU SIC and NSIC boxes in the same location and position as for Jobsite 2, Visit 1 as shown in Figure 6-14.

Upon arrival of the concrete, the jobsite technicians began sampling from the front of the load. This was not in accordance with Section 5.2.2 of AASHTO R60 (2020), as one should wait until at least 10% of the load has been discharged. After sampling, the jobsite technicians performed all fresh concrete tests and made cylinders for quality assurance testing. The research team made cylinders with the same concrete as the jobsite technicians. The data collected from the temperature probes was compiled and is shown in Figure 6-14.

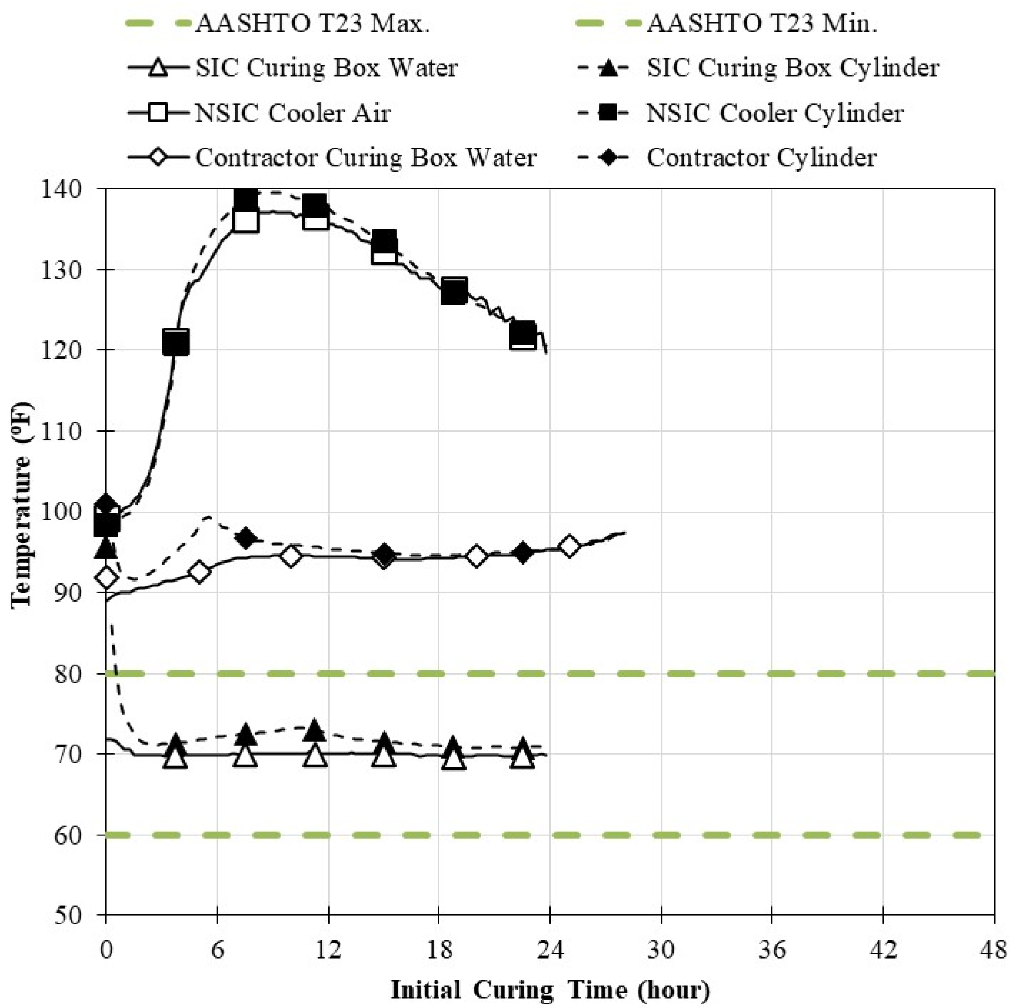

Figure 6-17: Jobsite 2, Visit 2–Temperature Results

The temperature in the NSIC cooler air was much higher than that of the SIC Curing Box water, as shown in Figure 6-17, while being exposed to the same amount of ambient temperature and sunlight. This directly contributed to the significant difference in concrete temperature measured in the concrete cylinders during the initial curing period. The corresponding strength results from the SIC, NSIC, and Contractor cylinders are shown in Table 6-6. The water temperature of the Contractor curing box was also above the specified 60 to 80°F range for the entirety of the initial curing duration. This also led to a significant decrease in the strength results for the Contractor's cylinders.

Table 6-6: Jobsite 2, Visit 2 Strength Results

Jobsite 2, Visit 2					
Curing Location	**Concrete Age (days)**	**Test Date**	**Average Compressive Strength (psi)**	**Strength Difference (%)**	**Average Initial Curing Temperature (°F)**
Outdoor AU Curing Box (SIC)	7	7/14/2022	3760	0	71.8
	28	8/4/2022	4640	0	
Outdoor Nonstandard Cooler (NSIC)	7	7/14/2022	2990	-20	137.3
	28	8/4/2022	3620	-22	
Contractor Curing Box	7	7/14/2022	3550	-6	98.4
	28	8/4/2022	4180	-10	

The average cylinder compressive strength and percent strength differences were calculated using Equations 6-1 and 6-2, respectively. The individual cylinder compressive strengths can be found in Appendix E. The percent differences are graphed in Figure 6-18.

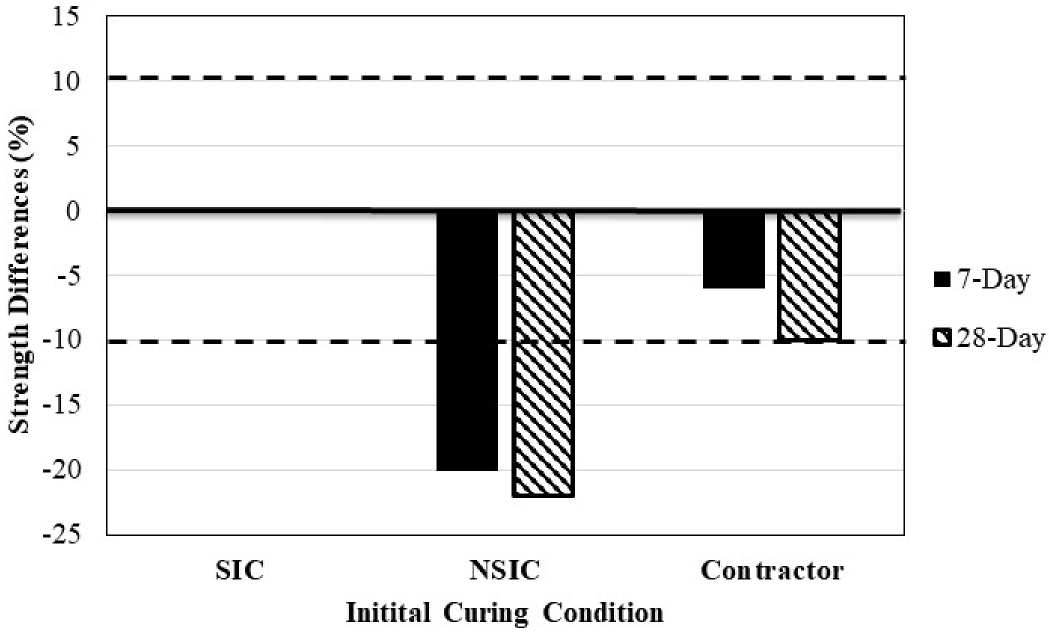

Figure 6-18: Jobsite 2, Visit 2–Strength Difference Results

6.3.2 JOBSITE 2, VISIT 3

Jobsite 2, Visit 3 was conducted on July 13th, 2022. Upon arrival to the jobsite, members of the research team placed the AU SIC and NSIC boxes in the same location and position as for Jobsite 2, Visit 1 as shown in Figure 6-14.

Upon arrival of the concrete, the jobsite technicians began sampling from the front of the load. This was not in accordance with Section 5.2.2 of AASHTO R60 (2020), as one should wait until at least 10% of the load has been discharged. After sampling, the jobsite technicians performed all fresh concrete tests and made cylinders for quality assurance testing. The research team made cylinders with the same concrete as the jobsite technicians. The data collected from the temperature probes was compiled and is shown in Figure 6-19.

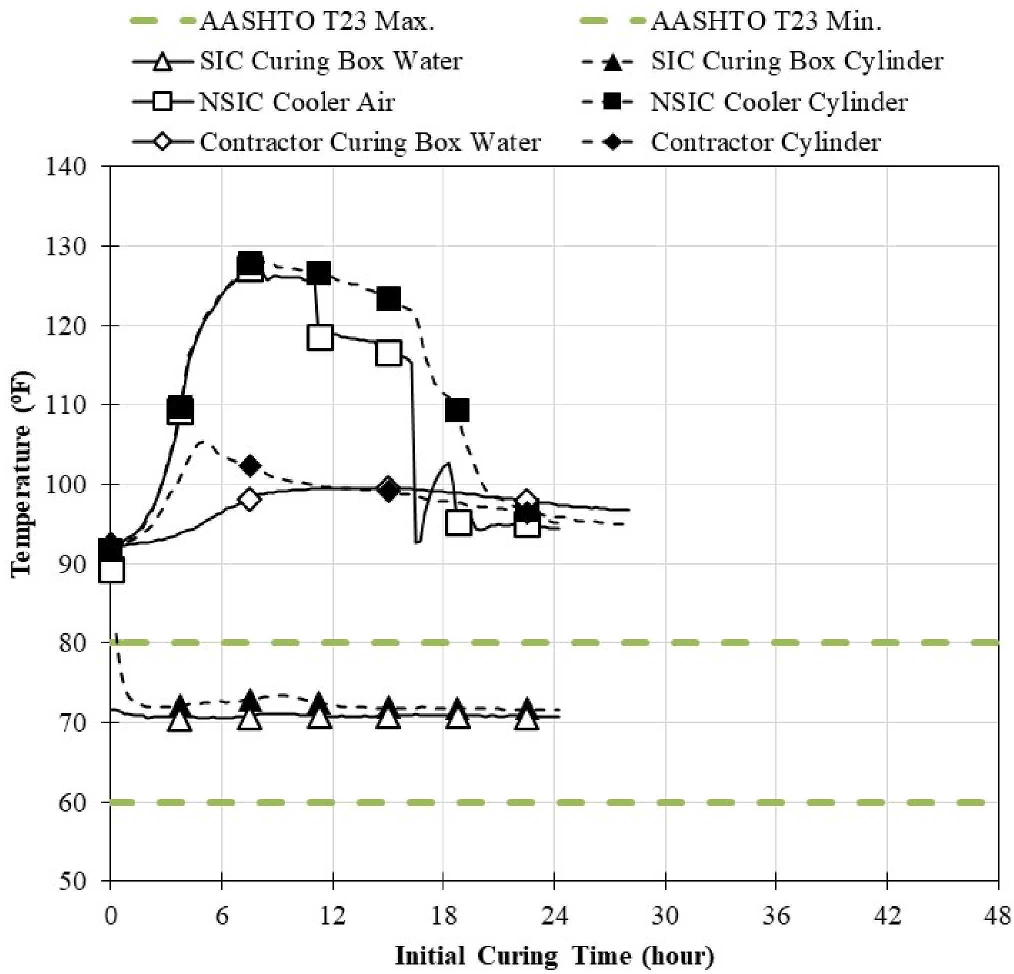

Figure 6-19: Jobsite 2, Visit 3–Temperature Results

The temperature of the NSIC cooler air was much higher than that of the SIC Curing Box water, as shown in Figure 6-19, while being exposed to the same amount of ambient temperature and sunlight. This directly contributed to the significant difference in concrete temperature measured in the concrete cylinders during the initial curing period. The sudden decrease in the NSIC cooler air was due to rain which suddenly dropped the temperature. The water temperature of the Contractor curing box was above the specified temperature range for the entirety of the initial curing duration. The corresponding strength results from the SIC, NSIC, and Contractor cylinders are shown in Table 6-7.

Table 6-7: Jobsite 2, Visit 3 Strength Results

Jobsite 2, Visit 3					
Curing Location	**Concrete Age (days)**	**Test Date**	**Average Compressive Strength (psi)**	**Strength Difference (%)**	**Average Initial Curing Temperature (°F)**
Outdoor AU Curing Box (SIC)	7	7/20/2022	5400	0	70.8
	28	8/10/2022	7290	0	
Outdoor Nonstandard Cooler (NSIC)	7	7/20/2022	4360	-19	109.1
	28	8/10/2022	5670	-22	
Contractor Curing Box	7	7/20/2022	4440	-18	91.2
	28	8/10/2022	6180	-15	

The average cylinder compressive strength and percent strength differences were calculated using Equations 6-1 and 6-2, respectively. The percent differences are illustrated in Figure 6-20. The individual cylinder compressive strengths can be found in Appendix E. The fact that the water temperature in the Contractor curing box was above the specified temperature range for the entirety of the initial curing duration directly resulted in a significant decrease in the strength results for the Contractor's cylinders.

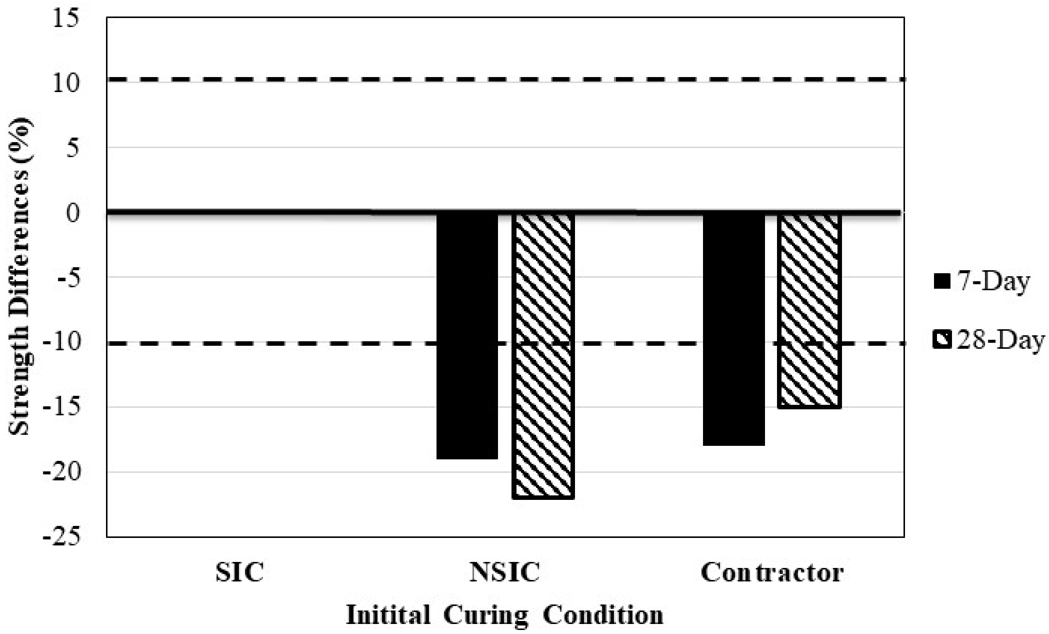

Figure 6-20: Jobsite 2, Visit 3–Strength Difference Results

6.4 JOBSITE 3

Jobsite 3 was located in Clanton, Alabama, and the sampling, field testing, and initial curing were all conducted at the same location where the concrete was placed. The Contractor curing box consisted of a beverage cooler retrofitted with a cooling apparatus. The Contractor curing box was plugged into a power source for each visit to Jobsite 3 and set at a temperature within the specified range; however, the Contractor had no means to record the minimum and maximum temperatures of the curing environment and therefore could not monitor whether their curing box was within the 60 to 80 °F temperature range during the entire initial curing period. This did not meet the requirements of AASHTO T23 (2018) or ALDOT 501 (2022), as one must ensure the initial curing environment is within the specified temperature range during the entire initial curing period using a maximum-minimum thermometer. The SIC and NSIC curing boxes were set up in the same location for each Jobsite 3 visit, and are shown in Figures 6-21 and 6-22, respectively.

Figure 6-21: Jobsite 3 SIC Curing Box

Figure 6-22: Jobsite 3 NSIC Curing Box

6.4.1 JOBSITE 3, VISIT 1

This jobsite visit was conducted on July 12th, 2022. Upon arrival to the jobsite, members of the research team began to set up all equipment to be used for the concrete testing and initial curing. Upon arrival of the concrete, the jobsite technicians discharged a full wheelbarrow of concrete from the truck before sampling. While this practice still does not meet the requirements of Section 5.2.2 of AASHTO R60 (2020), as one should wait until at least 10% of the load has been discharged before sampling, it was a conscientious effort to not sample from the first concrete discharged from the chute as such concrete is generally segregated and not representative of the rest of the truck. This practice, along with the proposed changes to ALDOT 501, is discussed in more detail in Chapter 7.

After sampling, the jobsite technicians performed all fresh concrete tests and made cylinders for quality assurance testing. The research team made cylinders with the concrete approved by the jobsite technicians. The data collected from the temperature probes was compiled and is shown in Figure 6-23.

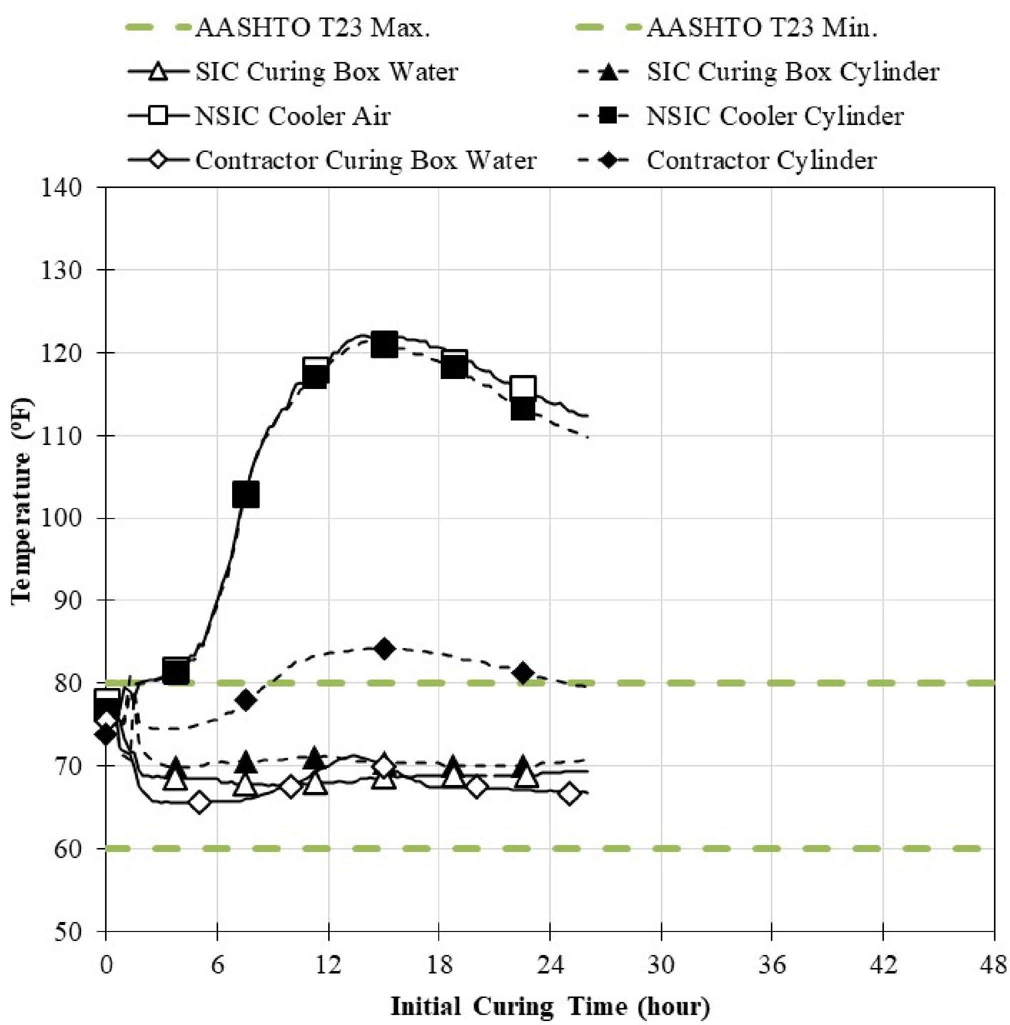

Figure 6-23: Jobsite 3, Visit 1–Temperature Results

As shown in Figure 6-23, the temperature in the NSIC cooler air was much higher than that of the SIC Curing Box water while being exposed to the same amount of ambient temperature and sunlight. While the Contractor curing box kept the water temperature well within the specified temperature range, the temperature of the Contractor's cylinders exceeded the 80 °F upper limit. This temperature difference between the Contractor's cylinders and Contractor curing box water is due to the Contractor cylinder curing box not being equipped with a water circulation pump. As a result, the water temperature at the bottom of the cooler where the temperature probe and cooling pipes were located, remained within the acceptable temperature range, however the temperature in the concrete cylinders did not. The corresponding strength results from the SIC, NSIC, and Contractor cylinders are shown in Table 6-8.

Table 6-8: Jobsite 3, Visit 1 Strength Results

Jobsite 3, Visit 1					
Curing Location	**Concrete Age (days)**	**Test Date**	**Average Compressive Strength (psi)**	**Strength Difference (%)**	**Average Initial Curing Temperature (°F)**
Outdoor AU Curing Box (SIC)	7	7/19/2022	4900	0	69.0
	28	8/9/2022	6330	0	
Outdoor Nonstandard Cooler (NSIC)	7	7/19/2022	4340	-11	107.9
	28	8/9/2022	5480	-13	
Contractor Curing Box	7	7/19/2022	4890	0	67.9
	28	8/9/2022	6360	0	

The average cylinder compressive strength and percent strength difference calculations were calculated using Equations 6-1 and 6-2, respectively. The individual cylinder compressive strengths can be found in Appendix E. The percent differences are graphed in Figure 6-24.

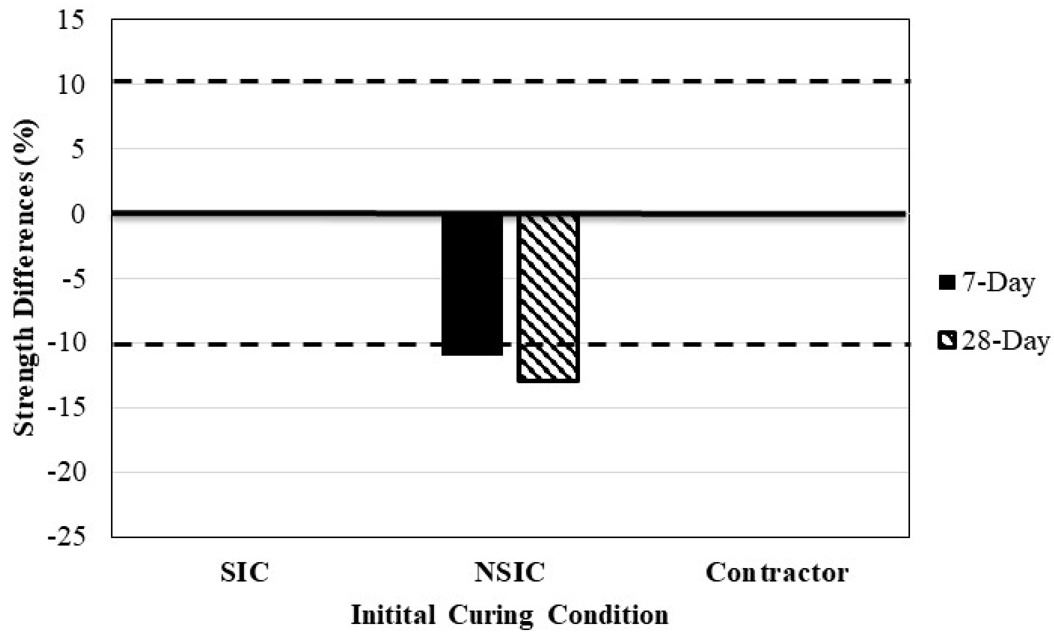

Figure 6-24: Jobsite 3, Visit 1–Strength Difference Results

6.4.2 JOBSITE 3, VISIT 2

This jobsite visit was conducted on July 21st, 2022. Upon arrival to the jobsite, members of the research team began to set up all equipment to be used for the concrete testing and curing. Upon arrival of the concrete at 4:30 am, the jobsite technicians discharged a full wheelbarrow of concrete from the truck before sampling. While this practice does not meet the requirements of Section 5.2.2 of AASHTO R60 (2020), as one should wait until at least 10% of the load has been discharged, it was a conscientious effort to not sample from the first concrete discharged from the chute as such concrete is generally segregated and not representative of the rest of the truck. This practice, along with the proposed changes to ALDOT 501, is discussed in more detail in Chapter 7.

After sampling, the jobsite technicians performed all fresh concrete tests and made cylinders for quality assurance testing. The research team made cylinders with the concrete approved by the jobsite technicians. The data collected from the temperature probes was compiled and is shown in Figure 6-25.

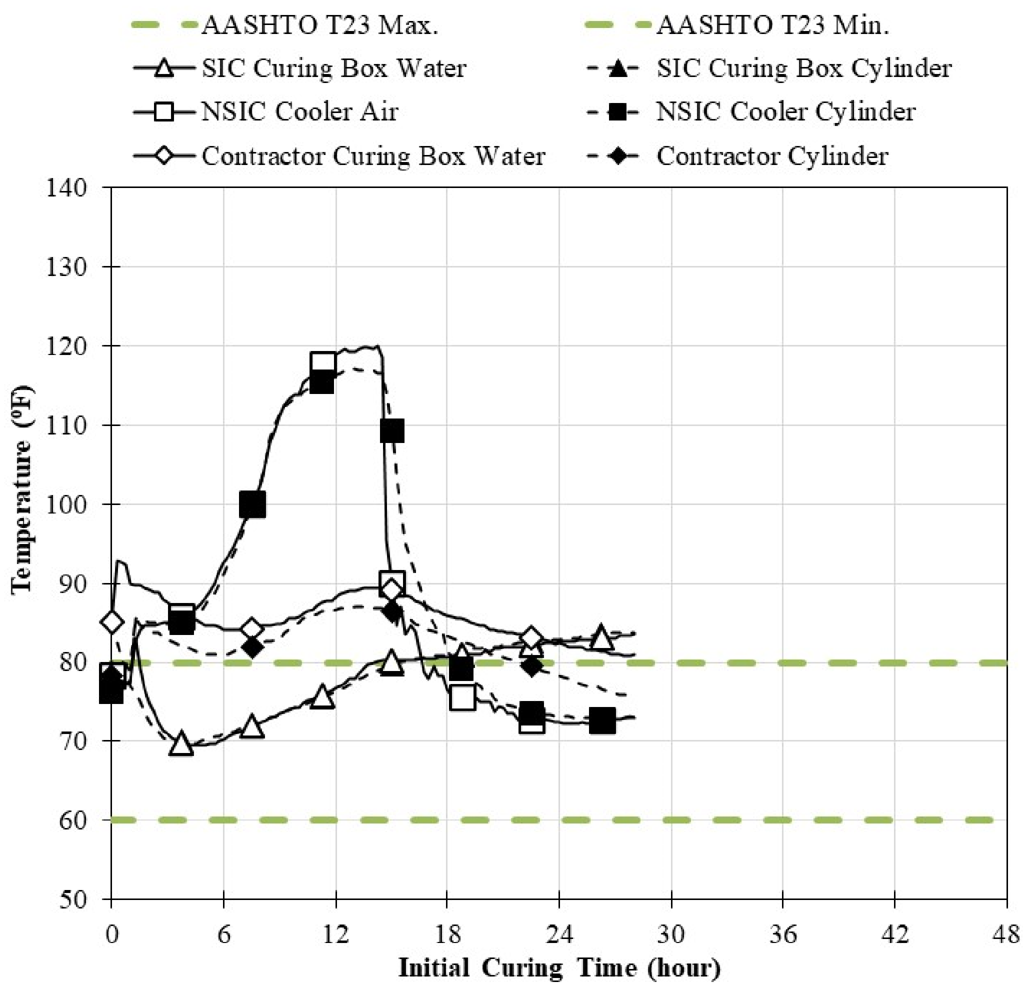

Figure 6-25: Jobsite 3, Visit 2–Temperature Results

The temperature in the NSIC cooler air was much higher than that of the SIC Curing Box water, as shown in Figure 6-25, while being exposed to the same amount of ambient temperature and sunlight. This directly contributed to the significant difference in concrete temperature measured in the concrete cylinders during the initial curing period. The sudden decrease in the NSIC cooler air was due to the time of day the concrete was poured. With the cylinders being made at 4:30 am, the sun was not up yet and therefore there was also a slower increase in temperature of the NSIC cooler air. The corresponding strength results from the SIC, NSIC, and Contractor cylinders are shown in Table 6-9.

Table 6-9: Jobsite 3, Visit 2 Strength Results

Jobsite 3, Visit 2					
Curing Location	**Concrete Age (days)**	**Test Date**	**Average Compressive Strength (psi)**	**Strength Difference (%)**	**Average Initial Curing Temperature (°F)**
Outdoor AU Curing Box (SIC)	7	7/28/2022	4670	0	77.9
	28	8/18/2022	5900	0	
Outdoor Nonstandard Cooler (NSIC)	7	7/28/2022	4440	-5	88.7
	28	8/18/2022	5270	-11	
Contractor Curing Box	7	7/28/2022	4950	6	85.7
	28	8/18/2022	6250	6	

The average cylinder compressive strength and percent strength difference calculations were determined with Equations 6-1 and 6-2, respectively. The individual cylinder compressive strengths can be found in Appendix E. The percent differences are illustrated in Figure 6-26. Although the Contractor curing box water exceeded the 80 °F upper limit, the relative 28-day compressive strength differences of the Contractor's cylinders remained within the ±10% acceptable limit and experienced a slight increase in compressive strength compared to the SIC cylinders. This was unexpected, and it is unknown as to why there was a slight increase in relative strength from the Contractor's cylinders, even though they were cured at a slightly higher initial curing temperature.

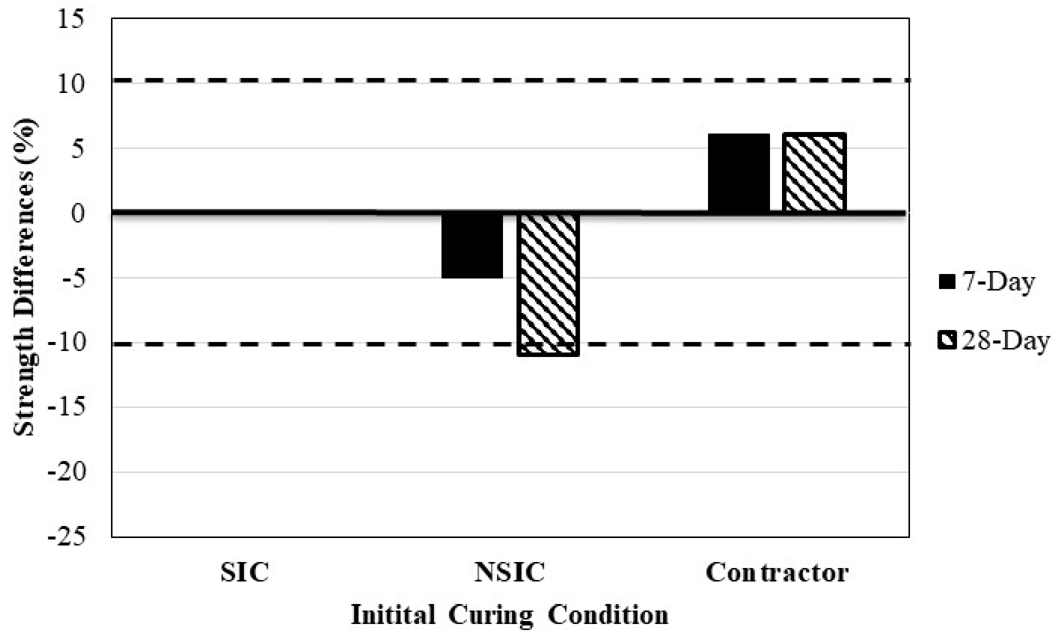

Figure 6-26: Jobsite 3, Visit 2–Strength Difference Results

6.5 JOBSITE 4

Jobsite 4 was located in Auburn, Alabama, and the sampling, field testing, and initial curing were all conducted at the same location the concrete was placed. The Contractor's curing method consisted of a curing box hooked up to a generator and is shown in Figure 6-27.

Figure 6-27: Jobsite 4 Contractor Curing Box

The Contractor curing box was plugged into a power source for Jobsite 4 and set at a temperature within the specified range; however, the Contractor had no means to record the minimum and maximum initial curing temperatures and could thus not monitor if this curing box was within the 60 to 80 °F temperature range during the entire initial curing period. This did not meet the requirements of ALDOT 501 (2022) and AASHTO T23 (2018), as one must ensure the initial curing environment is within the specified temperature range during the entire initial curing period using a maximum-minimum thermometer. The SIC and NSIC curing boxes were set up in the same location as the Contractor curing box and are shown in Figures 6-28 and 6-29.

Figure 6-28: Jobsite 4 SIC Curing Box

Figure 6-29: Jobsite 4 NSIC Curing Box

6.5.1 JOBSITE 4, VISIT 1

Jobsite 4, Visit 1 was conducted on August 11th, 2022. Upon arrival to the jobsite, members of the research team began to set up all equipment to be used for the concrete testing and curing. Upon arrival of the concrete, the jobsite technicians began sampling from the beginning of the load. This does not meet the requirements of Section 5.2.2 of AASHTO R60 (2020), as one should wait until at least 10% of the load has been discharged. After sampling, the jobsite technicians performed a slump test, however, they did not have the equipment to perform the air content test and therefore did not perform this test. This did not meet the requirements of ALDOT 501 (2022). The jobsite technicians and the research team then proceeded to make cylinders with the approved concrete. The data collected from the temperature probes was compiled and is shown in Figure 6-30.

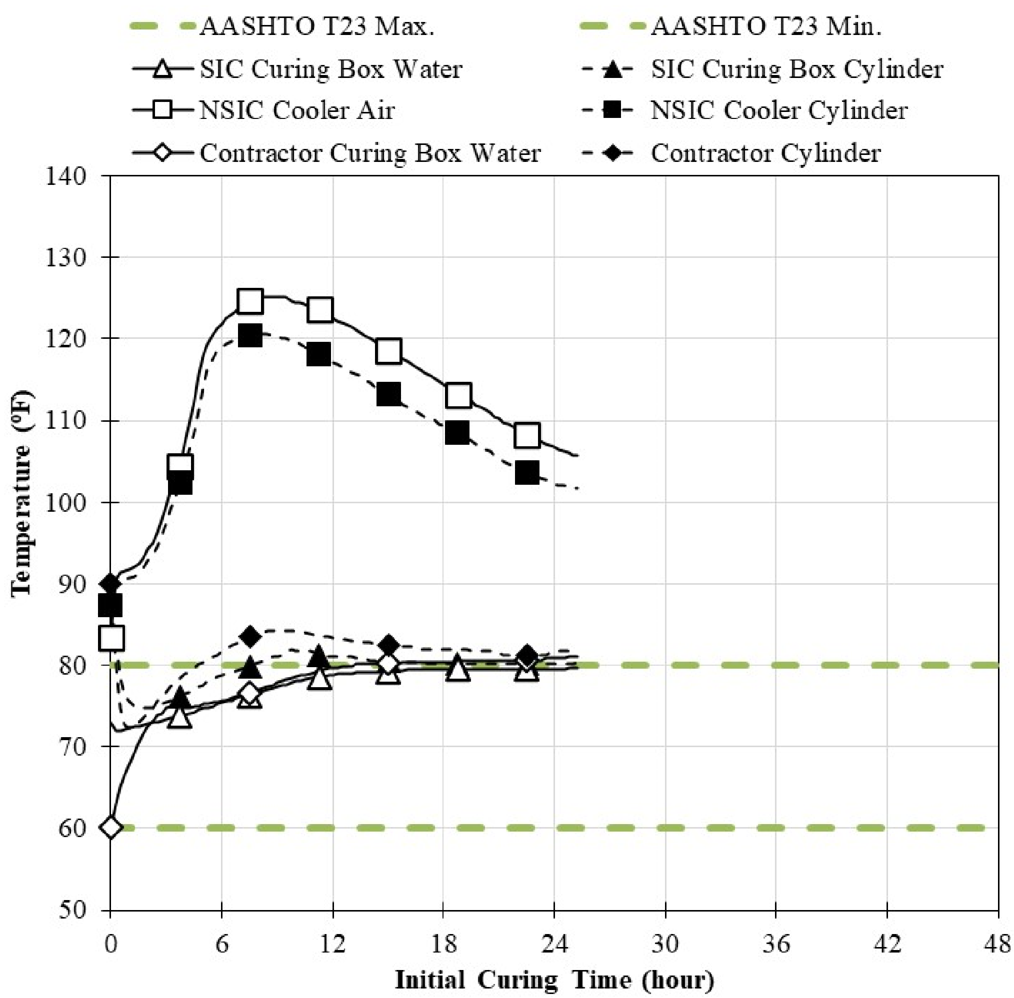

Figure 6-30: Jobsite 4, Visit 1–Temperature Results

The temperature in the NSIC cooler air was much higher than that of the SIC Curing Box water, as shown in Figure 6-30, while being exposed to the same amount of ambient temperature and sunlight. There is a significant difference in concrete temperatures measured in the concrete cylinders during the initial curing period. During the initial curing period, the generator for the SIC curing box was turned off at some point by an unknown individual as there was still fuel in the generator and the power switch was in the off position. This resulted in a steady rise of the water temperature inside the SIC curing box; however, it never exceeded the 80 °F upper limit; however, the SIC cylinder temperatures exceeded 80 °F. The water temperature inside the Contractor curing box also exceeded the 80 °F limit during the initial curing period. The corresponding strength results from the SIC, NSIC, and Contractor cylinders are shown in Table 6-10.

Table 6-10: Jobsite 4, Visit 1 Strength Results

Jobsite 4, Visit 1					
Curing Location	**Concrete Age (days)**	**Test Date**	**Average Compressive Strength (psi)**	**Strength Difference (%)**	**Average Initial Curing Temperature (°F)**
Outdoor AU Curing Box (SIC)	7	8/18/2022	2320	0	77.5
	28	9/8/2022	4380	0	
Outdoor Nonstandard Cooler(NSIC)	7	8/18/2022	2090	-10	113.3
	28	9/8/2022	3950	-10	
Contractor Curing Box	28	9/8/2022	4245	-3	77.8

The average cylinder compressive strength and percent strength difference calculations were determined using Equations 6-1 and 6-2, respectively. The 7-day strength value reported by the Contractor was an extreme outlier and therefore was not included in this report. The individual cylinder compressive strengths can be found in Appendix E. The percent differences are illustrated in Figure 6-31.

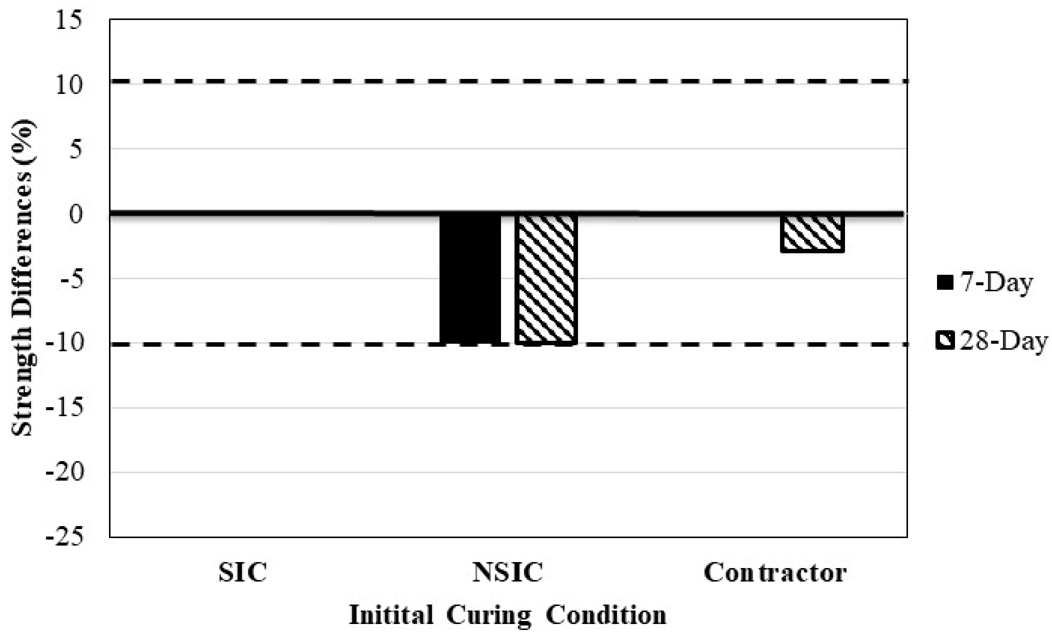

Figure 6-31: Jobsite 4, Visit 1–Strength Difference Results

6.6 SUMMARY OF RESULTS

6.6.1 SUMMARY OF INITIAL CURING TEMPERATURE RESULTS

A summary of the minimum, maximum, and average temperature from the SIC, NSIC, and Contractor curing environments for each jobsite visit is shown in Table 6-11. The temperature results from the nine jobsite visits show that temperatures inside the NSIC curing environment were above the 60 to 80 °F range specified in ALDOT 501 (2022) and AASHTO T23 (2018) for each jobsite visit. On average, the temperature in the NSIC cooler was 45°F higher than the SIC curing box for each jobsite visit, with maximum temperature in the NSIC reaching as high as 138°F.

Table 6-11: Summary of Temperature Results

Jobsite	Visit	Curing Environment	Initial Curing Temperature (°F)		
			Minimum	Maximum	Average
1	1	SIC	62.2	80.1	68.9
		NSIC	87.8	130.3	118.5
		Contractor	72.7	77.4	75.5
	2	SIC	67.8	71.6	69.3
		NSIC	92.5	135.3	124.0
		Contractor	72.7	78.4	75.8
	3	SIC	74.3	75.4	74.8
		NSIC	87.3	129.4	119.1
		Contractor	78.1	84.9	81.9
2	1	SIC	69.3	78.3	72.5
		NSIC	91.9	129.4	118.1
		Contractor	84.9	90.0	88.2
	2	SIC	69.4	71.8	69.9
		NSIC	99.3	137.3	126.6
		Contractor	88.9	98.4	94.3
	3	SIC	70.5	71.6	70.8
		NSIC	89.4	127.2	109.1
		Contractor	85.6	99.5	91.2
3	1	SIC	67.6	76.8	69.0
		NSIC	76.3	122.0	107.9
		Contractor	65.5	76.3	67.9
	2	SIC	69.6	83.5	77.9
		NSIC	72.3	120.0	88.7
		Contractor	80.8	92.8	85.7
4	1	SIC	72.0	79.7	77.5
		NSIC	83.5	125.1	113.3
		Contractor	60.1	81.0	77.8

6.6.2 Summary of Strength Results

A summary of the percent difference results obtained from the cylinders tested from all the jobsite visits is shown in Table 6-12. The extreme high initial curing temperatures of the NSIC test cylinders directly resulted in large decreases in 7- and 28-day compressive strengths when compared to the cylinders cured in the SIC curing environment. The average decrease in 28-day compressive strength across all nine jobsite visits of the NSIC test cylinders compared to the SIC test cylinders was 14% with a maximum decrease of 22%

measured for the 28-day strength of Jobsite 2, Visits 2 and 3. The maximum decrease in compressive strength for the test cylinders cured in the Contractor curing box compared to the SIC test cylinders was 18% at 7-days and 15% at 28-days on Jobsite 2, Visit 3. It is clear from the results that when the initial curing temperatures are not kept within the 60 to 80 °F range, then the 28-day compressive strength is often significantly reduced when compared to curing cylinders at initial curing temperatures that meet AASHTO T23 (2018) and ALDOT 501 (2022) requirements.

Table 6-12: Summary of Strength Difference Results

Jobsite	Visit	Curing Environment	Strength Difference (%)	
			7 day	28 day
1	1	SIC	0	0
		NSIC	-12	-13
		Contractor	3	2
	2	SIC	0	0
		NSIC	-16	-14
		Contractor	N.A.	N.A.
	3	SIC	0	0
		NSIC	-14	-13
		Contractor	-2	-6
2	1	SIC	0	0
		NSIC	N.A.	-12
		Contractor	N.A.	-4
	2	SIC	0	0
		NSIC	-20	-22
		Contractor	-6	-10
	3	SIC	0	0
		NSIC	-19	-22
		Contractor	-18	-15
3	1	SIC	0	0
		NSIC	-11	-13
		Contractor	0	0
	2	SIC	0	0
		NSIC	-5	-11
		Contractor	6	6
4	1	SIC	0	0
		NSIC	-10	-10
		Contractor	N.A.	-3

Note: N.A. = Not Available

6.6.3 SUMMARY OF JOBSITE PRACTICES

After reviewing the practices of jobsite technicians from nine jobsite visits of varying project types and concrete strengths, multiple requirements from ALDOT 501 (2022) and AASHTO T23 (2018) were commonly not being followed. The jobsite technicians at every jobsite visit did not discharge the first 10% of the load before sampling concrete as required in Section 5.2.2 of AASHTO R60 (2020). It was also determined from comparing the batch ticket of the approved batch and the observed actions of the jobsite technicians that in one instance, water was added to the load after sampling and fresh material property testing were performed, which also does not meet the requirement of Section 5.2.4 of AASHTO R60 (2020). For each jobsite visit except Jobsite 4, Visit 1, the jobsite technicians correctly performed all fresh property testing and molded their test cylinders according to AASHTO T23 (2018).

The minimum, maximum, and average curing environment temperature in the Contractor curing box for each jobsite visit is shown in Table 6-13. While the Contractor curing box at each jobsite had temperature control capabilities, the Contractor curing box at Jobsite 2 did not have any electricity provided to it for each visit and was thus never operational. This resulted in consistently higher temperatures in the Contractor curing box at Jobsite 2 when compared to the SIC curing environment temperatures. The average curing environment temperature in the Contractor curing box for each visit to Jobsite 2 was also higher than the average curing environment temperature of the Contractor curing box of every other jobsite visit. This is a direct result of the Contractor curing box of Jobsite 2 being the only one not plugged in to a continuous power source. This resulted in a 15 percent decrease in 28-day strength of the samples cured in the Contractor curing box of Jobsite 2.

While the Contractor curing box at Jobsites 1, 3, and 4 were plugged into a power source and set to operate within the 60 to 80 °F temperature range, they had no way to record the minimum and maximum temperatures in the curing environment as required in ALDOT 501 (2022) and AASHTO T23 (2018). As a result, there was no way for the project personnel to tell if their curing box remained within the 60 to 80°F for the entire initial curing duration. However, the temperature results shown in Table 6-13 from the temperature probes in the Contractor curing boxes provided by the research personnel shows that although the Contractor curing box was plugged in and set to a temperature inside the specified range, the water in the curing box still reached temperatures outside the specified range. Therefore, it is important to use a minimum-maximum thermometer as specified in ALDOT 501 (2022) and AASHTO T23 (2018). Note that with improvements in current methods to measure temperatures, there are various devices available that can not only record the temperatures but also automatically determine the minimum and maximum curing temperatures. This specification requirement was not met on any of the jobsites visited for this research project.

Table 6-13: Summary of Contractor Temperature Results

Jobsite	Visit	Contractor Curing Environment Temperature (°F)		
		Minimum	Maximum	Average
1	1	72.7	77.4	75.5
	2	72.7	78.4	75.8
	3	78.1	84.9	81.9
2	1	84.9	90.0	88.2
	2	88.9	98.4	94.3
	3	85.6	99.5	91.2
3	1	65.5	76.3	67.9
	2	80.8	92.8	85.7
4	1	60.1	81.0	77.8

Additionally, a test to determine the effectiveness of using a water circulation pump was conducted. The results presented and discussed in Section 6.2.2 show that without a water circulation pump, the water inside a cylinder curing box can potentially reach a 12°F difference in temperature from the top of the water to the bottom. However, by using a water circulation pump in the curing box water, the water temperature was consistent throughout the entire curing box. It is thus recommended that all cylinder curing boxes be required to use a water circulation pump as this provide a uniform water temperature.

CHAPTER 7
DISCUSSION OF IMPLEMENTATION RECOMMENDATIONS

7.1 INTRODUCTION

The purpose of this chapter is to provide recommended modifications to ALDOT 501.02 section (d) "Sampling and Inspection" based on the results covered in this report. The following recommended modifications are also based on the results and conclusions of the laboratory portion of this project (i.e., Phase 1). These recommendations include modifications to the current ALDOT 501.02 (2022) Section (d) regarding the materials and processes used for the sampling, initial curing, and transportation of concrete test specimens cured in the field. A markup of ALDOT 501.02 section (d), and a draft with the recommended changes, are shown in Appendices F and G.

7.2 INITIAL CURING TEMPERATURE RECOMMENDATIONS

After reviewing and comparing the temperature results discussed in Section 6.6.2, it was determined that cylinders exposed to temperatures over 80 °F experienced large relative strength differences when compared to the same concrete cylinders cured at 68 °F. However, those kept within the 60 to 80ºF range for the entire initial curing period remained within the acceptable relative strength difference limit of ±10% for every jobsite visit. These results are consistent with those of the laboratory portion of this project in which cylinders initially cured at temperatures greater than 78 °F experienced strength differences greater than ±10% when compared to the same cylinders initially cured at 68 °F. Additionally, some cylinders cured at 100°F exhibited a decrease in 28-day strength up to 23 %. Therefore, it is recommended that the 60 to 80 ºF range remain unaltered in ALDOT 501, as any increase of this range would result in significant decreases in the compressive strength of concrete test cylinders. Additionally, the high strength concrete temperature range of 68 ºF to 78 ºF from AASHTO T23 (2018) is not recommended to be added to ALDOT 501 due to the rarity of its use in the state of Alabama and the impact this would have on curing boxes in the state.

ALDOT 501 (2022) requires the monitoring and documentation of the minimum/maximum temperatures experienced by the concrete specimen during the initial curing period. This is in contrast with AASHTO T23 (2018), which only requires a minimum/maximum temperature record of the initial curing environment. After comparing the curing environment temperature and respective specimen temperature for each jobsite visit, the results clearly show that these temperatures are similar throughout the entire initial curing period. It is also not practical to require the measurement of concrete temperature because extra specimens would be needed to meet this requirement. Therefore, it is recommended that only a minimum/maximum temperature record of the initial curing environment (i.e., water in cylinder curing box) be required.

7.3 CYLINDER CURING BOX RECOMMENDATIONS

After analyzing the results presented in Chapter 6, it was determined that it is important for the cylinder curing box to be turned on and within the specified temperature range before the test cylinders are inserted. If the cylinder curing box is turned on at the time the cylinders are added, the temperature of the water may be outside the specified temperature range even if the curing box is set within the range, as it may take a few hours for the curing box to get the water temperature within the specified range. These first few hours outside the specified range can be detrimental to a cylinder's strength development and therefore, ensuring the curing box is on and the water temperature inside is within the specified range when the cylinders are added, is important.

It is also important for continuous power to be provided to the cylinder curing box. This can be accomplished with either wall power or with the use of a generator. Without access to continuous power, the heating and cooling capabilities of the cylinder curing box become unavailable and therefore, there is no way to maintain the initial curing environment within the specified temperature range. Note that fuel must be provided for the generator to make sure it runs for the entire initial curing period.

As shown in the results of the water circulation pump test presented in Section 6.1.2, there can be a significant gradient in water temperature within the curing box from the top of the water to the bottom. However, by using a water circulation pump, this temperature gradient is eliminated and the temperature throughout the curing box water is consistent. Therefore, it is also recommended that the cylinder curing box include a water circulation pump.

Lastly, as required in AASHTO T23 (2018) it is important that the cylinders are cured on a level surface to ensure the cylinder ends are level. Curing cylinders on an unlevel surface can cause the cylinder ends to be non-perpendicular to the cylinder axis and can cause up to an 8% decrease in compressive strength (Richardson (1991). Therefore, it is recommended that the supporting surface on which the cylinders are stored in the cylinder curing tank be level within 0.25 in./ft, as specified in Section 10.1.1 of AASHTO T23 (2018).

7.4 INITIAL CURING PERIOD RECOMMENDATIONS

While the initial curing period in AASHTO T23 (2018) and ASTM C31 (2021) is specified as "up to 48 hours", ALDOT 501 (2022) specifies an initial curing period of not less than 24 hours or more than 48 hours. However, the results and conclusions of the laboratory portion of this project showed that as long as the curing environment remained within the range of 60 to 80 ºF, the relative strength differences remained within the acceptable range of ±10 percent, even when initially cured for 72 hours. Therefore, it is recommended that the initial curing period in ALDOT 501 be changed to "not less than 24 hours or more than 72 hours". This additional 24 hours will allow concrete specimens made on a Friday to be transported to the laboratory on Monday and still meet the requirements of ALDOT 501.

7.5 SAMPLING RECOMMENDATIONS

After observing the sampling procedures of jobsite technicians across the various jobsite visits, the requirement in Section 5.2.2 of AASHTO R60 (2020) stating "no sample should be taken before 10 percent or after 90 percent of the batch has been discharged" was not followed at any of the jobsites. While the technicians at Jobsite 3 made a conscientious effort to not use the first concrete discharged from the chute by discharging one full wheelbarrow of concrete prior to sampling, which still does not meet the requirements of AASHTO R60 (2020). While it is still recommended that no sample should be taken before 10 percent or after 90 percent of the load has been discharged, if this is not practical, it is recommended that no less than 6 cubic feet (0.2 cubic meter) of concrete (e.g., approximately two, half-full wheelbarrow loads) be discharged from the truck before sampling to avoid the non-representative concrete. Two half-full wheelbarrows are used as an example of 6 cubic feet because a full wheelbarrow of concrete is very heavy and could cause injury when lifting. Even though "OSHA does not have a standard which sets limits on how much a person may lift or carry, the National Institute for Occupational Safety and Health has developed a mathematical model that helps predict the risk of injury based on the weight being lifted and other criteria" (Galassi 2015). Using this model, it was decided that two half-full wheelbarrows was reasonable and practical example of how to discharge 6 cubic feet of concrete before sampling.

7.6 RESPONSIBILITY RECOMMENDATIONS

Since ALDOT 501 is used for acceptance purposes of concrete, assigning responsibility to each aspect regarding the molding, curing, and testing of concrete test cylinders is very important. Using the observations from each jobsite visit, along with the conclusions of Obla (2018), it is recommended that the Contractor should be responsible for furnishing, without extra compensation, the cylinder curing box consistent with the current requirements of ALDOT 501 (2022). However, it is also recommended that continuous power (wall power or generator) for the cylinder curing box be the responsibility of the Contractor to ensure that it maintains its heating and cooling capabilities. This implies that the Contractor is also responsible for providing fuel if a generator is used to provide power to the cylinder curing box.

It is also recommended that the Contractor be responsible for providing temperature probes that continuously log the water temperature in the cylinder curing box. The Engineer should be assigned the responsibility to make and test the quality assurance concrete cylinders, as well as be responsible for using the temperature probes to monitor and record the minimum and maximum temperatures experienced in the water of the cylinder curing box during the initial curing period. This will allow the Engineer to assess that the cylinder curing box provided by the Contractor remains in accordance with the specified temperature range for the entire initial curing period.

7.6 ADDITIONAL RECOMMENDATIONS

At the conclusion of the initial curing period, the concrete test cylinders must be transported to their final curing location. If not transported properly, these cylinders can be damaged due to excessive shaking, freezing, loss of moisture, etc. Therefore, it is recommended that the specimens should be protected with suitable cushioning material during transportation to prevent damage from jarring. It is also recommended that during cold weather, the specimens should be protected from freezing with suitable insulation material and moisture loss should be prevented during transportation by leaving the tight-fitting plastic lids on the plastic molds. Additionally, it is recommended that the transportation time between initial and final curing does not exceed 4 hours. Each of these recommendations are taken directly from AASHTO T23 (2018).

For certain concrete mixtures that are heavily retarded, it is important to not move the cylinders until a certain amount of time after the concrete has reached final set. Therefore, in special applications where large dosages of chemical retarding admixtures are used, it is recommended that the concrete test cylinders should not be transported until at least 8 hours after final set as measured in accordance with AASHTO T197. This recommendation is also taken directly from Section 11.1 of AASHTO T23 (2018). Lastly, it is recommended that upon arrival to the laboratory, the cylinders should be removed from molds and within 30 minutes, placed in final curing in accordance with Section 10.1.3.1 of AASHTO T23 (2018). The purpose of this recommendation is to prevent loss of moisture from the cylinders between the time they are demolded and placed in final curing.

CHAPTER 8
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The work performed during this project is aimed at reviewing and updating current practices used to make, cure, transport, and test concrete cylinders used for quality assurance strength testing on ALDOT projects. In this chapter, the work performed is summarized, conclusions are offered, and recommendations are provided based on the completed work.

8.1 Summary of Work Performed

During Phase 1, laboratory work was done to determine the effect of initial curing temperature and duration on the 28-day compressive strength of concrete. Concrete cylinders were cured at initial curing temperatures of 60, 68, 78, 84, 90, and 100 ºF. Eight concretes were subjected to initial curing durations of 24 and 48 hours, while four concretes were subjected to initial curing durations of 72 hours. After initial curing was completed, the cylinders were moved to final curing in a moist cure room that maintained a temperature of 73.5 ± 3.5 ºF until compressive strength testing at 28 days. The effect of Type I and Type III portland cement and Class C fly ash, Class F fly ash, slag cement, and silica fume was assessed. Four verification batches were also produced to confirm the repeatability of the test results. In total, 576 6×12 in. concrete cylinders were produced and tested to determine the effect of various initial curing conditions on the 28-day concrete compressive strength.

During Phase 2, nine ALDOT jobsites were visited, and concrete delivered to the jobsite was sampled and concrete cylinders were made and placed in three different initial curing environments. One initial curing environment met all the requirements of AASHTO T 23 (2018) and ALDOT 501 (2022), the second was a simple cooler with no water inside and no temperature control, and the third was the one provided by the Contractor for the ongoing ALDOT project. For the first two initial curing environments, concrete cylinders were placed in them for 24 hours and then transported to the laboratory for final curing in accordance with AASHTO T 23 (2018). The cylinders initially cured in the Contractor curing box were removed and transported to the closest ALDOT laboratory by jobsite personnel as they normally would for the ongoing project. During the initial curing period, the temperature of the curing environment, as well as the temperature of the concrete specimens, were recorded for all initial curing environments. Concrete cylinders were then tested at 7 and 28 days in accordance with AASHTO T 22 (2022). The practices of jobsite technicians and the cylinder curing box provided by the Contractor were also evaluated to assess how they meet the requirements of AASHTO T 23 (2018) and ALDOT 501 (2022). The temperature and strength results along with the observed jobsite practices were then evaluated for each jobsite visit. Additionally, a water circulation pump test was performed to verify the effectiveness of using a water circulation pump to evenly distribute the water temperature in the cylinder curing box.

8.2 Conclusions

From the laboratory phase of this study (i.e., Phase 1), the following conclusions can are offered regarding the initial curing of concrete:

- When initial curing temperatures range from 60 to 80 °F, the change in 28-day compressive strength remains within acceptable limits.
- Once initial curing temperatures exceed 80 °F, many (approximately half) of the 28-day strengths are reduced by more than 10 percent.
- It is important to keep initial curing temperatures ranging from 60 to 80 °F, because a maximum strength difference of 23% (almost a quarter of the control strength) was measured when the initial curing temperature was 100 °F.
- When the initial curing temperature remains within 60 to 80 °F, then increasing the initial curing duration from 48 hour to 72 hour does not significantly affect the 28-day concrete compressive strength. The maximum initial curing duration can thus be increased from 48 to 72 hours, which will permit cylinders made on Fridays to be transported to their final curing location on Mondays.

From the field work phase of this study (i.e., Phase 2), the following conclusions are offered:

- When initial curing concrete cylinders not in accordance with AASHTO T 23 (2018) or ALDOT 501 (2022) it can result in up to a 22% decrease in 28-day compressive strengths. Therefore, the specified initial curing temperature range of 60 to 80°F required in AASHTO T 23 (2018) and ALDOT 501 (2022) should continue to be required and be enforced during ALDOT projects.
- Cylinder curing boxes are capable of maintaining a water temperature from 60 to 80°F when placed in the sun during summertime in Alabama as long as continuous power through either wall power or a generator is provided to the cylinder curing box. Therefore, ALDOT 501 must also require a continuous power source for the cylinder curing box. Adequate fuel must be provided if the power source is a generator.
- The Contractor should be assigned the responsibility to provide the cylinder curing box, a power source, fuel for the power source if it is a generator, and maximum minimum temperature probes that continuously record the water temperature in the cylinder curing box.
- It is only necessary to record the minimum and maximum temperature of the initial curing environment (i.e., water in cylinder curing box) and not the minimum and maximum temperatures of the concrete in the cylinders.
- The Engineer (jobsite technicians, testing agency, etc.) should be responsible for approving the cylinder curing box, power source, and temperature probes used to record the water temperature in the cylinder curing box. The Engineer should also be responsible for using the temperature probes to monitor and record the minimum and maximum temperatures experienced in the water of the cylinder curing box during the initial curing period. This will allow the Engineer to assess that

the cylinder curing box provided by the Contractor remains in accordance with the specified temperature range for the entire initial curing period.

- When not using a water circulation pump in the cylinder curing box, there can be a significant gradient in water temperature within the curing box from the top of the water to the bottom. However, by using a water circulation pump, this temperature gradient is eliminated and the temperature throughout the curing box water is consistent. Therefore, ALDOT 501 should require a water circulation pump be installed in all cylinder curing boxes.
- The supporting surface on which the cylinders are stored in the cylinder curing tank should be level within 0.25 in./ft, as specified in Section 10.1.1 of AASHTO T23 (2018).
- While no sample should be taken before 10 percent or after 90 percent of the load has been discharged, this is not always practical and was not done on any ALDOT jobsite visited. While it is still recommended that no sample should be taken before 10 percent or after 90 percent of the load has been discharged, if this is not practical, it is recommended that no less than 6 cubic feet (0.2 cubic meter) of concrete (e.g., approximately two, half-full wheelbarrow loads) be discharged from the truck before sampling to avoid the non-representative concrete.
- For special applications where large amounts of retarding chemical admixtures are used to delay the setting of concrete until after 16 hours, concrete cylinders should not be moved until at least 8 hours after final set, as measured in accordance with AASHTO T 197. This conclusion is consistent with Section 10.1.3.1 of AASHTO T 23 (2018).

8.3 Recommendations

From the results of the study the following recommendations are made:

- Require and enforce initial curing temperatures ranging from 60 to 80 °F for cylinders used for quality assurance strength testing on all ALDOT projects.
- Increase the maximum initial curing duration in ALDOT 501 (2022) from 48 hours to 72 hours.
- Before implementing the changes recommended in this report into ALDOT 501.02 Section (d), jobsite and industry personnel should be trained in order to understand and effectively implement the modifications to this specification.
- A maintenance and calibration schedule should be developed for the cylinder curing boxes and temperature probes used to record the minimum and maximum water temperature inside cylinder curing boxes.
- Proper documentation should be developed for the Engineer to approve the equipment provided by the Contractor to cure cylinders on jobsites.

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APPENDIX A

RESULTS COLLECTED FOR PHASE 1

A.1 CONCRETE COMPRESSIVE STRENGTH RESULTS

Table A-1: Compressive strength for 100% Type I PCC - 24 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 °F)
60 °F	6140	6190	3
	6240		
	6200		
68 °F	6040	6010	0
	6010		
	5990		
78 °F	5530	5450	-9
	5430		
	5380		
84 °F	5220	5190	-14
	5040		
	5320		
90 °F	5010	5070	-16
	5050		
	5150		
100 °F	4720	4850	-19
	4900		
	4940		

*Outlier

Table A-2: Compressive strength for 30% Class F Fly Ash - 24 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	4890	4920	1
	5030		
	4840		
68 °F	4940	4860	0
	4890		
	4750		
78 °F	4590	4590	-6
	4610		
	4570		
84 °F	4440	4530	-7
	4490		
	4660		
90 °F	4570	4540	-7
	4590		
	4450		
100 °F	4190	4280	-12
	4280		
	4360		

*Outlier

Table A-3: Compressive strength for 30% Class C Fly Ash - 24 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6290	6320	-1
	6140		
	6520		
68 °F	6320	6360	0
	6400		
	6360		
78 °F	6180	6200	-3
	6300		
	6120		
84 °F	6050	6000	-6
	5970		
	5980		
90 °F	5690	5740	-10
	5840		
	5680		
100 °F	5460	5570	-12
	5730		
	5530		

*Outlier

Table A-4: Compressive strength for 50% Slag Cement - 24 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6190	6040	7
	6030		
	5910		
68 °F	5840	5650	0
	5560		
	5560		
78 °F	5570	5390	-5
	5190		
	5420		
84 °F	5180	5070	-10
	5560*		
	4950		
90 °F	5030	5140	-9
	5100		
	5290		
100 °F	4790	4790	-15
	4790		
	4800		

*Outlier

Table A-5: Compressive strength for 10% Silica Fume - 24 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	7410	7430	8
	7300		
	7580		
68 °F	6670	6890	0
	7010		
	7000		
78 °F	5990	6260	-9
	6410		
	6370		
84 °F	5790	5870	-15
	5710		
	6100		
90 °F	5640	5700	-17
	5660		
	5800		
100 °F	5640	5520	-20
	5360		
	5560		

*Outlier

Table A-6: Compressive strength for 20% Class F Fly Ash with 30% Slag Cement - 24 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6790	7010	8
	7140		
	7110		
68 °F	6540	6490	0
	6420		
	6520		
78 °F	6540	6380	-2
	6290		
	6310		
84 °F	6020	6230	-4
	6400		
	6270		
90 °F	6380	6320	-3
	6350		
	6230		
100 °F	5760	5920	-9
	5930		
	6070		

*Outlier

Table A-7: Compressive strength for 20% Class F Fly Ash with 10% Silica Fume - 24 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6730	6570	9
	6530		
	6460		
68 °F	6030	6040	0
	6150		
	5930		
78 °F	5840	5850	-3
	5920		
	5790		
84 °F	5810	5650	-6
	5550		
	5590		
90 °F	5410	5390	-11
	5370		
	5390		
100 °F	5060	5050	-16
	5090		
	5000		

*Outlier

Table A-8: Compressive strength for 100% Type III PCC - 24 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	7560	7320	5
	7250		
	7140		
68 °F	7060	7000	0
	6890		
	7040		
78 °F	6800	6860	-2
	7070		
	6710		
84 °F	6880	6710	-4
	6820		
	6430		
90 °F	6780	6780	-3
	6760		
	6800		
100 °F	6150	6200	-11
	6270		
	6180		

*Outlier

Table A-9: Compressive strength for 100% Type I PCC - 48 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6410	6510	3
	6500		
	6620		
68 °F	6330	6310	0
	6190		
	6410		
78 °F	5440*	5960	-6
	5930		
	5990		
84 °F	5610	5550	-12
	5560		
	5470		
90 °F	5610	5590	-11
	5520		
	5640		
100 °F	5200	5280	-16
	5400		
	5250		

*Outlier

Table A-10: Compressive strength 30% Class F Fly Ash - 48 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	5500	5480	4
	5330		
	5620		
68 °F	5130	5270	0
	5440		
	5250		
78 °F	4940	5070	-4
	5150		
	5110		
84 °F	4830	4830	-8
	4730		
	4940		
90 °F	4810	4910	-7
	4960		
	4950		
100 °F	4940	4850	-8
	4800		
	4800		

*Outlier

Table A-11: Compressive strength for 30% Class C Fly Ash - 48 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6710	6880	4
	6890		
	7030		
68 °F	6530	6610	0
	6540		
	6770		
78 °F	6170	6300	-5
	6230		
	6510		
84 °F	6210	6330	-4
	6300		
	6490		
90 °F	6020	6060	-8
	5970		
	6200		
100 °F	5690	5660	-14
	5550		
	5750		

*Outlier

Table A-12: Compressive strength for 50% Slag Cement - 48 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6870	6960	3
	6860		
	7140		
68 °F	6690	6760	0
	6820		
	6760		
78 °F	6890	6700	-1
	6600		
	6600		
84 °F	6710	6660	-1
	6530		
	6730		
90 °F	6550	6440	-5
	6370		
	6390		
100 °F	6130	6190	-8
	6220		
	6210		

*Outlier

Table A-13: Compressive strength for 10% Silica Fume - 48 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	8860	8890	10
	8860		
	8960		
68 °F	7900	8070	0
	7910		
	8400		
78 °F	7760	7570	-6
	7460		
	7480		
84 °F	7040	7220	-11
	7350		
	7270		
90 °F	6870	6970	-14
	7170		
	6880		
100 °F	6370	6430	-20
	6430		
	6480		

*Outlier

Table A-14: Compressive strength for 20% Class F Fly Ash with 30% Slag Cement - 48 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6060	6310	9
	6350		
	6520		
68 °F	5550	5780	0
	5820		
	5980		
78 °F	5720	5810	1
	5980		
	5720		
84 °F	5410	5510	-5
	5640		
	5480		
90 °F	5510	5580	-3
	5580		
	5640		
100 °F	4740*	5260	-9
	5250		
	5270		

*Outlier

Table A-15: Compressive strength for 20% Class F Fly Ash with 10% Silica Fume - 48 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	5980	6090	9
	6090		
	6210		
68 °F	5530	5610	0
	5650		
	5660		
78 °F	5470	5360	-4
	5350		
	5270		
84 °F	5110	5000	-11
	5050		
	4830		
90 °F	4580	4700	-16
	4670		
	4850		
100 °F	4290	4320	-23
	4360		
	4300		

*Outlier

Table A-16: Compressive strength for 100% Type III PCC - 48 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	7500	7600	7
	7430		
	7860		
68 °F	7190	7070	0
	6870		
	7140		
78 °F	7210	7170	1
	7020		
	7270		
84 °F	6960	6910	-2
	6690		
	7090		
90 °F	6570	6710	-5
	6570		
	7000		
100 °F	6550	6560	-7
	6480		
	6650		

*Outlier

Table A-17: Compressive strength for 100% Type I PCC - 72 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6750	6570	4
	6450		
	6500		
68 °F	6210	6330	0
	6520		
	6270		
78 °F	6220	6050	-4
	5960		
	5980		
84 °F	5810	5870	-7
	6010		
	5800		
90 °F	5910	5880	-7
	5850		
	5870		
100 °F	5490	5620	-11
	5690		
	5680		

*Outlier

Table A-18: Compressive strength for 50% Slag - 72 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	7220	7240	3
	7190		
	7300		
68 °F	7280	7010	0
	6860		
	6890		
78 °F	6960	6880	-2
	6790		
	6410*		
84 °F	6570	6670	-5
	6790		
	6650		
90 °F	6720	6460	-8
	6420		
	6240		
100 °F	6280	6150	-12
	6220		
	5960		

*Outlier

Table A-19: Compressive strength for 10% Silica Fume - 72 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6320	6380	3
	6380		
	6450		
68 °F	6100	6210	0
	6220		
	6300		
78 °F	5730	5930	-5
	5880		
	6170		
84 °F	5400	5530	-11
	5710		
	5480		
90 °F	5370	5430	-13
	5470		
	5450		
100 °F	4890	5080	-18
	5080		
	5260		

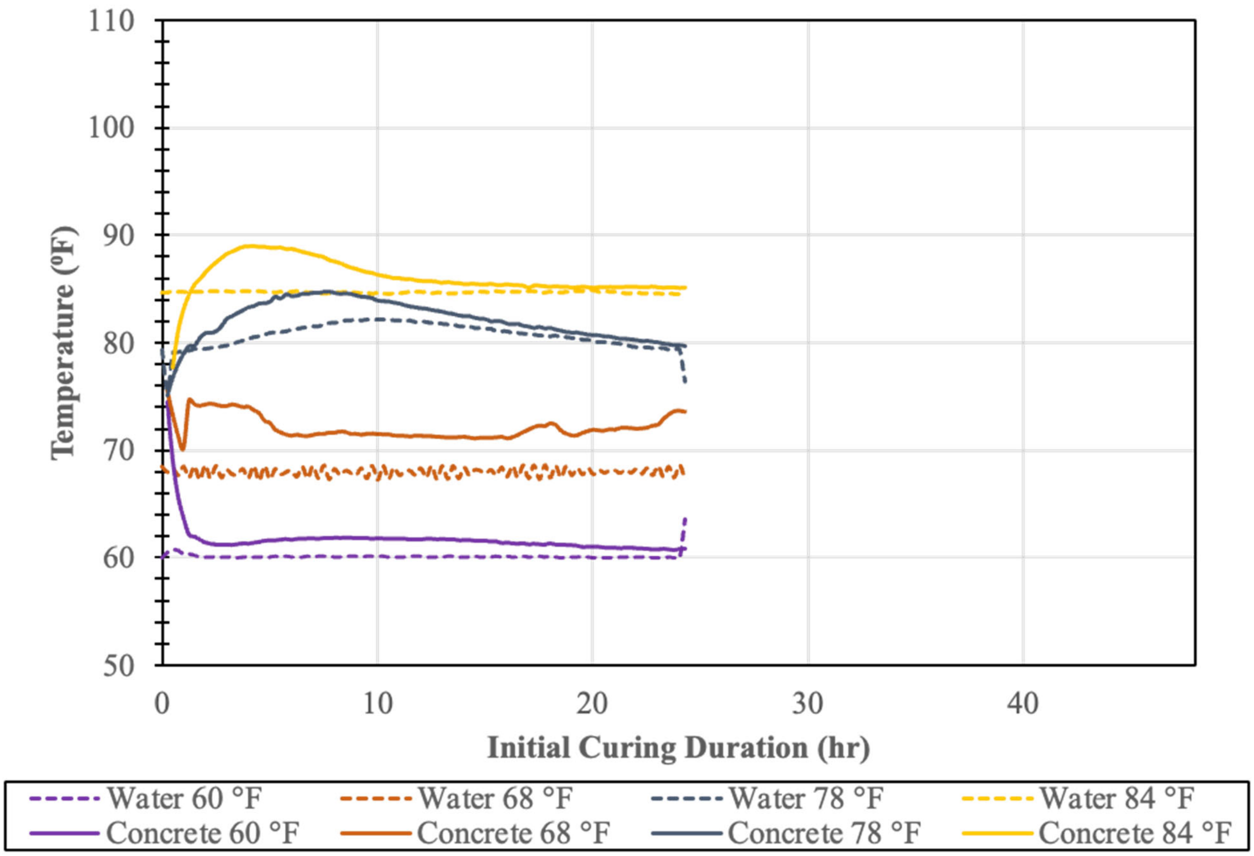
*Outlier

Table A-20: Compressive strength for 20% Class F Fly Ash with 10% Silica Fume - 72 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	5910	6010	5
	6080		
	6030		
68 °F	5660	5720	0
	5790		
	5700		
78 °F	5300	5210	-9
	5150		
	5190		
84 °F	4850	4950	-13
	5040		
	4960		
90 °F	4860	4820	-16
	4760		
	4850		
100 °F	4430	4460	-22
	4450		
	4510		

*Outlier

A.2: INITIAL CURING TEMPERATURE VERSUS TIME PLOTS



Note: 90 °F and 100 °F temperature probes malfunctioned.

Figure A-1: 100% Type I PCC 24 hours initial curing temperatures plot

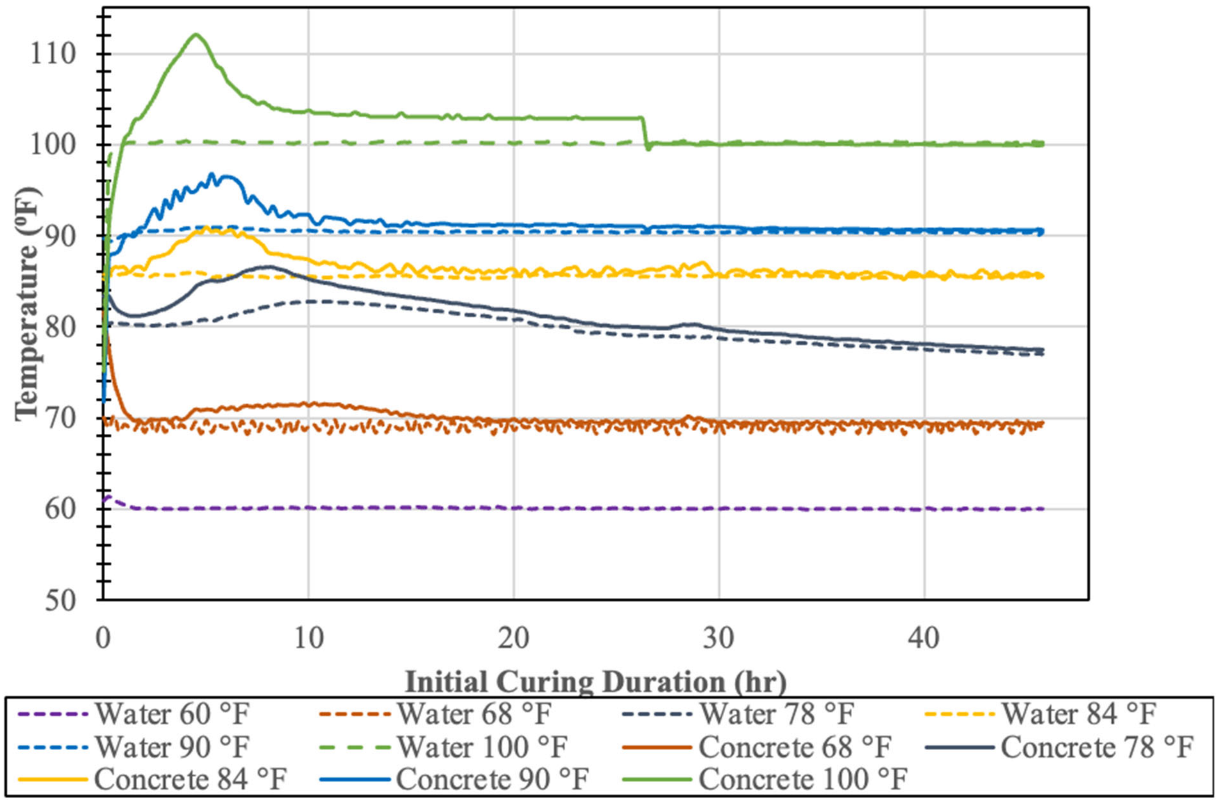


Figure A-2: 30% Class F Fly Ash 24 hours initial curing temperatures plot

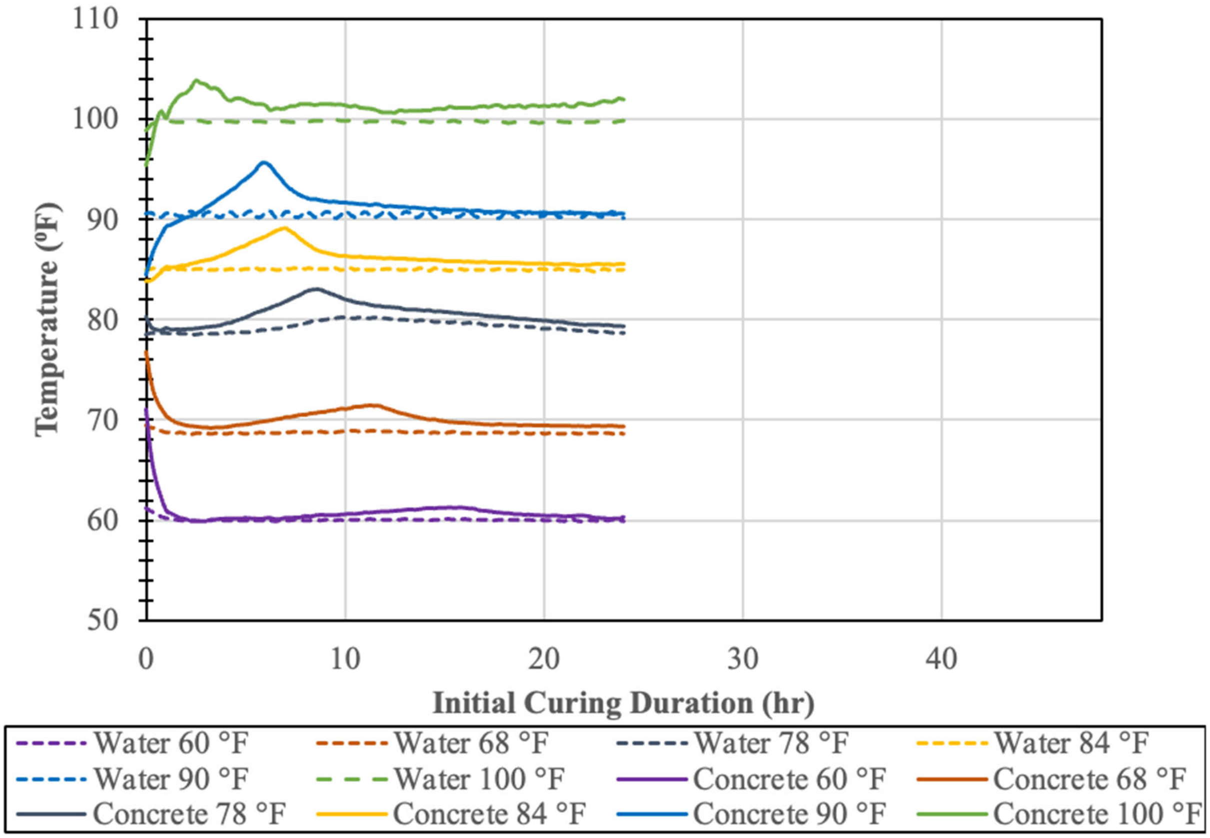


Figure A-3: 30% Class C Fly Ash 24 hours initial curing temperatures plot

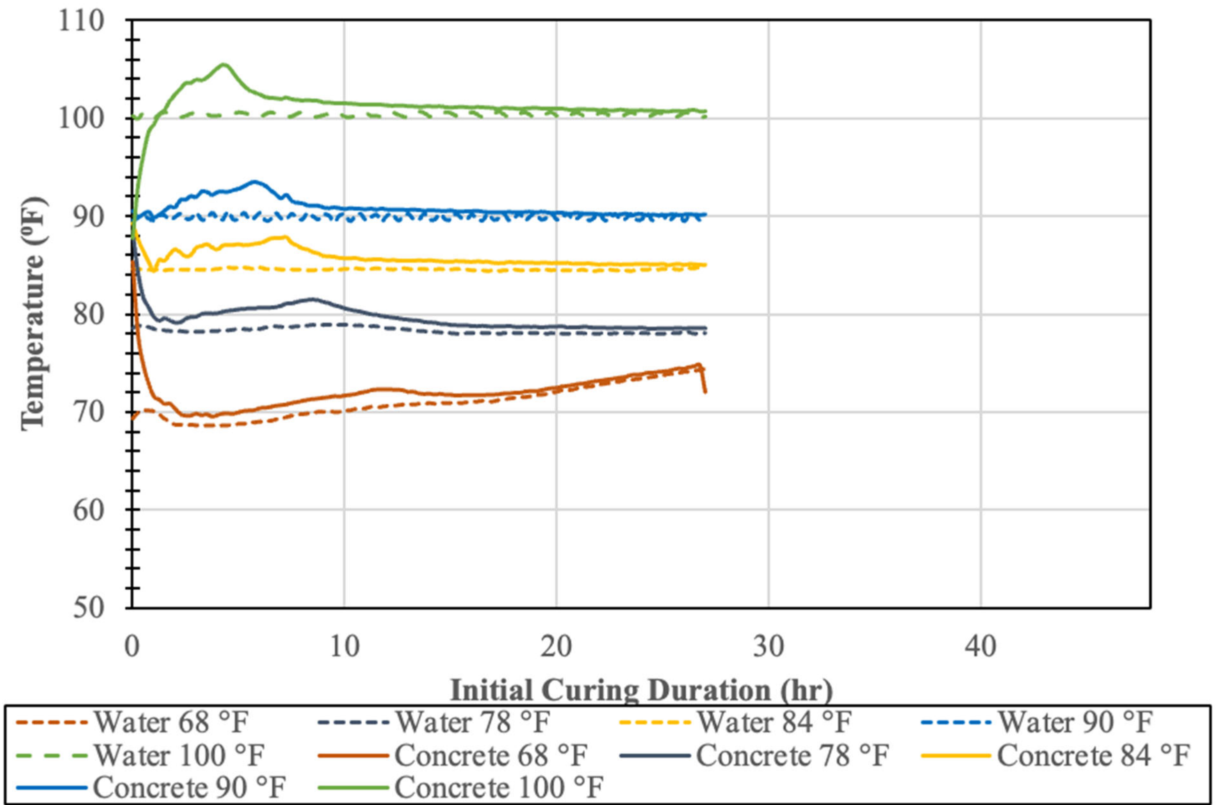


Figure A-4: 50% Slag Cement 24 hours initial curing temperatures plot

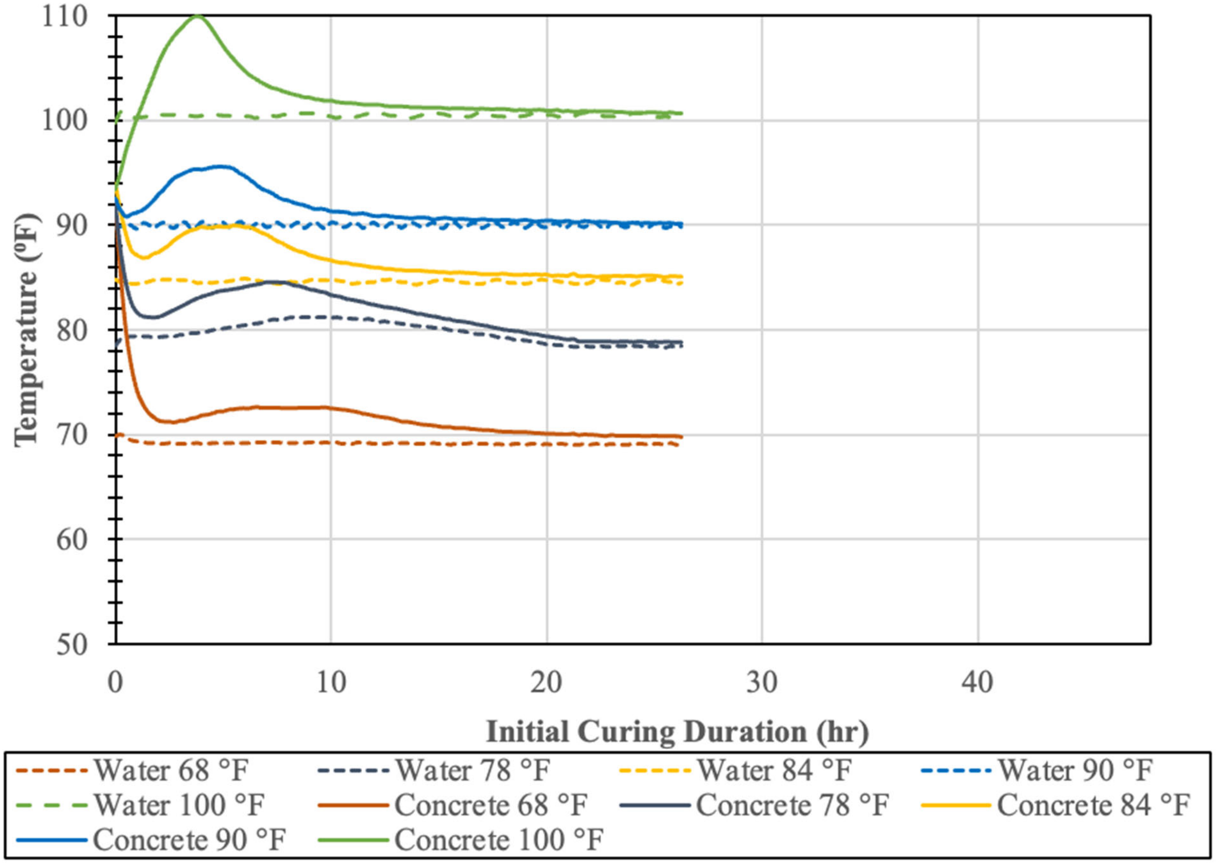


Figure A-5: 10% Silica Fume 24 hours initial curing temperatures plot

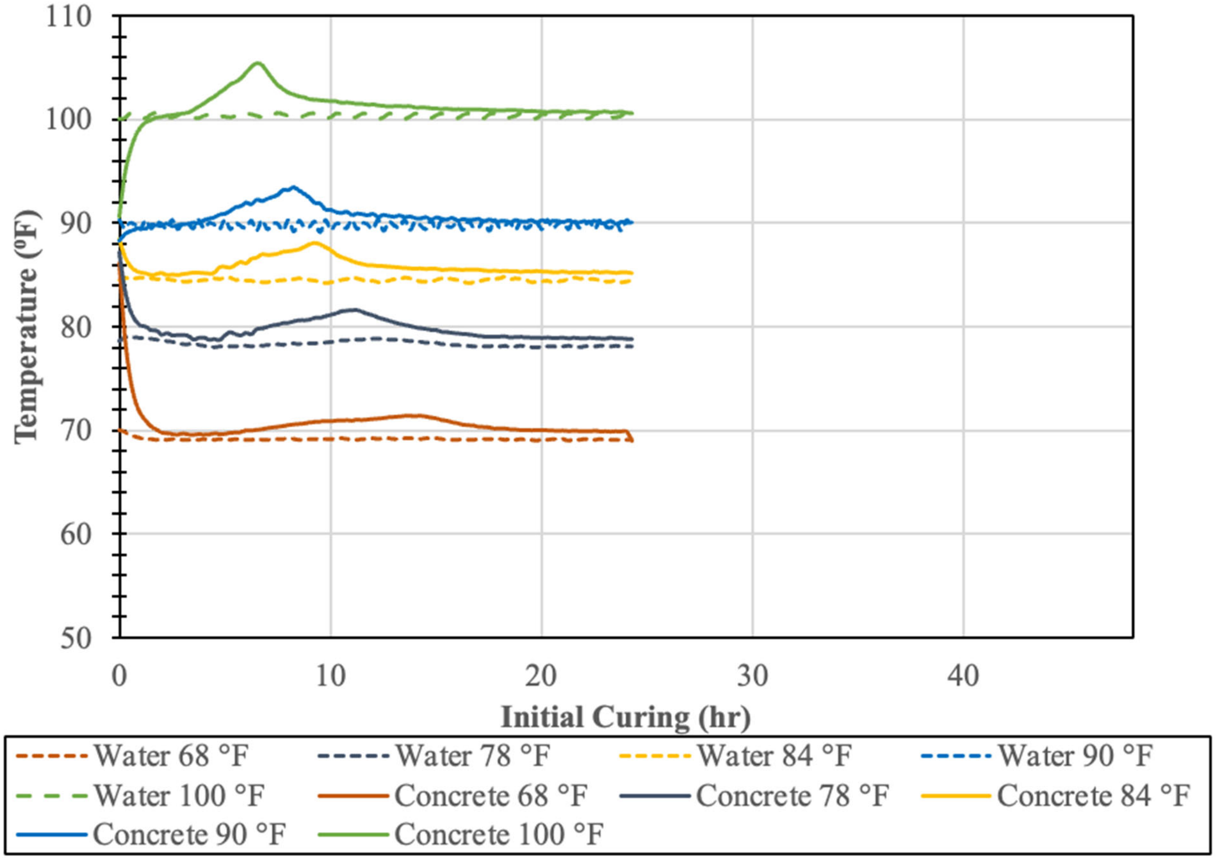


Figure A-6: 20% Class F Fly Ash with 30% Slag Cement 24 hours initial curing temperatures plot

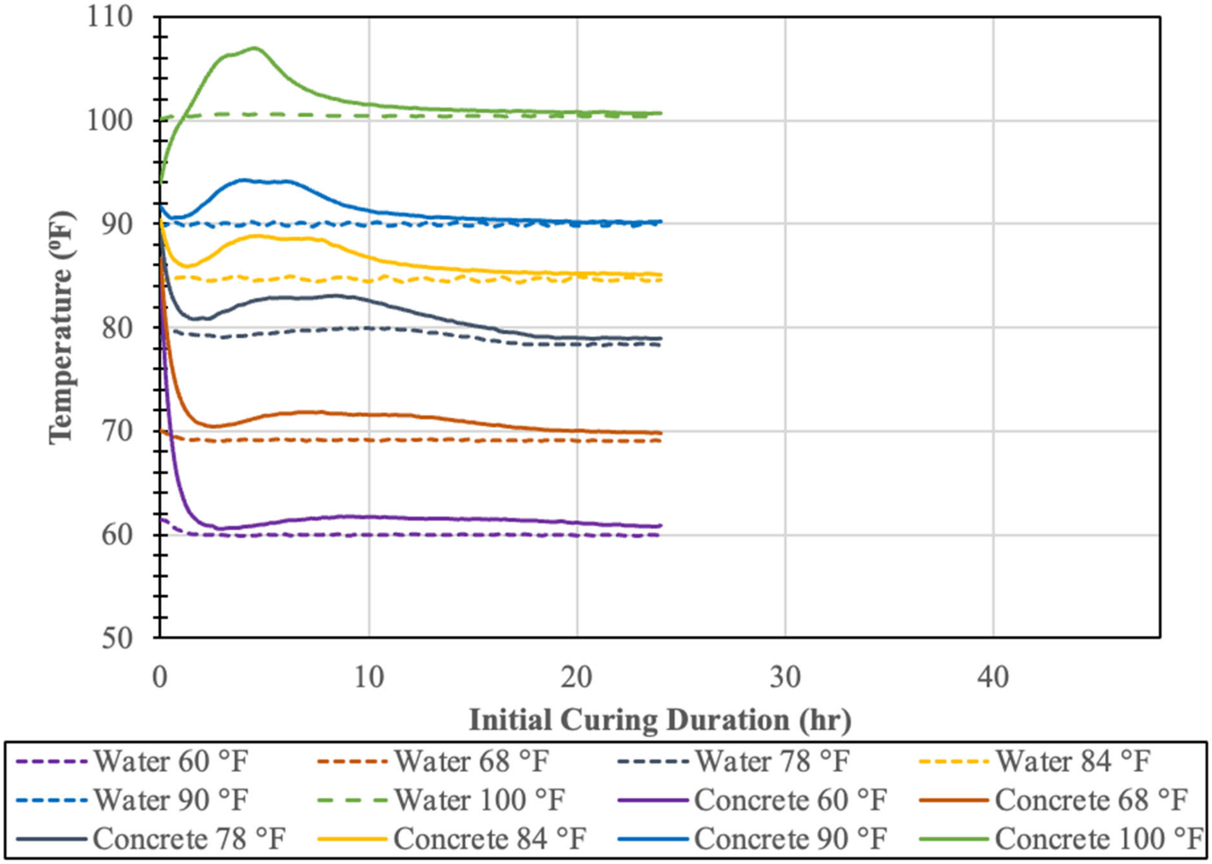


Figure A-7: 20% Class F Fly Ash with 10% Silica Fume 24 hours initial curing temperatures plot

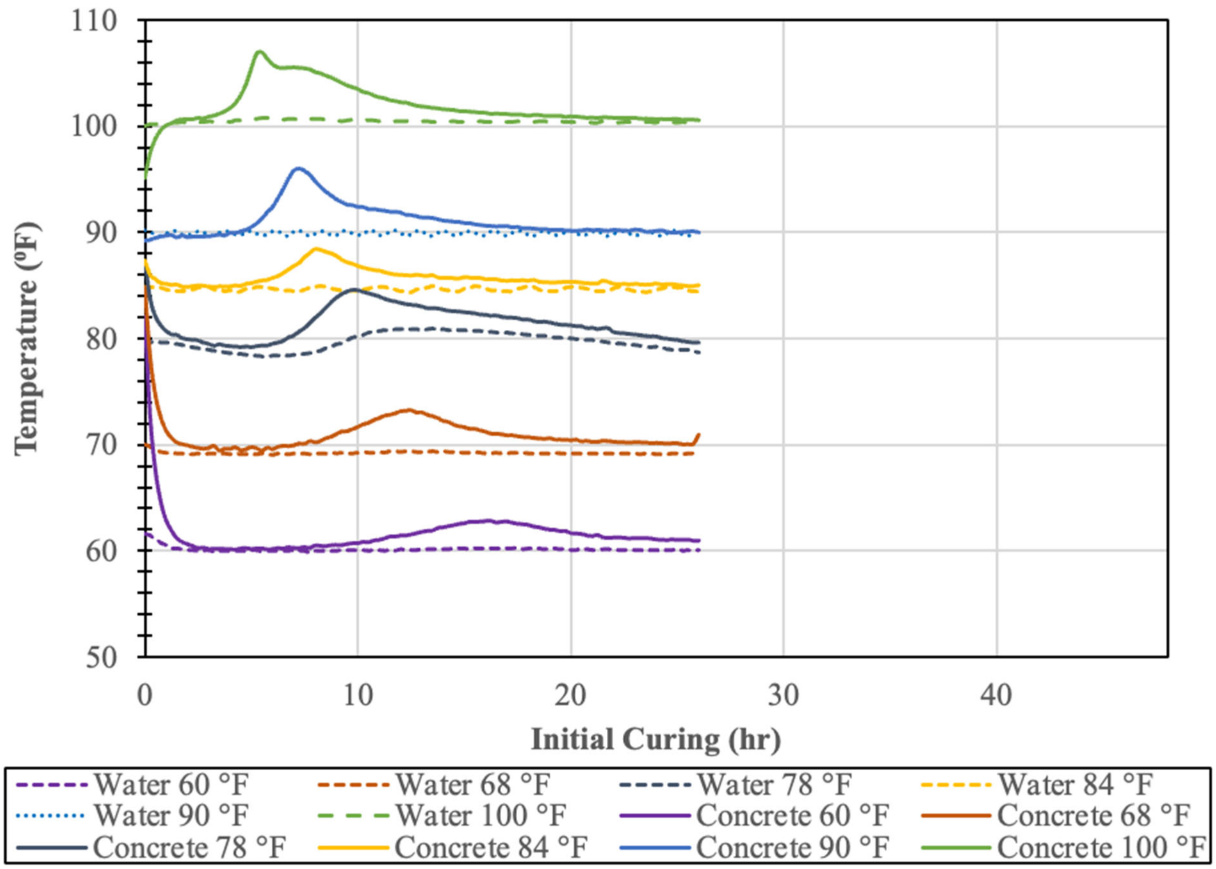
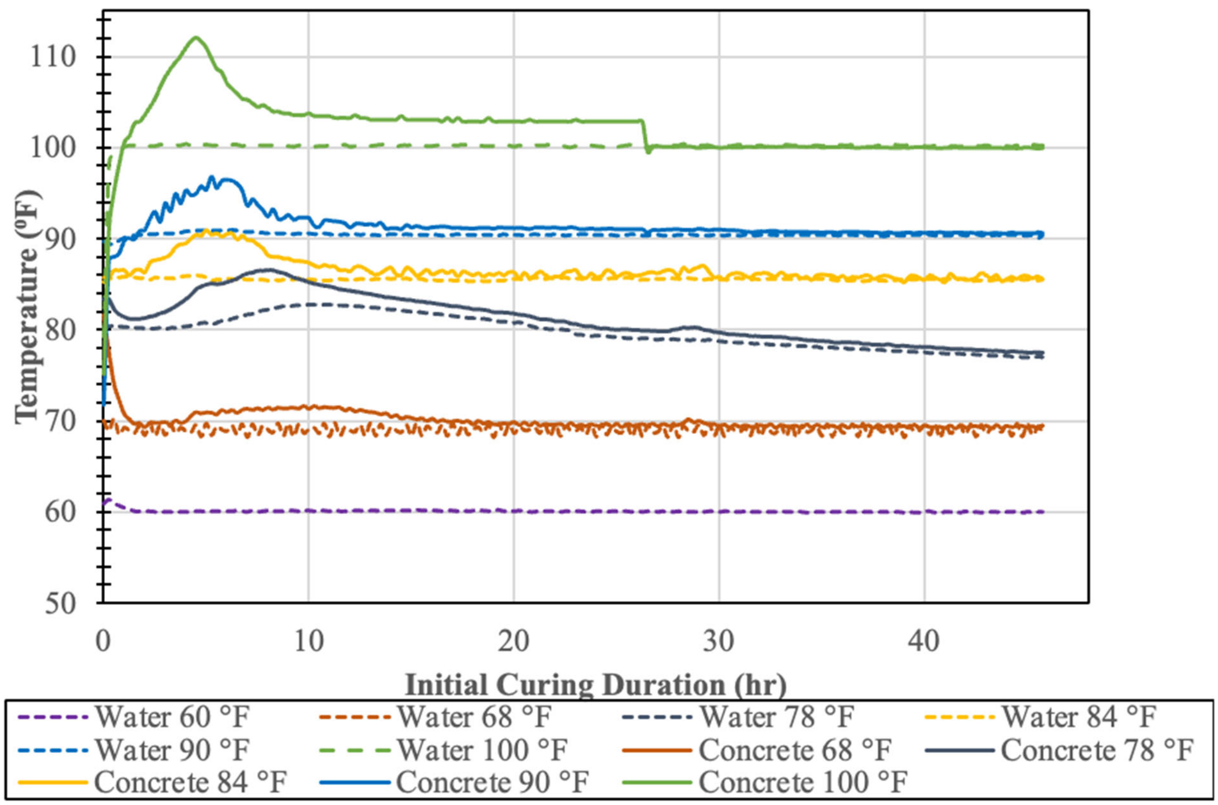


Figure A-8: 100% Type III PCC 24 hours initial curing temperatures plot



Note: 60 °F Concrete temperature probe malfunction

Figure A-9: 100% Type I PCC 48 hours initial curing temperatures plot

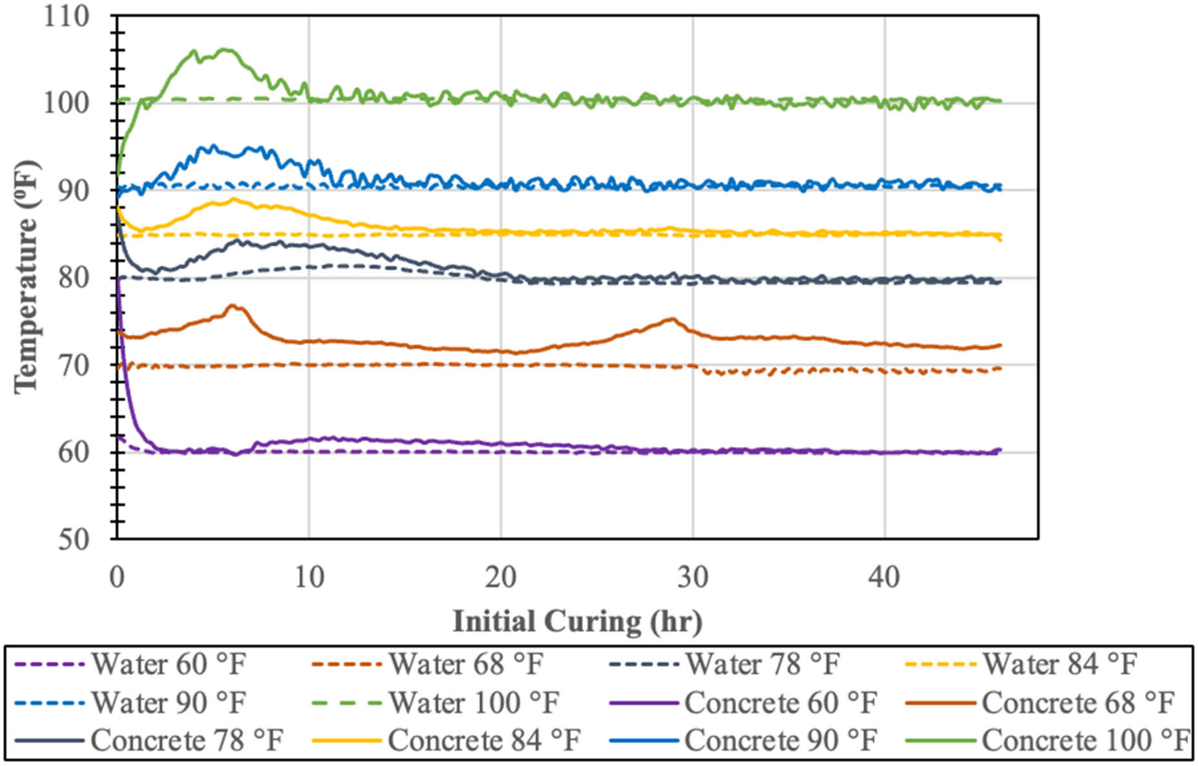


Figure A-10: 30% Class F Fly Ash 48 hours initial curing temperatures plot

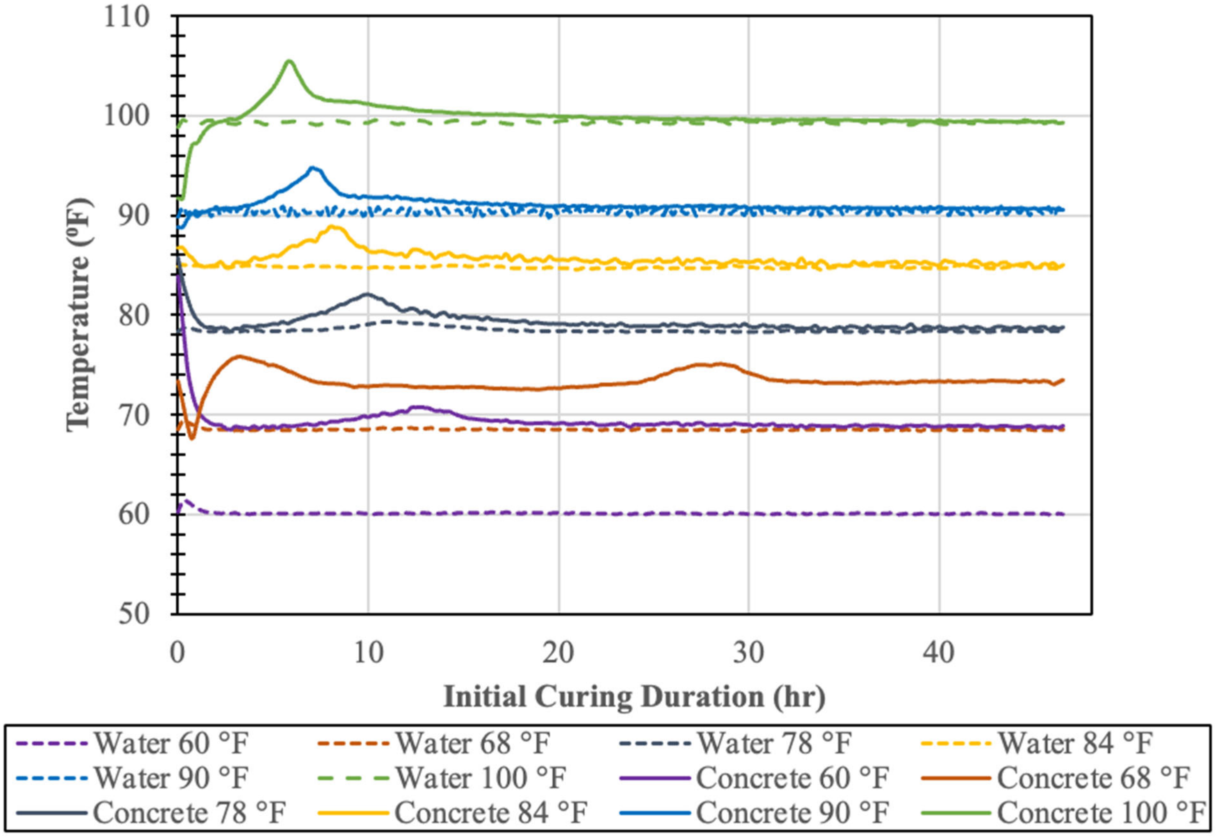


Figure A-11: 30% Class C Fly Ash 48 hours initial curing temperatures plot

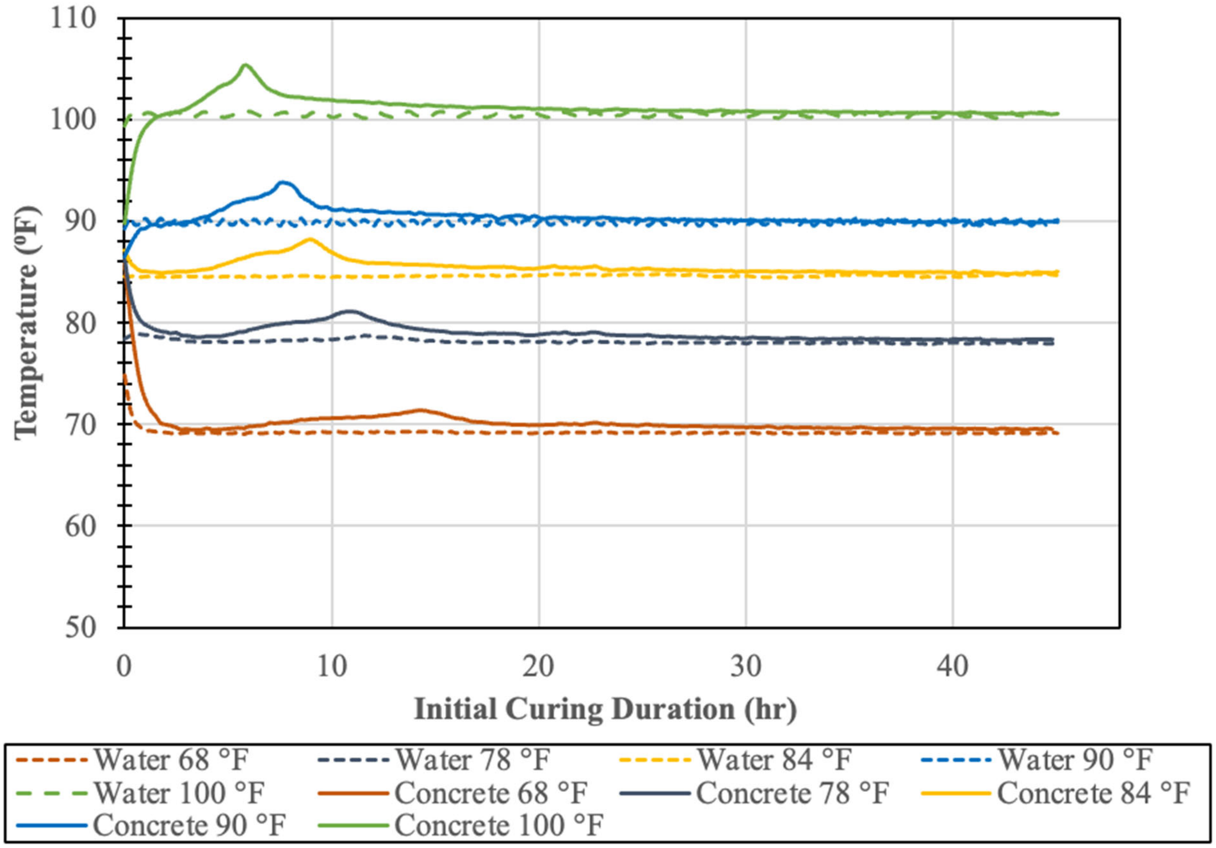


Figure A-12: 50% Slag Cement 48 hours initial curing temperatures plot

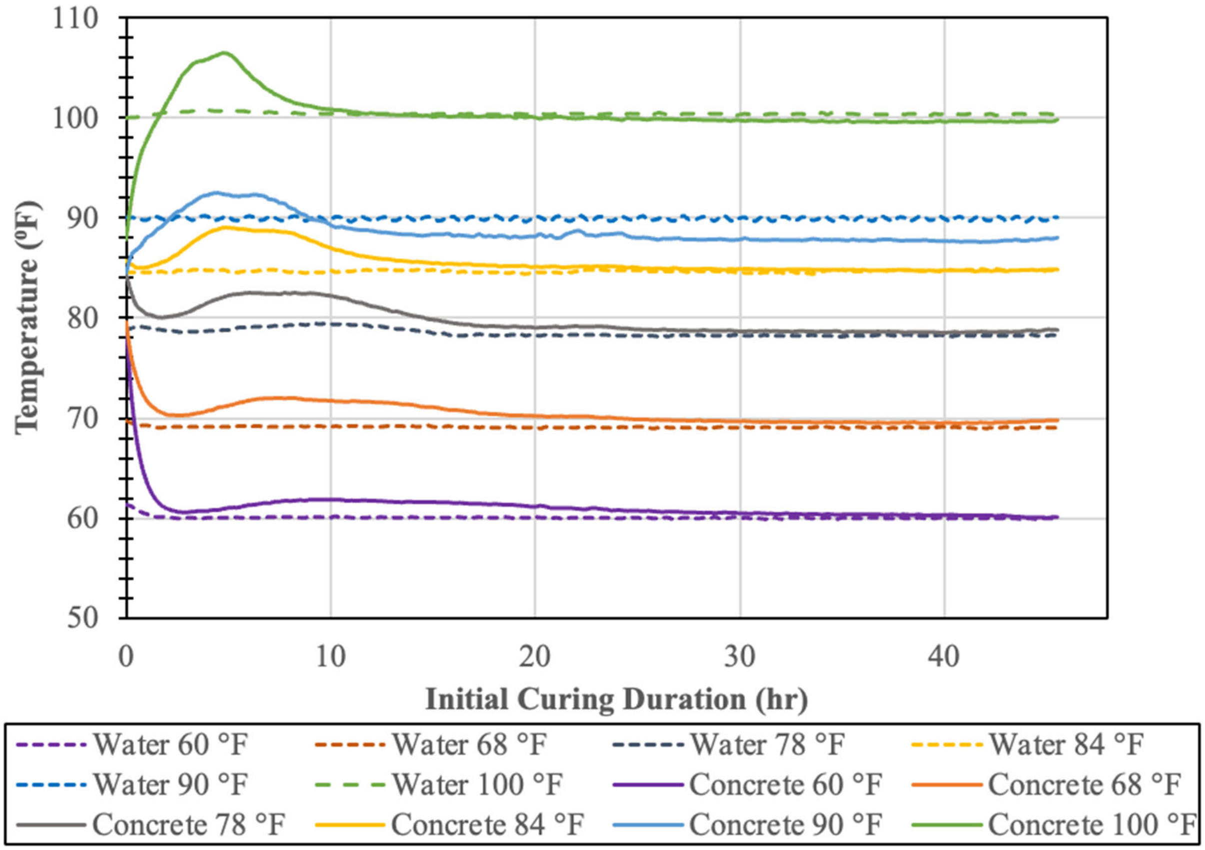


Figure A-13: 10% Silica Fume 48 hours initial curing temperatures plot

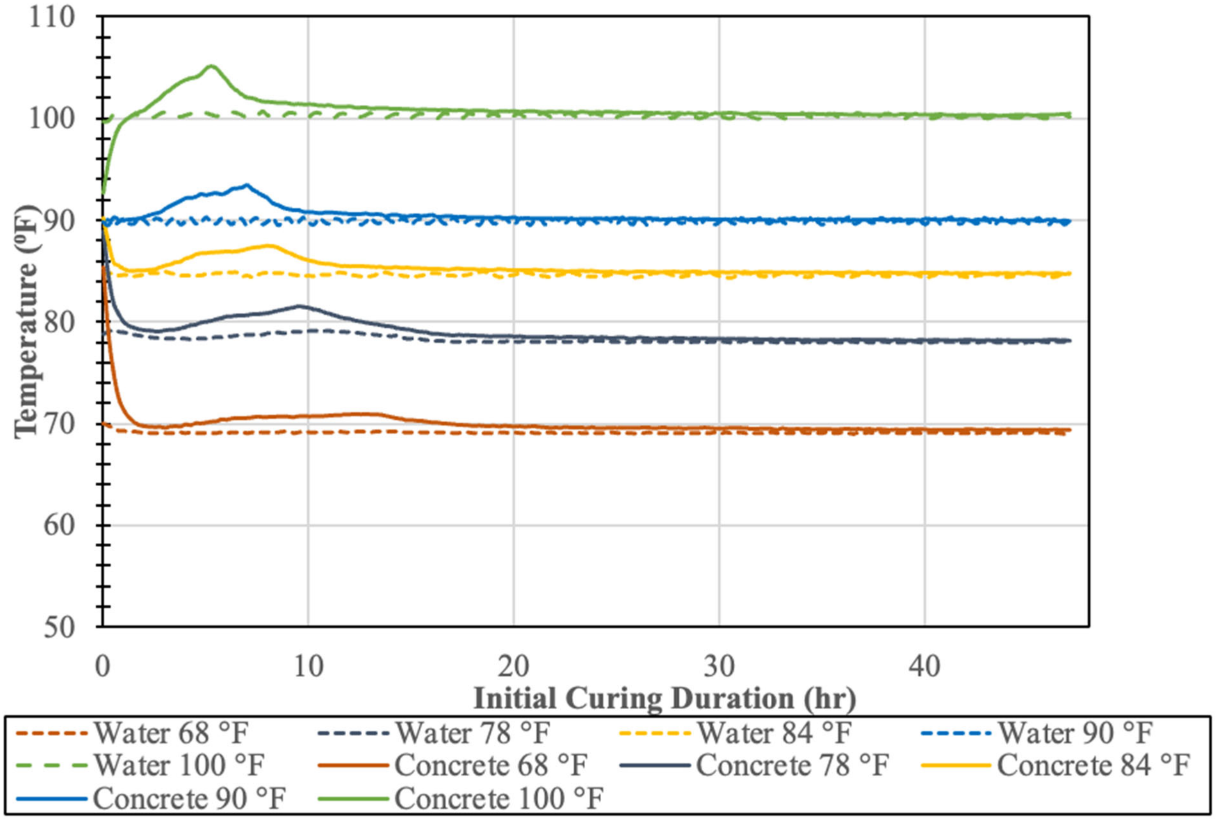


Figure A-14: 20% Class F Fly Ash with 30% Slag Cement 48 hours initial curing temperatures plot

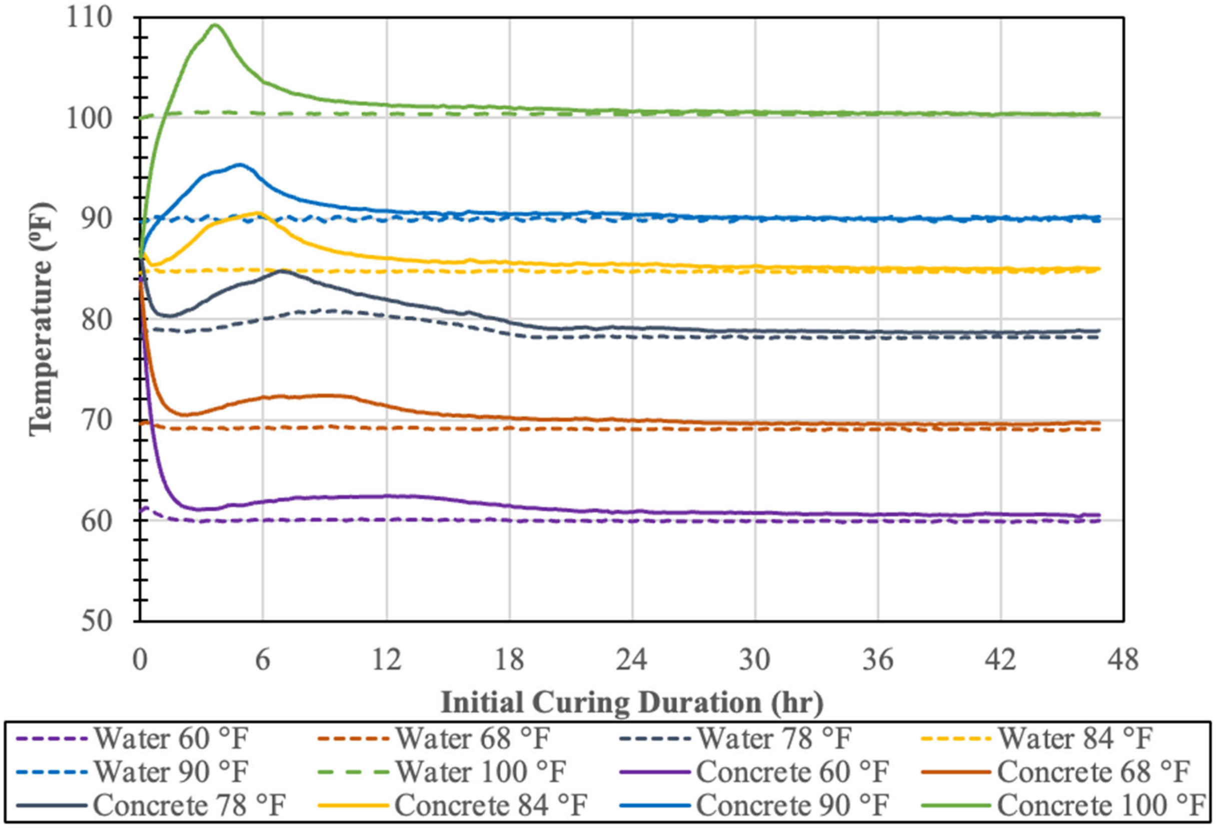


Figure A-15: 20% Class F Fly Ash with 10% Silica Fume 48 hours initial curing temperatures plot

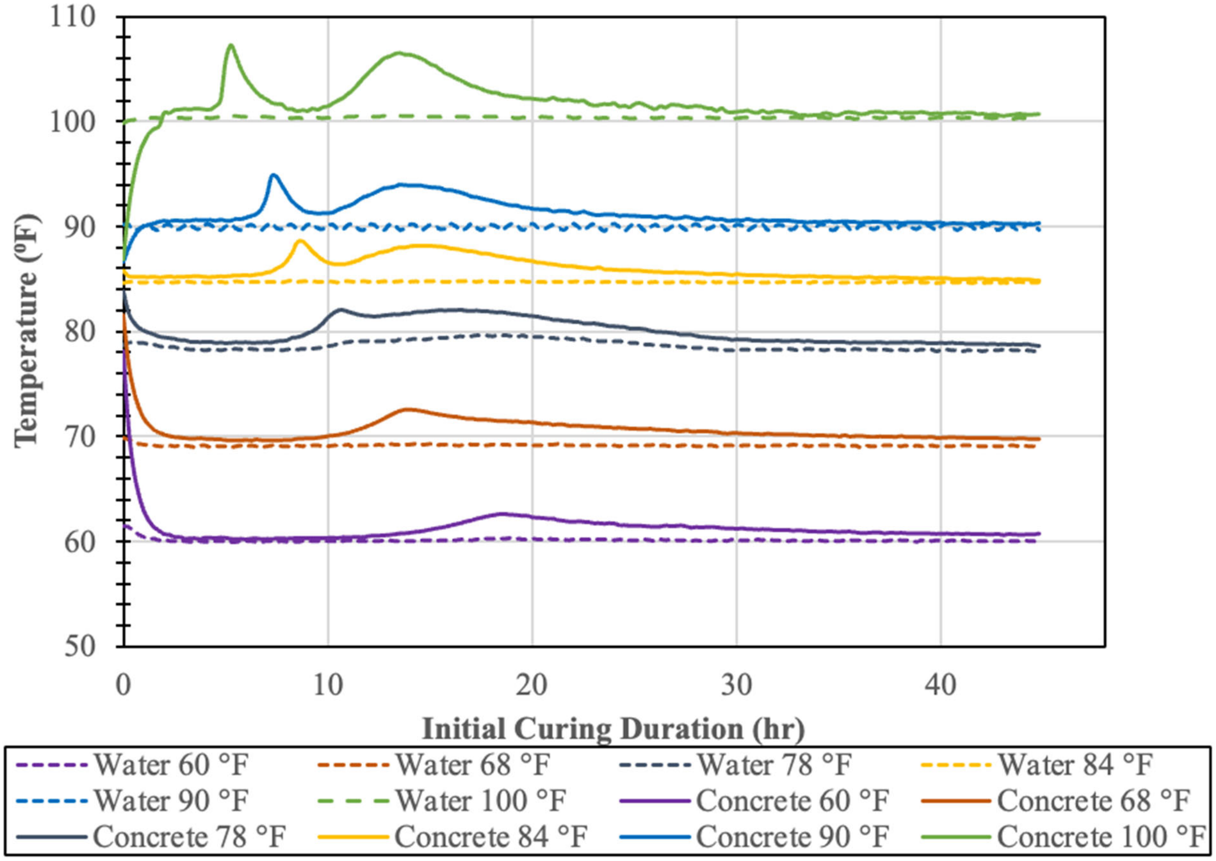


Figure A-16: 100% Type III 48 hours initial curing temperatures plot

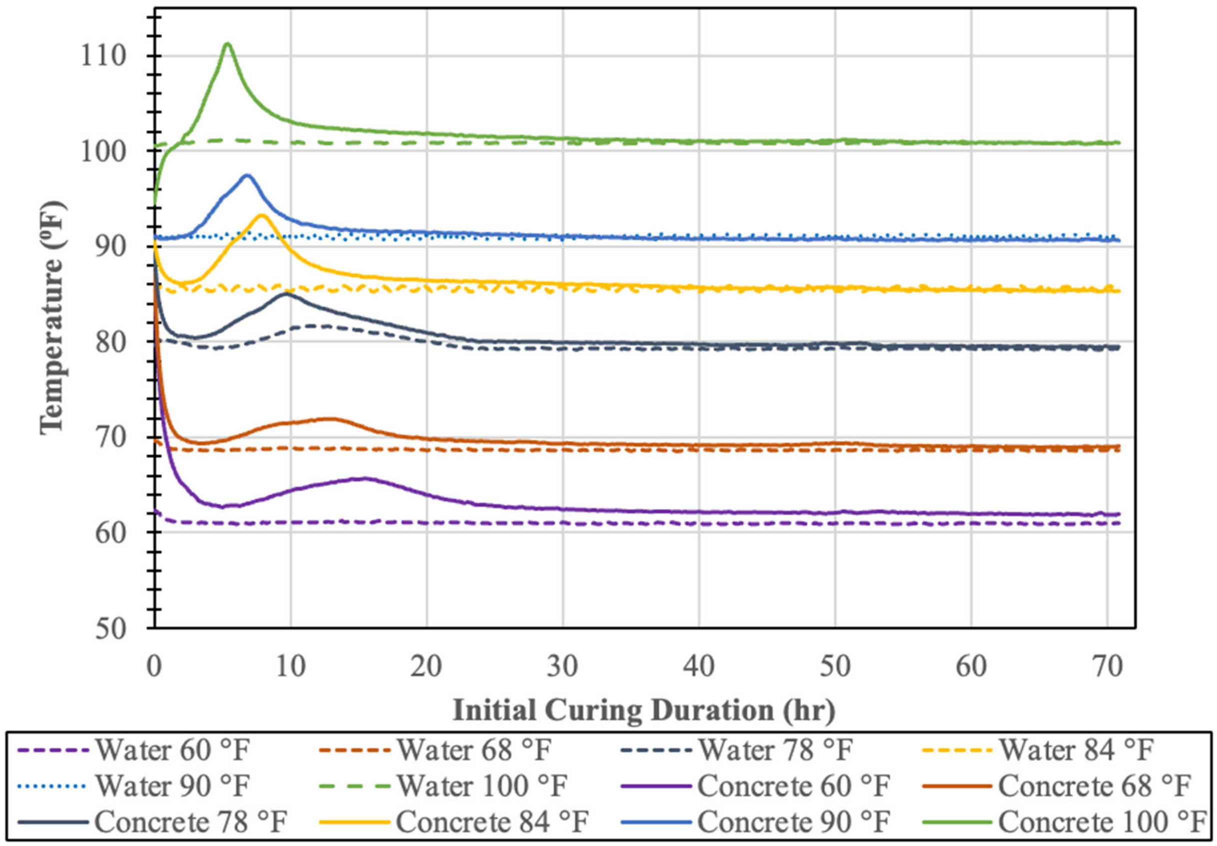


Figure A-17: 100% Type I PCC 72 hours initial curing temperatures plot

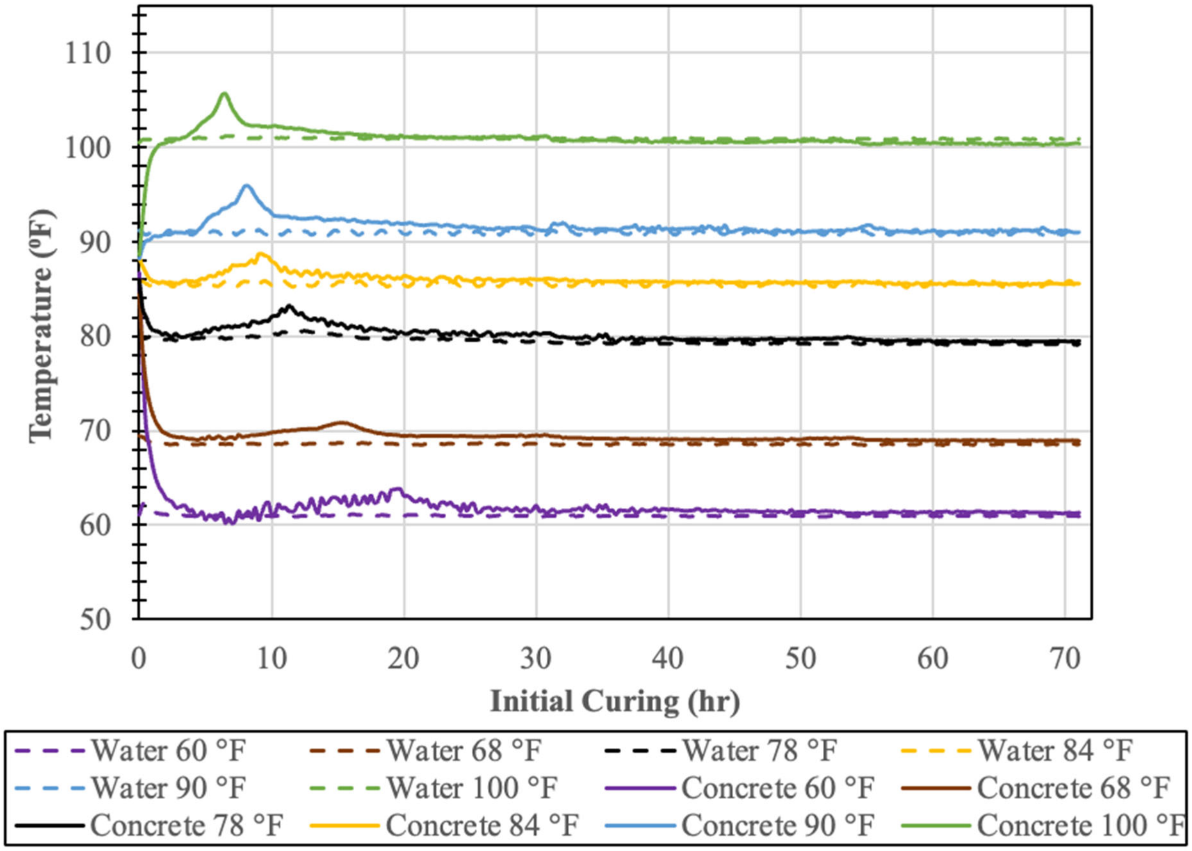


Figure A-18: 50% Slag Cement 72 hours initial curing temperatures plot

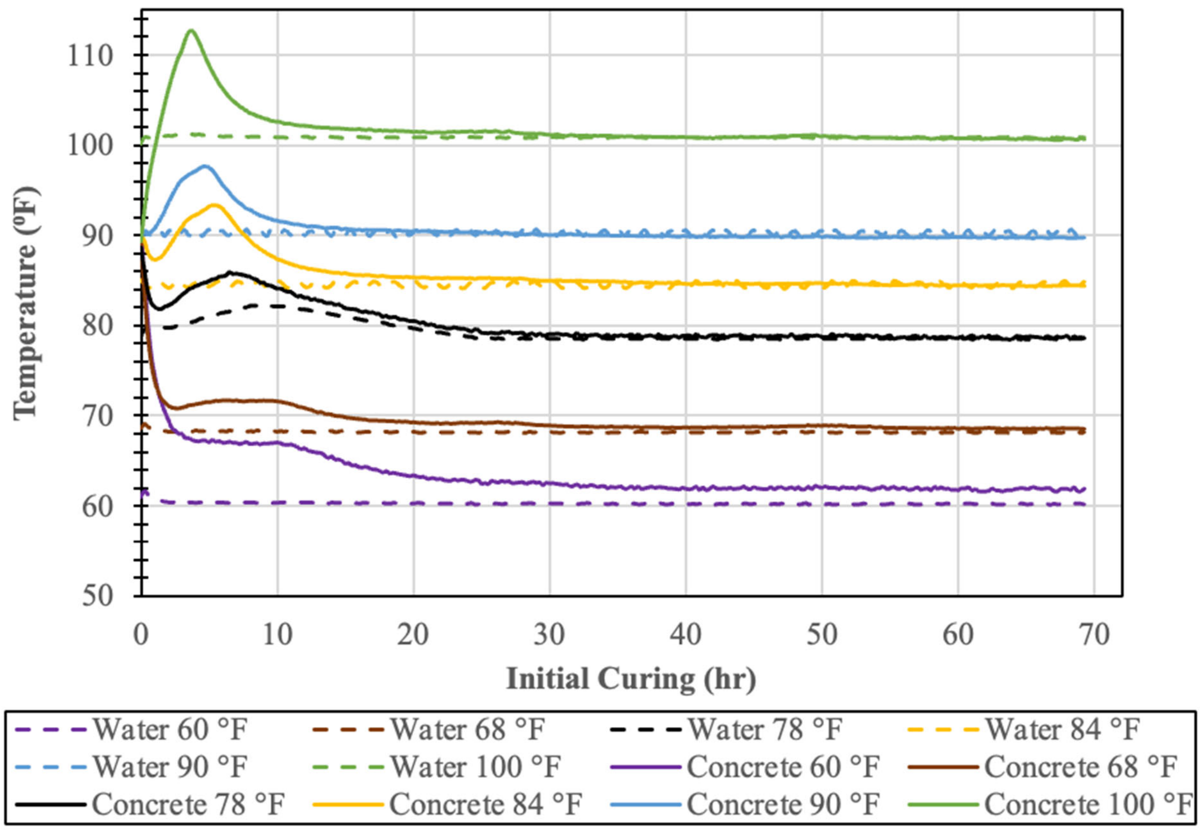


Figure A-19: 10% Silica Fume 72 hours initial curing temperatures plot

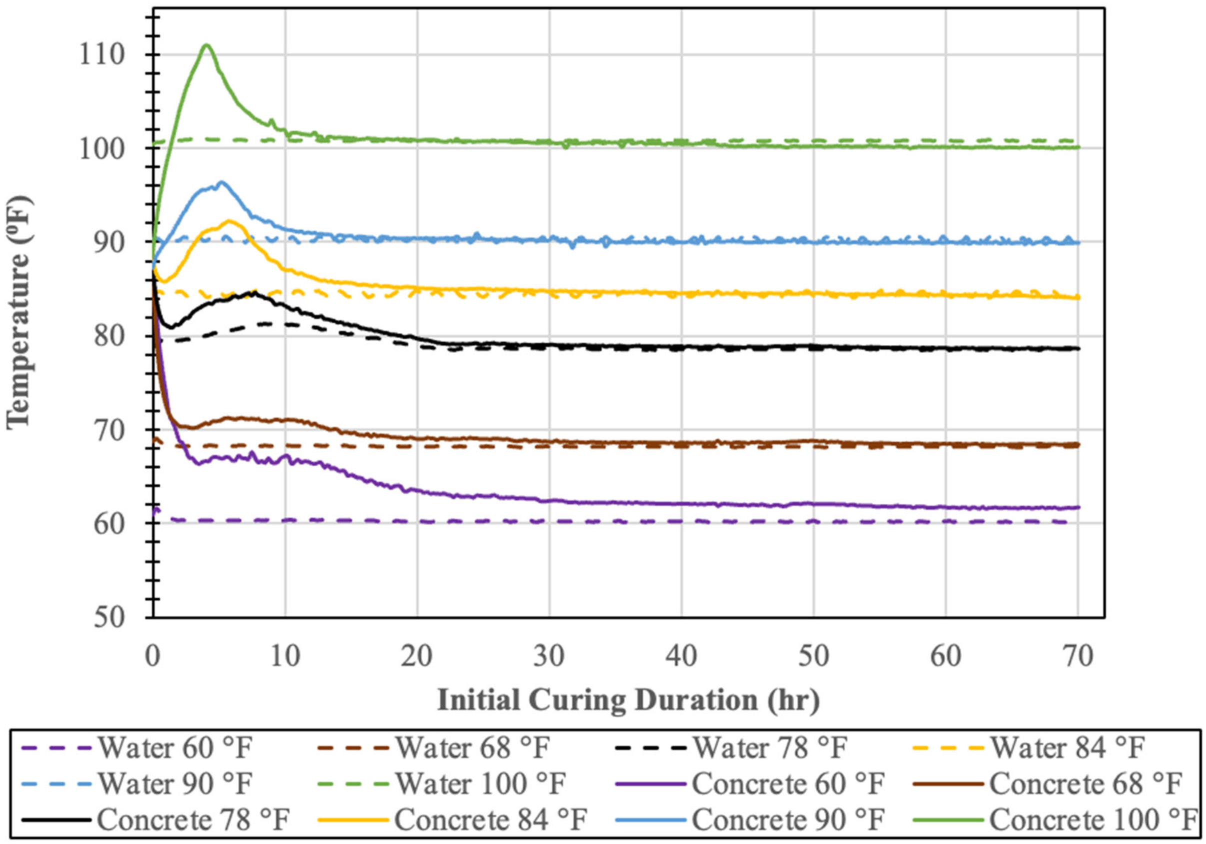


Figure A-20: 20% Class F Fly Ash with 10% Silica Fume 72 hours initial curing temperatures plot

APPENDIX B

VERIFICATION BATCHES FOR PHASE 1

B.1 COMPRESSIVE STRENGTH RESULTS OF VERIFICATION BATCHES

Table B-1: Compressive strength for verification of 100% Type III PCC - 24 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	7170	7110	2
	7070		
	7090		
68 °F	7140	7000	0
	6750		
	7100		
78 °F	6610	6650	-5
	6670		
	6670		
84 °F	6680	6580	-6
	6490		
	6570		
90 °F	6450	6470	-8
	6480		
	5810*		
100 °F	6150	5970	-15
	5820		
	5950		

*Outlier

Table B-2: Compressive strength for verification of 30% Class C Fly Ash Concrete - 24 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6910	6820	7
	6840		
	6720		
68 °F	6470	6370	0
	6250		
	6380		
78 °F	6370	6260	-2
	6110		
	6300		
84 °F	6350	6120	-4
	5860		
	6140		
90 °F	6030	6060	-5
	5970		
	6180		
100 °F	5300*	5640	-11
	5760		
	5510		

*Outlier

Table B-3: Compressive strength for verification of 50% Slag Cement Concrete - 24 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
60 °F	6660	6520	3
	6330		
	6570		
68 °F	6370	6350	0
	6210		
	6480		
78 °F	5580*	6050	-5
	6130		
	5970		
84 °F	5660	5780	-9
	5910		
	5770		
90 °F	5610	5680	-11
	5610		
	5810		
100 °F	5330	5410	-15
	5590		
	5320		

*Outlier

Table B-4: Compressive strength for verification of 100% Type I PCC - 48 hours initial curing

Curing Location	28-Day Compressive Strength (psi)	Average Compressive Strength (psi)	Strength Difference (% From 68 º F)
	6630		
60 °F	6430	6480	5
	6370		
	6110		
68 °F	6320	6200	0
	6180		
	5790		
78 °F	5630	5790	-7
	5960		
	5720		
84 °F	5910	5800	-6
	5760		
	5850		
90 °F	5520	5750	-7
	5880		
	5570		
100 °F	5290	5350	-14
	5200		

*Outlier

B.2 Relative Strength Difference Plots of Verification Batches

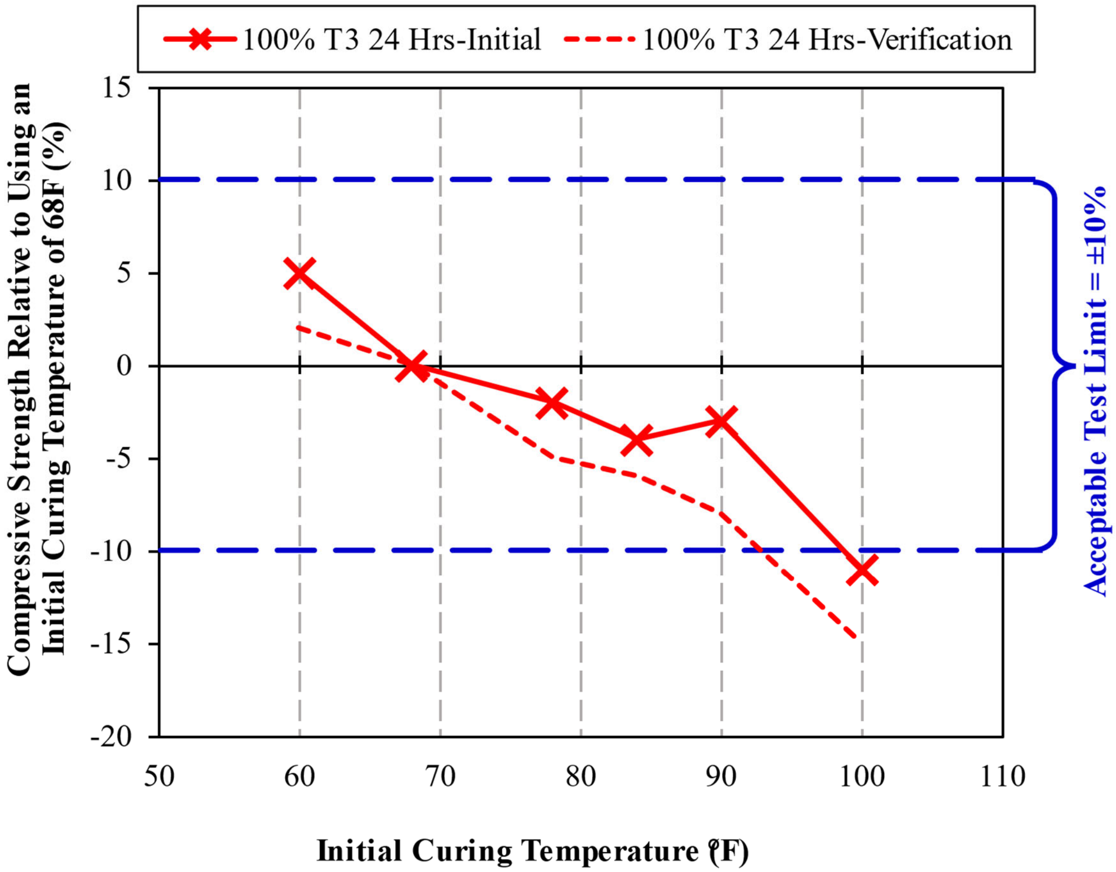


Figure B-1: Relative strength difference plot for verification of 100% Type III PCC - 24 hours initial curing

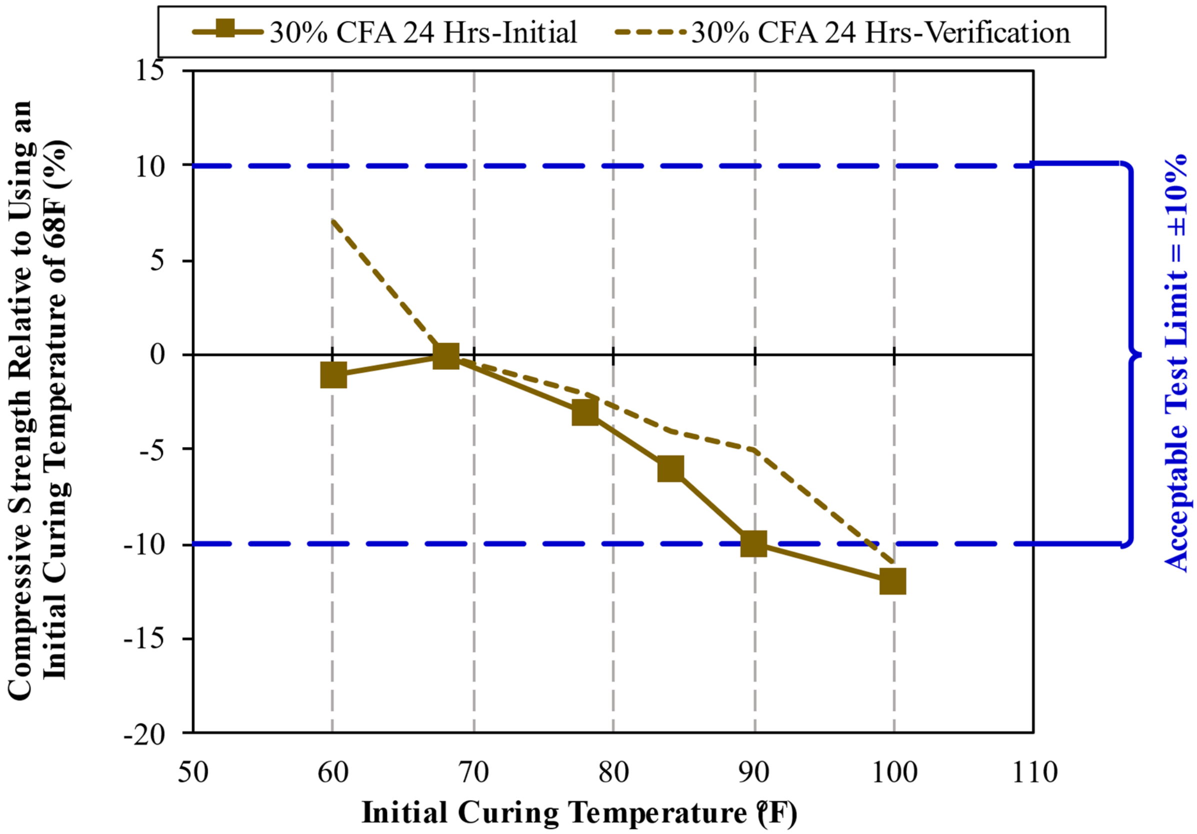


Figure B-2: Relative strength difference plot for verification of 30% Class F Fly Ash Concrete - 24 hours initial curing

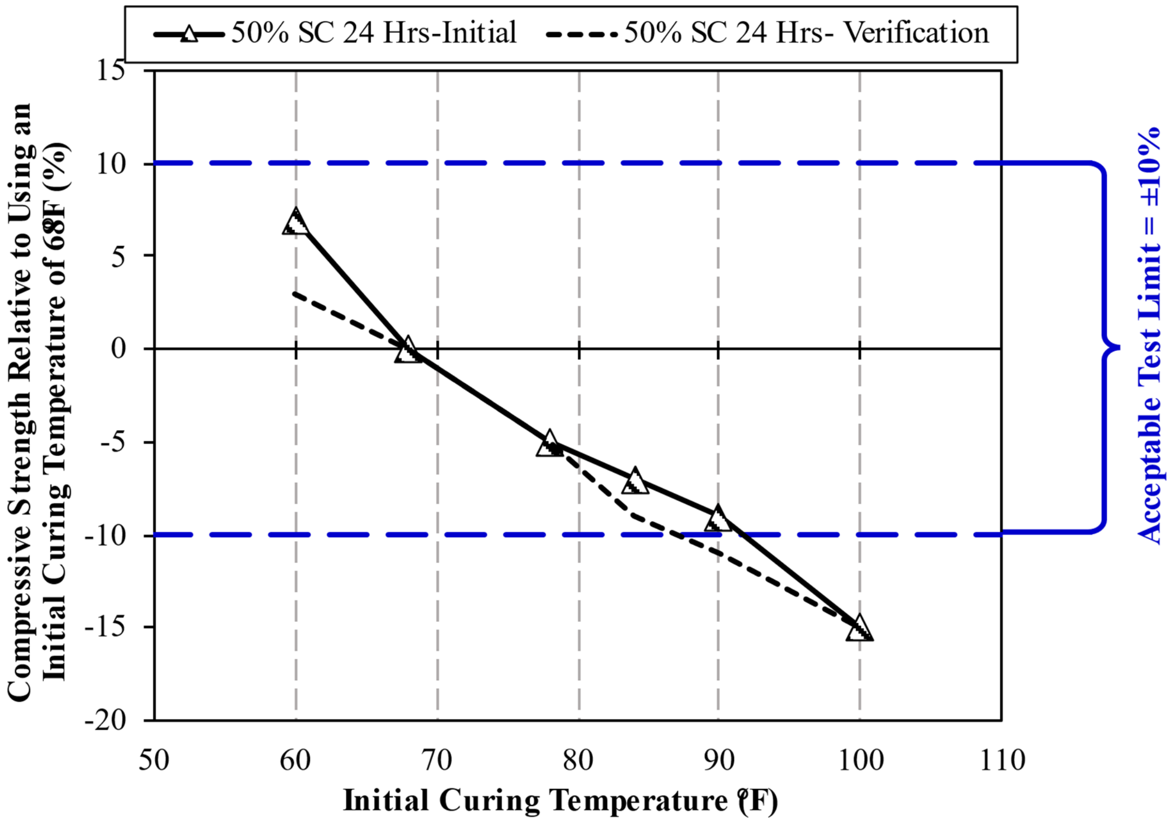


Figure B-3: Relative strength difference plot for verification of 50% Slag Cement Concrete - 24 hours initial curing

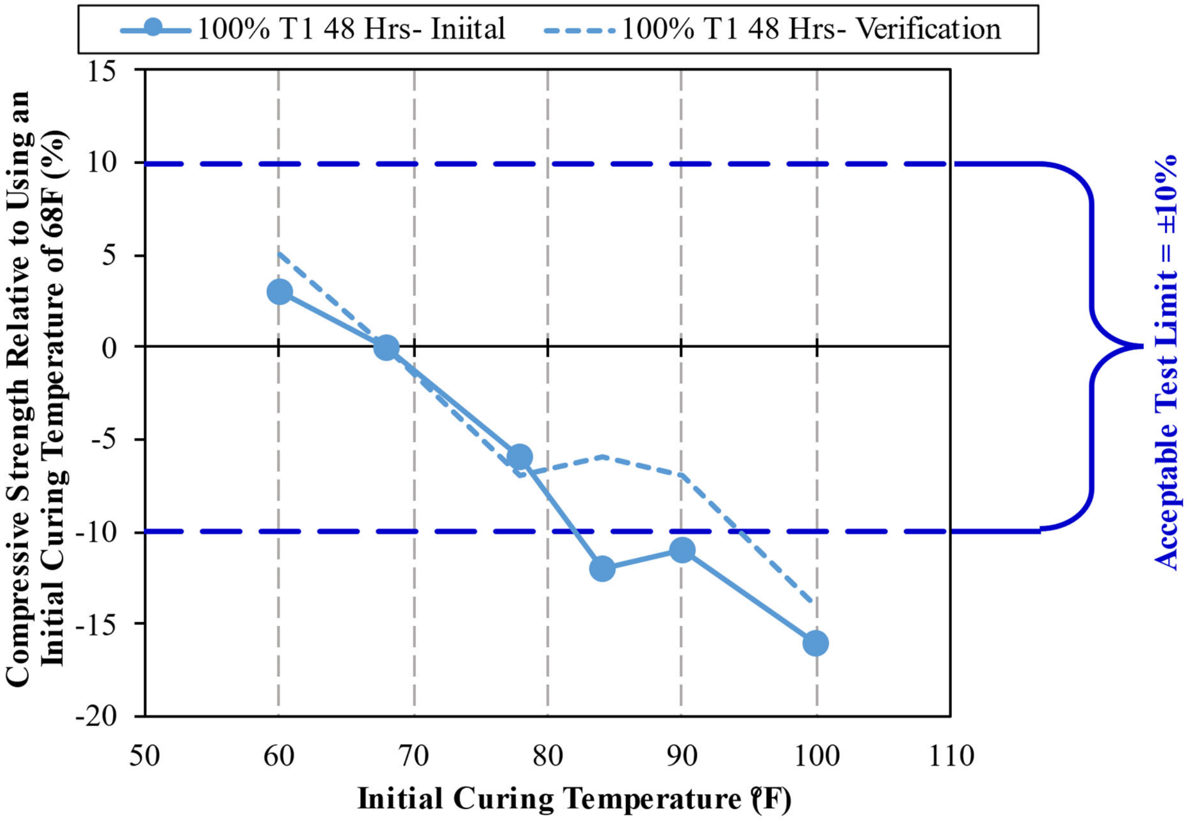


Figure B-4: Relative strength difference plot for verification of 100% Type I PCC - 48 hours initial curing

APPENDIX C
MIXING PROCEDURES FOR PHASE 1

C.1 Mixing Procedure for Conventional-Slump Concrete

Mix the concrete in the laboratory in accordance with ASTM C 192 (2019):

1. "**Butter**" the mixer by using cement, sand, and water to produce a mortar with similar proportions as the concrete to coat the mixer.
2. Drain mortar from the mixer.
3. Add **all coarse and fine aggregates** (alternate buckets of coarse and fine aggregates to help with proper mixing.)
4. Add approximately **80% of water**.
5. Add all air-entraining admixture (**AEA**) while mixer is running. **Mix the material thoroughly for 3 minutes.**
6. Add **all cementitious material** with the mixer running.
7. Disperse **all admixtures in the remaining mixing water (20%)**, and add the solution to the mixer with the mixer running.
8. After all ingredients are added, mix for **3 minutes**.
9. Rest for **3 minutes**.
10. Mix for **2 minutes**.
11. **Sample** concrete to test fresh properties, if acceptable = **Done**.
12. If any additional water-reducing admixtures are needed to adjust consistency: mix for 1 minute, rest for 2 minutes, and mix for 1 minute. Then, re-sample and test fresh properties.

Notes:

1. Cover the open end of the mixer during mixing, the rest period, and when stationary to prevent evaporation.
2. A different mixing procedure is need when using **silica fume**.

C.2 Mixing Procedure for Concrete with Silica Fume

Mix the concrete in the laboratory in accordance with ASTM C 192 (2019):

1. "**Butter**" the mixer by using cement, sand, and water to produce a mortar with similar proportions as the concrete to coat the mixer.
2. Drain mortar from the mixer.
3. Add **all coarse aggregates**
4. Add approximately **80% of water**.
5. Add **silica fume** slowly into the revolving mixer
6. Mix for **3 minutes**.
7. Add **all fine aggregates**
8. Add all air-entraining admixture (**AEA**) while mixer is running. **Mix the material thoroughly for 3 minutes.**
9. Add **all cementitious material** with the mixer running.
10. Mix for **1.5 minutes**.
11. Disperse **all admixtures in the remaining mixing water (20%)** and add the solution to the mixer with the mixer running.
12. After all ingredients are added, mix for **3 minutes**.
13. Rest for **3 minutes**.
14. Mix for **2 minutes**.
15. **Sample** concrete to test fresh properties, if acceptable = **Done**.
16. If any additional water-reducing admixtures are needed to adjust
    a. consistency: mix for 3 minutes, rest for 3 minutes, and mix for 2 minutes.
    b. Then, re-sample and test fresh properties.

Notes:

1. Cover the open end of the mixer during mixing, the rest period, and when stationary to prevent evaporation.
2. When using **silica fume**, a significant amount of **high-range water-reducing admixture**

APPENDIX D

ALDOT 501.02 (2022) SECTION (D), ORIGINAL DOCUMENT

SECTION 501
STRUCTURAL PORTLAND CEMENT CONCRETE

501.01 Description.

The work under this Section shall cover the furnishing of portland cement concrete to be used in constructing concrete structures. Structures shall include but are not limited to bridges of all types, box culverts, headwalls, retaining walls, and other miscellaneous structures.

501.02 Materials.

(d) Sampling and Inspection.

Production of required aggregate gradation in the concrete mixture shall be the Contractor's responsibility.

Cement, aggregates, water, and chemical and mineral admixtures shall be accepted on the basis of requirements currently listed in the Department's Testing Manual.

The Department reserves the right to take samples of aggregates from stockpiles, cementitious materials from storage bins, and chemical admixtures from storage tanks at the mixing or batching plant and to make further tests as needed as the basis for continued acceptance of the materials.

The Contractor shall furnish, without extra compensation, samples of the materials and the concrete mixture for making tests and test specimens as required to comply with the Department's Testing Manual. Additional testing may be required if deemed necessary by the Engineer.

The Contractor shall furnish, without extra compensation, a protected environment for all concrete test cylinders produced incidental to any placement of concrete. This shall be accomplished by supplying a cylinder curing box with a minimum capacity of 22 test cylinders 6" X 12" {150 mm X 300 mm} in size, equipped with heating/cooling capabilities, automatic temperature control, and a maximum/minimum (high/low) temperature readout. The protective environment shall be capable of protecting all specimens within the following specification requirements and it shall be available at each site when concrete is placed and then maintained until such time that all specimens have been transported from the project to the testing facility. The Engineer, prior to beginning any concrete placement, shall approve each protective environment.

Immediately after being struck off, the concrete test specimens shall be moved to the protective environment where they shall remain for an initial curing period of not less than 24 hours or more than 48 hours. During the initial curing period, the specimens shall be stored in a moist environment at a temperature range between 60 ºF to 80 ºF {16 ºC to 27 ºC}, preventing any loss of moisture for up to 48 hours. At all times the temperature in and between concrete specimens shall be controlled by shielding the specimens from cooling/heating devices and direct rays of the sun.

A temperature record of the specimens shall be established by means of maximum/minimum (high/low) thermometers supplied by the Contractor. Only plastic molds shall be used for concrete specimens to be immersed in water.

Concrete specimens that are to be transported to the laboratory for standard curing within 48 hours shall remain in the molds in a moist environment, until they are received in the laboratory, removed from molds, and placed in standard curing.

Concrete specimens that are not transported to the laboratory for standard curing within 48 hours shall be removed from the molds within 24 ± 8 hours and standard curing used until transported to the laboratory. During the standard curing period, the specimens shall be stored at a temperature of 73 ± 3 ºF {23 ± 2 ºC} using the cylinder curing box defined above. Standard curing shall comply with AASHTO T 23 "Making and Curing Concrete Test Specimens in the Field", Standard Curing section.

Figure D-1: ALDOT 501.02 (2022) Section (d), Original Document

APPENDIX E
COMPRESSIVE STRENGTH RESULTS FOR PHASE 2

Table E-1: Jobsite 1, Visit 1 Individual Cylinder Strength Results

Jobsite 1, Visit 1				
Curing Location	**Concrete Age (days)**	**Test Date**	**Test Time**	**Compressive Strength (psi)**
Outdoor AU Curing Box (SIC)	7	8/17/2021	9:40	4290
	7	8/17/2021	9:43	4420
	7	8/17/2021	9:46	4290
	28	9/7/2021	10:30	5760
	28	9/7/2021	10:35	5770
	28	9/7/2021	10:40	5840
Outdoor Nonstandard Cooler (NSIC)	7	8/17/2021	9:50	3810
	7	8/17/2021	9:53	3800
	7	8/17/2021	9:56	3840
	28	9/7/2021	10:45	5010
	28	9/7/2021	10:50	5050
	28	9/7/2021	10:55	5010
Contractor Curing Box	7	8/17/2021	10:05	4470
	28	9/7/2021	10:05	5870
	28	9/7/2021	10:05	5920

Table E-2: Jobsite 1, Visit 2 Individual Cylinder Strength Results

Jobsite 1, Visit 2				
Curing Location	**Concrete Age (days)**	**Test Date**	**Test Time**	**Compressive Strength (psi)**
Outdoor AU Curing Box (SIC)	7	8/19/2021	9:40	4290
	7	8/19/2021	9:43	4420
	7	8/19/2021	9:46	4290
	28	9/9/2021	10:30	5760
	28	9/9/2021	10:35	5770
	28	9/9/2021	10:40	5840
Outdoor Nonstandard Cooler (NSIC)	7	8/19/2021	9:50	3810
	7	8/19/2021	9:53	3800
	7	8/19/2021	9:56	3840
	28	9/9/2021	10:45	5010
	28	9/9/2021	10:50	5050
	28	9/9/2021	10:55	5010

Table E-3: Jobsite 1, Visit 3 Individual Cylinder Strength Results

Jobsite 1, Visit 3				
Curing Location	**Concrete Age (days)**	**Test Date**	**Test Time**	**Compressive Strength (psi)**
Outdoor AU Curing Box (SIC)	7	8/26/2021	11:30	3900
	7	8/26/2021	11:35	3990
	7	8/26/2021	11:40	4020
	28	9/16/2021	11:00	5460
	28	9/16/2021	11:05	5330
	28	9/16/2021	11:10	5560
Outdoor Nonstandard Cooler (NSIC)	7	8/26/2021	11:45	3460
	7	8/26/2021	11:50	3340
	7	8/26/2021	11:55	3490
	28	9/16/2021	11:20	4680
	28	9/16/2021	11:30	4720
	28	9/16/2021	11:35	4770
Contractor Curing Box	7	8/26/2021	11:28	3910
	28	9/16/2021	11:28	5020
	28	9/16/2021	11:28	5180

Table E-4: Jobsite 2, Visit 1 Individual Cylinder Strength Results

Jobsite 2, Visit 1				
Curing Location	**Concrete Age (days)**	**Test Date**	**Test Time**	**Compressive Strength (psi)**
Outdoor AU Curing Box (SIC)	7	6/30/2022	N.A.	N.A.
	7	6/30/2022	N.A.	N.A.
	7	6/30/2022	N.A.	N.A.
	28	7/21/2022	10:30	5460
	28	7/21/2022	10:35	5330
	28	7/21/2022	10:40	5560
Outdoor Nonstandard Cooler (NSIC)	7	6/30/2022	N.A.	N.A.
	7	6/30/2022	N.A.	N.A.
	7	6/30/2022	N.A.	N.A.
	28	7/21/2022	10:45	4680
	28	7/21/2022	10:50	4720
	28	7/21/2022	10:55	4770
Contractor Curing Box	7	6/30/2022	N.A.	3910
	28	7/21/2022	N.A.	5020
	28	7/21/2022	N.A.	5180

Note: N.A. = Not Available

Table E-5: Jobsite 2, Visit 2 Individual Cylinder Strength Results

Jobsite 2, Visit 2				
Curing Location	**Concrete Age (days)**	**Test Date**	**Test Time**	**Compressive Strength (psi)**
Outdoor AU Curing Box (SIC)	7	7/14/2022	9:40	3800
	7	7/14/2022	9:43	3740
	7	7/14/2022	9:46	3750
	28	8/4/2022	10:30	4600
	28	8/4/2022	10:35	4790
	28	8/4/2022	10:40	4540
Outdoor Nonstandard Cooler (NSIC)	7	7/14/2022	9:50	3000
	7	7/14/2022	9:53	3010
	7	7/14/2022	9:56	2950
	28	8/4/2022	10:45	3570
	28	8/4/2022	10:50	3620
	28	8/4/2022	10:55	3670
Contractor Curing Box	7	7/14/2022	N.A.	3550
	28	8/4/2022	N.A.	4150

Note: N.A. = Not Available

Table E-6: Jobsite 2, Visit 3 Individual Cylinder Strength Results

Jobsite 2, Visit 3				
Curing Location	**Concrete Age (days)**	**Test Date**	**Test Time**	**Compressive Strength (psi)**
Outdoor AU Curing Box (SIC)	7	7/20/2022	12:00	5360
	7	7/20/2022	12:05	5530
	7	7/20/2022	12:10	5310
	28	8/10/2022	9:15	7379
	28	8/10/2022	9:20	7367
	28	8/10/2022	9:25	7128
Outdoor Nonstandard Cooler (NSIC)	7	7/20/2022	12:15	4330
	7	7/20/2022	12:20	4410
	7	7/20/2022	12:25	4330
	28	8/10/2022	9:30	5668
	28	8/10/2022	9:35	5633
	28	8/10/2022	9:40	5716
Contractor Curing Box	7	7/20/2022	N.A.	3550
	28	8/10/2022	N.A.	4150

Note: N.A. = Not Available

Table E-7: Jobsite 3, Visit 1 Individual Cylinder Strength Results

Jobsite 3, Visit 1				
Curing Location	**Concrete Age (days)**	**Test Date**	**Test Time**	**Compressive Strength (psi)**
Outdoor AU Curing Box (SIC)	7	7/19/2022	N.A.	4980
	7	7/19/2022	N.A.	4760
	7	7/19/2022	N.A.	4970
	28	8/9/2022	N.A.	6070
	28	8/9/2022	N.A.	6310
	28	8/9/2022	N.A.	6620
Outdoor Nonstandard Cooler (NSIC)	7	7/19/2022	N.A.	4060
	7	7/19/2022	N.A.	4480
	7	7/19/2022	N.A.	4470
	28	8/9/2022	N.A.	5560
	28	8/9/2022	N.A.	5520
	28	8/9/2022	N.A.	5360
Contractor Curing Box	7	7/19/2022	N.A.	4890
	28	8/9/2022	N.A.	6240
	28	8/9/2022	N.A.	6330
	28	8/9/2022	N.A.	6500
	28	8/9/2022	N.A.	6180

Note: N.A. = Not Available

Table E-8: Jobsite 3, Visit 2 Individual Cylinder Strength Results

Jobsite 3, Visit 2				
Curing Location	**Concrete Age (days)**	**Test Date**	**Test Time**	**Compressive Strength (psi)**
Outdoor AU Curing Box (SIC)	7	7/28/2022	N.A.	4500
	7	7/28/2022	N.A.	4860
	7	7/28/2022	N.A.	4650
	28	8/18/2022	N.A.	5850
	28	8/18/2022	N.A.	6000
	28	8/18/2022	N.A.	5840
Outdoor Nonstandard Cooler (NSIC)	7	7/28/2022	N.A.	4570
	7	7/28/2022	N.A.	4190
	7	7/28/2022	N.A.	4550
	28	8/18/2022	N.A.	5130
	28	8/18/2022	N.A.	5420
	28	8/18/2022	N.A.	5260
Contractor Curing Box	7	7/28/2022	N.A.	4950
	28	8/18/2022	N.A.	6320
	28	8/18/2022	N.A.	6180

Note: N.A. = Not Available

Table E-9: Jobsite 4, Visit 1 Individual Cylinder Strength Results

Jobsite 4, Visit 1				
Curing Location	Concrete Age (days)	Test Date	Test Time	Compressive Strength (psi)
Outdoor AU Curing Box (SIC)	7	8/18/2022	N.A.	3520
	7	8/18/2022	N.A.	3440
	28	9/8/2022	N.A.	4330
	28	9/8/2022	N.A.	4420
Outdoor Nonstandard Cooler (NSIC)	7	8/18/2022	N.A.	3160
	7	8/18/2022	N.A.	3100
	28	9/8/2022	N.A.	3970
	28	9/8/2022	N.A.	3950
	28	9/8/2022	N.A.	3940
Contractor Curing Box	7	8/18/2022	N.A.	N.A.
	28	9/8/2022	N.A.	4250

Note: N.A. = Not Available

APPENDIX F

ALDOT 501.02 (2022) SECTION (D) WITH MODIFICATIONS

SECTION 501
STRUCTURAL PORTLAND CEMENT CONCRETE

501.01 Description.

The work under this Section shall cover the furnishing of portland cement concrete to be used in constructing concrete structures. Structures shall include but are not limited to bridges of all types, box culverts, headwalls, retaining walls, and other miscellaneous structures.

501.02 Materials.

(d) Sampling and Inspection.

Production of required aggregate gradation in the concrete mixture shall be the Contractor's responsibility.

Cement, aggregates, water, and chemical and mineral admixtures shall be accepted on the basis of requirements currently listed in the Department's Testing Manual.

The Department reserves the right to take samples of aggregates from stockpiles, cementitious materials from storage bins, and chemical admixtures from storage tanks at the mixing or batching plant and to make further tests as needed as the basis for continued acceptance of the materials.

The Contractor shall furnish, without extra compensation, samples of the materials and the concrete mixture for making tests and test ~~specimens~~ cylinders as required to comply with the Department's Testing Manual. Additional testing may be required if deemed necessary by the Engineer.

The Contractor shall furnish for all concrete test cylinders produced, without extra compensation, ~~a protected environment for all concrete test cylinders produced incidental to any placement of concrete. This shall be accomplished by supplying~~ a cylinder curing box ~~with a minimum capacity of 22 test cylinders 6" X 12" {150 mm X 300 mm} in size,~~ equipped with heating/cooling capabilities, a water circulation pump, ~~,~~ and automatic temperature control capable of maintaining a water temperature range from 60˚F to 80˚F {16˚C to 27˚C}. ~~, and a maximum/minimum (high/low) temperature readout. The protective environment shall be capable of protecting all specimens within the following specification requirements and it shall be~~ The cylinder curing box shall be on a level surface with the supporting surface on which the cylinders are stored level within 0.25 inch/ft {20 mm/m}~~.~~ and available at each site when concrete is placed. ~~and on a level surface within 0.25 in/ft {20 mm/m}, then maintained until such time that all specimens have been transported from the project to the testing facility~~The water in the cylinder curing box shall range from 60˚F to 80˚F {16˚C to 27˚C} prior to the addition of any concrete cylinder. Only plastic molds shall be used for concrete ~~specimens~~cylinders to be immersed in water. ~~.~~ The Engineer, prior to beginning any concrete placement, shall approve each ~~protective environment~~cylinder curing box.

The Contractor shall be responsible for providing continuous power (wall power or generator) for the cylinder curing box during the initial curing period of cylinders. The Contractor shall also be responsible for providing fuel if a generator is used to power the cylinder curing box.

The Engineer shall be responsible for ensuring that no sample is taken before 10 percent or after 90 percent of the batch has been discharged; however, if this is not practical, then no less than 6 cubic feet or 0.2 cubic yards {0.2 cubic meter} of concrete (e.g., approximately two, half-full wheelbarrow loads) shall be discharged from the truck before sampling to remove non-representative concrete.

Immediately after being struck off and sealed with tight-fitting plastic lids, the concrete test cylinders shall be moved to the ~~protective environment~~cylinder curing box where they shall remain for an initial curing period of not less than 24 hours or more than ~~48~~ 72 hours. During the initial curing period, the ~~specimens~~ cylinders shall be stored in ~~a moist environment~~the cylinder curing box with the water ~~at a~~ temperature range ~~between~~ from 60 ºF to 80 ºF {16 ºC to 27 ºC} ~~, preventing any loss of moisture~~ for up to ~~48~~ 72 hours. ~~At all times the temperature in and between concrete specimens shall be controlled by shielding the specimens from cooling/heating devices and direct rays of the sun.~~ The water inside the cylinder curing box shall not be allowed to drop more than 2 inches {50 mm} from the top of any cylinder after the cylinders have been placed in the curing box.

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A temperature record of the specimens shall be established The Contractor shall be responsible for providing by means of maximum/minimum (high/low) thermometers or temperature probes that continuously logrecord the water temperature in the cylinder curing box at intervals of 30 minutes or less. The Engineer shall be responsible for monitoring and documenting the temperature record of the water in the cylinder curing box. The Engineer, prior to beginning any concrete placement, shall approve the temperature probes used to measure the water temperature in the cylinder curing boxsupplied by the Contractor. Only plastic molds shall be used for concrete specimens to be immersed in water.

Concrete specimens cylinders that are to be transported to the laboratory for standard final curing within 48 72 hours after molding.shall remain in the molds in a moist environment, until they are received in the laboratory, removed from molds, and placed in standard curing. During transportation, protect the cylinders with suitable cushioning material to prevent damage from jarring. During cold weather, protect the cylinders from freezing with suitable insulation material. Prevent moisture loss during transportation by leaving the tight-fitting plastic lids on the plastic molds. Transportation time shall not exceed 4 hours. Upon arrival to the laboratory, the cylinders shall be removed from molds and within 30 minutes placed in final curing in accordance with AASHTO T 23 "Making and Curing Concrete Test Specimen in the Field".

In special applications that are not often encountered (e.g., very large drilled shafts), a large amount of retarding chemical admixture could be used to delay setting of the concrete until after 16 hours. In these special applications, concrete cylinders should not be moved too early and in accordance with AASHTO T 23 the cylinders shall not be transported until at least 8 h after final set as measured in accordance with AASHTO T 197.

Concrete specimens that are not transported to the laboratory for standard curing within 48 hours shall be removed from the molds within 24 ± 8 hours and standard curing used until transported to the laboratory. During the standard curing period, the specimens shall be stored at a temperature of 73 ± 3 ºF {23 ± 2 ºC} using the cylinder curing box defined above. Standard curing shall comply with AASHTO T 23 "Making and Curing Concrete Test Specimens in the Field", Standard Curing section.

*Note the following for information only: All green highlighted parts are from AASHTO T 23 (2018).

Figure F-2: ALDOT 501.02 (2022) Section (d) with Modifications, Page 2

APPENDIX G

ALDOT 501.02 (2022) SECTION (D), PROPOSED DRAFT

SECTION 501
STRUCTURAL PORTLAND CEMENT CONCRETE

501.01 Description.

The work under this Section shall cover the furnishing of portland cement concrete to be used in constructing concrete structures. Structures shall include but are not limited to bridges of all types, box culverts, headwalls, retaining walls, and other miscellaneous structures.

501.02 Materials.

(d) Sampling and Inspection.

Production of required aggregate gradation in the concrete mixture shall be the Contractor's responsibility.

Cement, aggregates, water, and chemical and mineral admixtures shall be accepted on the basis of requirements currently listed in the Department's Testing Manual.

The Department reserves the right to take samples of aggregates from stockpiles, cementitious materials from storage bins, and chemical admixtures from storage tanks at the mixing or batching plant and to make further tests as needed as the basis for continued acceptance of the materials.

The Contractor shall furnish, without extra compensation, samples of the materials and the concrete mixture for making tests and test cylinders as required to comply with the Department's Testing Manual. Additional testing may be required if deemed necessary by the Engineer.

The Contractor shall furnish for all concrete test cylinders produced, without extra compensation, a cylinder curing box equipped with heating/cooling capabilities, a water circulation pump, and automatic temperature control capable of maintaining a water temperature range from 60˚F to 80˚F {16˚C to 27˚C}. The cylinder curing box shall be on a level surface with the supporting surface on which the cylinders are stored level within 0.25 inch/ft {20 mm/m} and available at each site when concrete is placed. The water in the cylinder curing box shall range from 60˚F to 80˚F {16˚C to 27˚C} prior to the addition of any concrete cylinder. Only plastic molds shall be used for concrete cylinders to be immersed in water. The Engineer, prior to beginning any concrete placement, shall approve each cylinder curing box.

The Contractor shall be responsible for providing continuous power (wall power or generator) for the cylinder curing box during the initial curing period of cylinders. The Contractor shall also be responsible for providing fuel if a generator is used to power the cylinder curing box.

The Engineer shall be responsible for ensuring that no sample is taken before 10 percent or after 90 percent of the batch has been discharged; however, if this is not practical, then no less than 6 cubic feet or 0.2 cubic yards {0.2 cubic meter} of concrete (e.g., approximately two, half-full wheelbarrow loads) shall be discharged from the truck before sampling to remove non-representative concrete.

Immediately after being struck off and sealed with tight-fitting plastic lids, the concrete test cylinders shall be moved to the cylinder curing box where they shall remain for an initial curing period of not less than 24 hours or more than 72 hours. During the initial curing period, the cylinders shall be stored in the cylinder curing box with the water temperature range from 60 ºF to 80 ºF {16 ºC to 27 ºC} for up to 72 hours. The water inside the cylinder curing box shall not be allowed to drop more than 2 inches {50 mm} from the top of any cylinder after the cylinders have been placed in the curing box.

The Contractor shall be responsible for providing temperature probes that continuously record the water temperature in the cylinder curing box at intervals of 30 minutes or less. The Engineer shall be responsible for monitoring and documenting the temperature record of the water in the cylinder curing box. The Engineer, prior to beginning any concrete placement, shall approve the temperature probes used to measure the water temperature in the cylinder curing box.

Concrete cylinders are to be transported to the laboratory for final curing within 72 hours after molding. During transportation, protect the cylinders with suitable cushioning material to prevent damage from jarring. During cold weather, protect the cylinders from freezing with suitable insulation material. Prevent moisture loss during transportation by leaving the tight-fitting plastic lids on the plastic molds. Transportation time shall not exceed 4 hours. Upon arrival to the laboratory, the

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cylinders shall be removed from molds and within 30 minutes placed in final curing in accordance with AASHTO T 23 “Making and Curing Concrete Test Specimen in the Field”. In special applications that are not often encountered (e.g., very large drilled shafts), a large amount of retarding chemical admixture could be used to delay setting of the concrete until after 16 hours. In these special applications, concrete cylinders should not be moved too early and in accordance with AASHTO T 23 the cylinders shall not be transported until at least 8 h after final set as measured in accordance with AASHTO T 197.

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