Development of Jobsite Cylinder Curing Practices for the Alabama Concrete Industry

By

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Abstract

In concrete construction projects, quality assurance test cylinders are made to evaluate the quality of the concrete delivered to a jobsite. In order to accurately evaluate these cylinders, they must be cured according to specific requirements. The Alabama Department of Transportation outlines these specifications in ALDOT 501.02 section (d) “Sampling and Inspection”.

Nine jobsite visits were conducted to review and evaluate the current practices used by jobsite technicians and contractors to sample and cure concrete test cylinders as well as assess the effects of non-standard curing on the 28-day compressive strength when exposed to summertime placement conditions. To accomplish this, at each jobsite visit, samples of the provided concrete were collected, cylinders made, and cured in two different initial curing environments. The 28-day compressive strength results of these cylinders were then compared along with the temperature data within each jobsite visit.

The results clearly indicate that a significant decrease in 28-day compressive strength occurs when cylinders are cured in conditions different than those required by ALDOT 501 (2022) and AASHTO T 23 (2018). The maximum decrease in 28-day compressive strength was 22%. Additionally, it was found that cylinder curing boxes supplied with continuous power and a water circulation pump were capable of maintaining the specified water temperature range of 60 to 80°F for the entire initial curing duration. Therefore, it is recommended that continuous power be provided for the cylinder curing box along with fuel if a generator is used for the power source. Lastly, the results show that it is only necessary to record the minimum and maximum temperatures of the water in the cylinder curing box and not the temperature of the concrete specimens. Recommended changes to ALDOT 501 to improve the jobsite curing practices are provided in this thesis.

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Lastly, I would like to thank and give glory to God, for everything I have is a gift from you. I am completely undeserving of the love and blessings you have and continue to bestow upon me and for that I dedicate my work and my life to you. Thank you for all the people who you have put in my life that brought me to where I am today.

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Chapter 1: Introduction

1.1 Background

Quality assurance is an important part to any construction project but especially when cast-in-place concrete is involved. While slump, temperature, and air content tests evaluate fresh concrete properties, concrete test cylinders are made to evaluate the 28-day compressive strength of the concrete. These concrete cylinders are made and initially cured on the jobsite, transported to the testing facility for final curing under controlled conditions, and then tested in compression at 28 days in accordance with relevant AASHTO standards in order to provide an indication of the quality of the concrete produced by the concrete supplier as delivered to the jobsite. There are many factors however that can negatively affect the compressive strength results of these cylinders such as temperature, molding environment, transportation, etc. If the test cylinders are not made, cured, and transported according to the relevant AASHTO standards, it can be detrimental to a project's timeline, budget, and safety.

The initial curing period occurs at the jobsite where concrete test cylinders are placed in a protective environment for 24 to 48 hours within a temperature range of 60 to 80°F. This temperature range refers to the temperature of the water surrounding the cylinders and not the temperature inside the concrete (Obla, et al. 2018). This is accomplished using a cylinder curing box shown in Figure 1-1.

Figure 1-1: Typical Cylinder Curing Box

(Humboldt Manufacturing Company, Elgin, Illinois 2023)

After the initial curing period, the cylinders are transported to the laboratory, demolded, and placed in final curing according to AASHTO T 23 (2018). Final curing consists of placing the cylinders in lime-saturated water tanks or moist cure rooms that maintain a temperature of 73°F ± 3°F. Then after 28-days, the cylinders are removed from final curing and tested in accordance with AASHTO T 22 (2022) to determine their 28-day compressive strength.

Curing temperature has a significant impact on concrete compressive strength. Concrete test cylinders not cured in accordance with AASHTO T 23 (2018) often experience high temperatures and loss of moisture during the initial curing period, which result in significant decreases in 28-day compressive strength reported by Obla et al. (2018) and Samarai et al. (1983). This is a common problem in the Alabama concrete industry as there have been numerous instances where the initial curing temperature requirements for quality assurance test cylinders are not met. While problems have been discovered with cylinder curing boxes, it is unclear if the curing boxes are not functioning properly for the entire initial curing duration, if they are just unable to adequately maintain their water temperature from 60 to 80°F during the high temperature conditions experienced in Alabama during summer months, or if the specifications regarding initially curing concrete test cylinders are just not being followed.

1.2 Research Significance

ALDOT 501 “Structural Portland Cement Concrete” is the standard specification for structural concrete construction in in the state of Alabama and ALDOT 501.02 section (d) “Sampling and Inspection”, attached in Appendix A, specifies the correct way to sample, make, cure, and transport quality assurance concrete test cylinders. The 28-day compressive strength results of these concrete test cylinders are the means used to determine the acceptance of placed concrete. Therefore, this section is extremely important to owners, concrete suppliers, and contractors as there are many factors that can negatively affect the compressive strength of the test cylinders. Unfortunately, some aspects of ALDOT 501.02 section (d) have become overlooked and ignored in recent years resulting in numerous 28-day strength results that were less than the specified 28-day compressive strength. Figure 1-2 shows examples of improper jobsite curing practices that satisfy neither ALDOT 501 (2022) nor AASHTO T 23 (2018).

Figure 1-2: Improper Initial Curing of Concrete Cylinders (NRMCA 2014)

When concrete test cylinders are cured improperly and subsequently produce low compressive strength results, it leads to questions being asked about:

1) The quality of the concrete delivered to a site.
2) The strength of the in-place concrete.
3) The practices used to make, cure, transport, and test concrete cylinders on ALDOT projects.
4) How to use core testing to determine if the in-place concrete is substandard or acceptable.

If the concrete cylinders that produced the low strength test results were not cured in accordance with ALDOT 501, then there is no way of knowing if the delivered concrete had inadequate strength or if it was not cured properly. When this happens, a concrete investigation ensues, usually involving concrete cores to determine the suitability of the potentially substandard concrete. "If the investigation results show that the concrete fails to meet the contract requirements, the contractor shall be responsible for the cost of the investigation to include, but not limited to, per-diem, travel expenses, and sampling and testing" (ALDOT 501 2022). When low 28-day cylinder results occur, it opens up the project to multiple delays and liabilities as all stakeholders are forced to investigate the causes of the low 28-day cylinder strengths. Frequently, these financial burdens due to investigation results and schedule delays are forwarded to the concrete supplier by the contractor leading to a dispute as to which party is truly responsible. Therefore, it is extremely important that ALDOT 501 is as clear and practical as possible in order to avoid concrete investigations and the resulting disputes regarding financial responsibility.

1.3 Project Objectives

The objectives of this study are as follows:

1. To review all current practices used to make, cure, transport, and test concrete cylinders for ALDOT projects.
2. To assess the effects of non-standard curing practices on the 28-day cylinder strength
3. To evaluate new and improved practices used to make, cure, transport, and test concrete cylinders.
4. To improve and clarify ALDOT 501.02 section (d) "Sampling and Inspection."

1.4 Project Scope

The scope of this project was to get a more accurate representation of the current practices used to make and cure concrete test cylinders in the field as well as how such practices affect the 28-day compressive strength. To accomplish this, 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 Auburn research team aimed to sample concretes from various project types and specified 28-day compressive strengths. The complete experimental plan can be found in Chapter 3.

1.5 Organization of Thesis

Chapter 2 explores and discusses literature related to concrete hydration, sampling, and curing along with the related AASHTO standards. 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. Chapter 3 discusses the experimental plan developed for this project including the materials and process used to execute the project objectives. Chapter 4 presents the results from each jobsite visit including temperature data, compressive strength results, and recorded observations of jobsite technician testing practices. Chapter 5 discusses the recommendations and proposed alterations to ALDOT 501, section (d) “Sampling and Inspection” based on the results presented in Chapter 4. Finally, Chapter 6 summarizes the conclusions drawn from the results and the recommendations for future studies.

Chapter 2: Literature Review

2.1 Basics of Concrete Hydration

Concrete is the most commonly used construction material across the globe (Wang, et al. 2023). Concrete is a composite material composed of water, cement, and aggregate, which provides substantial strength, durability, permeability, and fire resistance while still remaining economical (Peyvandi, et al. 2013). When water is added to cement, each of the compounds undergoes a process called hydration and contributes to the final concrete product (Arslan, et al. 2017). The hydration of cement particles produces hydration products that act as the glue that holds the aggregates together, forming concrete. As the hydration process continues, more and more of the cement is transformed into hydration products, causing the mixture to gain strength and transition from a viscous liquid to a solid.

The entire hydration process includes five stages. First, tricalcium aluminate (C_3A) and sulfate interact in the new cement-water solution as the concrete is initially produced. The developing concrete then remains in a dormant period as it is transported, placed, and finished. After the dormant period, the acceleration stage begins, which determines the rate at which the concrete hardens and enters final set. This stage can occur anywhere between 1 and 12 hours after the concrete is mixed and can be regulated by retarding and accelerating chemical admixtures. Then the deceleration stage occurs which ultimately determines the rate of early strength gain and is followed by the steady stage determining later-age strength (Mindess et al. 2003). While the exact beginning and ending of these stages vary from concrete to concrete, they provide an overview of the hydration process (Bullard, et al. 2010).

Hydration is exothermic and the heat developed during the process is known as the heat of hydration. The peak level of heat of hydration happens at the end of the acceleration phase (Phase 3), as shown in Figure 2-1. As the hydration process occurs, concrete starts to stiffen, losing its plasticity and gaining strength. This stiffening process is called setting (Samarai et al. 1983). There are two types of setting, initial and final. Initial setting is generally referred to as the beginning of stiffening, while final setting is usually marked by the disappearance of all plasticity. The level of heat of hydration and subsequent duration of hydration can determine the time of both initial and final setting (Samarai et al. 1983). In a study on the effects of high temperatures on the properties of fresh concrete, Samarai et al. (1983) concluded that temperature is particularly important when it comes to concrete properties because as the heat of hydration increases, the duration through which it occurs decreases.

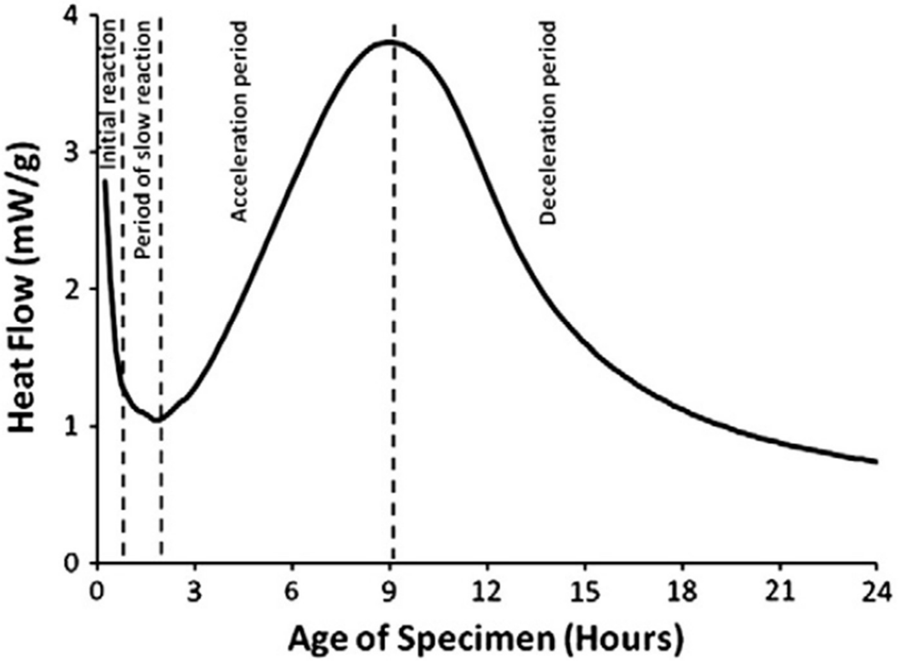


Figure 2-1: Periods of Concrete Hydration (Bullard, et al. 2010)

2.2 What is Curing?

Strength has long been the fundamental property used by engineers to assess the quality and performance of concrete. While concrete strength is a function of mixture proportions, water-to-cement ratio (w/c), and the degree of hydration of cementitious materials; the degree of hydration is greatly controlled by the conditions experienced by the concrete specimens after they are made (Idowu 2017). Using this knowledge, the American Concrete Institute defines curing 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).

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. Furthermore, effective curing regimes can enhance concrete’s microstructure, which is conducive to the improvement of durability (Wang, et al. 2023).

2.3 Consequences of Improper Curing

Concrete can lose some of its durability characteristics when proper procedures for curing are not followed. As explained in Section 2.2, there are many factors that affect concrete strength development as well as durability. Improper curing can alter the intended characteristics of the concrete because curing conditions affect cement hydration, pore structures, and concrete strength (Peyvandi, et al. 2013). Kaplan (2019) states that ineffective curing procedures usually result in the limitation of strength gains and the occurrence of defects such as microcracks and poor quality surfaces. As a result, the concrete cannot achieve the expected mechanical strength, which greatly reduces the safety, reliability, and lifespan of concrete structures (Kaplan, et al. 2019). Some major effects of improper curing are listed below (Punmia and Jain 2003).

- Miniature cracks appearing on concrete surfaces.
- A lack of heat of hydration resulting in the development of internal cracks.
- Uneven strength distribution resulting in an overall strength reduction.
- An increase in concrete permeability and resulting decrease in durability.
- Reduced resistance to freeze thaw and corrosion effects.

The severeness of the effects resulting from improper curing will be greater in members that are directly exposed to the elements. The consequences of these effects can be extreme both economically and legally, and can sometimes result in structural collapse and loss of life (Basheer, Kropp and Cleland 2001).

A study by Idowu (2017) investigated the impact of improper curing on various concrete properties, including compressive strength and drying shrinkage. The results of this study determined that improper curing frequently leads to a decrease in compressive strength due to a reduction in degrees of hydration of the concrete. The study also revealed that improper curing of concrete mixtures with fly ash blends has an even greater detrimental effect.

2.4 Factors that Affect Concrete Compressive Strength

2.4.1 Curing Temperature

Temperature is one of the main factors that affects the strength development of concrete. During the initial curing period, the rate of hydration of the concrete greatly depends on the temperature at which it is cured. Figure 2-2 shows how curing temperature affects the heat of hydration development of cement while Figure 2-3 shows how elevated curing temperatures affect the initial rate of cement hydration. As the curing temperature is increased, the heat of hydration increases significantly, and its duration is greatly reduced as the initial rate of cement hydration is much higher.

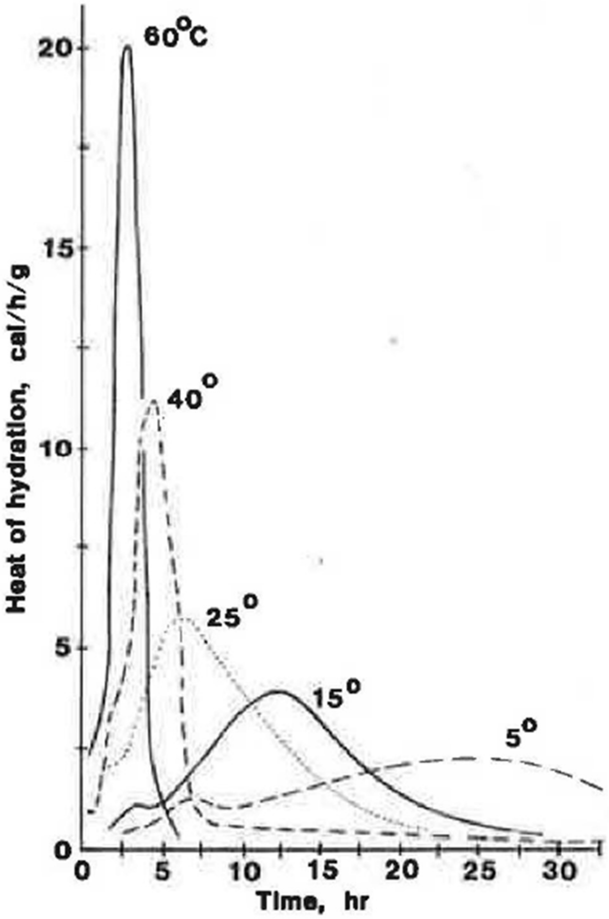


Figure 2-2: Effect of Curing Temperature on Heat of Hydration (Samarai et al. 1983)

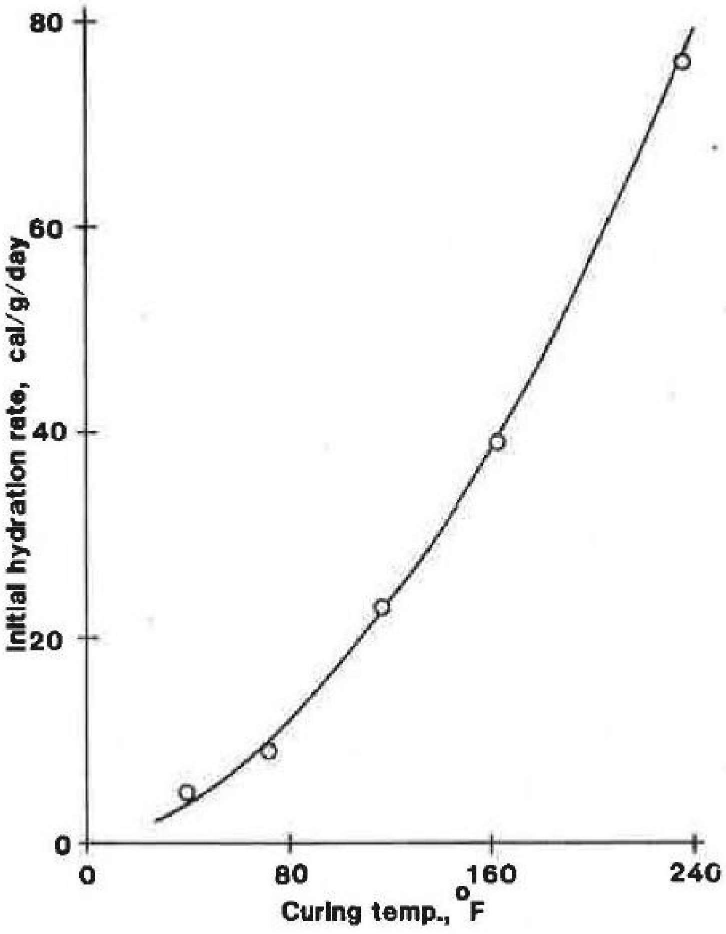


Figure 2-3: Effect of Curing Temperature on Rate of Cement Hydration

(Samarai et al. 1983)

As explained in Section 2.2, the heat of hydration and its duration have a great impact on the time at which initial and final set occur. While the standard time of initial set of portland cement ranges from approximately 2 to 4 hours after placement and 5 to 8 for final set, high temperatures can greatly accelerate these times (Samarai et al. 1983). In fact, an increase in curing temperature from 59 to 86°F reduces the time of initial set by approximately half, as shown in Figure 2-5.

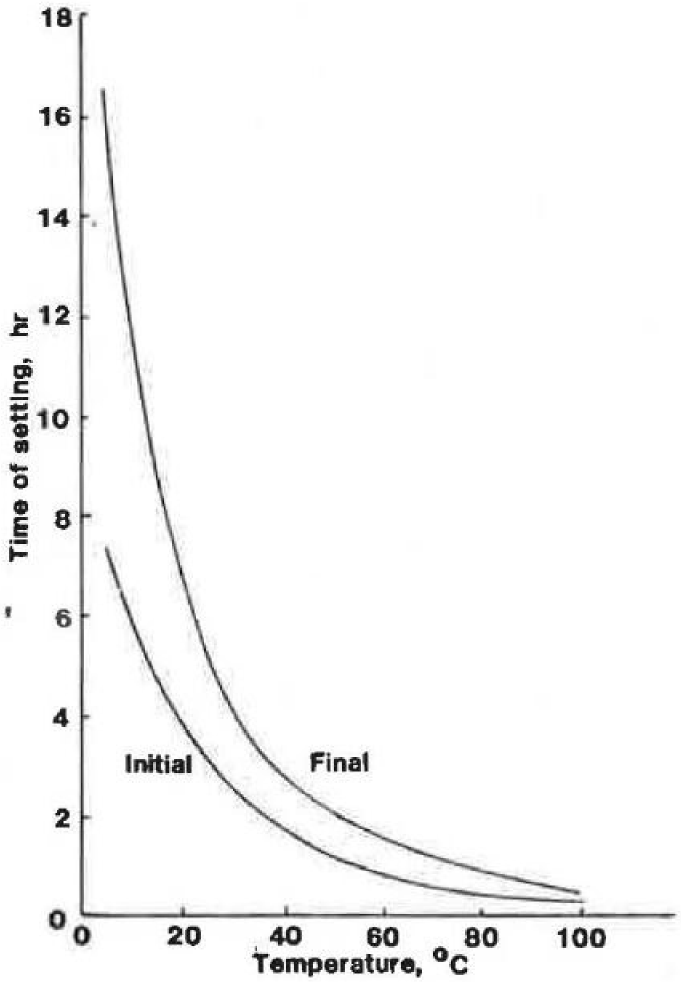


Figure 2-4: Effect of Curing Temperature on Time of Setting (Venuat 1974)

Ultimately, the increased rate of setting due to high curing temperatures, leads to an increase in early strength gain. However, due to the increased rate of setting and therefore increased rate of hydration, this will result in greater difficulty with handling, finishing, curing and an increased possibility of cold joints which can decrease compressive strength (Samarai et al.1983).

Obla et al. (2018) further confirmed the effects of elevated curing temperatures on the 28-day compressive strength of concrete test cylinders. These results are shown in Table 2-1.

Table 2-1: Effect of High Initial Curing Temperatures on 28-day Compressive Strength (Obla, et al. 2018)

Type of 1-day Initial Curing	Temperature Range, °F (°C)	Relative Strength, %
Outdoor exposure: curing box with thermostatic control; in water	71 to 76 (22 to 24)	100
Laboratory: immersed in lime water (control)	76 to 82 (24 to 28)	100
Laboratory: in air	78 to 82 (26 to 28)	88
Outdoor exposure to sunlight: not protected	71 to 107 (22 to 42)	85
Outdoor exposure: covered with wet burlap and plastic	94 to 140 (34 to 60)	83

Note: Specimens were molded at 86°F (30°C) at the jobsite and subjected to the initial curing condition for 24 hours; transferred to standard moist room at 73°F (23°C) for curing until test age of 28 days

After curing concrete cylinders under various hot weather conditions, it was determined that elevated initial curing temperatures can cause up to a 20% reduction in compressive strength (Obla, et al. 2018). As shown in Table 2-1, When the curing environment was changed from a water-controlled environment to an air environment, there was a 12% decrease in strength. The most extreme case was outdoor exposure covered in wet burlap and plastic which resulted in initial curing temperatures of up to 140 degrees and a strength reduction of 17%, even though the cylinders were only in this environment for 24 hours. The test results also showed that specimens exposed to ambient conditions without temperature control exhibited strength reductions of 15-17% when compared to the temperature-controlled specimen (Obla, et al. 2018).

These findings are also consistent with the findings of White (2023) in which cylinders were tested at six different initial curing temperatures for a variety of different concrete mixtures. Using the initial curing temperature of 68°F as a reference, the results showed that for initial curing temperatures exceeding 80°F, cylinders exhibited more than a 10% decrease in 28-day strength. When cylinders were cured at 100°F, some cylinders showed as much as a 23% decrease in compressive strength (White 2023).

2.4.2 Relative Humidity During Curing

Humidity and moisture control is very important when it comes to concrete curing and especially during the initial curing period. If concrete is permitted to dry without being cured, moisture from the surface will evaporate and result in insufficient water for cement hydration. Also, there will be a moisture gradient across the section which will lead to development of uneven strength (Idowu 2017).

The study from Obla et al. (2018) discussed in Section 2.4.1 also investigated the effects of differing levels of relative humidity on 28-day compressive strength. Three different humidity levels were investigated and the results of such are shown in Table 2-2.

Table 2-2: Effects of Relative Humidity on 28-day Compressive Strength (Obla et al. 2018)

Initial Curing Conditions	Relative 28-day Strength, %*		
Temperature	37°F (3°C) at 100% RH	73°F (23°C) at 60% RH	100°F (38°C) at 25% RH
1 day in air^T	100	92	88
3 days in air^T	93	89	78

*In comparison with compressive strength of 5590 psi (38.5 Mpa) determined for specimens moist cured at 73°F and 100% RH from the time of molding until testing

[T] Specimens were molded at 73°F, subjected to initial curing conditions, and transferred to standard moist room at 73°F for curing until test age of 28 days.

As shown in Table 2-2, the 28-day strength is highly affected by a decrease in relative humidity for normal-strength concrete, especially when paired with an increase in temperature. These results are consistent with that of a study by Bloem (1969) which showed that “even at proper temperatures, air curing can lower strengths up to 18% depending on the length of air curing”.

The data and conclusions from this study are consistent with that of Arslan, et al. (2017) that studied the effects of different curing conditions on compressive strength of concrete. Arslan, et al. (2017) findings confirmed that the durability of concrete structures is greatly influenced by the curing of concrete. These results are shown in Figure 2-5. After curing concrete specimens in 3 different environments and testing their compressive strength at 6 different ages, it was clear that the compressive strength of concrete samples cured in water in accordance with ASTM C 31 (2019) were all relatively greater than the other samples of the same age (Arslan, et al. 2017). Additionally, the compressive strength of concrete samples without any type of curing that were placed in an open-air environment with no moisture control were the least for all ages (Arslan, et al. 2017).

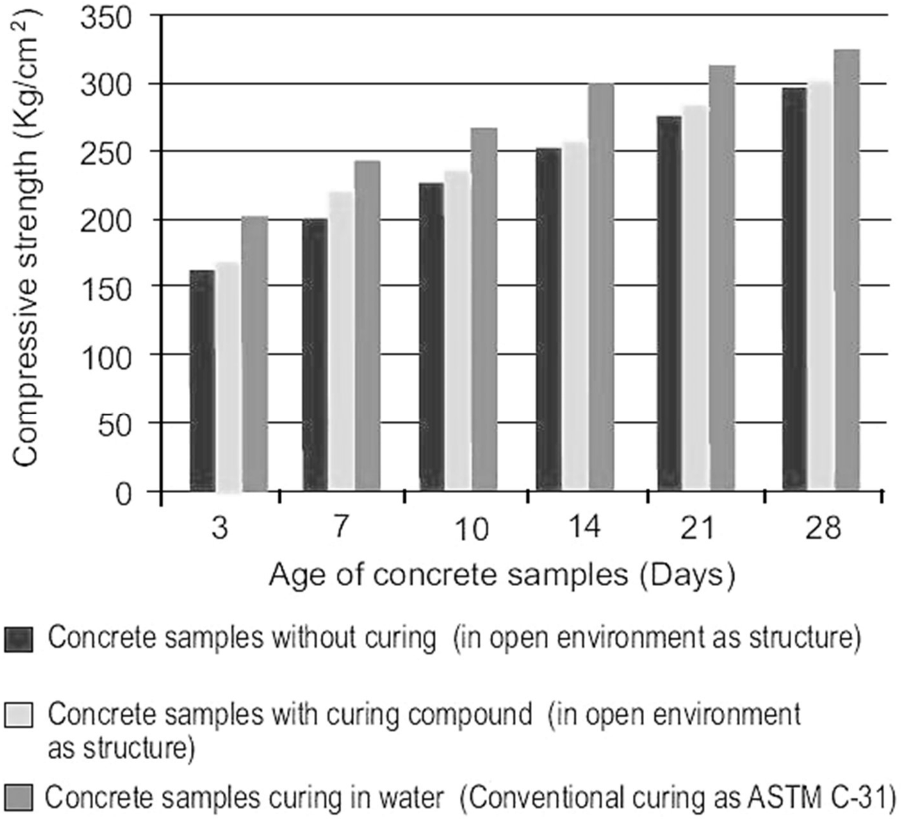


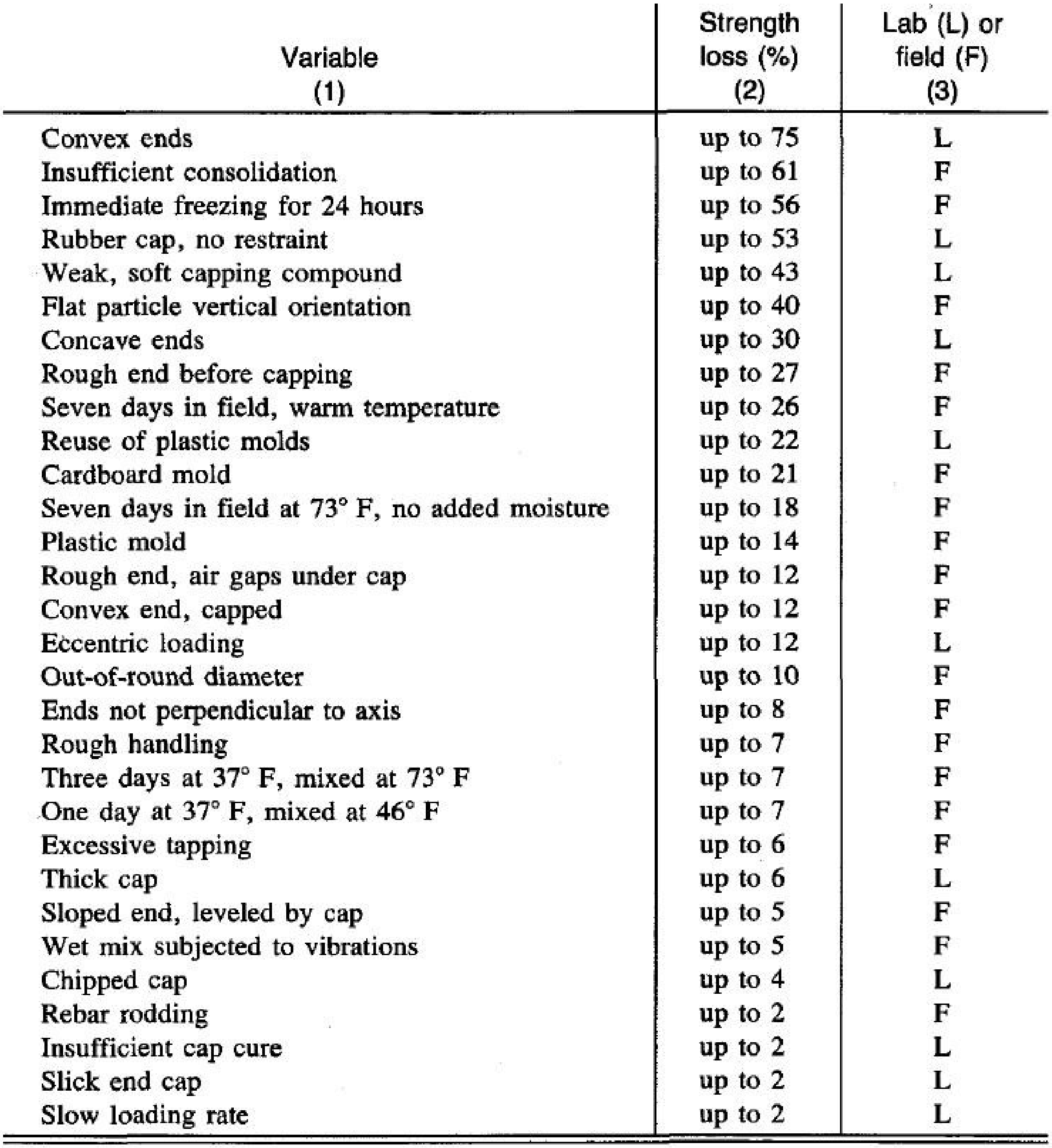
Figure 2-5: Compressive Strengths of Different Curing Environments (Arslan, et al. 2017)

Additionally, humidity control during curing is even more important when it comes to high-strength concrete (Carrasquillo et al. 1981). At early ages, high-strength concrete has a much higher strength development than normal-strength concrete due to the increase in heat of hydration from larger cement contents. As a result, the reduction in compressive strength due to a lack of humidity is even more magnified for high-strength concrete than for normal-strength concrete (Carrasquillo et al. 1981).

2.4.3 Additional Factors

While temperature and humidity are important factors that could lead to low concrete cylinder strengths, there are many other factors that can cause a decrease in the compressive strength of concrete test cylinders. Table 2-3 lists these factors with their approximated potential resulting percent strength losses. Richardson (1991) developed this table from a literature review on the whole testing process for compressive strength of concrete test cylinders including sampling, casting, initial curing, transporting, laboratory curing, capping, and testing.

Table 2-3: Other Factors Affecting Concrete Compressive Strength (Richardson 1991)



Variable (1)	Strength loss (%) (2)	Lab (L) or field (F) (3)
Convex ends	up to 75	L
Insufficient consolidation	up to 61	F
Immediate freezing for 24 hours	up to 56	F
Rubber cap, no restraint	up to 53	L
Weak, soft capping compound	up to 43	L
Flat particle vertical orientation	up to 40	F
Concave ends	up to 30	L
Rough end before capping	up to 27	F
Seven days in field, warm temperature	up to 26	F
Reuse of plastic molds	up to 22	L
Cardboard mold	up to 21	F
Seven days in field at 73° F, no added moisture	up to 18	F
Plastic mold	up to 14	F
Rough end, air gaps under cap	up to 12	F
Convex end, capped	up to 12	F
Eccentric loading	up to 12	L
Out-of-round diameter	up to 10	F
Ends not perpendicular to axis	up to 8	F
Rough handling	up to 7	F
Three days at 37° F, mixed at 73° F	up to 7	F
One day at 37° F, mixed at 46° F	up to 7	F
Excessive tapping	up to 6	F
Thick cap	up to 6	L
Sloped end, leveled by cap	up to 5	F
Wet mix subjected to vibrations	up to 5	F
Chipped cap	up to 4	L
Rebar rodding	up to 2	F
Insufficient cap cure	up to 2	L
Slick end cap	up to 2	L
Slow loading rate	up to 2	L

While all nonstandard techniques reviewed rendered a decrease in compressive strength, there was a wide range of levels of strength loss with a maximum of 75% (Richardson 1991). It is important to note the variables “seven days in the field, warm temperature” and “seven days in the field at 73°F, no added moisture” rendered possible strength losses of up to 26% and up to 18%, respectively. This is consistent with results of the studies discussed in Sections 2.4.1 and 2.4.2 in which initial curing temperatures over 80°F and losses in moisture both result in a reduction in compressive strength.

Although this list may seem excessive, by following the correct ASTM or AASHTO standards, the effect of these factors can be avoided and lead to many fewer problems with low strength results (Richardson 1991).

2.5 Review of AASHTO Standards

The American Association of State Highway and Transportation Officials (AASHTO) publishes many standards, test protocols, and guidelines related to concrete construction and is the basis upon which the majority of state construction specification are written. AASHTO T 23, Making and Curing Concrete Test Specimens in the Field, provides standardized requirements for making, curing, protecting, and transporting concrete test specimens under field conditions (AASHTO 2018). Important sections from AASHTO T 23 and other AASHTO standards related to concrete sampling, molding, and curing quality assurance test specimens in the field are discussed in this section.

2.5.1 Sampling

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 R 60, Sampling Freshly Mixed Concrete.” Section 5.2.2 of AASHTO R 60 (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.

2.5.2 Molding

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.

2.5.3 Curing

To avoid the many negative consequences of improper curing discussed in Section 2.3, 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.

It is important to note that the compressive strength results of cylinders cured for acceptance testing or quality assurance purposes do not represent the in-place concrete strength. Standard curing consists of initial curing, AASHTO T 23 (2018) Section 10.1.2, and final curing, AAHSTO T 23 (2018) Section 10.1.3. During initial curing, specimens are to be stored for a period up to 48 hours in a temperature range from 60 to 80°F on a level surface that prevents moisture loss from the specimen. For concrete mixtures with a specified compressive strength of 6000 psi or greater, the temperature range should be between 68 and 78°F. Additionally, all specimens shall be shielded from direct sunlight and any radiant heating devices. Lastly, the temperature of the curing environment shall be recorded using a maximum and minimum thermometer to ensure it stays within the specified temperature range (AASHTO T 23 2018).

Upon completion of the initial curing period, specimens are to be removed from their initial curing location and moved to their final curing location within 30 minutes after removing the specimens from their molds. Final curing consists of placing the specimens in storage tanks or moist rooms that can always maintain free water on their surfaces at a temperature of 73.5 ± 3.5°F (AASHTO T 23 2018).

2.6 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 T 23 (2018) and ASTM C 31 (2021). This comparison is shown in Table 2-4.

Table 2-4: ALDOT 501 (2022) versus AASHTO T 23 (2018) and ASTM C 31 (2021)

Initial Curing Requirements		Specification		
		ALDOT 501 (2022)	AASHTO T 23 (2018)	ASTM C 31 (2021)
Duration:	"Up to 48 hrs"		X	X
	"24-48 hrs"	X		
Temperature range:	60-80°F	X	X	X
	if >6000 psi: 68-78°F		X	X
A temperature record of the **specimens** using a maximum/minimum thermometer.		X		
A temperature record of the **curing environment** using a maximum-minimum thermometer.			X	X
Minimum curing tank size		22 cylinders	none	none
Transportation	Not Allowed "Until at least 8 hours after final set"		X	X

Note: X = covered in the specification

As shown the Table 2-4 above, there are a couple of major differences between AASHTO T 23 (2023), ASTM C 31(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 T 23 (2018) and ASTM C 31 (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 T 23 (2018) and ASTM C 31 (2021), which both require that transportation of concrete cylinders can not occur until at least 8 hours after final set.

After comparing ALDOT 501 (2022) to AASHTO T 23 (2018) and ASTM C 31 (2021), other state DOT specifications were reviewed to see whether they followed AASHTO 23 (2018), ASTM C 31 (2021), or had their own custom set of specifications. Table 2-5 lists these results, while Figure 2-6 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 T 23 (2018)		ASTM C 31 (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				

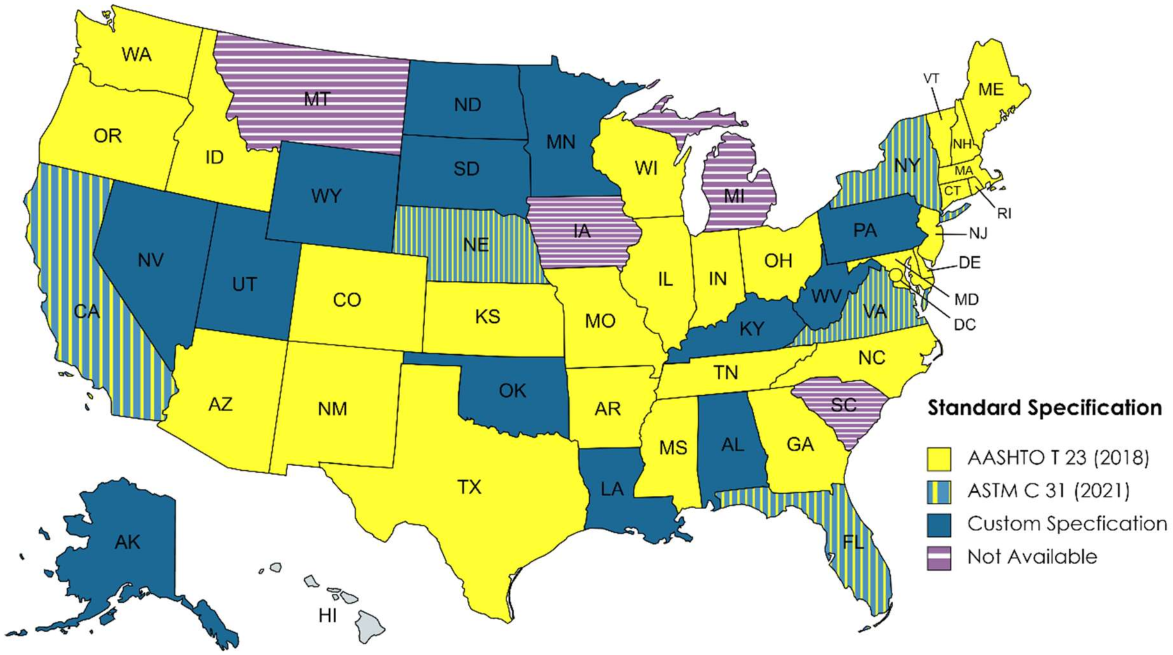


Figure 2-6: Standard Specification Used for Initial Curing of Concrete Test Specimens

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 T 23 (2018) for most of their requirements, however they differ from AASHTO T 23 (2018) on a few certain specific requirements which therefore require them to be placed in a separate category.

While AASHTO T 23 (2018) and ASTM C 31 (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 T 23 (2018) was compared from state to state. Table 2-6 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 2-6 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 T 23 (2018) and ASTM C 31 (2021) specify the initial curing temperature range for high strength concrete as 68-78°F. After reviewing each state DOT, Figure 2-7 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.

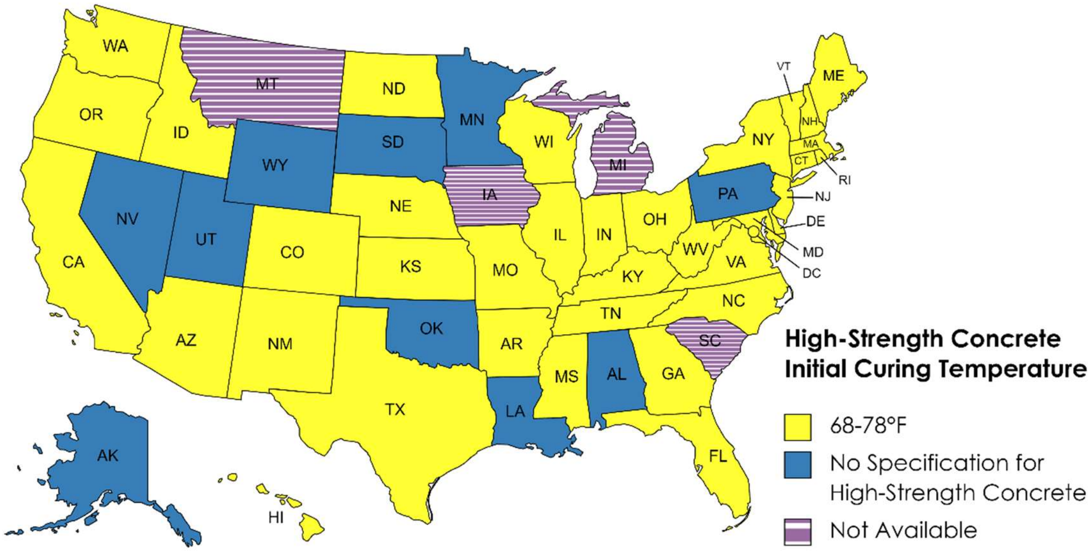


Figure 2-7: Initial Curing Temperature Range for High Strength Concrete

Next, the specification requirement regarding the duration of the initial curing period was investigated for each state. While most states follow AASHTO T 23 (2018) and ASTM C 31 (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 2-7. While the states that followed AASHTO T 23 (2018) or ASTM C 31 (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 12-14 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 T 23 (2018) is that ALDOT 501 (2022) requires a minimum/maximum temperature recording of the concrete specimen temperature while AASHTO T 23 (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" X 12")”. Only 4 states had a specified minimum initial curing box size, as shown in Table 2-8.

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: Experimental Plan

This chapter provides details of the plan developed and executed to review all 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 materials used, as well as the manner in which the practices of the site personnel were reviewed.

3.1 Experimental Approach

3.1.1 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 standard initial cure (SIC), non-standard initial cure (NSIC), and the Contractor curing box. The standard initial cure (SIC) consisted of a curing box filled with water that met all the criteria put forth in AASHTO T 23 (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 give a minimum and maximum temperature readout of both the curing environment temperatures as well as the specimen temperatures. More details regarding the temperature probes are discussed in section 3.2.1. The SIC curing box also had a capacity of 22 6x12 in. cylinders as required by ALDOT 501 (2022). 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 3.2.2. An example of this SIC environment is shown in Figure 3-1.

Figure 3-1: 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 3-2.

Figure 3-2: Example of NSIC Environment

The other curing method examined was that used by the contractor for 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 curing environment were different for each jobsite visited. The details of the contractor's curing box for each individual jobsite visit are discussed in Chapter 4. An example of a contractor's curing environment is shown in Figure 3-3.


[redacted]

Figure 3-3: Example of Contractor Curing Environment

3.1.2 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 of adherence to 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 3-1.

Table 3-1: Jobsite types

		Project Type			Concrete Strength (psi)		
		Bridge Deck	Box Culvert	Curb and Gutter	3000	4000	5000
Jobsite Visits	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		

3.1.3 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 3-4. The cylinders initially cured in the Contractor's curing box were removed and transported to the closest ALDOT laboratory.

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°F and maintained a relative humidity of 100% in accordance with ALDOT 501 (2022) and AASHTO T 23 (2018). This room is shown in Figure 3-5.

Figure 3-4: Cylinder Transportation apparatus

Figure 3-5: Final Curing Room

3.1.4 Compressive Strength Testing Plan

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 a Forney Automatic cylinder testing machine shown in Figure 3-6. The testing was conducted in accordance with AASHTO T 22 (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 and the test results were relayed to AU research personnel for use in this report.

Figure 3-6: Compression Testing Machine

3.1.5 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 T 23 (2018). Table 3-2 shows a summary of the major ALDOT 501 (2022) and AASHTO T 23 (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 3-2: Sample Evaluation Checklist

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
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

3.2 Materials

3.2.1 Temperature Probes

To record the minimum and maximum temperatures of the curing environment, temperature probes from Exact Technologies were selected and used. The Exact technologies 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 AU personnel to check the temperature development of the curing environment as well as the cylinders themselves. This equipment is shown in Figure 3-7.

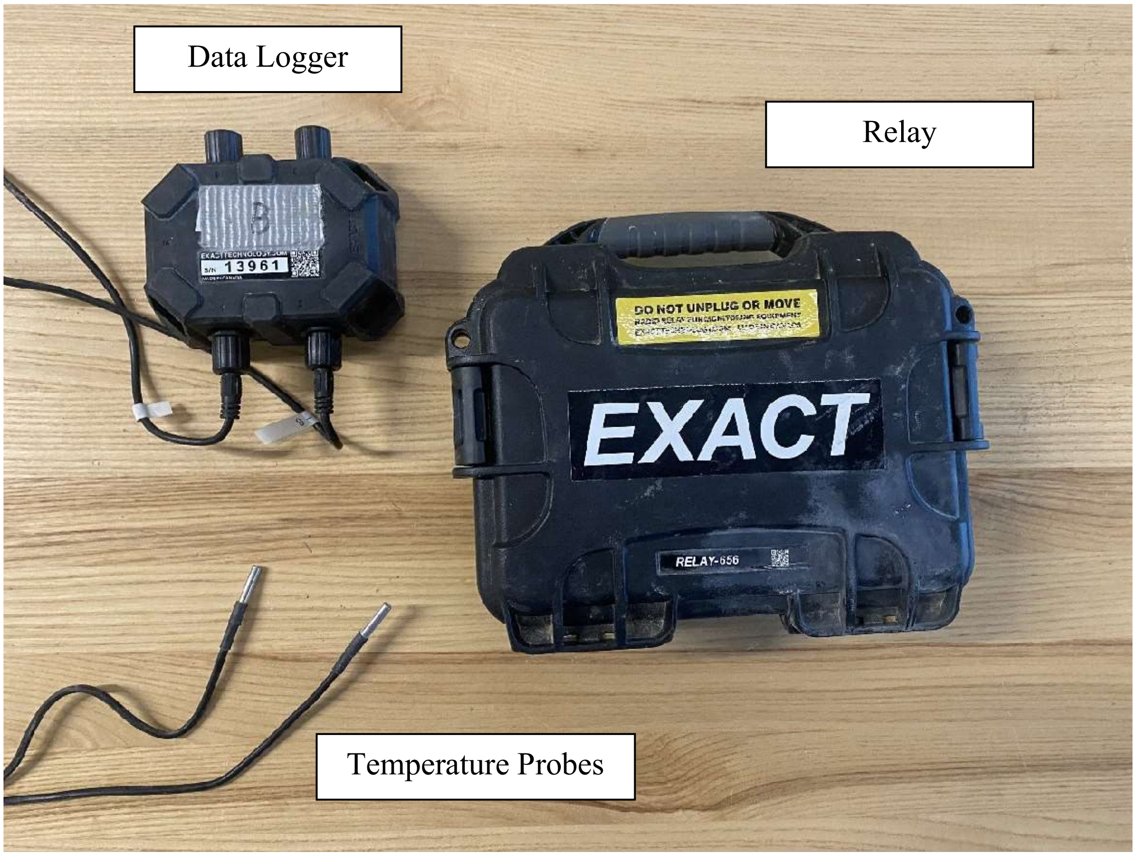


Figure 3-7: Temperature Monitoring Equipment

For each jobsite visit, six temperature probes were used, with two in each curing environment. 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's curing environment, 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.

3.2.2 Generator

To ensure the SIC environment stayed within the acceptable temperature range specified in ALDOT 501 (2022) and AASHTO T 23 (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 3-8. 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 laboratory 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 3-8: Generator used to provide power to SIC Curing Box

3.3 Setup and Testing at Each Jobsite

Upon arrival to the jobsite, all equipment was unloaded from the truck. 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’s curing boxes were checked and confirmed to be within the 60-

80°F temperature range. This is important as it states in ALDOT 501 (2022) and AASHTO T 23 (2018) that the curing environment must be in the specified range before the concrete arrives.

Upon arrival of the concrete truck, the Auburn research team observed the testing technicians and filled out the evaluation checklist described in section 3.1.5. After the fresh concrete properties passed their respective tests, Auburn research personnel, certified as grade 1 ACI concrete field-testing technicians, sampled concrete by filling up a full wheelbarrow and began making cylinders in accordance with AASHTO T 23 (2018). Then, the cylinders were capped and placed in their respective curing environment. Lastly, the probes to record the concrete specimen temperatures were inserted into straws and then into the cylinders to record their temperatures. Figure 3-9 shows the Auburn research team making cylinders on a flat shaded area. The initial curing duration of the cylinders cured in SIC and NSIC was 24 hours while the duration of the jobsite cylinders was dependent on when the jobsite staff would transport them to their final curing location and therefore varied for each jobsite visit.

Figure 3-9: Auburn Research Personnel Making Cylinders

Chapter 4: Presentation of Results

4.1 Overview of Jobsite Visits

In this chapter, the results are given and discussed for the jobsite visits performed under the experimental plan described in chapter 3. For each jobsite visit, the practices of the jobsite technicians and contractor are reviewed, followed by the temperature and concrete compressive strength results. The acceptability of these results is based off of the ranges discussed in Section 4.1.1. The effects of certain jobsite practices on the acceptability of 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, AU research personnel also compared the approved batch proportions to the actual supplied batch proportions. This was done to evaluate the quality of the concrete provided as well as to assess that the amount of water added at the jobsite did not exceed the approved amount.

4.1.1 Acceptable ranges

To properly 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 T 23 (2018). Therefore, when the temperature of an initial curing environment exceeded the 60-80°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 acceptable difference range presented in AASHTO T 22 (2018) for three 6 x 12 in. cylinders cured under field conditions, shown in Table 4-1, ±10% was selected as the acceptable range for compressive strength results.

Table 4-1: Acceptable Range for Cylinder Strengths (AASHTO T 22 2018)

	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

4.2 Jobsite 1

Jobsite 1 was located in Opelika, Alabama, and consisted of a narrow construction work zone that was limited for space. As a result, all concrete sampling, testing, and cylinder making was 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 the majority of the day. 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 curing method 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 evenly throughout the curing box. The contractor’s initial curing box was placed inside a large garage and plugged into wall power as shown in Figure 4-1.

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Figure 4-1: Jobsite 1 Contractor Curing Box

4.2.1 Jobsite 1, Visit 1

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

Upon arrival of the concrete, the jobsite technicians began sampling from the front of the load. This was also not in accordance with AASHTO R60-12 5.2.4 (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 to meet all specification requirements. Once the concrete was approved, AU 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 AASHTO R60-12 5.2.4 (2020), which states that samples should not be obtained until after all the water and admixtures have been added. All testing equipment (slump cone, air meter, thermometer, etc..) was prepared and ready for the arrival of the concrete.

The data collected from the Exact Technologies temperature probes were compiled and are shown in Figure 4-2. It is significant to note that the SIC curing box did not contain a water circulation pump for the water inside the curing box. This caused the water temperature to vary significantly with depth as the cooling pipe was on the bottom of the cooler. This is believed to have caused the SIC cylinder temperatures to be higher than that of the contractor’s even with a colder water temperature. After learning this lesson, it was decided for future jobsite visits to ensure a water circulation pump was added to the 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 a cylinder curing box. The results of this test are presented and discussed in Section 4.2.2.

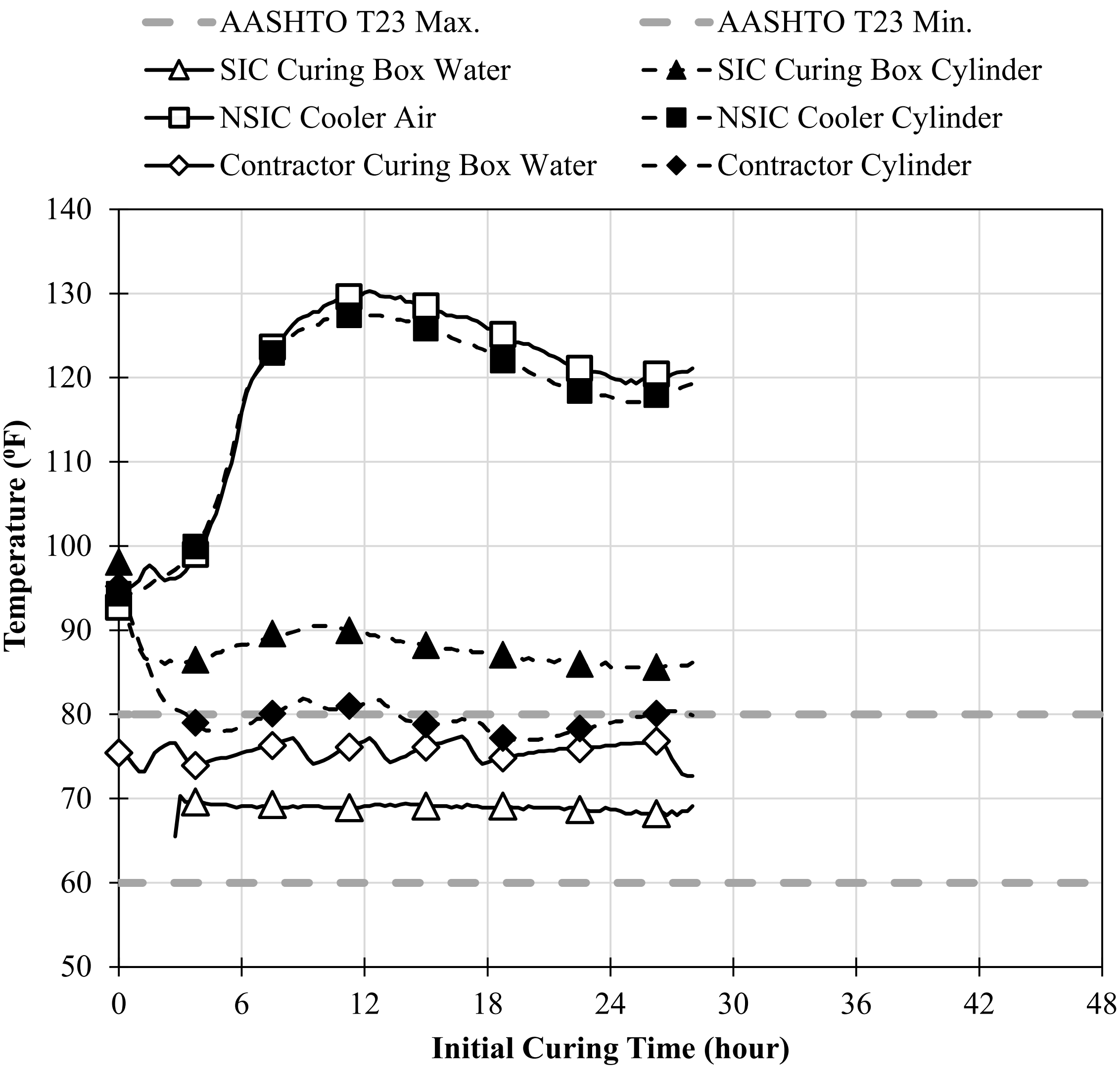

Figure 4-2: Jobsite 1, Visit 1, Temperature Results

The NSIC cooler air had a much higher temperature than that of the SIC Curing Box Water, shown in Figure 4-2, 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.

As discussed in Section 3.3, 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 1.

$$\mu = \frac{\sum X_i}{n} \qquad \text{(Equation 1)}$$

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 4-2. The individual cylinder compressive strength results can be found in Appendix B. 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 1.

Table 4-2: 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 calculations were performed using Equation 2.

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

These strength differences were based on the average cylinder strength of the cylinders cured in the SIC and are also summarized in Table 4-2. The SIC cylinders were used as the baseline from which to compare the other curing methods because they were cured and tested with in accordance with the requirements of AASHTO T 23 (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 4-3.

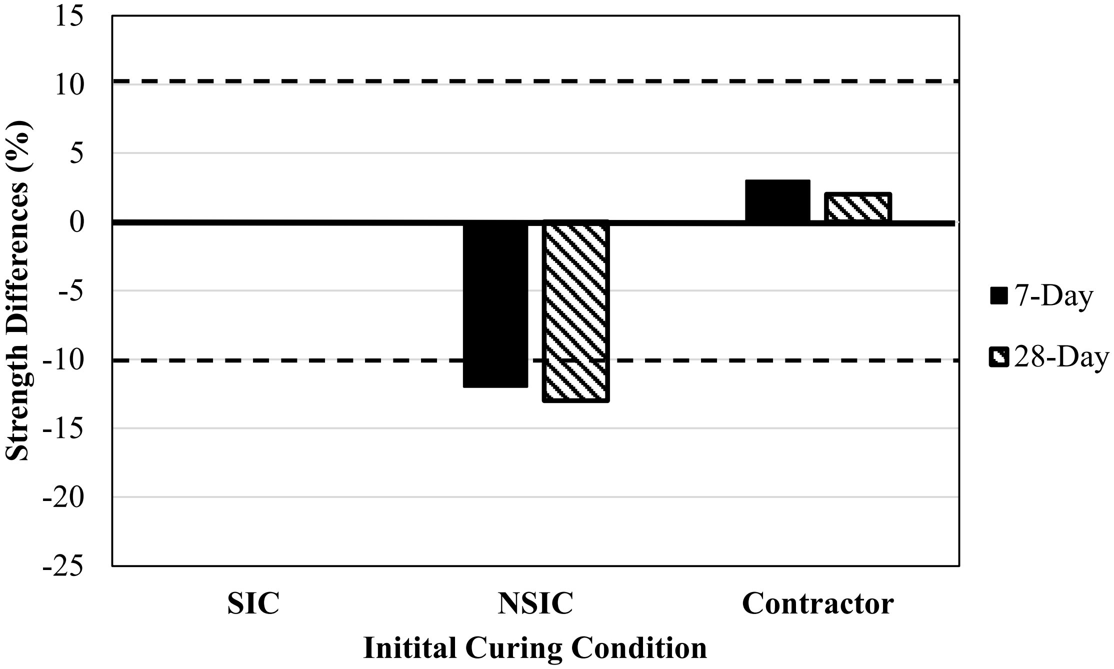

Figure 4-3: Jobsite 1, Visit 1 Strength Difference Results

4.2.2 Water Circulation Pump Test

After analyzing the temperature results from Jobsite 1, Visit 1, Auburn 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 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 4-4.

Figure 4-4: Circulation Pump Test Setup

The water circulation pump test was conducted in three phases. The first phase 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 4-5.

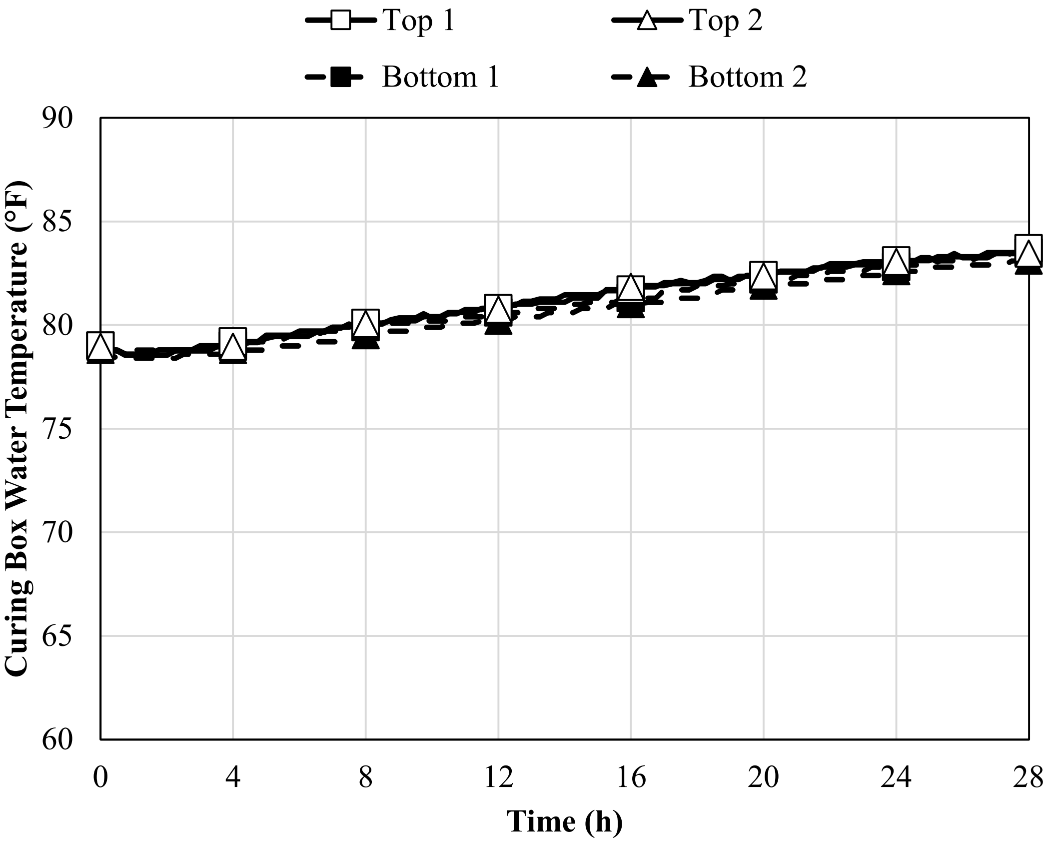

Figure 4-5: Water Circulation Pump Test, Phase One Results

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

Phase two immediately followed phase one and consisted of turning on the cylinder curing box and setting it at 68°F. The water circulation pump remained unplugged for phase two as the purpose of phase two 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 two are shown in Figure 4-6

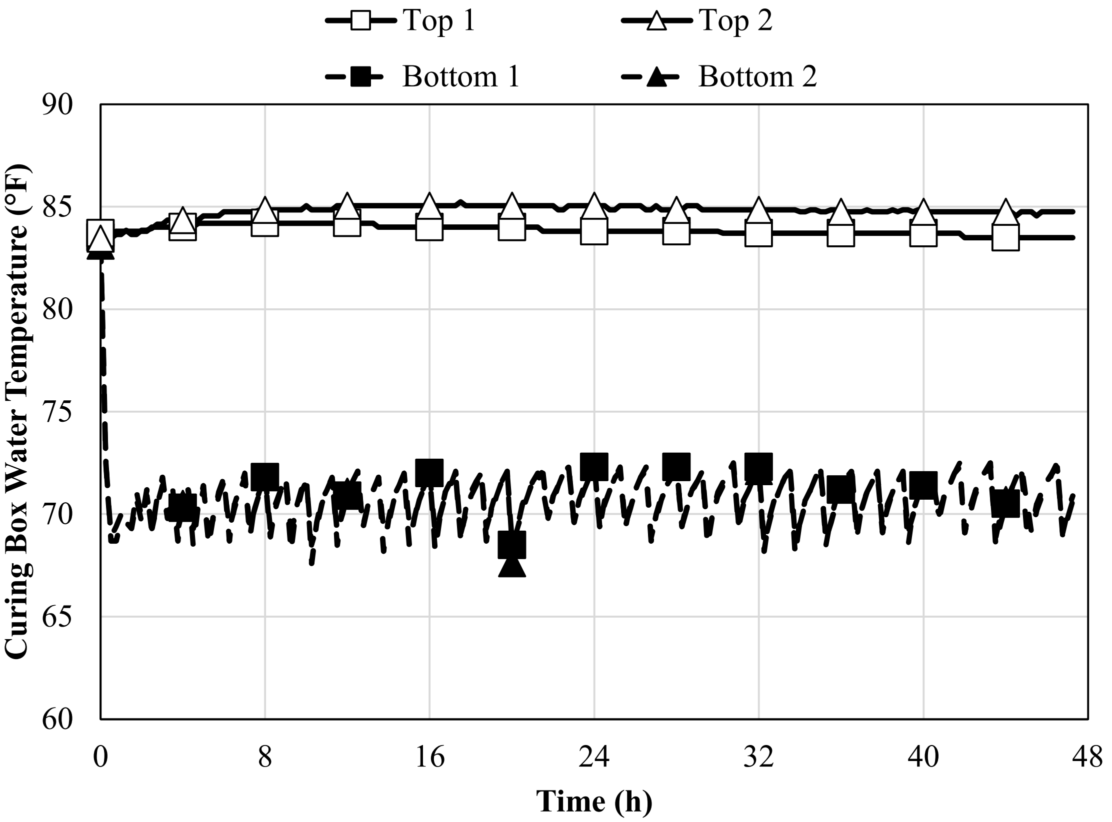

Figure 4-6: Water Circulation Pump Test, Phase Two Results

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 two, an approximate 12°F difference from the bottom of the curing box just 10 in. below.

Phase 3 immediately followed phase two and consisted of plugging in 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 three was to see the effectiveness of using a water circulation pump. The temperature results from phase three are shown in Figure 4-7.

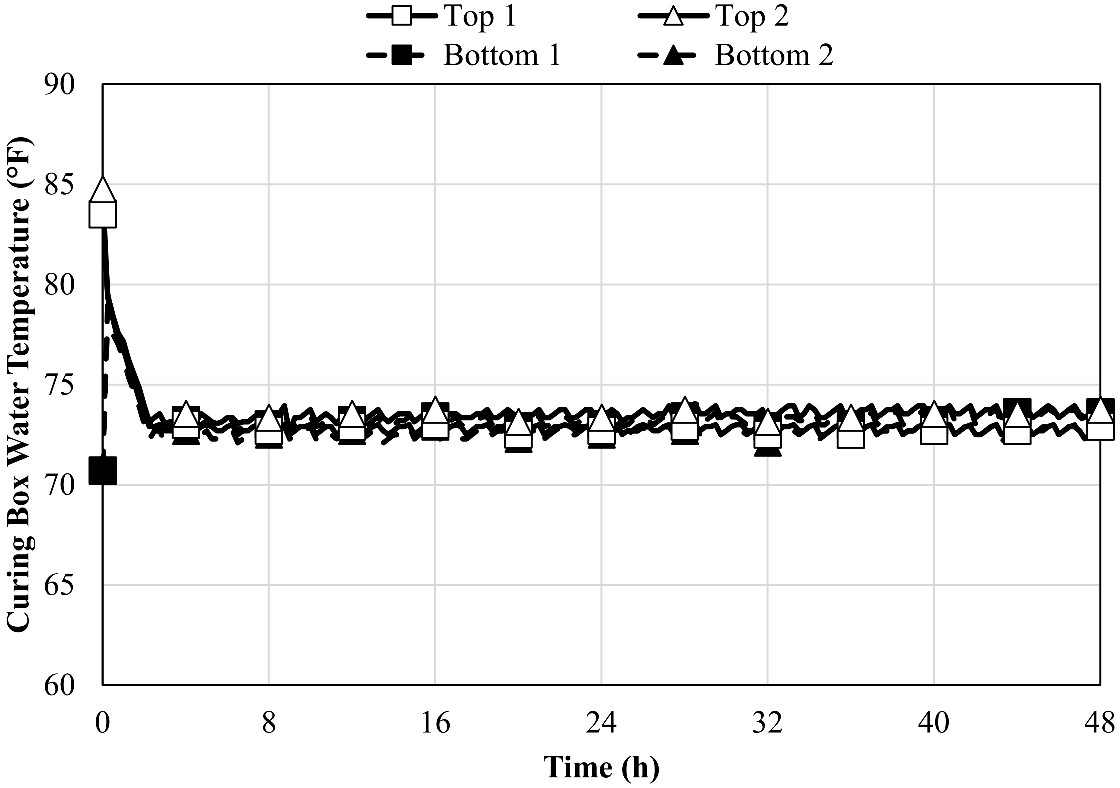

Figure 4-7: Water Circulation Pump Test, Phase Three Results

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 whole curing box became consistent. This is extremely important when curing concrete cylinders as higher temperatures can cause concrete test cylinders to lose 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.

4.2.3 Jobsite 1, Visit 2

Visit 2 of Jobsite 1 was performed on August 12th, 2021. The contractor’s 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 AASHTO R60-12 5.2.4 (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, shown in Figure 4-8, 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 AU research personnel made cylinders with the concrete provided by the concrete supplier.

Figure 4-8: ALDOT Technicians Performing Fresh Concrete Property Tests

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

The data collected from the Exact Technologies temperature probes was compiled and is shown in Figures 4-9. 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.

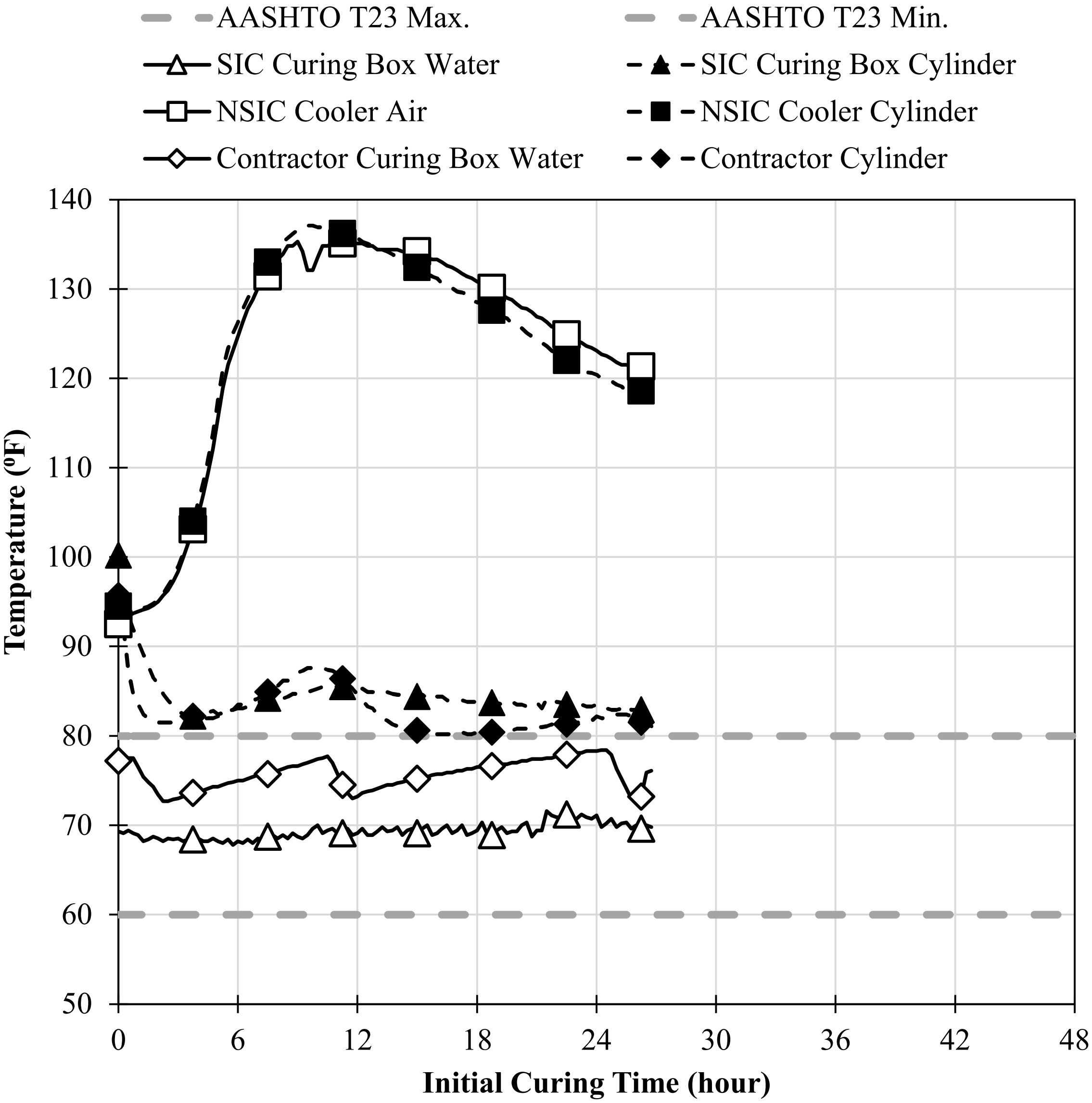

Figure 4-9: Jobsite 1, Visit 2 Temperature Results

The temperature of the NSIC cooler air was much higher than that of the SIC Curing Box water, shown in Figure 4-9, 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, AU research personnel still put a cylinder with a temperature probe in the contractor's 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 4-3.

Table 4-3: 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 1 and 2, respectively. The contractor did not make any cylinders as they rejected the batch due to 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 B. The percent differences are illustrated in Figure 4-10.

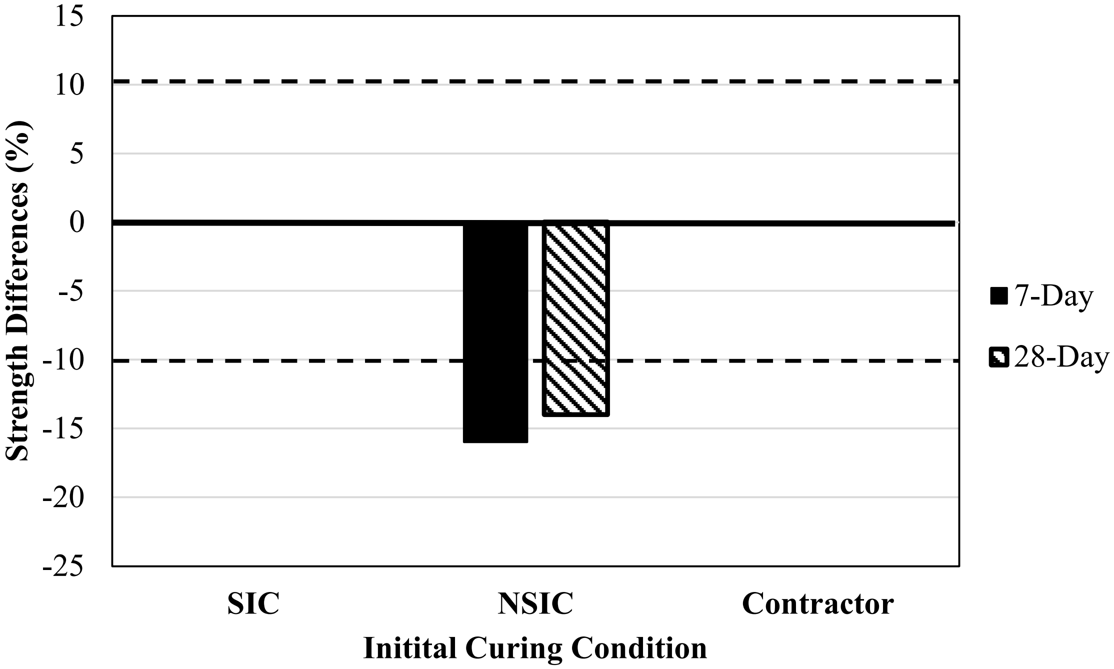

Figure 4-10: Jobsite 1, Visit 2 Strength Differences Results

4.2.4 Jobsite 1, Visit 3

Jobsite 1, Visit 3 was performed on August 19th, 2021. The contractor's curing box was on and within the 60-80°F temperature range before the concrete was delivered. The contractor's 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 AASHTO R60-12 5.2.4 (2020), as one should wait until at least 10% of the load has been discharged. After sampling, jobsite technicians performed all fresh concrete property tests and made cylinders to meet all specification requirements. The AU research team made cylinders with the concrete approved by the jobsite technicians. The data collected from the Exact Technologies temperature probes was compiled and is shown in Figure 4-11.

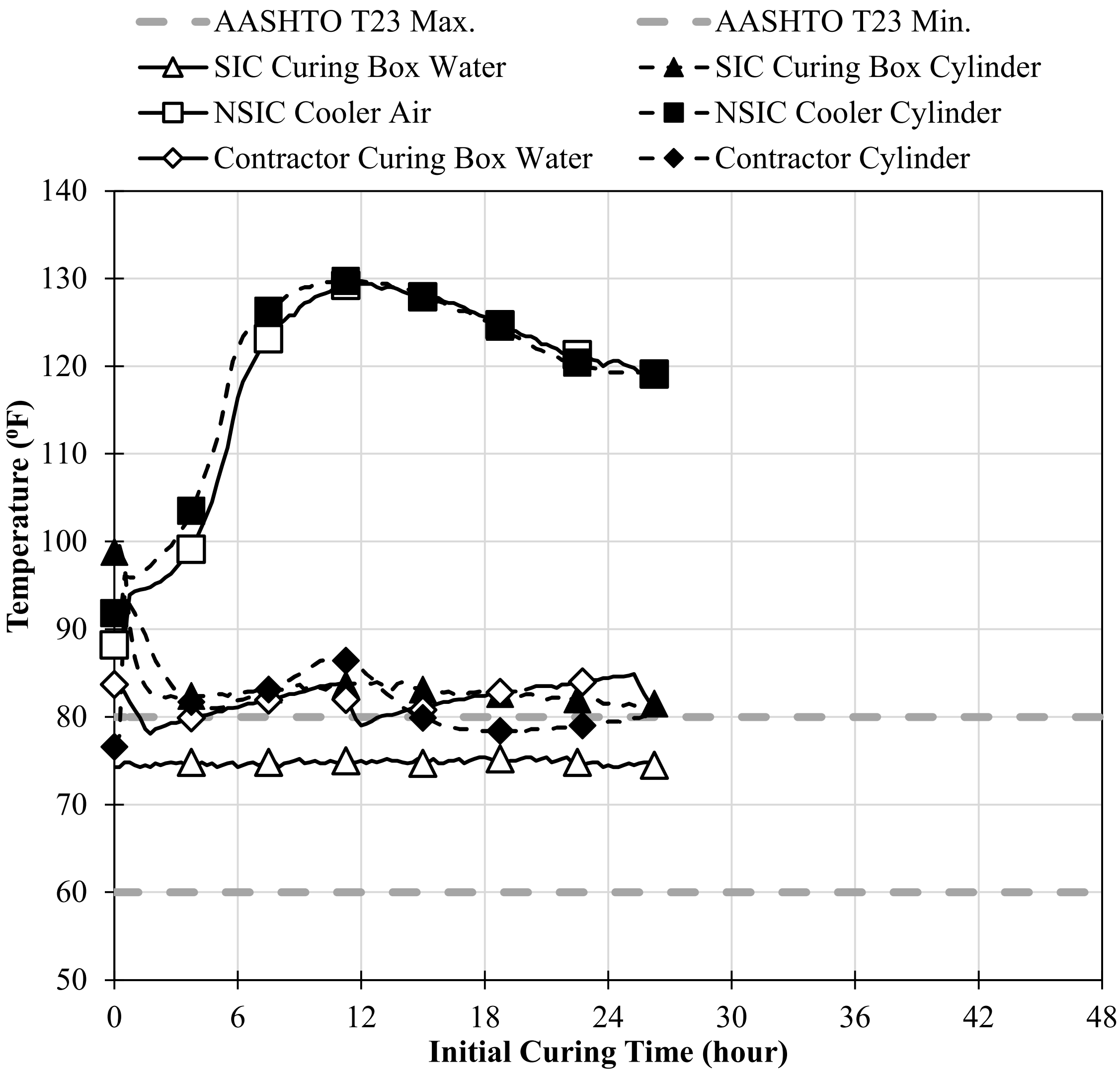

Figure 4-11: Jobsite 1, Visit 3 Temperature Results

The temperature of the NSIC cooler air was much higher than that of the SIC Curing Box water, shown in Figure 4-11, 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's cylinder 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 4-4.

Table 4-4: 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 1 and 2, respectively. The individual cylinder compressive strengths can be found in Appendix B. The percent differences are illustrated in Figure 4-12.

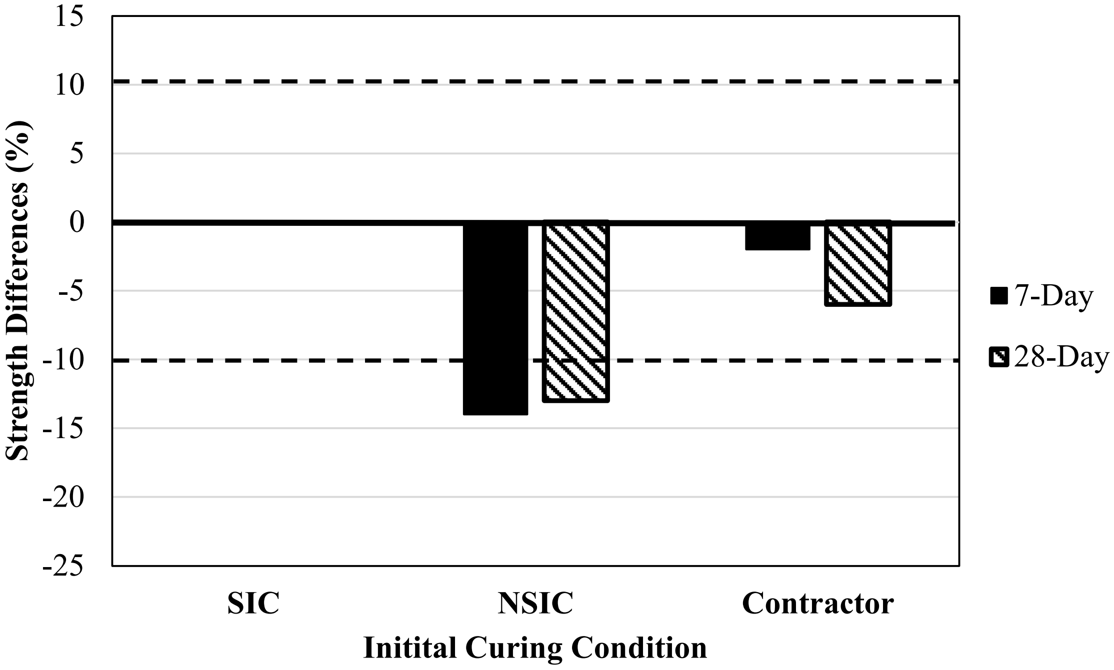

Figure 4-12: Jobsite 1, Visit 3 Strength Difference Results

4.3 Jobsite 2

Jobsite 2 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 very similar to the Auburn University SIC Curing Box and is shown in Figure 4-13. The contractor's 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 60-80°F temperature range. This was in violation of ALDOT 501 (2022) and 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.


[redacted]
[redacted]

Figure 4-13: Jobsite 2 Contractor Curing Box

4.3.1 Jobsite 2, Visit 1

Jobsite 2, Visit 1 was conducted on June 23rd, 2022. Upon arrival to the Jobsite, members of the AU research team began to set up all equipment to be used for the concrete testing and curing. The AU SIC box was set up next to the Contractor's curing box to achieve the most identical 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 4-14.

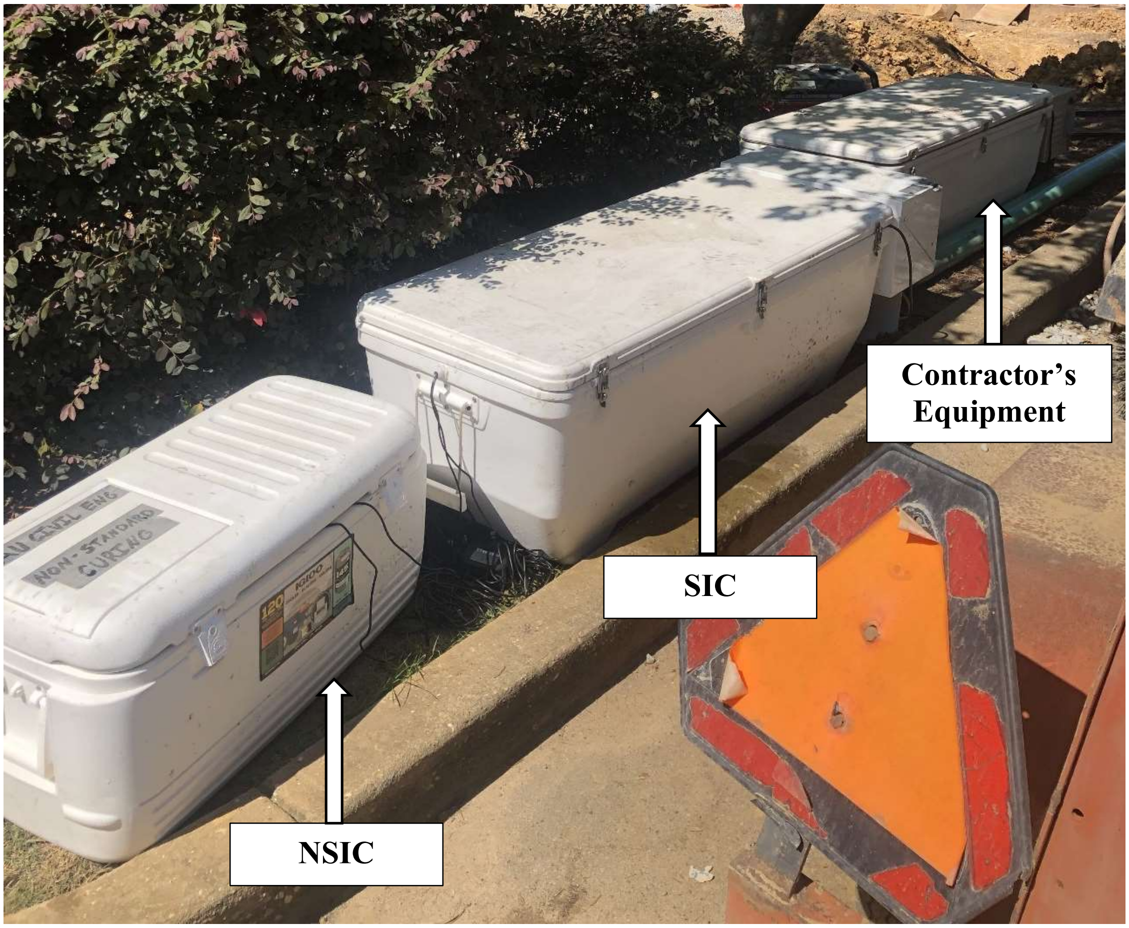

Figure 4-14: Jobsite 2, Visit 1 Cylinder Curing Box Equipment

Upon arrival of the concrete, the jobsite technicians began sampling from the front of the load. This was not in accordance with AASHTO R60-12 5.2.4 (2020), as one should wait until at least 10% of the load has been discharged. After sampling, the jobsite technicians performed all concrete tests and made cylinders to meet all specification requirements. AU research personnel then made cylinders with the concrete approved by the jobsite technicians. The data collected from the Exact Technologies temperature probes was compiled and is shown in Figure 4-12.

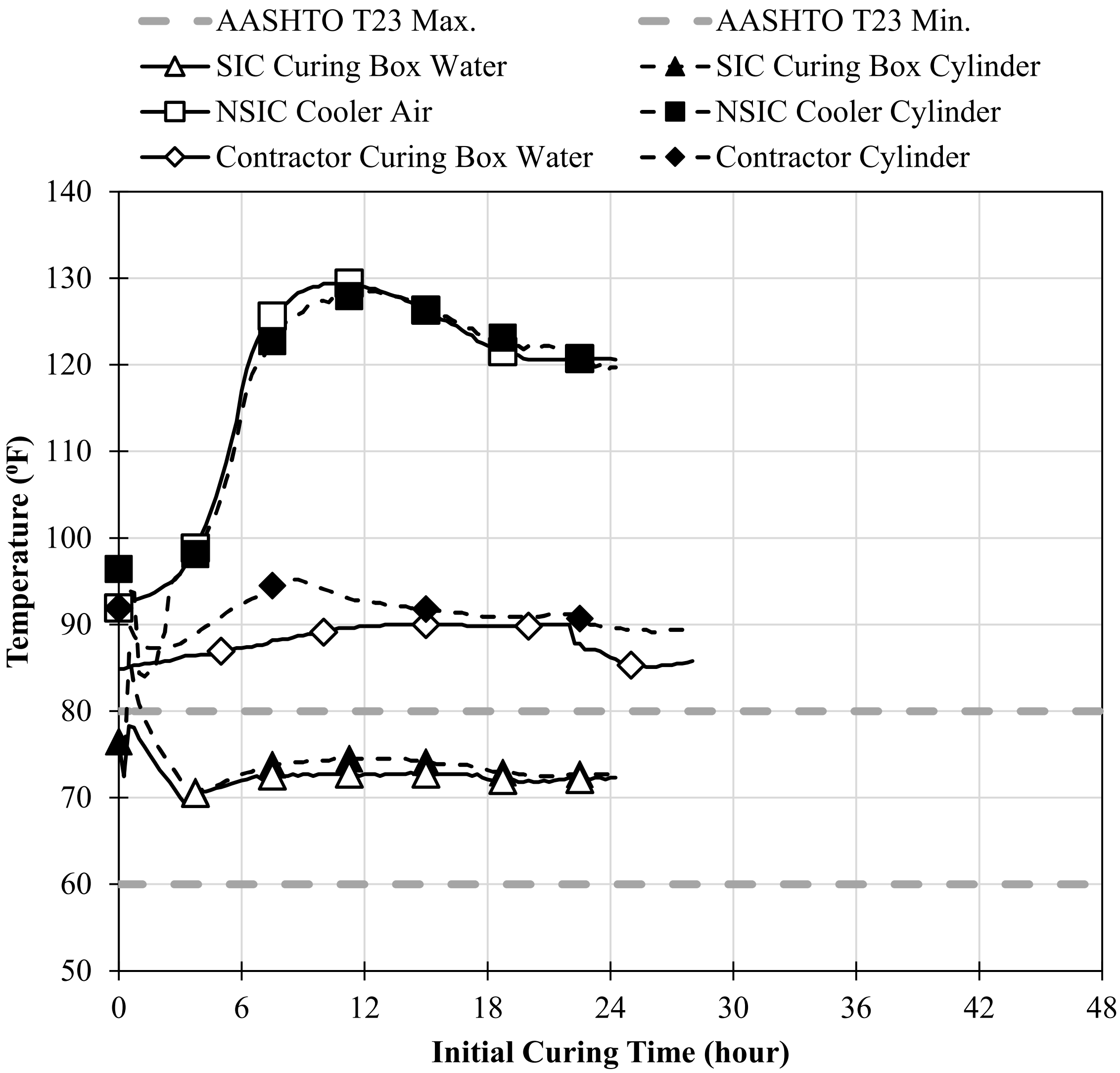

Figure 4-15: Jobsite 2, Visit 1 Temperature Results

The temperature in the NSIC cooler air was much higher than that of the SIC Curing Box water, as shown in Figure 4-15, 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's cylinder curing box also exceeded the 80°F 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's cylinder curing box was unable to be turned on and therefore to regulate the water temperature inside. The corresponding strength results from the SIC, NSIC, and contractor cylinders are shown in Table 4-5. The 7-day strength results for the SIC and NSIC cylinders were unavailable as these additional cylinders were not made by AU personnel.

Table 4-5: 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 1 and 2, respectively. The individual cylinder compressive strengths can be found in Appendix B. The percent differences are illustrated in Figure 4-16.

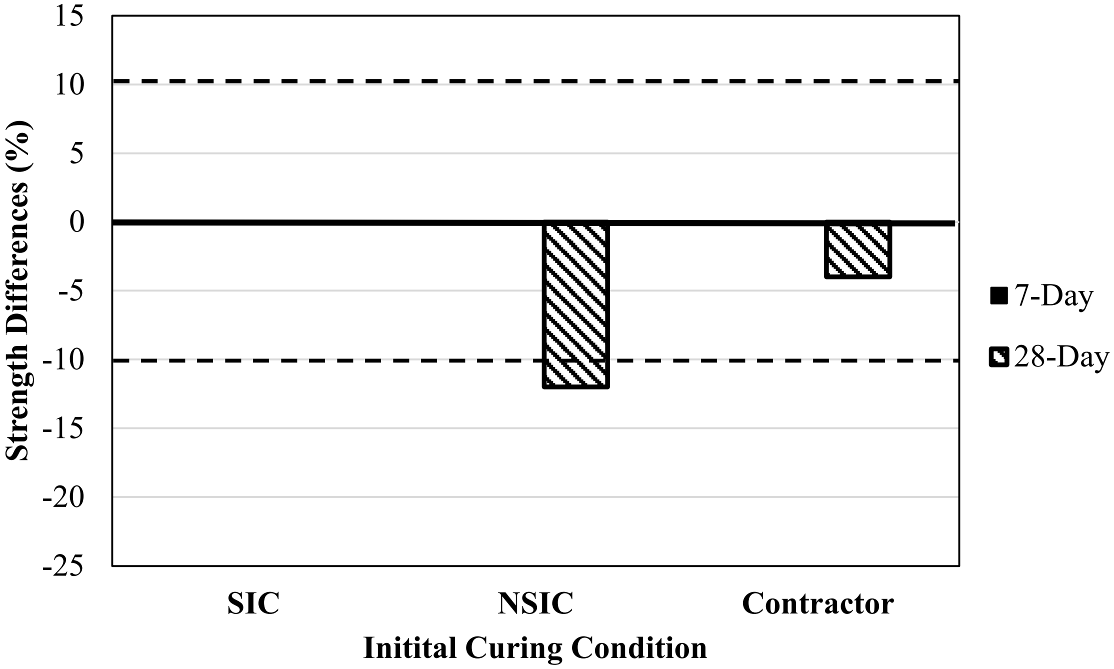

Figure 4-16: Jobsite 2, Visit 1 Strength Difference Results

4.3.2 Jobsite 2, Visit 2

Jobsite 2, Visit 2 was conducted on July 7th, 2022. Upon arrival to the jobsite, members of the AU research team began to set up all equipment to be used for the concrete testing and curing. The AU SIC and NSIC boxes were set up in the same location and position as for Jobsite 2, Visit 1, and are shown in Figure 4-14.

Upon arrival of the concrete, the jobsite technicians began sampling from the front of the load. This was not in accordance with AASHTO R60-12 5.2.4 (2020), as one should wait until at least 10% of the load has been discharged. After sampling, the jobsite technicians performed all fresh concrete property tests and made cylinders to meet all specification requirements. The AU research team made cylinders with the same concrete as the jobsite technicians. The data collected from the Exact Technologies temperature probes was compiled and is shown in Figure 4-14.

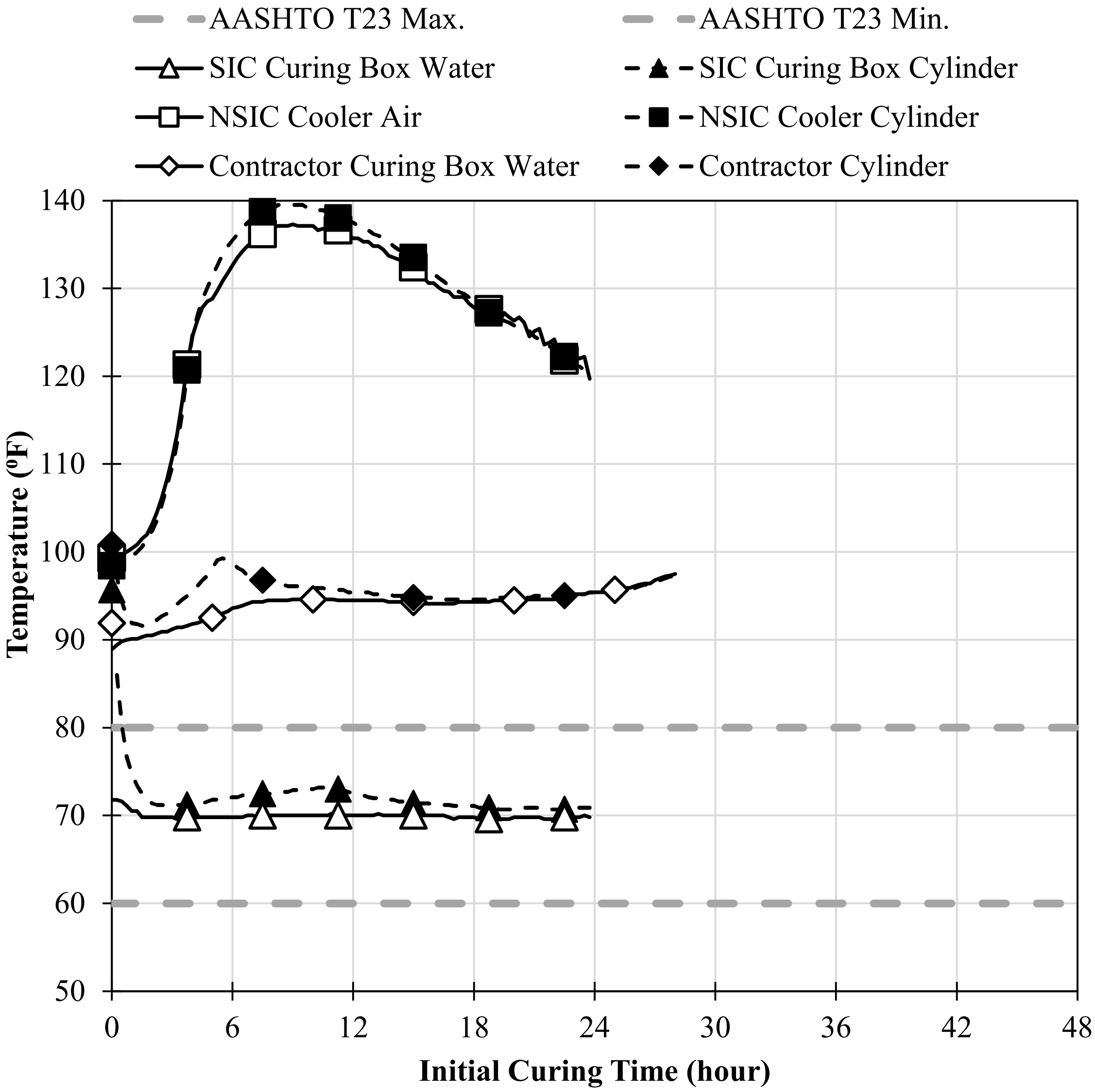

Figure 4-17: Jobsite 2, Visit 2 Temperature Results

The temperature in the NSIC cooler air was much higher than that of the SIC Curing Box water, as shown in Figure 4-17, 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 water temperature of the contractor's curing box was also above the specified 60-80°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. The corresponding strength results from the SIC, NSIC, and Contractor cylinders are shown in Table 4-6.

Table 4-6: 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 1 and 2, respectively. The individual cylinder compressive strengths can be found in Appendix B. The percent differences are illustrated in Figure 4-18.

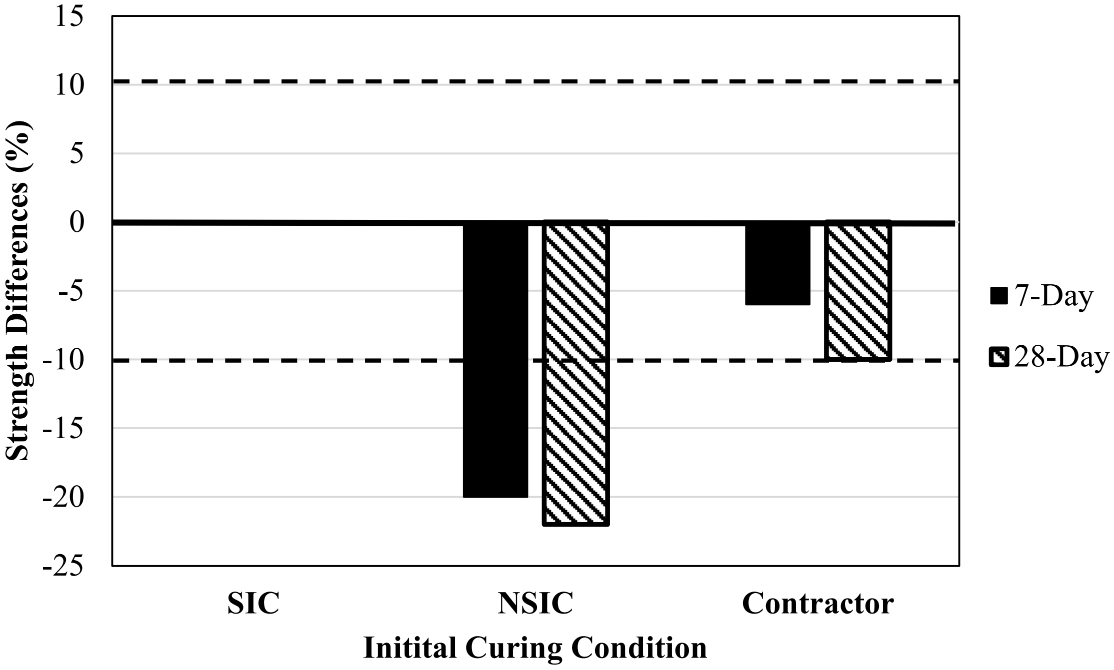

Figure 4-18: Jobsite 2, Visit 2 Strength Difference Results

4.3.3 Jobsite 2, Visit 3

Jobsite 2, Visit 3 was conducted on July 13th, 2022. Upon arrival to the jobsite, members of the AU research team began to set up all equipment to be used for the concrete testing and curing. The AU SIC and NSIC boxes were set up in the same location and position as for Jobsite 2, Visit 1 and are shown in Figure 4-14.

Upon arrival of the concrete, the jobsite technicians began sampling from the front of the load. This was not in accordance with AASHTO R60-12 5.2.4 (2020), as one should wait until at least 10% of the load has been discharged. After sampling, the jobsite technicians performed all fresh concrete property tests and made cylinders to meet all specification requirements. The AU research team made cylinders with the same concrete as the jobsite technicians. The data collected from the Exact Technologies temperature probes was compiled and is shown in Figure 4-19.

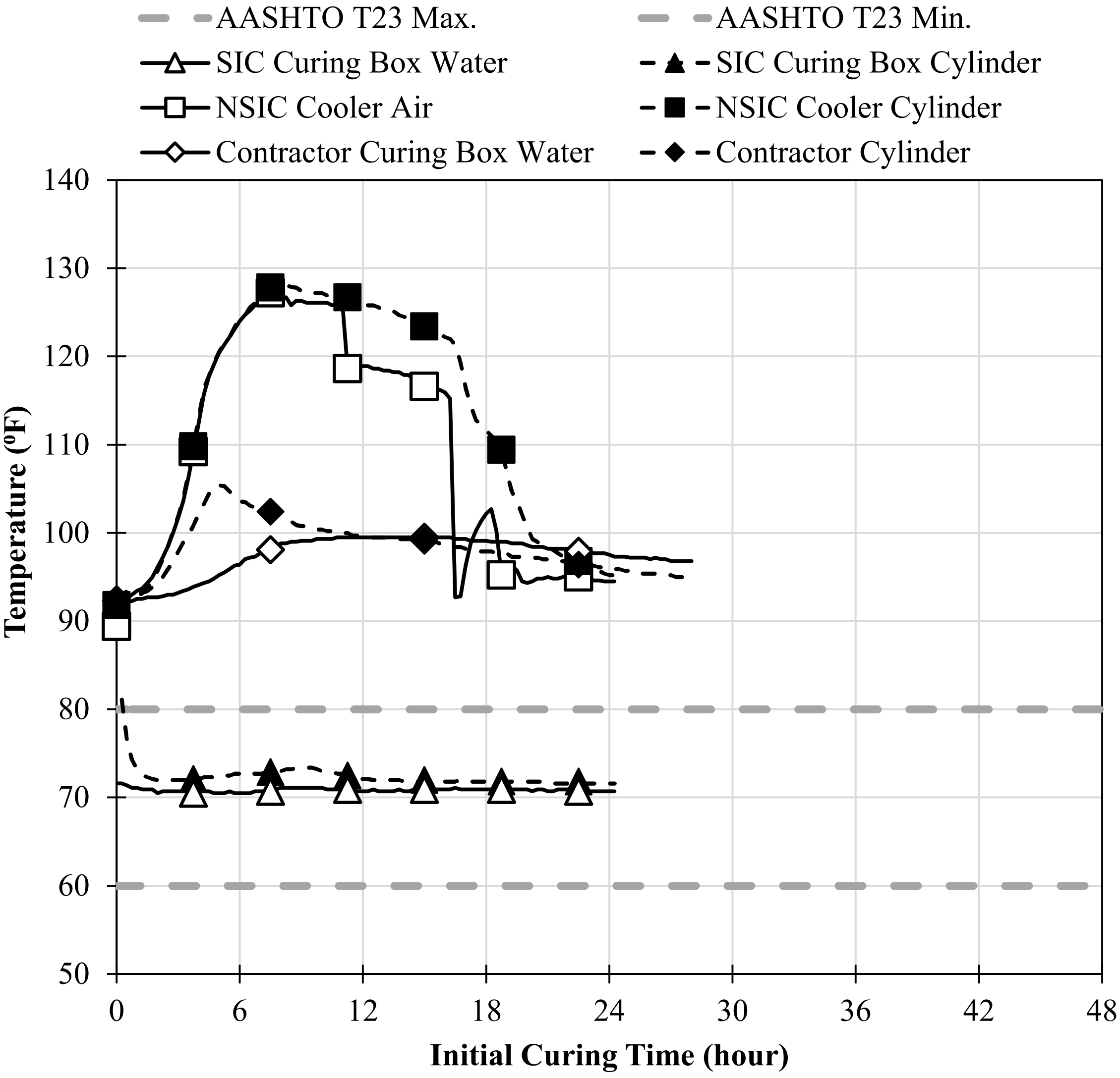

Figure 4-19: Jobsite 2, Visit 3 Temperature Results

The temperature of the NSIC cooler air was much higher than that of the SIC Curing Box water, as shown in Figure 4-19, 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's 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 4-7.

Table 4-7: 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 1 and 2, respectively. The individual cylinder compressive strengths can be found in Appendix B. The fact that the water temperature in the Contractor's 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. The percent differences are illustrated in Figure 4-20.

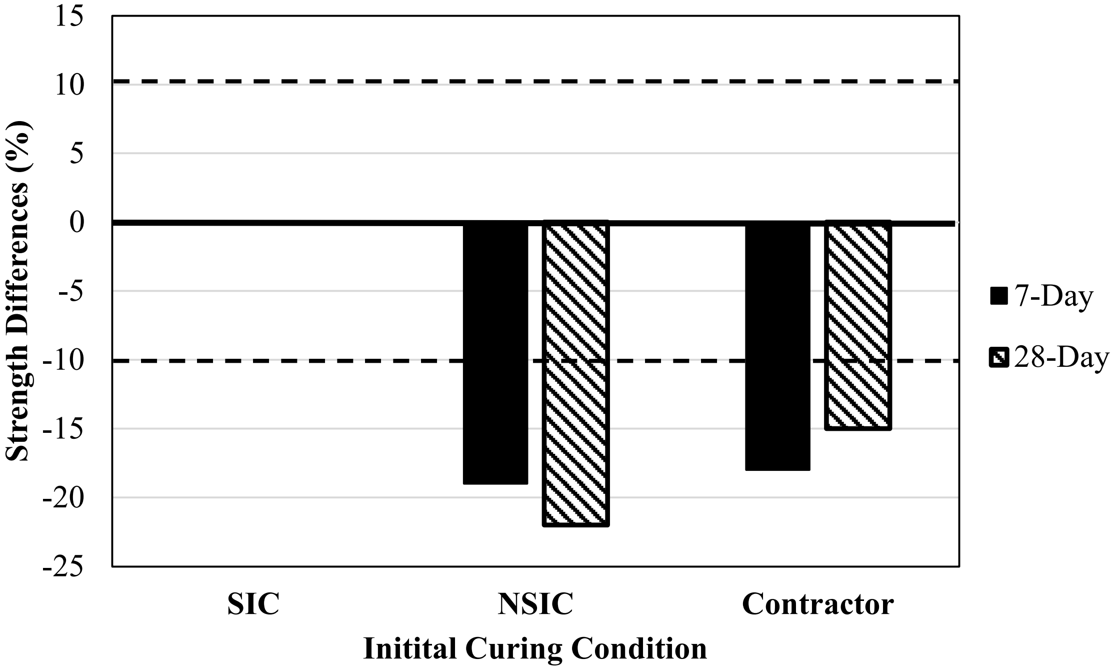

Figure 4-20: Jobsite 2, Visit 3 Strength Difference Results

4.4 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's curing method consisted of a Yeti cooler retrofitted with a cooling apparatus. Although the contractor's curing box was plugged into a power source for each visit to Jobsite 3 and set at a temperature within the specified range, 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 60-80°F temperature range during the entire initial curing period. This was in violation of AASHTO T23 (2018) and 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 4-21 and 4-22, respectively.

Figure 4-21: Jobsite 3 SIC Curing Box

Figure 4-22: Jobsite 3 NSIC Curing Box

4.4.1 Jobsite 3, Visit 1

This jobsite visit was conducted on July 12th, 2022. Upon arrival to the jobsite, members of the AU 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 is still in violation of AASHTO R60-12 5.2.4 (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 beginning of the truck as such concrete is generally segregated and not representative of the rest of the truck. This effort, along with the specification, is discussed in more detail in Chapter 5.

After sampling, the jobsite technicians performed all fresh concrete property tests and made cylinders to meet all specification requirements. The AU research team made cylinders with the concrete approved by the jobsite technicians. The data collected from the Exact Technologies temperature probes was compiled and is shown in Figure 4-23.

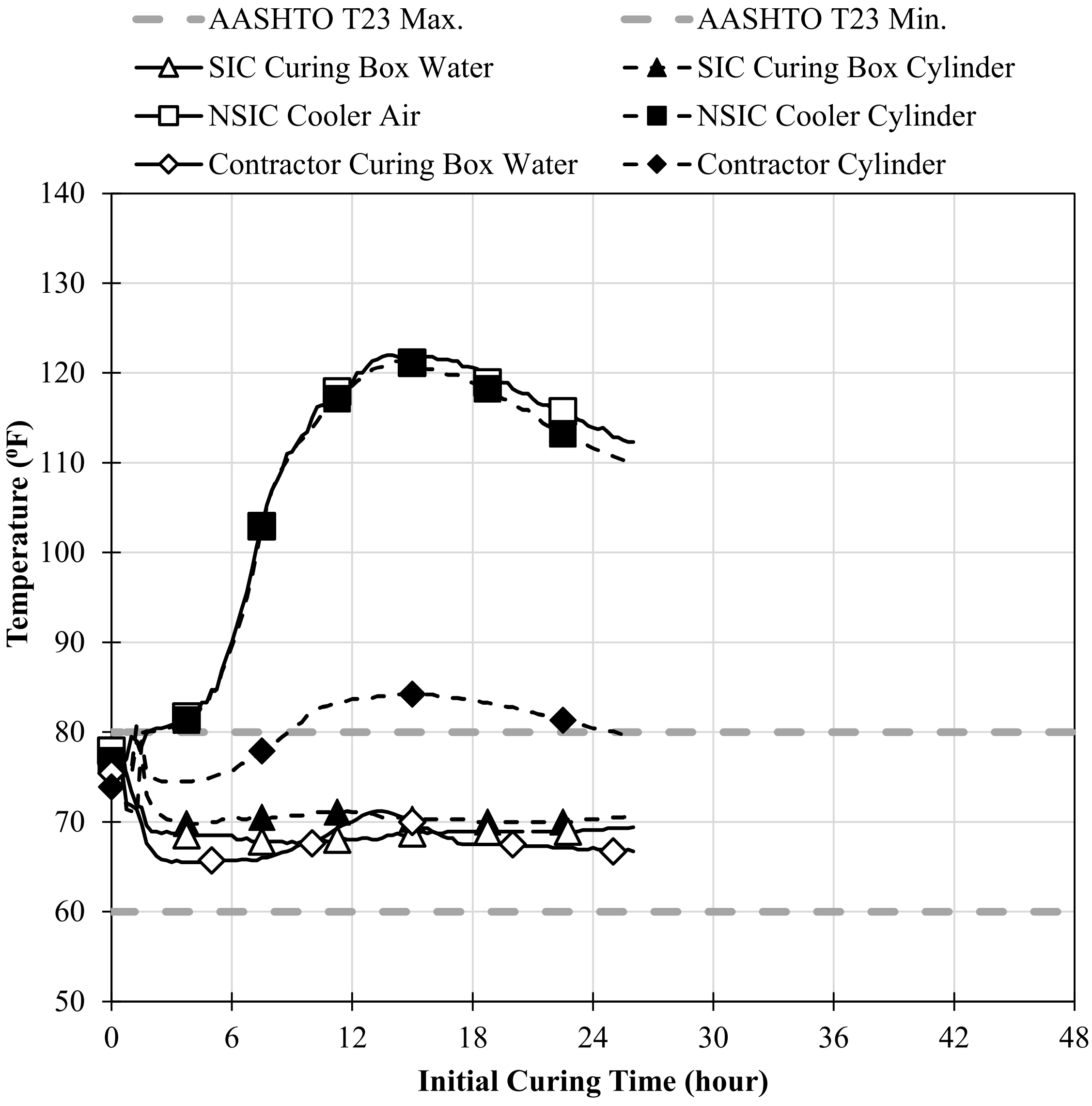

Figure 4-23: Jobsite 3, Visit 1 Temperature Results

The temperature in the NSIC cooler air was much higher than that of the SIC Curing Box water, as shown in Figure 4-23, 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. While the Contractor's curing box kept the water temperature well within the specified temperature range, the temperature of the Contractor's cylinders exceeded the 80°F limit. This temperature difference between the Contractor's cylinders and Contractor's curing box water is due to the Contractor's 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 remained within the acceptable 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 4-8.

Table 4-8: 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 1 and 2, respectively. The individual cylinder compressive strengths can be found in Appendix B. The percent differences are illustrated in Figure 4-24.

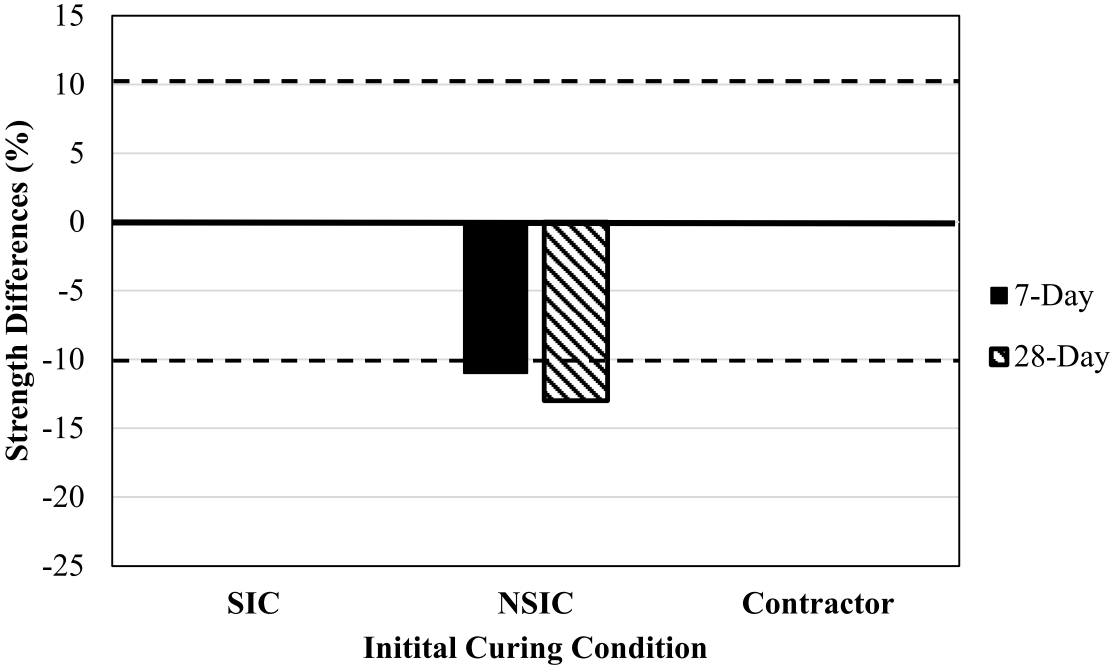

Figure 4-24: Jobsite 3, Visit 1 Strength Difference Results

4.4.2 Jobsite 3, Visit 2

This jobsite visit was conducted on July 21st, 2022. Upon arrival to the jobsite, members of the AU 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 is still in violation of AASHTO R60-12 5.2.4 (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 beginning of the truck as such concrete is generally segregated and not representative of the rest of the truck. This effort, along with the specification, is discussed in more detail in Chapter 5.

After sampling, the jobsite technicians performed all fresh concrete property tests and made cylinders to meet all specification requirements. The AU research team made cylinders with the concrete approved by the jobsite technicians. The data collected from the Exact Technologies temperature probes was compiled and is shown in Figure 4-25.

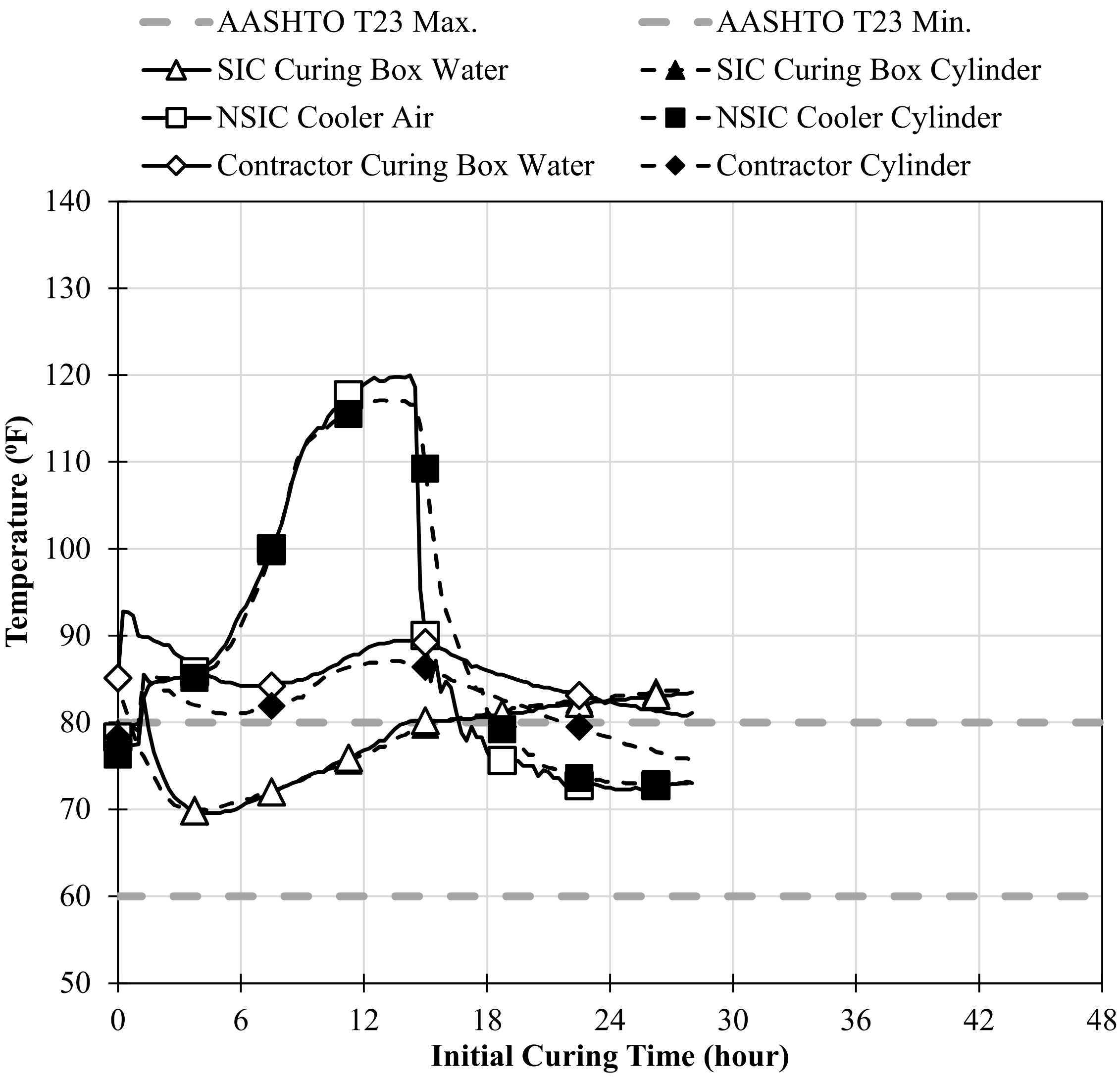

Figure 4-25: Jobsite 3, Visit 2 Temperature Results

The temperature in the NSIC cooler air was much higher than that of the SIC Curing Box water, as shown in Figure 4-25, 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 4-9.

Table 4-9: 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 made using Equations 1 and 2 respectively. The individual cylinder compressive strengths can be found in Appendix B. The percent differences are illustrated in Figure 4-26. Although the

Contractor's curing box water exceeded the 80°F limit, the relative 28-day compressive strength differences of the contractor 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 cylinders, even though they were cured at a slightly higher water temperature.

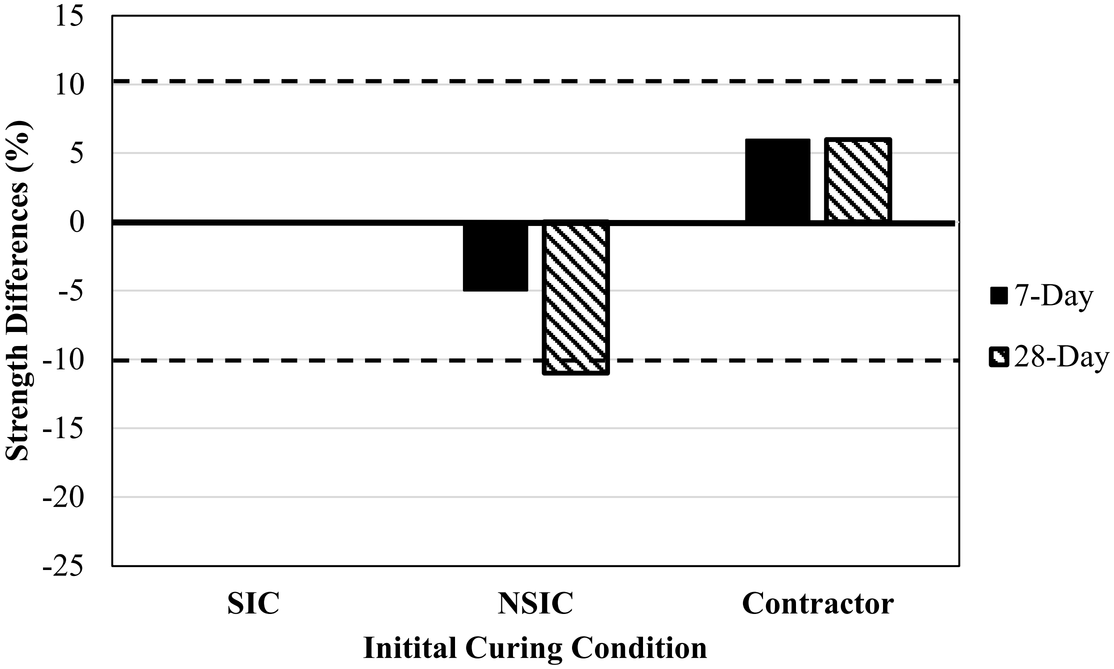

Figure 4-26: Jobsite 3, Visit 2 Strength Difference Results

4.5 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 4-27.

Figure 4-27: Jobsite 4 Contractor Curing Box

Although the contractor's curing box was plugged into a power source for Jobsite 4 and set at a temperature within the specified range, the contractor had no means to record the minimum and maximum temperature ranges of the curing environment and therefore could not monitor if their curing box was within the 60-80°F temperature range during the entire initial curing period. This was in violation with 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's cylinder curing box and are shown in Figures 4-28 and 4-29.

Figure 4-28: Jobsite 4 SIC Curing Box

Figure 4-29: Jobsite 4 NSIC Curing Box

4.5.1 Jobsite 4, Visit 1

Jobsite 4, Visit 1 was conducted on August 11th, 2022. Upon arrival to the jobsite, members of the AU 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 is a violation of AASHTO R60-12 5.2.4 (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 materials to perform the air content test and therefore did not perform this test. This was in violation of ALDOT 501 (2022) and AASHTO T 23 (2018) section 8.2. The jobsite technicians and the AU research team then proceeded to make cylinders with the approved concrete. The data collected from the Exact Technologies temperature probes was compiled and is shown in Figure 4-30.

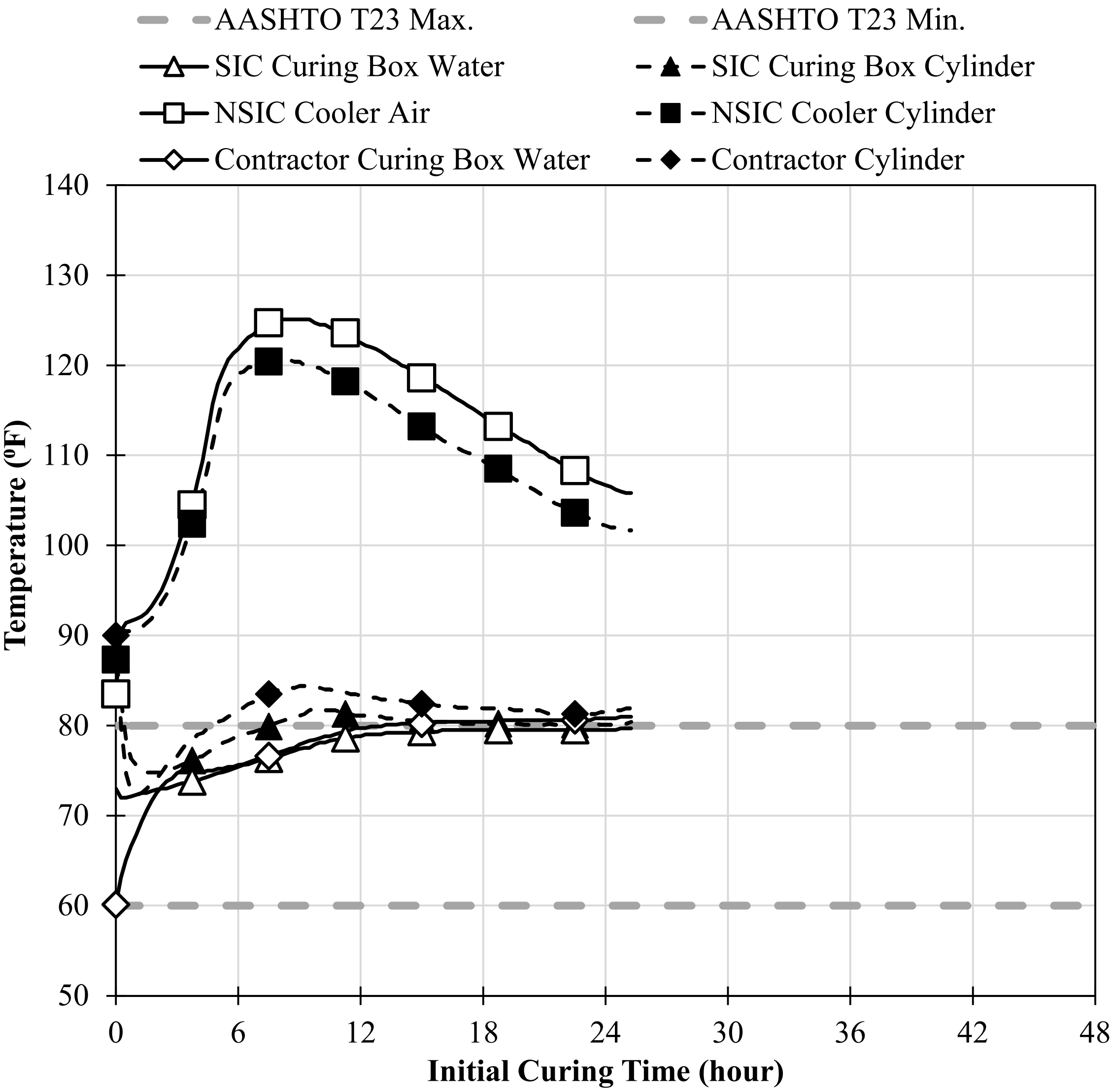

Figure 4-30: Jobsite 4, Visit 1 Temperature Results

The temperature in the NSIC cooler air was much higher than that of the SIC Curing Box water, as shown in Figure 4-30, 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. During the initial curing period, the generator for the SIC curing box was mysteriously turned off at some point during the initial curing period as there was still fuel in the generator and the power switch was off. This resulted in a steady rise of the water temperature inside. As a result, the SIC cylinder temperatures exceeded the 80 °F limit as the water temperature approached the limit. 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 4-10.

Table 4-10: 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 made using Equations 1 and 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 B. The percent differences are illustrated in Figure 4-31.

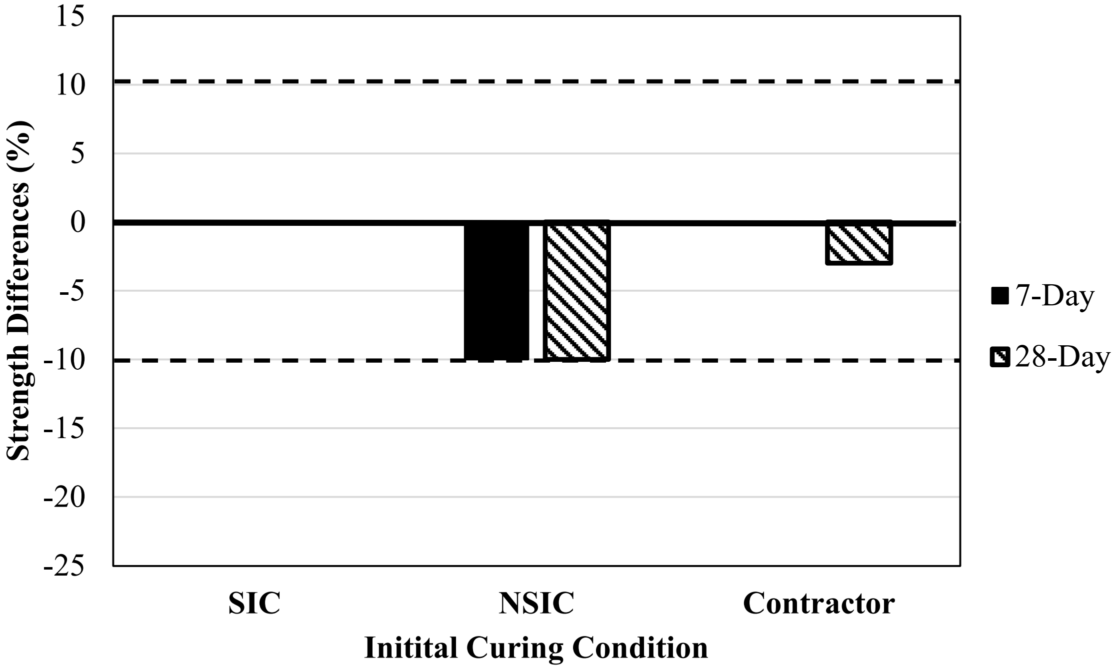

Figure 4-31: Jobsite 4, Visit 1 Strength Difference Results

4.6 Summary of Results

4.6.2 Summary of Initial Curing Temperature Results

The temperature results from the nine jobsite visits show that temperatures inside the NSIC curing environment were above the 60-80°F range specified in ALDOT 501 (2022) and AASHTO T 23 (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 temperatures reaching as high as 138°F. 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 4-11.

Table 4-11: 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

4.6.2 Summary of Strength Results

The extreme increase in curing temperatures of the NSIC test cylinders directly resulted in large decreases in 7-day and 28-day compressive strength results when compared to the test cylinders cured in the SIC curing environment. A summary of the percent difference results obtained from the cylinders tested from all the jobsite visits is shown in Table 4-12.

Table 4-12: 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

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 28-day percent decrease of 22% from 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 from Jobsite 2, Visit 3. It is clear from the results that when the initial curing temperature is not kept within the 60 to 80 °F range, then the 28-day compressive strength is often reduced when compared to curing test cylinders at initial curing temperatures that meet AASHTO T 23 (2018) requirements.

4.6.3 Summary of Jobsite Practices

After reviewing the practices of jobsite technicians from nine jobsite visits of varying project types and concrete strength, multiple specifications from ALDOT 501 (2022) and AASHTO T 23 (2018) were commonly not followed. The jobsite technicians at every jobsite visit failed to discharge the first 10% of the load before sampling concrete as stated in AASHTO R60-12 5.2.4 (2020) and referenced in AASHTO T23 (2018). It was also determined from comparing the batch ticket to 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. This was also in violation of AASHTO R 60-12 5.2.4 (2020). The purpose and importance of these sampling specifications were discussed in Section 2.5.1.

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 T 23 (2018). While the contractor curing box at each jobsite possessed temperature regulation capabilities, the contractor curing box at Jobsite 2 did not have any access to electricity for each visit and therefore was not turned on. This resulted in consistently higher temperatures in the contractor's curing box when compared to the SIC curing environment temperatures as it was plugged into a generator and within the 60-80°F range specified in AASHTO T 23 (2018) for the entire initial curing period. The average curing environment temperature in the contractor's curing box for each visit to Jobsite 2 was 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 28-day strength decrease of 15 percent in the samples cured in the Contractor's curing box. The minimum, maximum, and average curing environment temperature in the contractor curing box for each jobsite visit is shown in Table 4-13.

Table 4-13: 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	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	77.8

While the contractor curing box at Jobsites 1, 3, and 4 were plugged into a power source and set within the 60-80°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 T 23 (2018). As a result, there was no way for the Contractor to tell if their curing box remained within the 60-80°F for the entire initial curing duration. However, the results from the temperature probes in the contractors' curing boxes used by Auburn University 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 T 23 (2018). This specification was not met on any of the jobsite visits performed.

Additionally, a test to determine the effectiveness of using a water circulation pump was conducted. The results presented and discussed in Section 4.2.2 show that without a water circulation pump, the water inside a cylinder curing box can have 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.

Chapter 5: Implementation of Results

5.1 Introduction

The purpose of this chapter is to provide recommended modifications to ALDOT 501.02 section (d) “Sampling and Inspection” based on the results presented and discussed in Chapter 4. The following recommended modifications are also based on the results and conclusions of the laboratory portion of the project performed by White (2023). 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 C and D.

5.2 Initial Curing Temperature Recommendations

After reviewing and comparing the temperature results discussed in Section 4.6.2, 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 (White 2023). 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 (White 2023). Additionally, some cylinders cured at 100°F exhibited a decrease in 28-day strength up to 23%. Therefore, it is recommended that the 60 ºF to 80 ºF (16 ºC to 27 ºC) 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 (20 ºC to 26 ºC) from AASHTO T 23 (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 T 23 (2018), discussed in Section 2.5.3, 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.

5.3 Cylinder Curing Box Recommendations

After analyzing the results presented in Chapter 4, 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 4.1.2, 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, 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 shown in Table 2-3 from Section 2.4.3. Therefore, it is recommended that the supporting surface on which the cylinders are stored be level within 0.25 in./ft (20 mm/m), as specified in AASHTO T 23 (2018).

5.4 Initial Curing Period Recommendations

While the initial curing period in AASHTO T 23 (2018) and ASTM C 31 (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 White (2023) in the laboratory portion of this project showed that as long as the curing environment remained within the 60 ºF to 80 ºF (16 ºC to 27 ºC), the relative strength differences remained within ±10%, even when initially cured for 72 hours. Therefore, it is recommended that the initial curing period 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 remain in accordance with ALDOT 501.

5.5 Sampling Recommendations

After observing the sampling procedures of jobsite technicians across the various jobsite visit, the requirement from AASHTO R 60 (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 visited. While the technicians at Jobsite 3 made a conscientious effort to obtain a representative sample of the load by discharging one full wheelbarrow of concrete prior to sampling, it is still a violation of AASHTO R 60 (2020) and ALDOT 501 (2022). 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 a safe and practical example of how to discharge 6 cubic feet of concrete before sampling.

5.6 Responsibility Recommendations

Since ALDOT 501 is used for acceptance purposes of concrete, specifying responsibility of 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 provided by the Contractor to ensure that it maintains its heating and cooling capabilities. This implies that the Contractor is also responsible for providing fuel if the continuous power source is a generator. 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 test cylinders, as well as be responsible for using the temperature probes to monitor and record the minimum and maximum temperatures experienced in the cylinder curing box water 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.

5.6 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 from jarring, 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 T 23 (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 experienced 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 T 197. This recommendation is also taken directly from AASHTO T 23 (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 AASHTO T 23 “Making and Curing Concrete Test Specimen in the Field”. 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 6: Summary, Conclusions, and Recommendations

6.1 Project Summary

The research presented in this thesis was performed as part of a larger research project funded by ALDOT to investigate jobsite cylinder curing practices for the purpose of updating ALDOT 501.02 Section (d) “Sampling and Inspection” for the Alabama concrete industry. All practices used to sample, make, cure, transport, and test concrete cylinders on ALDOT projects were reviewed. In order to accomplish these tasks, nine jobsite visits were performed on a variety of project types with different concrete strengths.

During each of the nine jobsite visits, samples of the provided concrete were taken and concrete cylinders were made and placed in two different curing environments. One curing environment was in strict accordance with AASHTO T 23 (2018) and ALDOT 501 (2022), while the other was a simple cooler with no water inside and no temperature control. Concrete cylinders were placed in each initial curing method for 24 hours and then transported to the laboratory for final curing in accordance with AASHTO T 23 (2018). During the initial curing period, the temperature of the curing environment, as well as the temperature of the concrete specimens, were recorded for both curing environments as well as for the Contractor’s curing box using temperatures probes which recorded temperatures in 15-minute intervals. Concrete cylinders were then tested at 7 and 28 days in accordance with AASHTO T 22 (2022).

The practices of jobsite technicians and the Contractor-provided cylinder curing box were also evaluated for their adherence to AASHTO T 23 (2018) and ALDOT 501 (2022). The temperature and strength results along with the observed jobsite practices were then compared within each jobsite visit.

Additionally, a water circulation test was performed to test the effectiveness of a water circulation pump to provide a uniform water temperature inside a cylinder curing box. This test was conducted by placing a cylinder curing box set at 68°F inside an environmental chamber set at 100°F. Then the water temperature inside the curing box was recorded at the top and bottom of the curing box for 48 hours with and without the water circulation pump running.

6.2 Research Conclusions

Based on the work performed in this study, the following conclusions are made:

- Initially curing concrete cylinders not in accordance with AASHTO T 23 (2018) or ALDOT 501 (2022) can result in decreased 28-day compressive strengths up to 22%. 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 specified in ALDOT 501 (2022). This conclusion is consistent with White (2023).
- 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 specimens themselves.
- 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 the cylinder curing box has access to continuous power either through wall power or a generator. 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 responsible for providing the cylinder curing box, power source, fuel for power source, and maximum minimum temperature probes that

continuously record the water temperature in the cylinder curing box at intervals no less than 30 minutes.

- 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 monitoring and documenting the minimum and maximum temperature of the water in the cylinder curing box for the entire initial curing period.
- When not using a water circulation pump in the cylinder curing box, there is a significant temperature gradient between the top and bottom of the water inside a cylinder curing box. 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.
- Concrete test cylinders must be cured on a surface level within 0.25 in./ft (20 mm/m), as specified in AASHTO T 23 (2018). This will avoid up to an 8% decrease in compressive strength from cylinders ends not perpendicular with axis (Richardson 1991).
- ALDOT 501 should modify their initial curing period requirement to “not less than 24 hours or more than 72 hours” (White 2023). This will allow cylinders made on a Friday to be able to be kept in initial curing until Monday and still be in accordance with ALDOT 501.
- While no sample should be taken before 10 percent, or after 90 percent, of the load has been discharged, this is not always practical; therefore, it should be made to allow that no less than 6 cubic feet (0.2 cubic meter) of concrete (e.g., approximately two, half-full

wheelbarrow loads) should 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 the requirements in AASHTO T 23 (2018).

6.3 Research Recommendations

- Before implementing into ALDOT 501.02 Section (d), industry personnel should be trained in order to understand and implement the modifications to this specification.
- Diagrams should be developed that detail the proper temperature probe installment locations and water circulation pump locations inside a cylinder curing box.
- A maintenance and calibration schedule should be developed for cylinder curing boxes and temperature probes used to record the minimum and maximum water temperature inside the curing boxes.
- Proper documentation should be developed for the Engineer to approve the materials provided by the Contractor.

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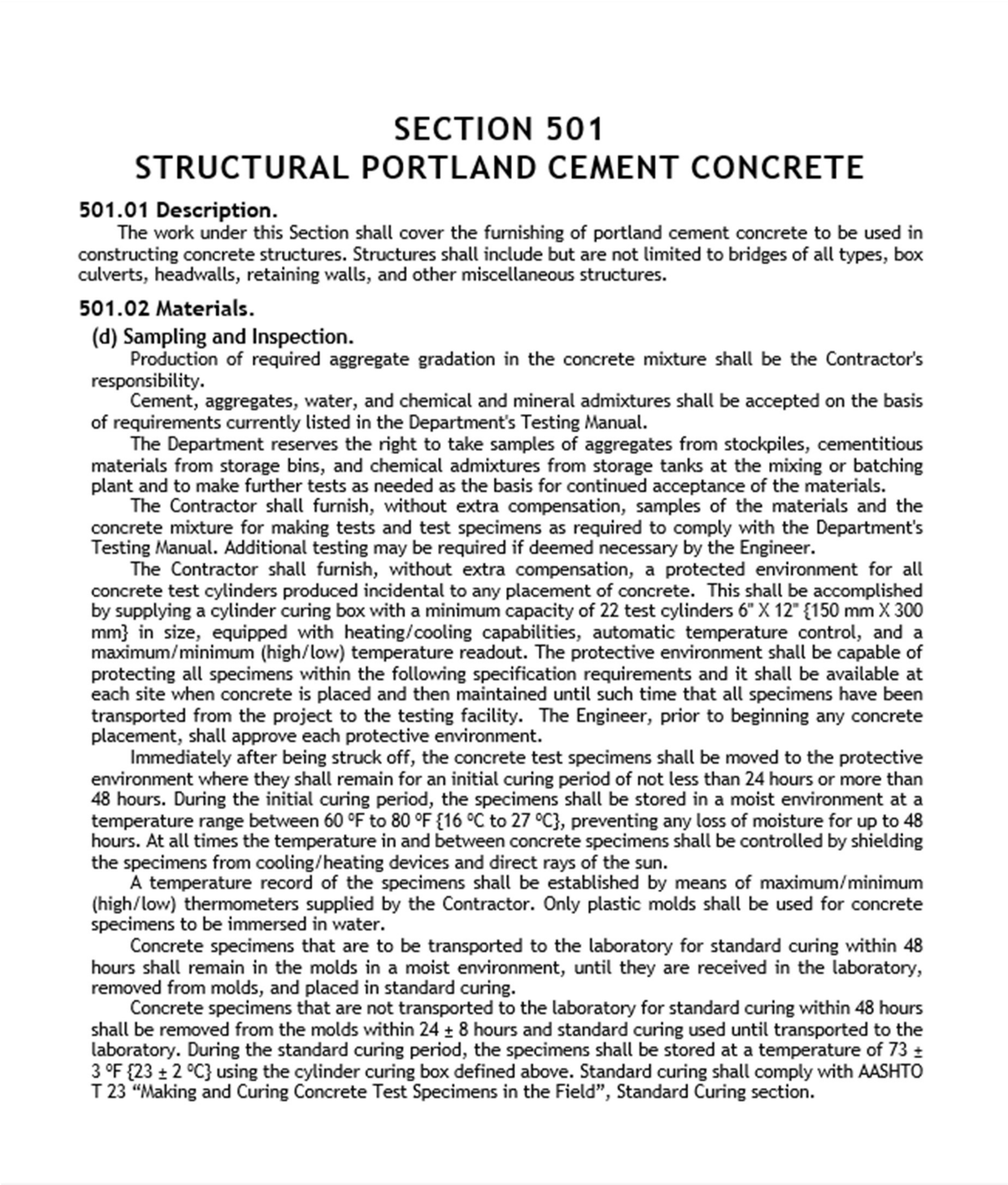
Appendix A: ALDOT 501.02 (2022) Section (d), Original Document



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 °F to 80 °F {16 °C to 27 °C}, 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 °F {23 ± 2 °C} 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 A-1: ALDOT 501.02 (2022) Section (d), Original Document

Appendix B: Individual Cylinder Compressive Strength Results

Table B-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 B-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 B-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 B-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 B-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 B-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 B-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 B-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

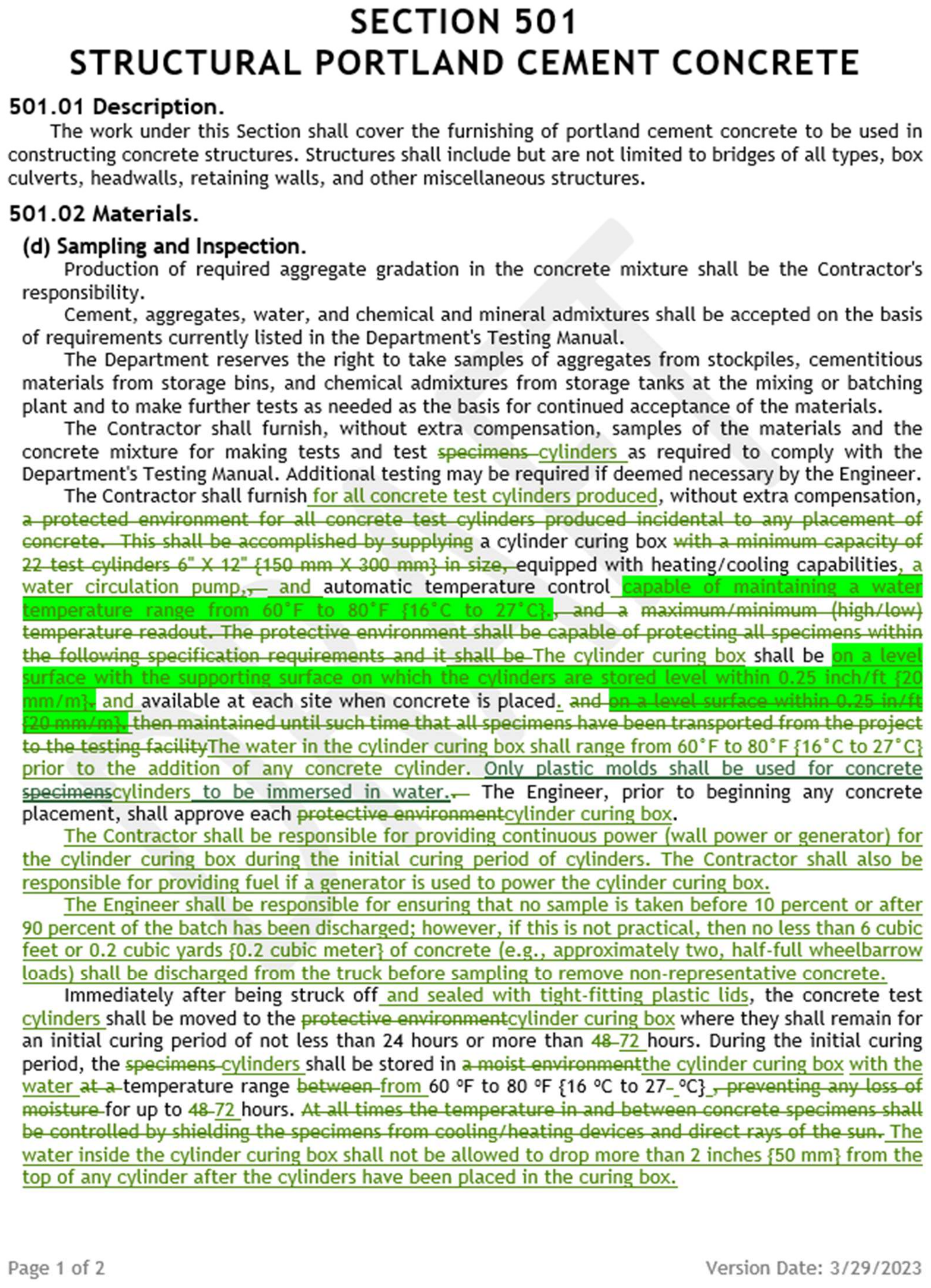
Note: N.A. = Not Available

Table B-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 C: 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.

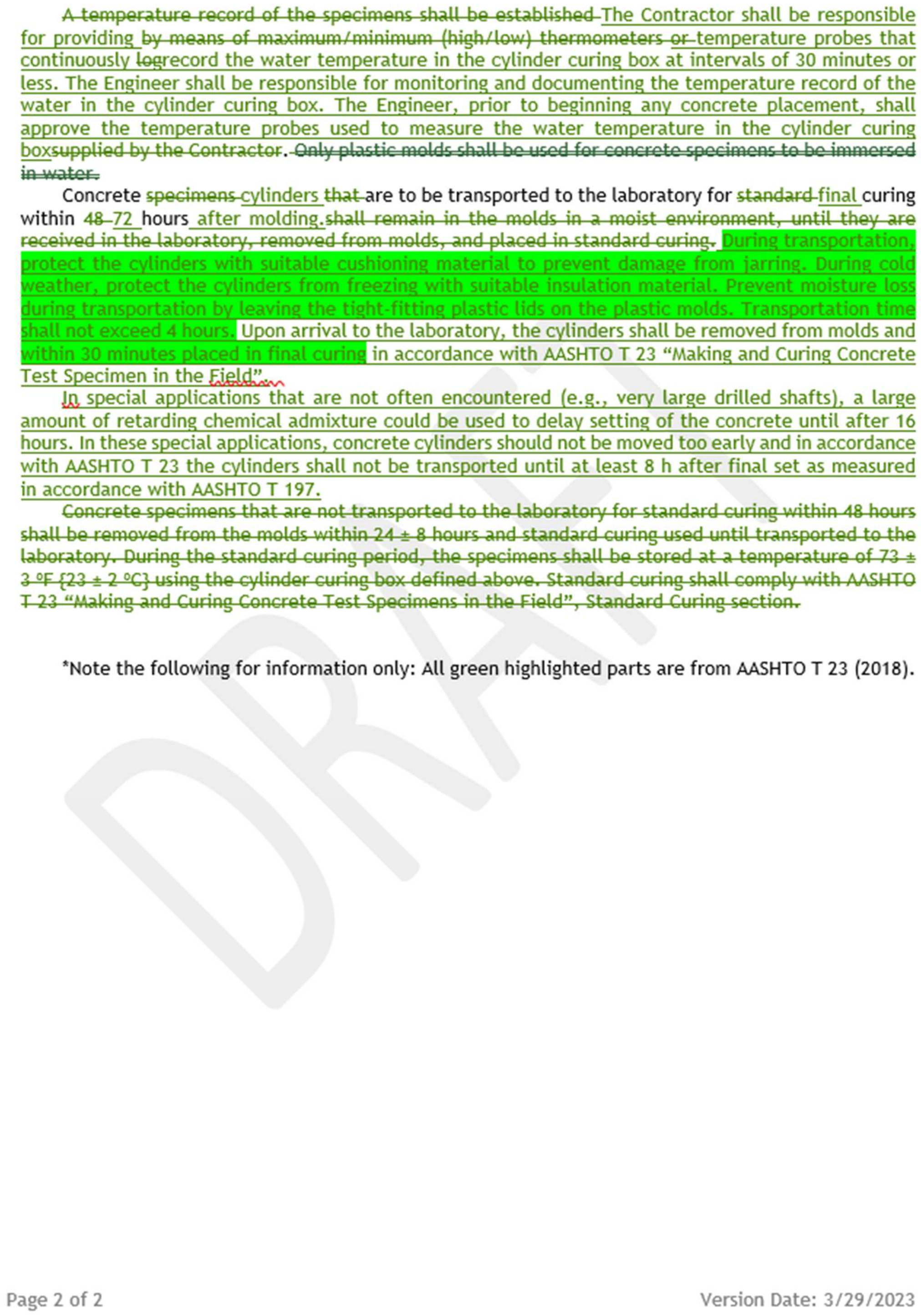
The Contractor shall be responsible for providing continuous power (wall power or generator) for the cylinder curing box during the initial curing period of cylinders. The Contractor shall also be responsible for providing fuel if a generator is used to power the cylinder curing box.

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.

Page 1 of 2 Version Date: 3/29/2023

Figure C-1: ALDOT 501.02 (2022) Section (d) with Modifications, Page 1



~~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 ~~log~~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~~supplied 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".

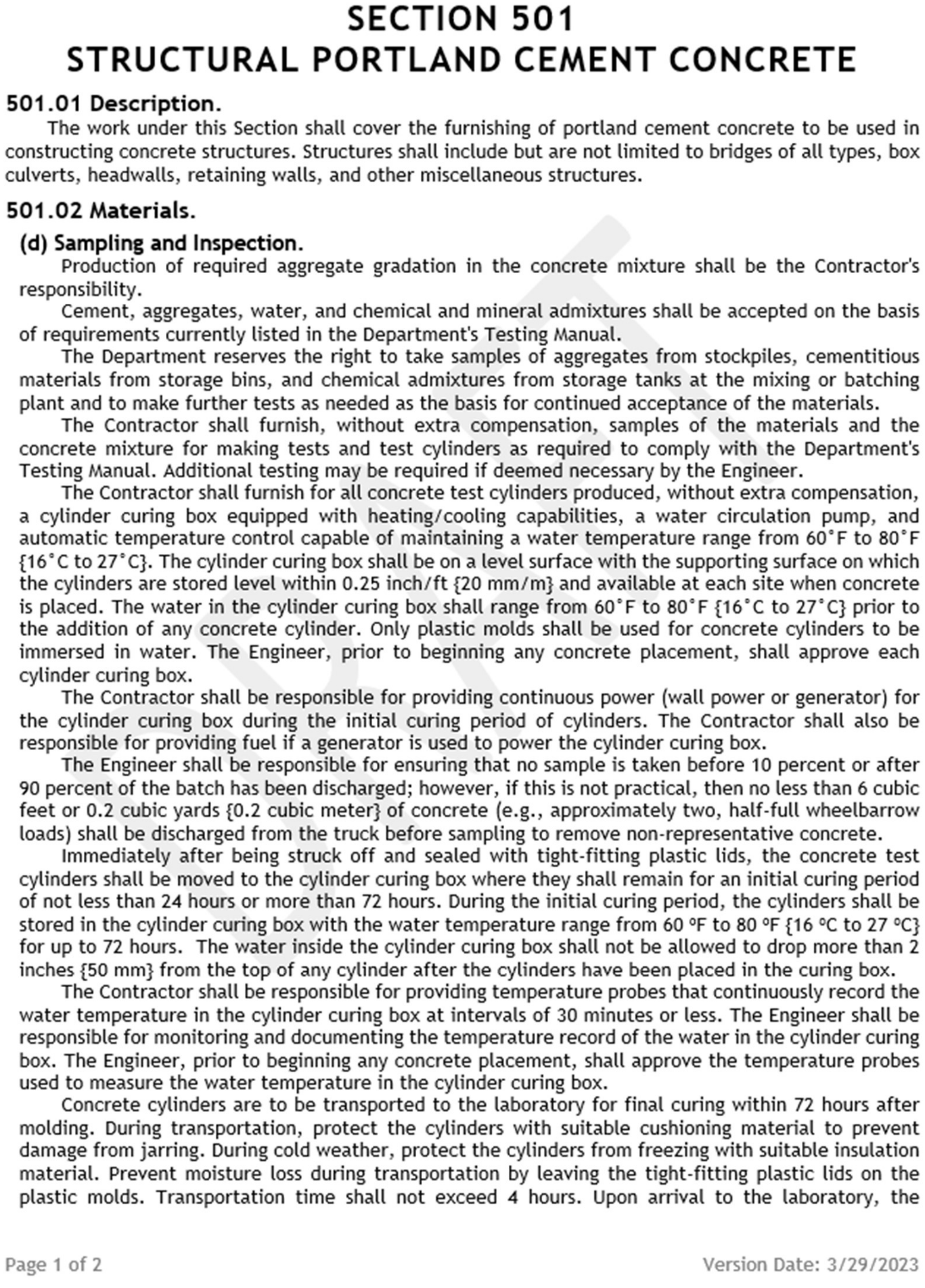
In special applications that are not often encountered (e.g., very large drilled shafts), a large amount of retarding chemical admixture could be used to delay setting of the concrete until after 16 hours. In these special applications, concrete cylinders should not be moved too early and in accordance 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 C-2: ALDOT 501.02 (2022) Section (d) with Modifications, Page 2

Appendix D: 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

Figure D-1: ALDOT 501.02 (2022) Section (d), Proposed Draft, Page 1

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.

Figure D-2: ALDOT 501.02 (2022) Section (d), Proposed Draft, Page 2