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Samuel Ginn College of Engineering

Highway Research Center

Impact of Initial Curing of Cylinders on Concrete Strength

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Alabama Transportation Conference

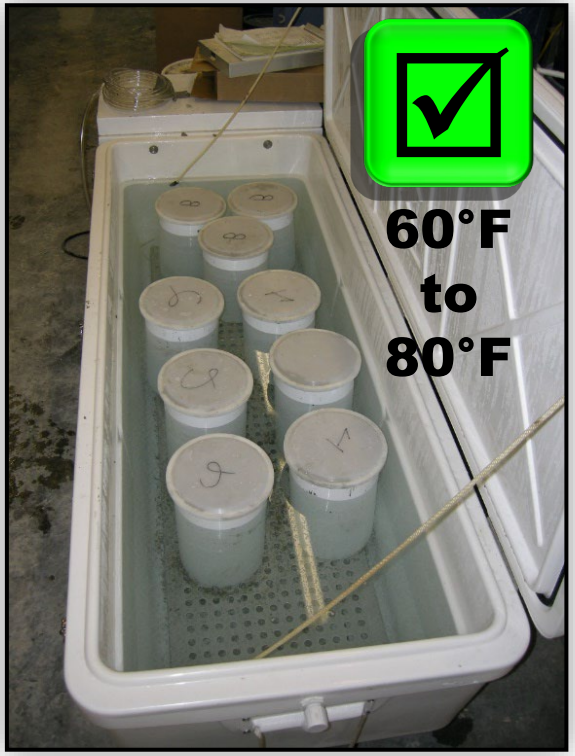
Introduction

- In recent years, numerous low 28-day concrete cylinder strengths have been measured on ALDOT projects
- Questions:
  - Is the quality of the concrete delivered to site acceptable?
  - Is the in-place concrete strength acceptable?
  - Were acceptable practices followed to make, cure, transport, and test concrete cylinders?

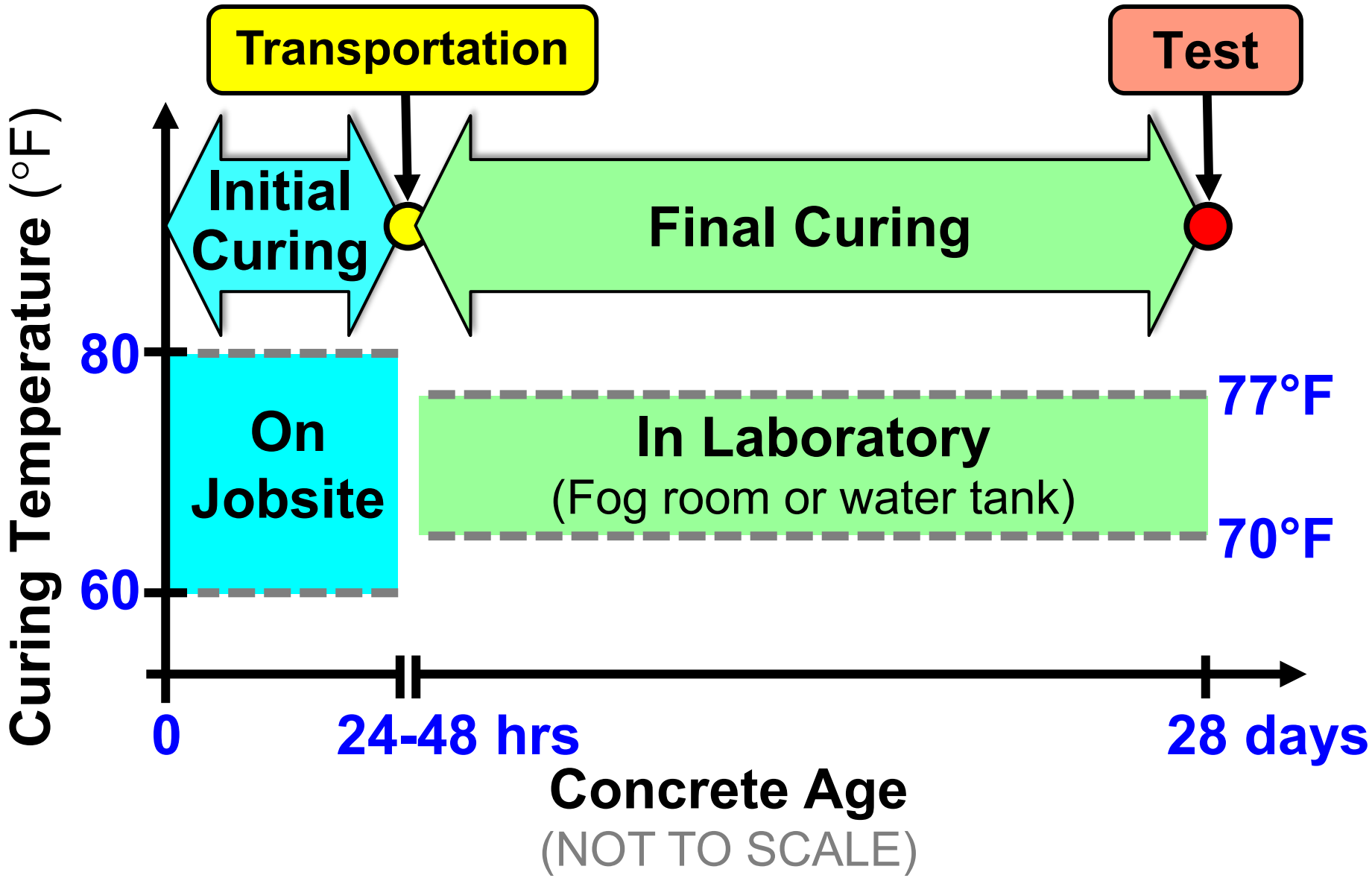
Introduction

- The increase in low breaks has resulted in a need to assess ALDOT's standard curing practices for the acceptance of concrete

- AASHTO T23 (2018) and ALDOT 501 (2022) are standard specifications to make and cure concrete test cylinders on ALDOT projects
  - Curing of cylinders at **specific moisture** conditions and **temperatures** are critical parts of both specifications



What is **Initial Curing**? (AASHTO T23 or ASTM C39)



Presentation Objectives

- Quantify the effect of **initial curing temperature** on the 28-day compressive strength
  - What is the effect of initial curing temperatures above 80°F on strength?
- Quantify the effect of **24-, 48-, and 72-hour initial curing duration** on the 28-day compressive strength
  - Can we extend the maximum initial curing duration from 48 hours to 72 hours?
- Introduce parts of the **new ALDOT 501 spec.** to cure **quality assurance** cylinders

Presentation Overview

- **Introduction**
- Experimental Work
- Review and Discussion of Results
- New ALDOT Specification Requirements
- Closing Comments

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Curing of Cylinders

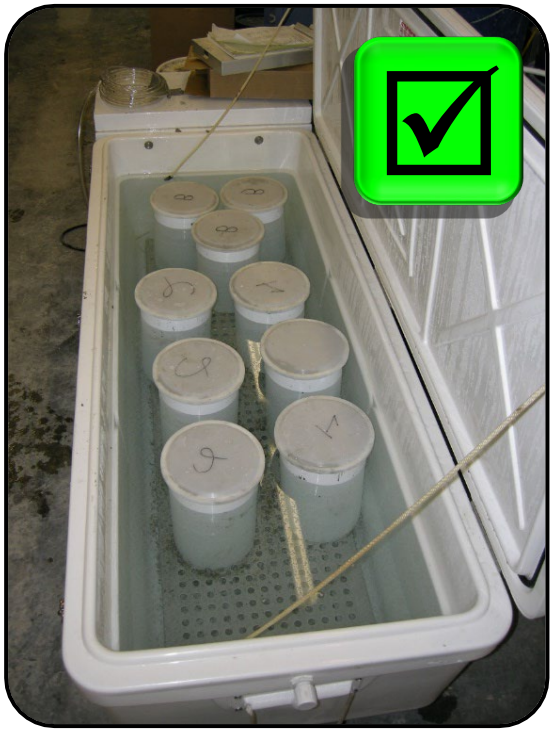
- Standards for making, curing, protecting, and transporting concrete cylinders:
  1. **AASHTO T23 – Standard Curing**
     Cylinders made and cured in the field for **acceptance** and quality control testing

     Today's Focus
  2. **AASHTO T23 – Field Curing**
     Cylinders made and cured in the field to determine:
     - form or shoring removal time,
     - termination of curing and protection,
     - opening to service, etc.

AASHTO T23 – **Standard Curing**

1. Initial Curing:

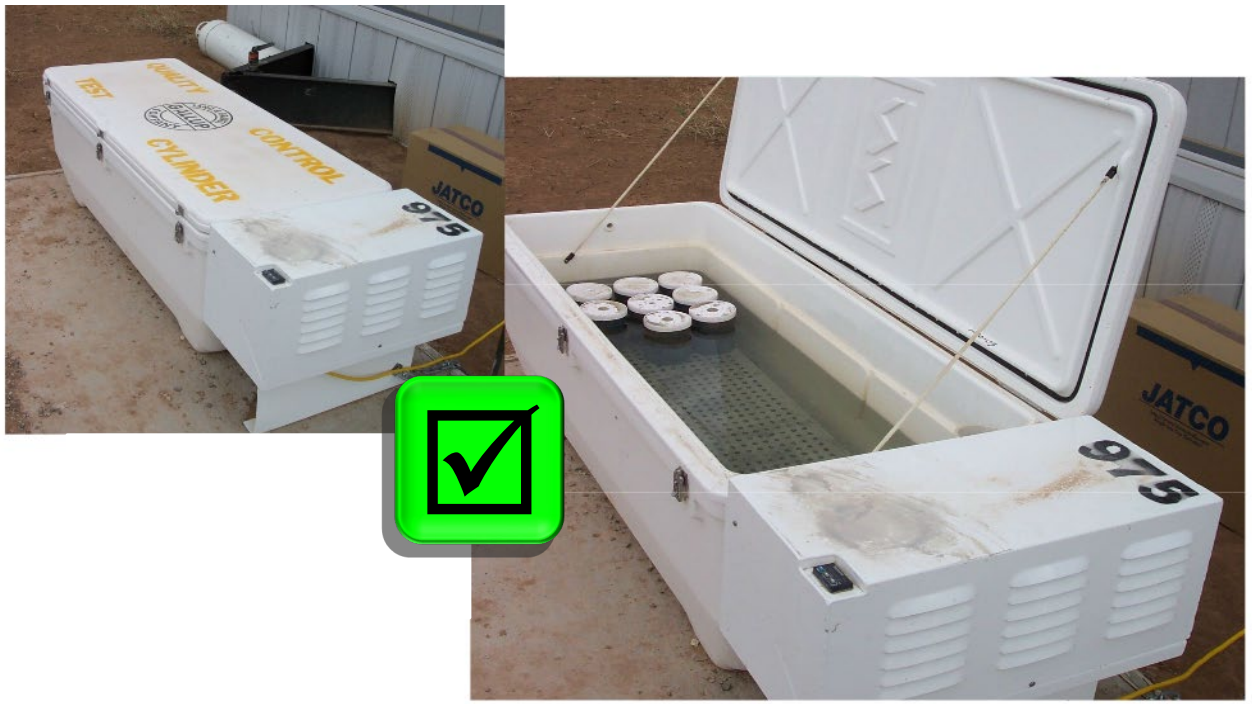
- May last up to 48 hrs
- Cylinders at job site and in molds
- Shield specimens from direct exposure to sunlight
- Store cylinders in an environment that prevents moisture loss
- **Temperature:**
  - **60 to 80°F when f'_c < 6,000 psi**
  - 68 to 78°F when $f'_c \geq 6{,}000$ psi
- Record the minimum and maximum temperatures reached during the initial curing period



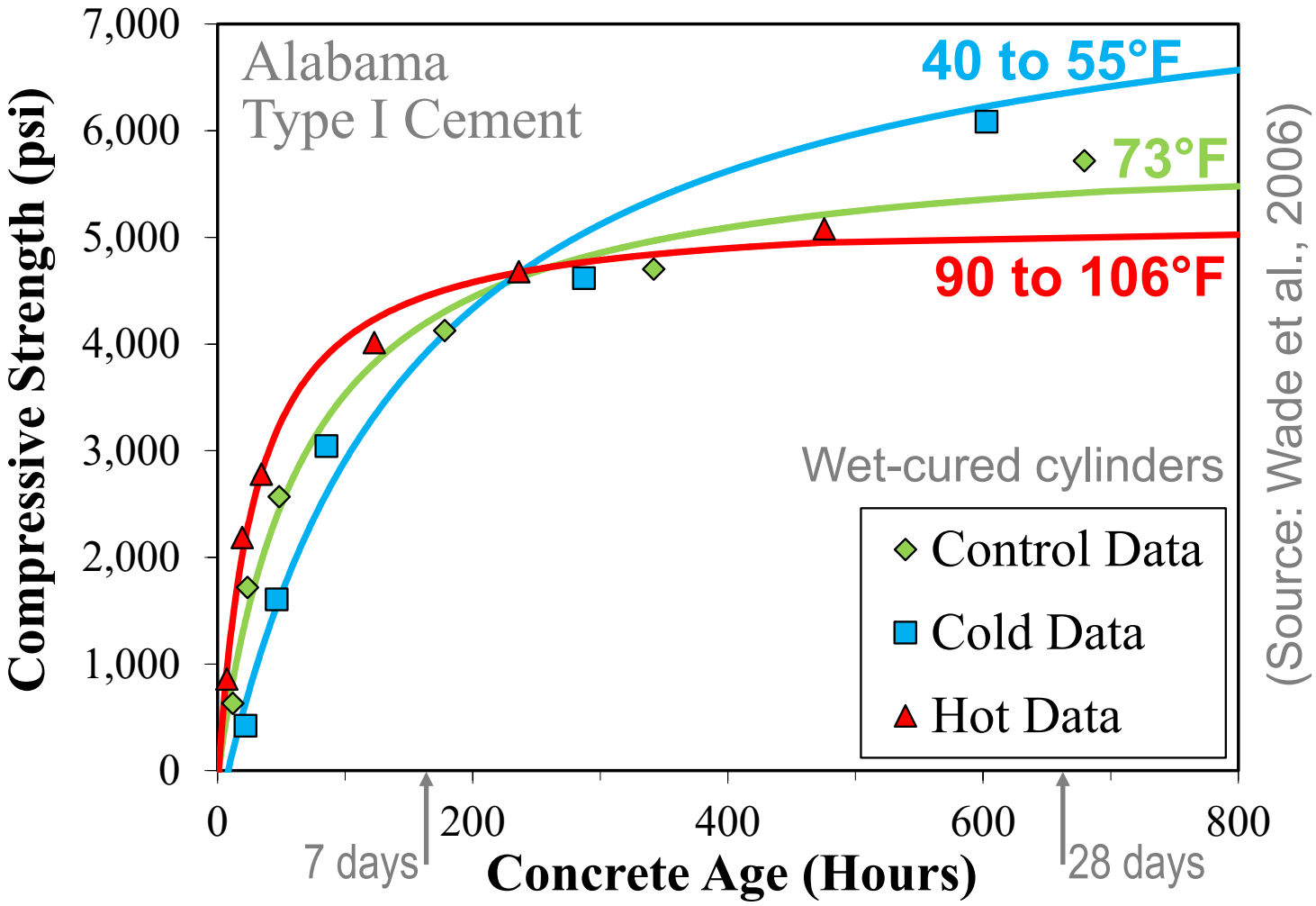
ALDOT 501 – Cylinder Curing Box

1. Initial Curing: ALDOT 501

- **The Contractor** shall furnish a **cylinder curing box** equipped with heating and cooling capabilities
- During initial curing, specimens shall be stored in a **moist** environment between **60 to 80°F**



Why require Curing between 60 to 80°F?



Is an Insulated Cooler without Water Control Good Enough?

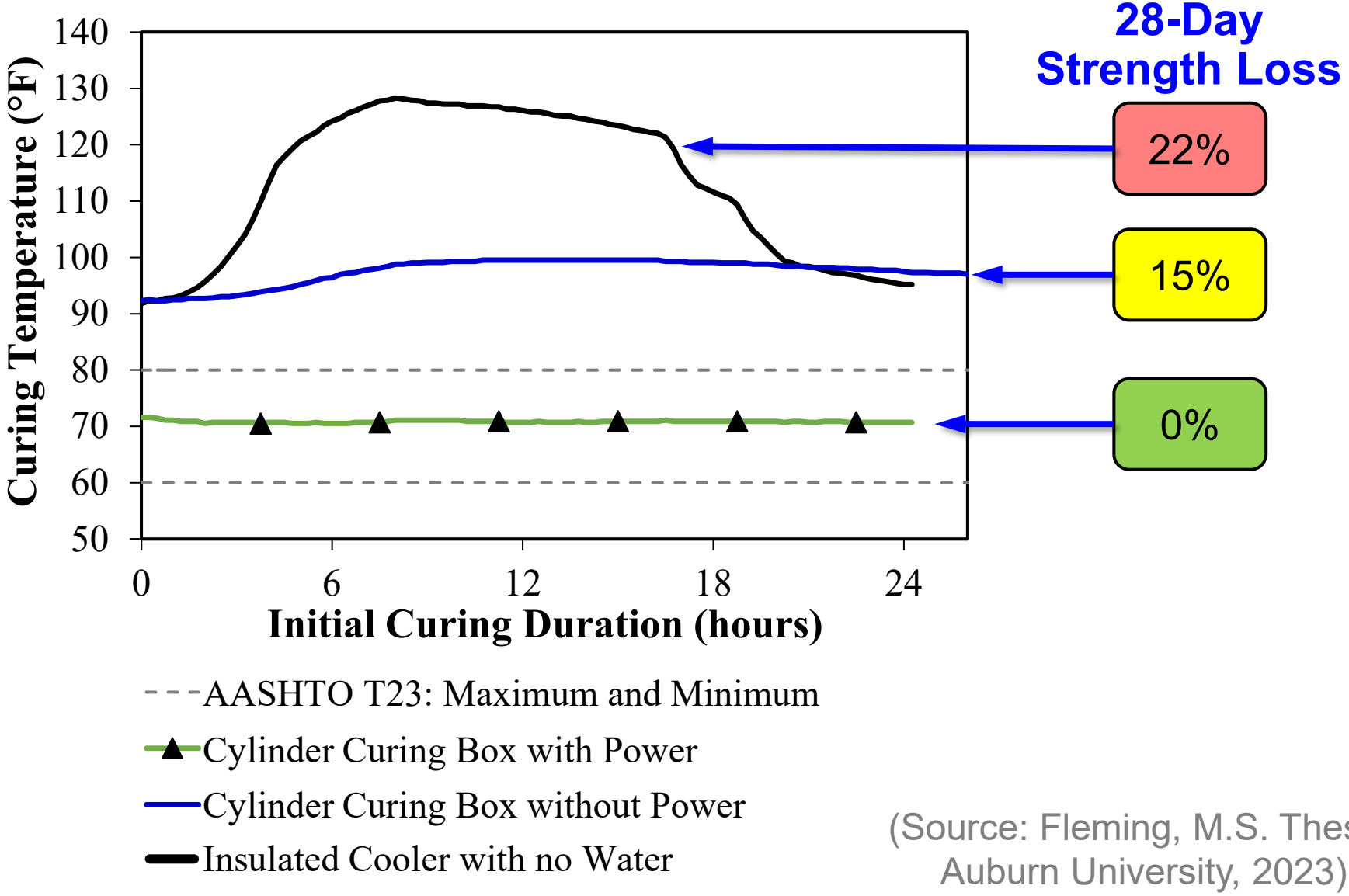
Cylinder Curing Box without Power

Cylinder Curing Box with Power

Insulated Cooler with no Water

(Source: Fleming, M.S. Thesis, Auburn University, 2023)

Is an Insulated Cooler without Water Control Good Enough?



(Source: Fleming, M.S. Thesis, Auburn University, 2023)

AASHTO T23: Initial Curing

1. Initial Curing:

- During initial curing, specimens shall be stored in a **moist** environment between **60 to 80°F**

Coolers without temperature control do not meet AASHTO requirements

Plywood box without temperature control do not meet AASHTO requirements

(Pictures from John Sorrell and Gene Hightower, ACIA, 2019)

AASHTO T23: Initial Curing

1. Initial Curing:

- During initial curing, specimens shall be stored in a **moist** environment between **60 to 80°F**

These initial curing methods meet ALDOT requirements

(Pictures from John Sorrell and Gene Hightower, ACIA, 2019)

AASHTO T23: Transporting Cylinders

2. Transport cylinders:

- Transport cylinders to the lab within **48 hours** after casting
  - Wait more than **8 hrs after final set** before starting to transport to lab
- Keep transportation time ≤ 4 hrs
- Protect cylinders with cushioning material to prevent damage
- Protect cylinders with **insulation** from freezing during cold weather
- **Prevent moisture** loss during transportation (e.g. use tight fitting plastic caps)

AASHTO T23 – **Standard** Curing

3. Final Curing:

- **Start final curing** after initial cure, and within 30 minutes of removal from molds
- **Temperature: 73.5°F ± 3.5°F**
- **Maintain free water on concrete surface at all times** (except when capping and just before [≤ 3 hours] testing)
  - Moist-cure rooms (fog room)
  - Lime-saturated water tank

(Picture: D&C of Concrete Mixtures, PCA, 2016)

Presentation Overview

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- **Experimental Work**
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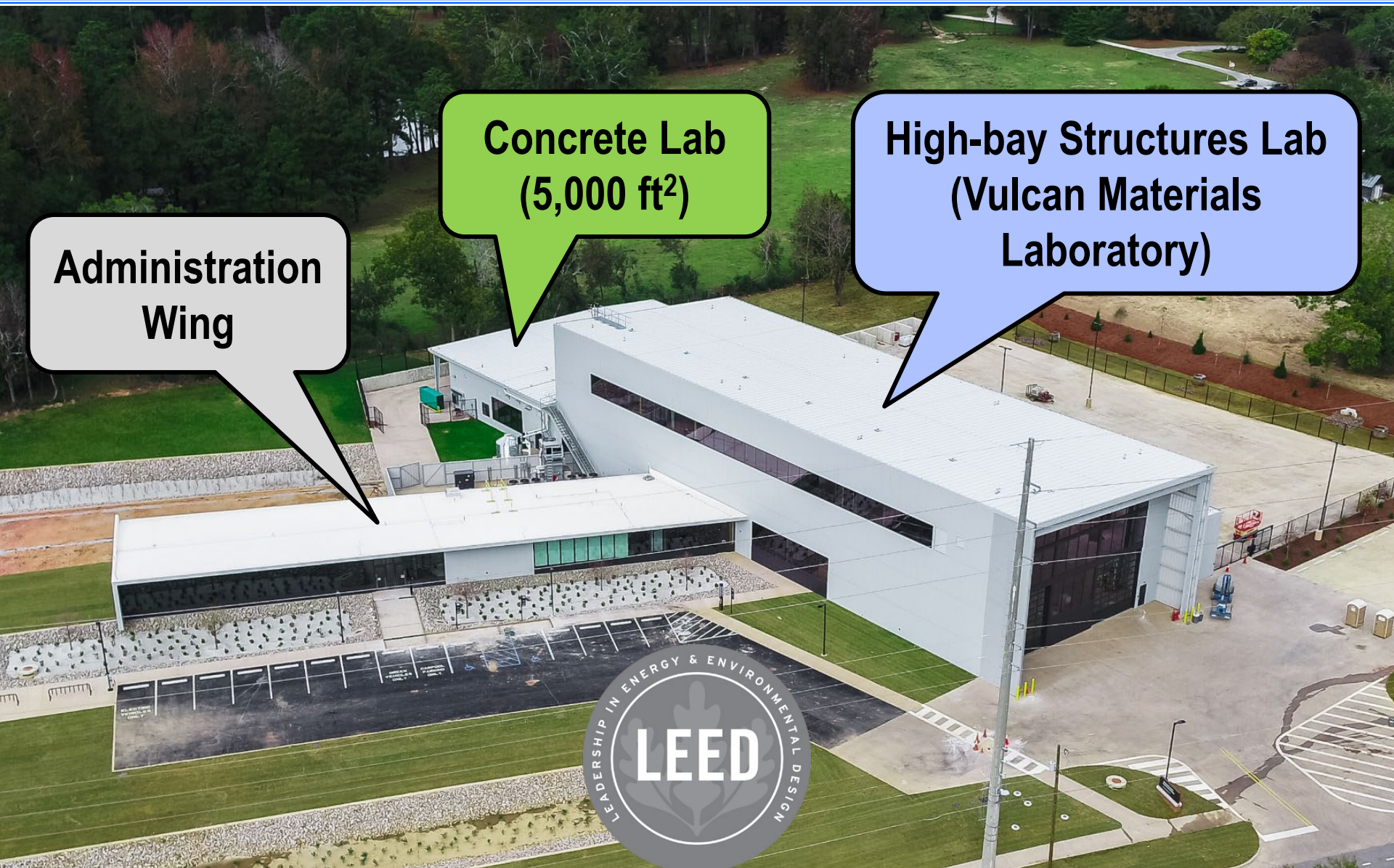
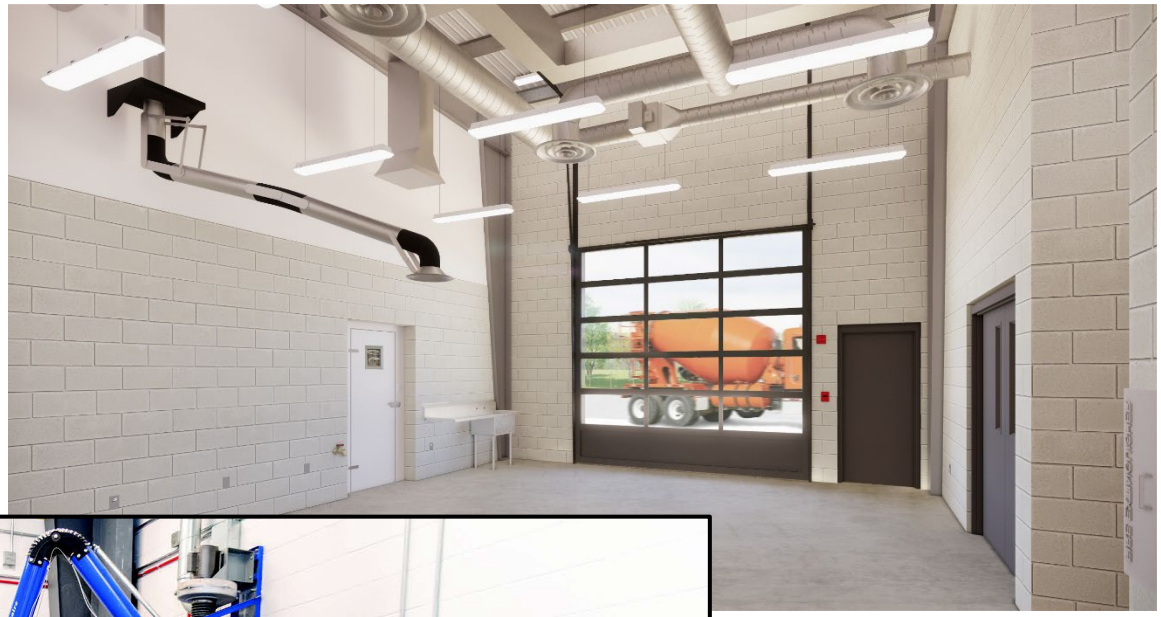
Advanced Structural Engineering Laboratory



Structural Concrete Materials Laboratory

Opened November 2020



Experimental Work

- Prepared various concretes to quantify the effect of different initial curing conditions on the 28-day compressive strength
- Evaluated:
  - Six (6) **initial curing temperatures**
  - Three (3) **initial curing durations**
- After initial curing, all cylinders received final curing in 100% moist room at 73.5°F ± 3.5°F
- All cylinders were tested at 28 days
- Fresh concrete was prepared at elevated temperatures to mimic **hot weather conditions**

Experimental Work

- **6 Initial Curing Temperatures:**
  - **60 °F**
  - **68 °F** (Control)
  - **78 °F**

  } **In Spec.**

  - **84 °F**
  - **90 °F**
  - **100 °F**

  } **Out of Spec.**
- **3 Initial Curing Durations:**
  - **24 Hours**
  - **48 Hours**

  } **In Spec.**

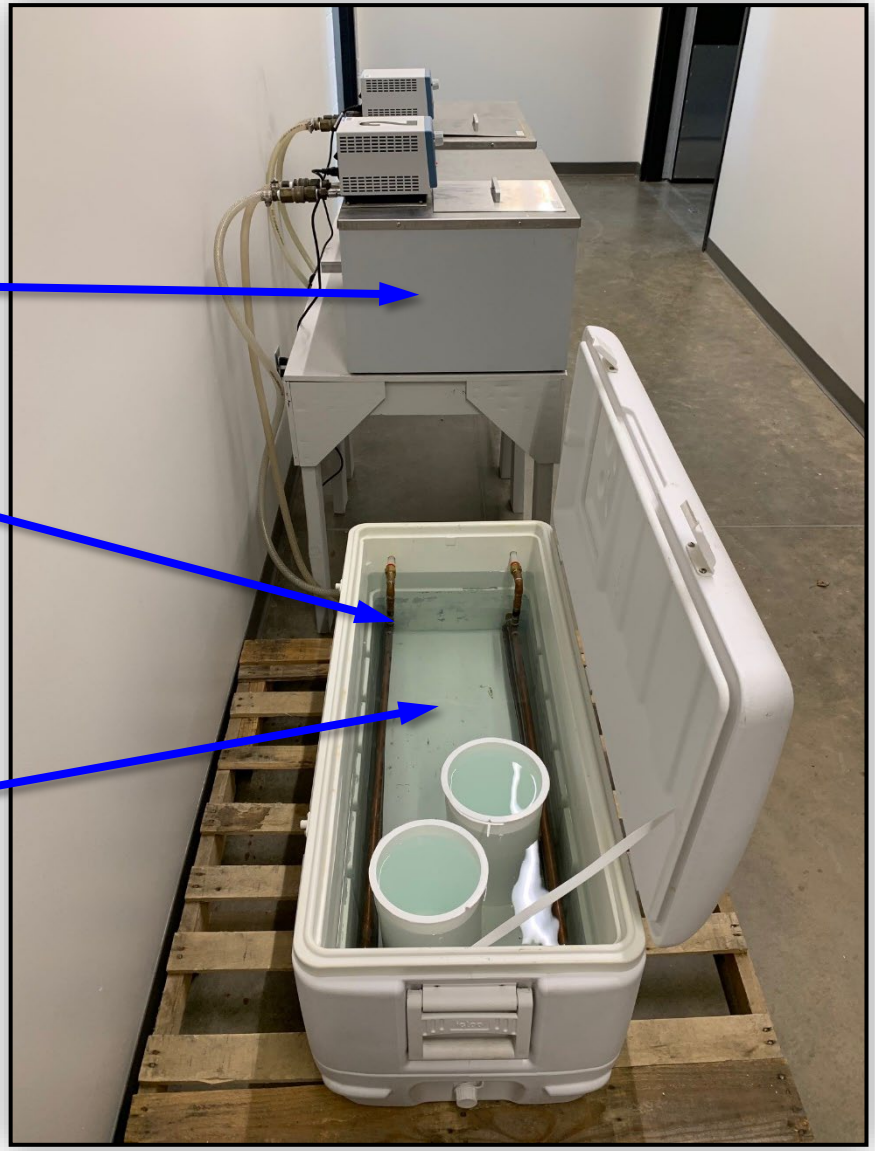
  - **72 Hours**

  } **Out of Spec.**
- **Final Curing:**
  - **73.5 ± 3.5 °F and 100% RH** for remainder of 28 days

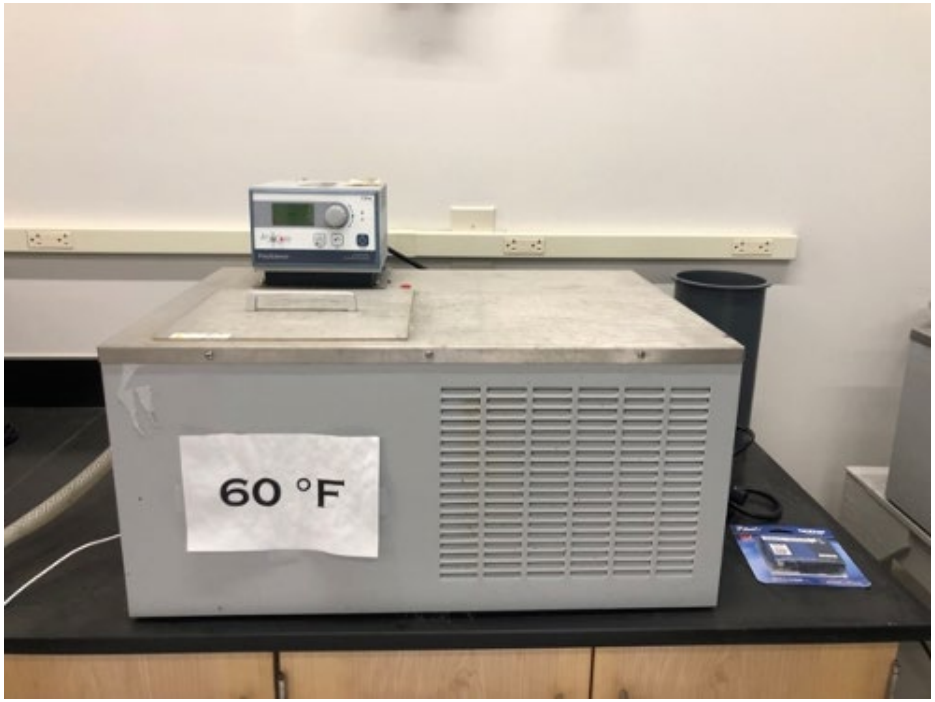
- **8 Concretes:**
  - 100% Type I
  - 30% Class F Fly Ash
  - 30% Class C Fly Ash
  - 50% Slag Cement
  - 10% Silica Fume
  - 20% Class F Fly Ash & 30% Slag
  - 20% Class F Fly Ash & 10% Silica
  - 100% Type III
- **Compressive Strength:**
  - Test at 28 days
  - Range: 4300 to 8900 psi

Experimental Work: Initial Curing Tanks

- Equipment:
  - Circulator
  - Copper pipes
  - Curing tank with internal water circulating pump



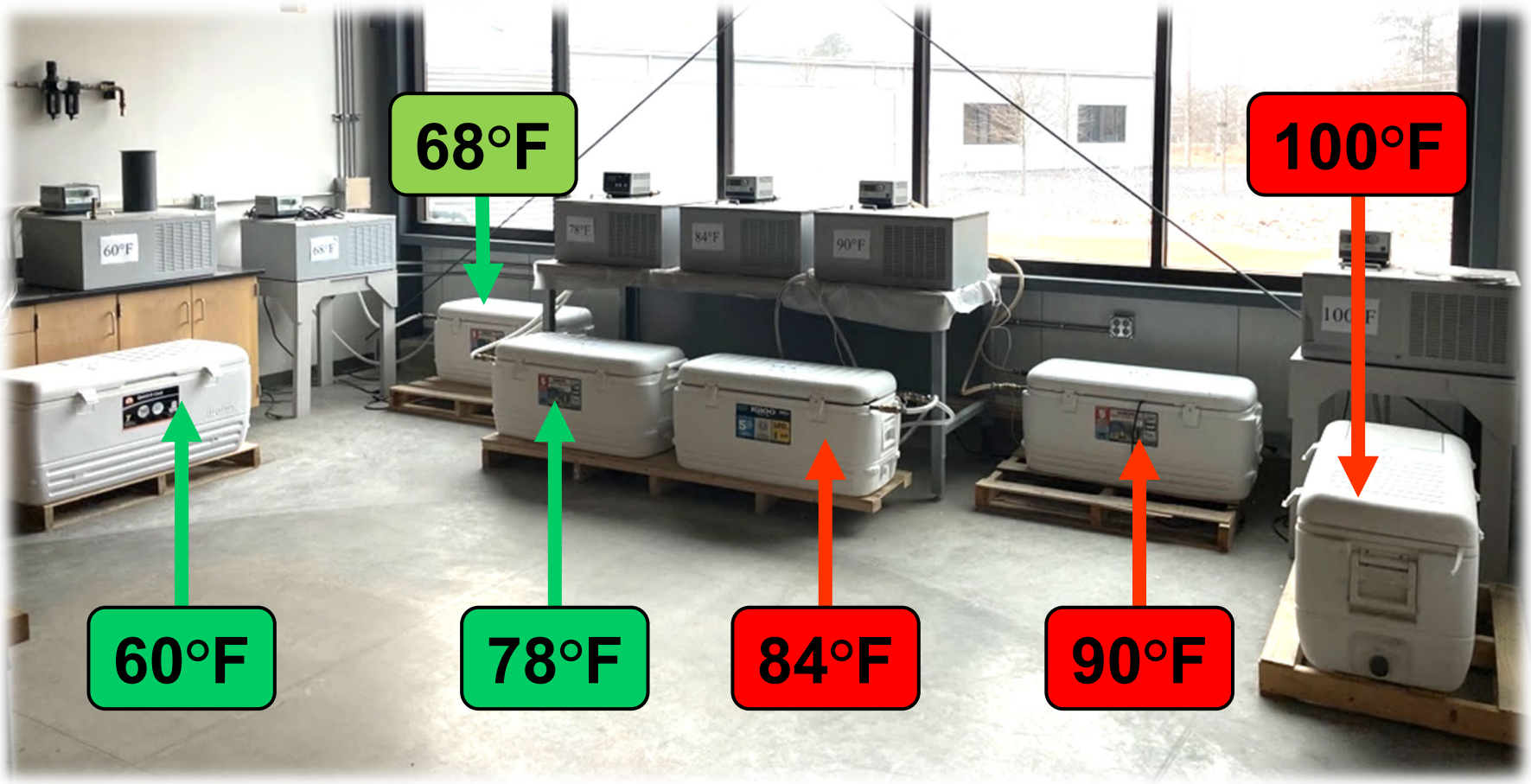
Experimental Work: Initial Curing Tanks



Water Circulator

Initial Curing Tank

Experimental Work: Initial Curing Tanks



Experimental Work

Final Curing

73.5 ± 3.5 °F and 100% RH

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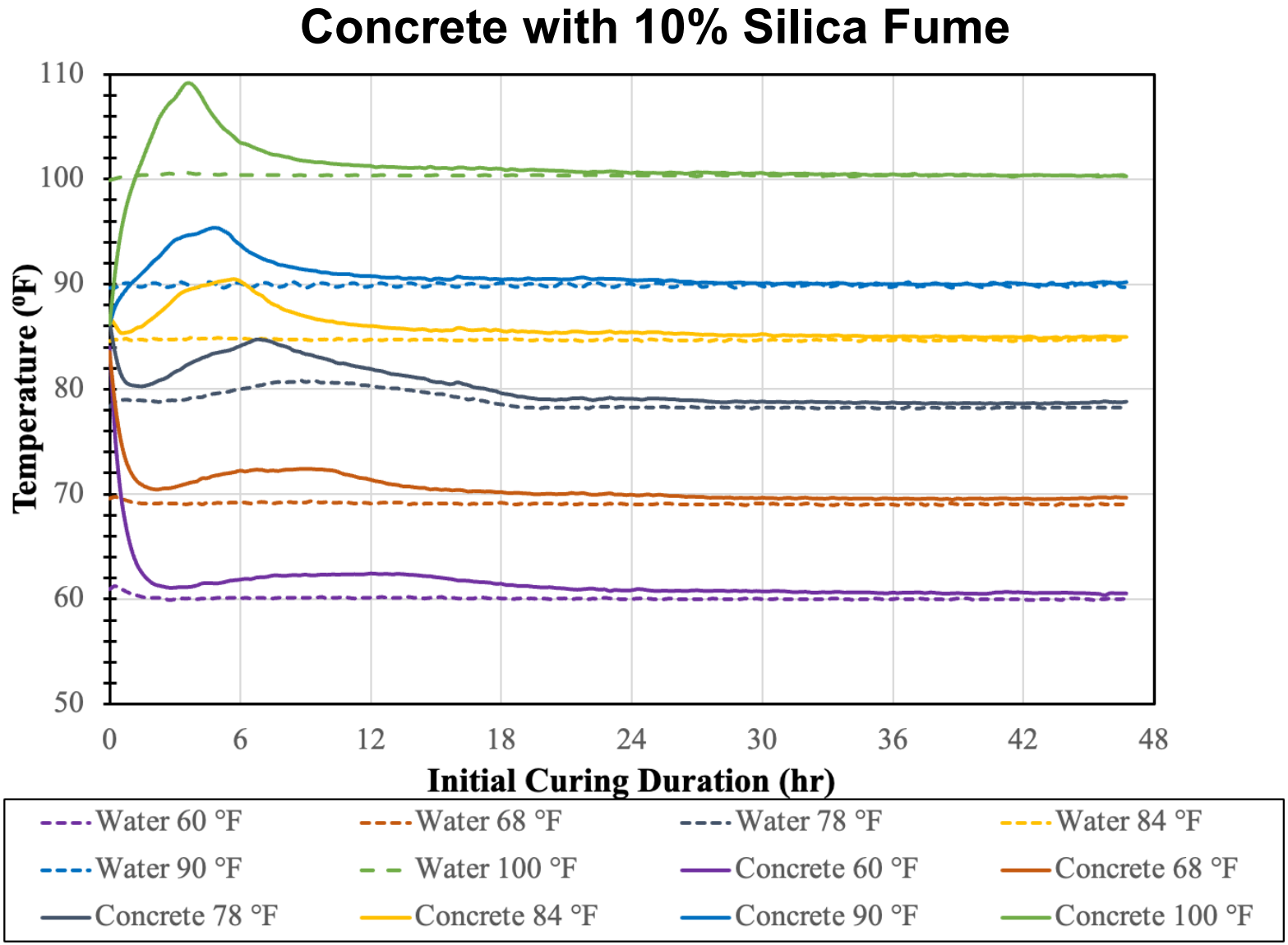
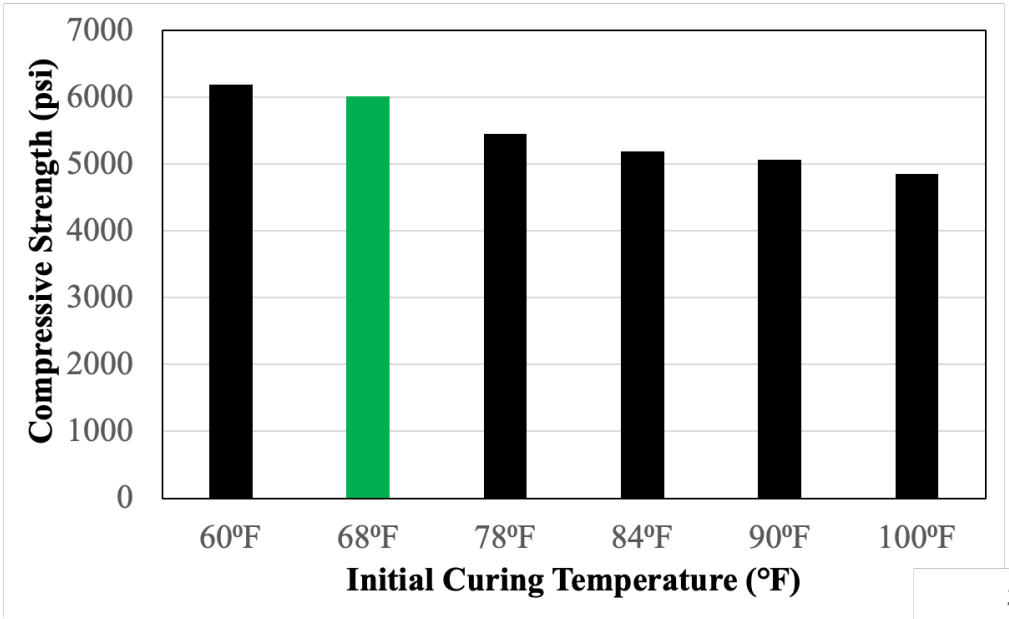
Typical Temperature Development

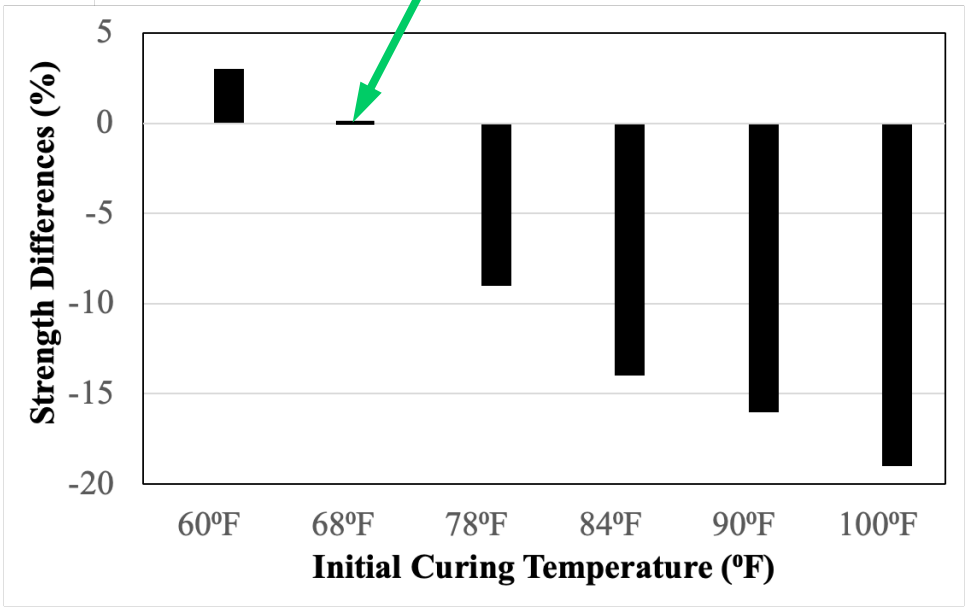


Example Strength Results: 100% PCC

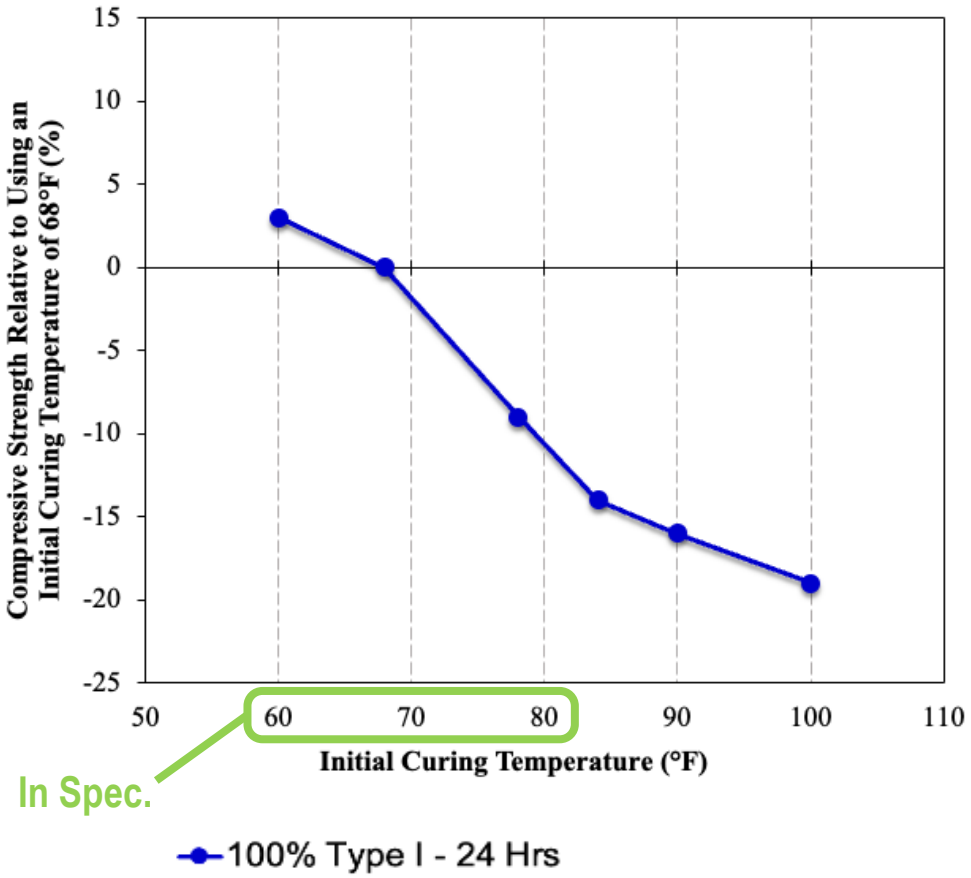


Initial Curing = 24 hrs

0% Strength Difference at 68 °F



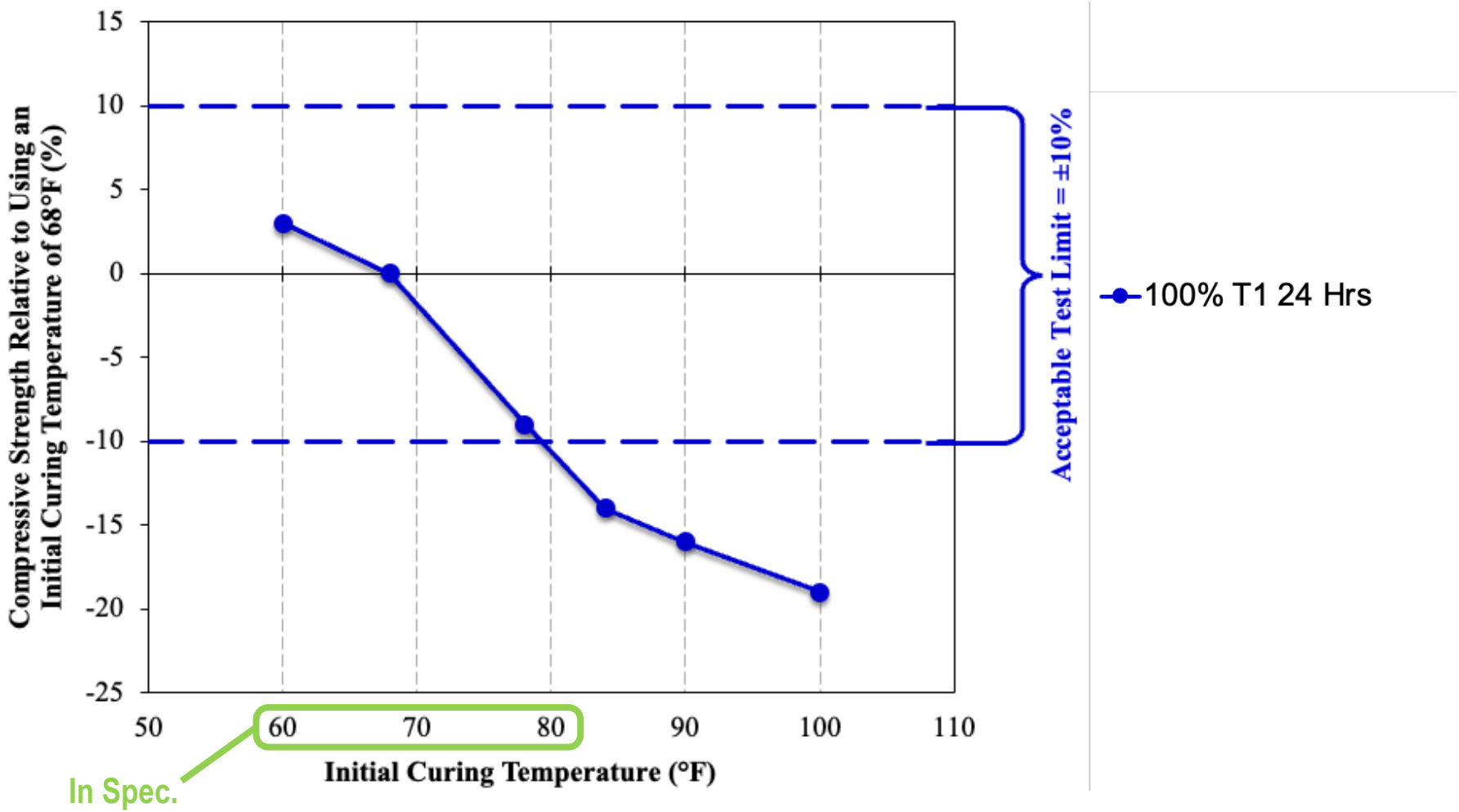
Comparison of 28-Day Strengths



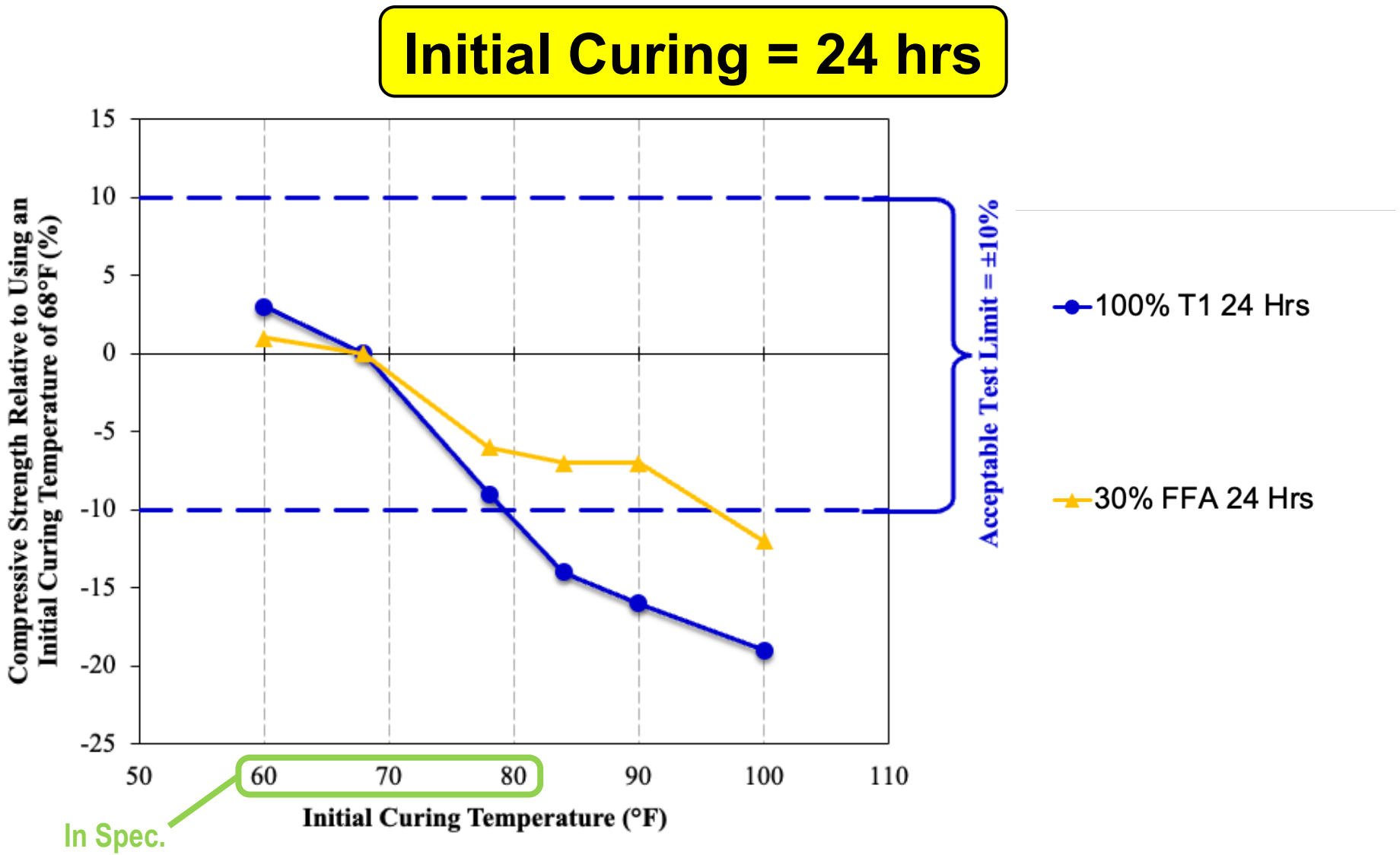
- What is an acceptable limit for strength differences?
- AASHTO T22 (2022) limit for three laboratory cylinders tested by the same operator is **±7.8%**
- We have many cylinders cured at different initial curing temperatures and therefore a larger range should be used
- **±10% was determined as an acceptable limit**

24-Hour Initial Curing: Strength Differences

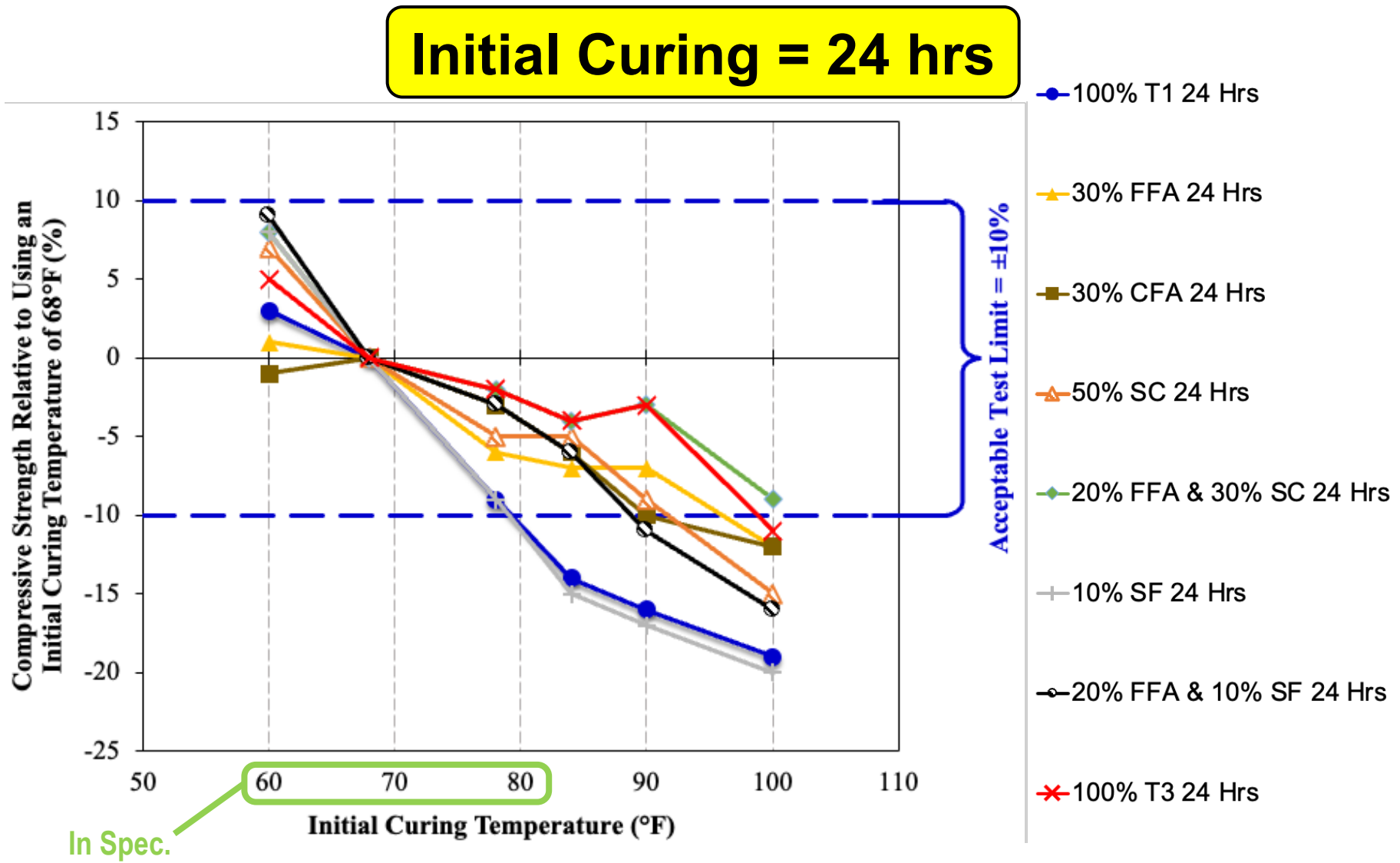
Initial Curing = 24 hrs



24-Hour Initial Curing: Strength Differences



24-Hour Initial Curing: Strength Differences



24-Hour Initial Curing: Strength Differences

	28-day Strength Differences				
Concrete Types	60 ºF	78 ºF	84 ºF	90 ºF	100 ºF
100% Type I Cement	3	-9	-14	-16	-19
30% FFA	1	-6	-7	-7	-12
30% CFA	-1	-3	-6	-10	-12
50% SC	7	-5	-5	-9	-15
10% SF	8	-9	-15	-17	**-20**
20% FFA & 30% SC	8	-2	-4	-3	-9
20% FFA & 10% SF	9	-3	-6	-11	-16
100% Type III Cement	5	-2	-4	-3	-11

Within ±10%

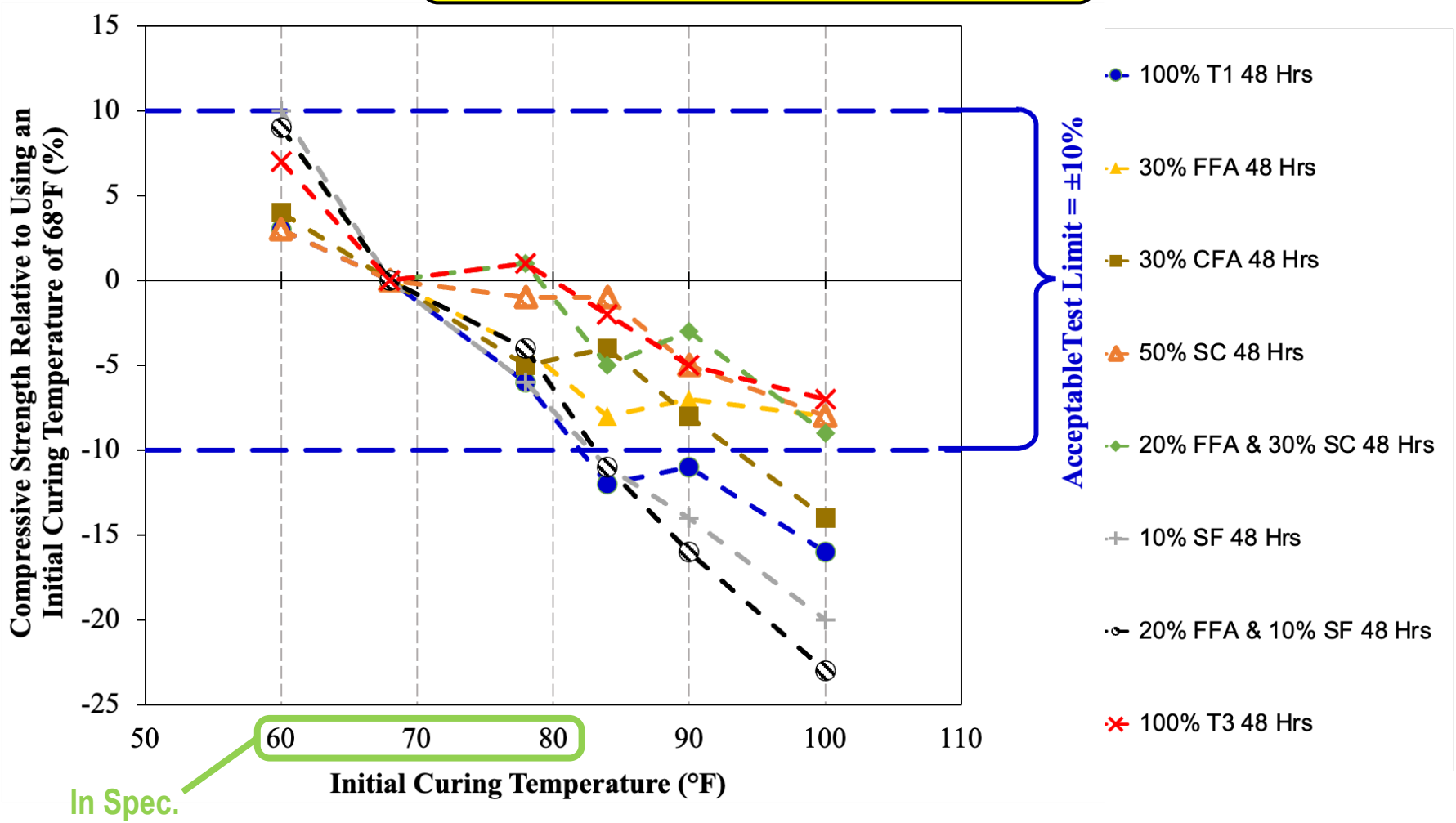
Outside ±10%

Initial curing temperature **within** specification

Initial curing temperature **out of** specification

48-Hour Initial Curing: Strength Differences

Initial Curing = 48 hrs



48-Hour Initial Curing: Strength Differences

	28-day Strength Differences				
Concrete Types	60 ºF	78 ºF	84 ºF	90 ºF	100 ºF
100% Type I Cement	3	-6	-12	-11	-16
30% FFA	4	-4	-8	-7	-8
30% CFA	4	-5	-4	-8	-14
50% SC	3	-1	-1	-5	-8
10% SF	10	-6	-11	-14	-20
20% FFA & 30% SC	9	1	-5	-3	-9
20% FFA & 10% SF	9	-4	-11	-16	**-23**
100% Type III Cement	7	1	-2	-5	-7

Within ±10%

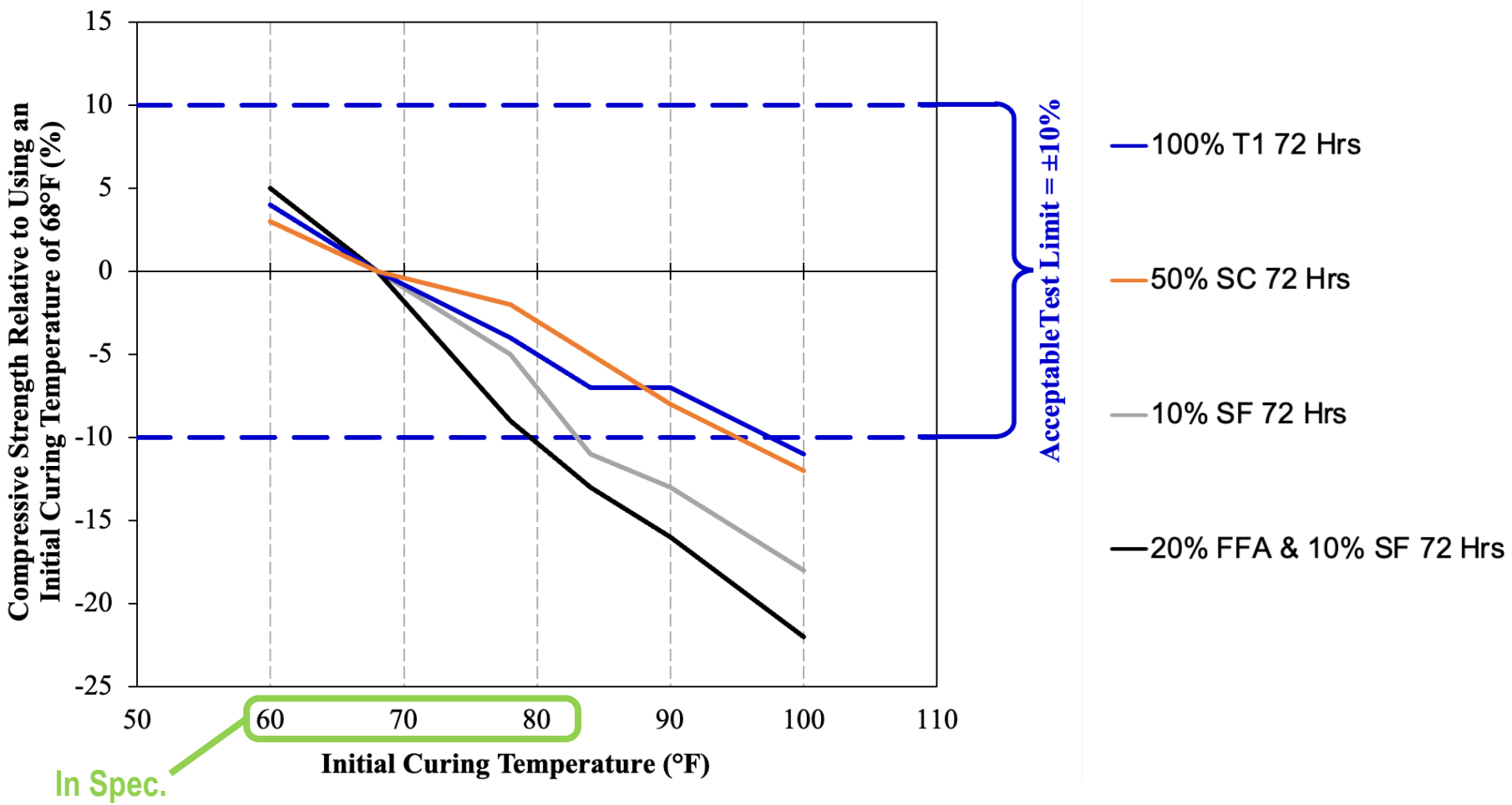
Outside ±10%

Initial curing temperature **within** specification

Initial curing temperature **out of** specification

72-Hour Initial Curing: Strength Differences

Initial Curing = 72 hrs



72-Hour Initial Curing: Strength Differences

Initial Curing = 72 hrs

	28-day Strength Differences				
Concrete Types	60 ºF	78 ºF	84 ºF	90 ºF	100 ºF
100% Type I Cement	4	-4	-7	-7	-11
50% SC	3	-2	-5	-8	-12
10% SF	3	-5	-11	-13	-18
20% FFA & 10% SF	5	-9	-13	-16	**-22**

Within ±10%

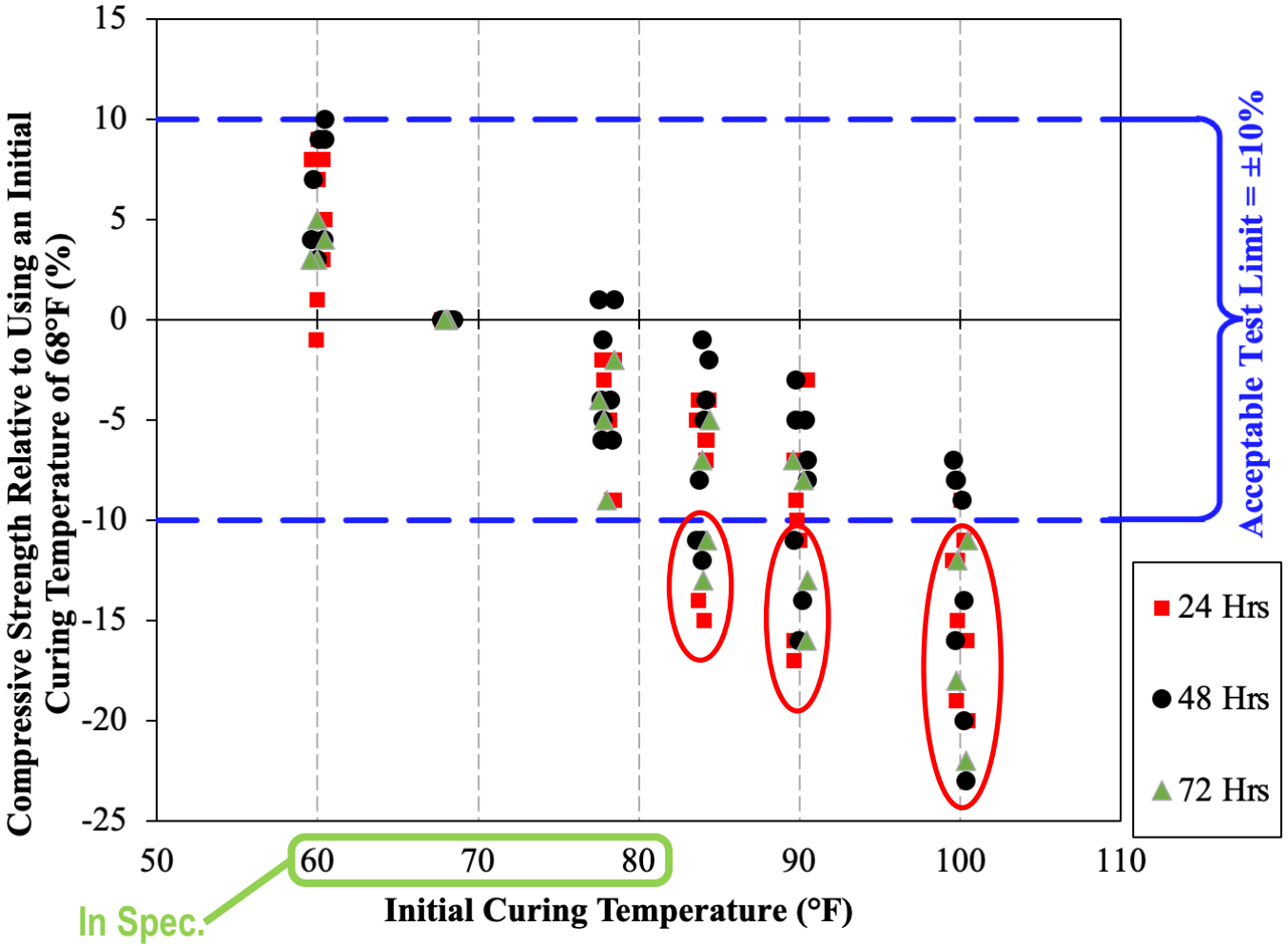
Outside ±10%

Initial curing temperature **within** specification

Initial curing temperature **out of** specification

All Initial Curing Durations

Initial Curing = 24, 48 and 72 hrs



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New ALDOT Specification Requirements

- Recommended changes to ALDOT 501

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 °F to 80 °F {16 °C to 27 °C} ~~, 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.

~~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 °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.~~

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

New ALDOT Specification Requirements

- **Initial Curing:**
  - The **60 to 80 ºF** range should remain unaltered in ALDOT 501 and this initial curing temperature should be **enforced**
  - The initial curing period can last for up to **72 hours**
  - Require the use of **temperature probes** to continuously record the water temperature in cylinder curing boxes

New ALDOT Specification Requirements

- **Cylinder Curing Box (Part 1 of 2):**
  - Provide **continuous power** (generator or wall power) for cylinder curing boxes
    - Without access to continuous power, the heating and cooling capabilities of the cylinder curing box become unavailable
    - Note that **fuel** must be provided for the **generator** to make sure it runs for the entire initial curing period

New ALDOT Specification Requirements

- **Cylinder Curing Box (Part 2 of 2):**
  - Cylinder curing boxes should include a **water circulation pump** to create a uniform water temperature throughout the cylinder curing box
  - The supporting surface on which the cylinders are stored should be level within 0.25 in./ft (20 mm/m), as specified in AASHTO T 23 (2018)

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Closing Comments

- **Conclusions from experimental work:**
  - When initial curing temperature remains between 60 to 80 °F, the change in 28-day strength remains within the acceptable limits
  - Once initial curing temperatures exceed 80 °F, the 28-day strength of many concretes (approximately half) were reduced by 10% or more
  - When the initial curing temperature was 100 °F a maximum strength loss of 23% (almost ¼ of the strength) was measured

Closing Comments

- **Conclusions from experimental work:**
  - **Initial Curing Duration:**

    When the initial curing temperature remains within 60 to 80 °F, then initial curing duration varying from 24 to **72 hours** do not significantly affect the 28-day strength
- **Recommendations**
  - Increase the maximum initial curing duration in ALDOT 501 from 48 to 72 hours
    - Cylinders made on a Friday and transported to the laboratory on Monday will now meet spec.

Closing Comments

Curing test specimens:

- Variation in standard curing of test specimens can significantly affect the measured strength
- **It is critical that <u>all</u> specified initial curing conditions are followed for cylinders**
  - Make sure concrete curing boxes are ready (including power demands) to stay within specified temperatures during the whole initial curing duration

References

- AASHTO T22. 2022. *Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens*. American Association of State Highway and Transportation Official. Washington, D.C.
- AASHTO T23. 2018. *Standard Method of Test for Making and Curing Concrete Specimens in the Field*. American Association of State Highway and Transportation Official. Washington, D.C.
- ALDOT Section 501. 2022. *Structural Portland Cement Concrete. Standard Specifications for Highway Construction Specification*. Alabama Department of Transportation. Montgomery, AL.
- Fleming, K.R. 2023. *Development of Jobsite Cylinder Curing Practices for the Alabama Concrete Industry*. M.S. Thesis, Auburn University, AL
- NRMCA. 2014. *Low Concrete Cylinder Strength*, CIP 9, National Ready Mixed Concrete Association, Silver Springs, Maryland
- Wade, S.A., A.K. Schindler, R.W. Barnes, and J.M. Nixon. 2006. *Evaluation of the Maturity Method to Estimate Concrete Strength*. ALDOT Project 930-590, Final Report, Highway Research Center, Auburn University, AL.

Acknowledgements

- **ALDOT Contributions:**
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  - **Construction Bureau:**
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  - Jackson White, M.S. Student
- **Alabama Concrete Industries Association:**
  - John Sorrell, ACIA Executive Director

Thank you for listening.

Questions are welcome !

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