Impact of Initial Curing of Cylinders on Concrete Strength

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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)

**Concrete Age**

**Curing Temperature (°F)**

- On Jobsite
  - Initial Curing
  - Transportation

- In Laboratory
  - Final Curing
    - Fog room or water tank

- Test

**Curing Temperature**

- 77°F
- 70°F

**Concrete Age**

- 0
- 24-48 hrs
- 28 days

(Not to scale)
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
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
  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.
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
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?

(Source: Wade et al., 2006)

Compressive Strength (psi) vs. Concrete Age (Hours) for Wet-cured cylinders with Alabama Type I Cement.

- Control Data (73°F)
- Cold Data (40 to 55°F)
- Hot Data (90 to 106°F)

Concrete Age (Hours):
- 0 hours
- 7 days (24 hours)
- 28 days (800 hours)

(2005-07-01)
Is an Insulated Cooler without Water Control Good Enough?

July 2022 in Alabama

Cylinder Curing Box with Power

Cylinder Curing Box without Power

Insulated Cooler with no Water

(Source: Fleming, M.S. Thesis, Auburn University, 2023)
Is an Insulated Cooler without Water Control Good Enough?

![Graph showing curing temperature over time.]

- **AASHTO T23: Maximum and Minimum**
- **Cylinder Curing Box with Power**
- **Cylinder Curing Box without Power**
- **Insulated Cooler with no Water**

28-Day Strength Loss:
- 22%
- 15%
- 0%

**Curing Temperature (°F)**

**Initial Curing Duration (hours)**

(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)
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)
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
Presentation Overview

- Introduction
- **Experimental Work**
- Review and Discussion of Results
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Advanced Structural Engineering Laboratory

Administration Wing

Concrete Lab (5,000 ft²)

High-bay Structures Lab (Vulcan Materials 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
  - 84 °F
  - 90 °F
  - 100 °F

- **3 Initial Curing Durations:**
  - 24 Hours
  - 48 Hours
  - 72 Hours

- **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

- 60°F
- 68°F
- 78°F
- 84°F
- 90°F
- 100°F
Experimental Work

Final Curing

73.5 ± 3.5 °F and 100% RH
Presentation Overview

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Typical Temperature Development

Concrete with 10% Silica Fume

Initial Curing Duration (hr)

Temperature (°F)

- Water 60 °F
- Water 68 °F
- Water 78 °F
- Water 84 °F
- Water 90 °F
- Water 100 °F
- Concrete 60 °F
- Concrete 68 °F
- Concrete 78 °F
- Concrete 84 °F
- Concrete 90 °F
- Concrete 100 °F
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

Compressive Strength Relative to Using an Initial Curing Temperature of 68°F (%)

Acceptable Test Limit = ±10%

100% T1 24 Hrs

In Spec.
24-Hour Initial Curing: Strength Differences

Initial Curing = 24 hrs

- Compressive Strength Relative to Using an Initial Curing Temperature of 68°F (%)
- Initial Curing Temperature (°F)
- Acceptable Test Limit = ±10%

100% T1 24 Hrs
30% FFA 24 Hrs

In Spec.
24-Hour Initial Curing: Strength Differences

Initial Curing = 24 hrs

Compressive Strength Relative to Using an Initial Curing Temperature of 68°F (%)

Acceptable Test Limit = ±10%

In Spec.
# 24-Hour Initial Curing: Strength Differences

<table>
<thead>
<tr>
<th>Concrete Types</th>
<th>60 °F</th>
<th>78 °F</th>
<th>84 °F</th>
<th>90 °F</th>
<th>100 °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Type I Cement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30% FFA</td>
<td>1</td>
<td>-6</td>
<td>-7</td>
<td>-7</td>
<td>-12</td>
</tr>
<tr>
<td>30% CFA</td>
<td>-1</td>
<td>-3</td>
<td>-6</td>
<td>-10</td>
<td>-12</td>
</tr>
<tr>
<td>50% SC</td>
<td>7</td>
<td>-5</td>
<td>-5</td>
<td>-9</td>
<td>-15</td>
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<tr>
<td>10% SF</td>
<td>8</td>
<td>-9</td>
<td>-15</td>
<td>-17</td>
<td>-20</td>
</tr>
<tr>
<td>20% FFA &amp; 30% SC</td>
<td>8</td>
<td>-2</td>
<td>-4</td>
<td>-3</td>
<td>-9</td>
</tr>
<tr>
<td>20% FFA &amp; 10% SF</td>
<td>9</td>
<td>-3</td>
<td>-6</td>
<td>-11</td>
<td>-16</td>
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<tr>
<td>100% Type III Cement</td>
<td>5</td>
<td>-2</td>
<td>-4</td>
<td>-3</td>
<td>-11</td>
</tr>
</tbody>
</table>

- **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

Compressive Strength Relative to Using an Initial Curing Temperature of 68°F (%) vs. Initial Curing Temperature (°F)

- 100% T1 48 Hrs
- 30% FFA 48 Hrs
- 30% CFA 48 Hrs
- 50% SC 48 Hrs
- 20% FFA & 30% SC 48 Hrs
- 10% SF 48 Hrs
- 20% FFA & 10% SF 48 Hrs
- 100% T3 48 Hrs

Acceptable Test Limit = ±10%

In Spec.
# 48-Hour Initial Curing: Strength Differences

## 28-day Strength Differences

<table>
<thead>
<tr>
<th>Concrete Types</th>
<th>60 °F</th>
<th>78 °F</th>
<th>84 °F</th>
<th>90 °F</th>
<th>100 °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Type I Cement</td>
<td>3</td>
<td>-6</td>
<td>-12</td>
<td>-11</td>
<td>-16</td>
</tr>
<tr>
<td>30% FFA</td>
<td>4</td>
<td>-4</td>
<td>-8</td>
<td>-7</td>
<td>-8</td>
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<tr>
<td>30% CFA</td>
<td>4</td>
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<tr>
<td>50% SC</td>
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<td>10% SF</td>
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<td>-20</td>
</tr>
<tr>
<td>20% FFA &amp; 30% SC</td>
<td>9</td>
<td>1</td>
<td>-5</td>
<td>-3</td>
<td>-9</td>
</tr>
<tr>
<td>20% FFA &amp; 10% SF</td>
<td>9</td>
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<td>-11</td>
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<td>-23</td>
</tr>
<tr>
<td>100% Type III Cement</td>
<td>7</td>
<td>1</td>
<td>-2</td>
<td>-5</td>
<td>-7</td>
</tr>
</tbody>
</table>

- **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

Compressive Strength Relative to Using an Initial Curing Temperature of 68°F (%)

- 50% SC 72 Hrs
- 100% T1 72 Hrs
- 10% SF 72 Hrs
- 20% FFA & 10% SF 72 Hrs

Acceptable Test Limit = ±10%

Initial Curing Temperature (°F)

In Spec.
# 72-Hour Initial Curing: Strength Differences

## Initial Curing = 72 hrs

<table>
<thead>
<tr>
<th>Concrete Types</th>
<th>60 °F</th>
<th>78 °F</th>
<th>84 °F</th>
<th>90 °F</th>
<th>100 °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Type I Cement</td>
<td>4</td>
<td>-4</td>
<td>-7</td>
<td>-7</td>
<td>-11</td>
</tr>
<tr>
<td>50% SC</td>
<td>3</td>
<td>-2</td>
<td>-5</td>
<td>-8</td>
<td>-12</td>
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<tr>
<td>10% SF</td>
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<td>5</td>
<td>-9</td>
<td>-13</td>
<td>-16</td>
<td>-22</td>
</tr>
</tbody>
</table>

**28-day Strength Differences**

- **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

Acceptable Test Limit = ±10%

In Spec.
Presentation Overview

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- Closing Comments
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 admixtures shall be accepted on the basis of requirements currently listed in the Department’s Testing Manual.

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 all concrete test cylinders produced, without extra compensation, a test specimen for all concrete test cylinders produced for use in concrete placed under this Section. This specimen shall be stored at a temperature of 50°F ± 10°F and in a moisture atmosphere of 100% RH.

The testing environment shall be capable of protecting all specimens within the following specific requirements and shall be the condition in which the cylinder curing box shall be started.

A temperature record of the specimen shall be established: The Contractor shall be responsible for providing means of maximum/minimum (high/low) thermometers at 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 testing 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 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.

A temperature record of the specimen shall be established: The Contractor shall be responsible for providing means of maximum/minimum (high/low) thermometers at 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 testing 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 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.

Upon arrival at the laboratory, the cylinders shall be removed from molds and placed in concrete curing boxes that are maintained at a temperature of 50°F ± 10°F and in a moist atmosphere of 100% RH.

*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 °F** 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.
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
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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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.
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 all 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

- NRMCA. 2014. *Low Concrete Cylinder Strength*, CIP 9, National Ready Mixed Concrete Association, Silver Springs, Maryland
Acknowledgements

◆ **ALDOT Contributions:**
  ◆ **Materials and Tests 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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