Evaluation of In-Place Concrete Strength by Core Testing

By: Anton Schindler, PhD, PE, FACI
Co-authors: Adam Carroll, MS Student
Aaron Grubbs, MS Student
Robert Barnes, PhD, PE, FACI

Presentation Overview

- **Introduction**
- Background
- Experimental Work and Results
- Closing Remarks

Quality Assurance Cylinders

- Cylinders made from concrete delivered to site, made and cured in accordance with AASHTO T23, and tested at 28 days:
  - **First 24 to 48 hrs:**
    - $f'_c < 6,000$ psi, then cured at 60 to 80 °F
  - **After 48 hrs:** Moist-cured between 73 ± 3°F
  - **PURPOSE:** Provide an indication of the strength (quality) of the concrete delivered to the construction site

Quality Assurance Cylinders

- Controlled Temperature = 73°F
- Controlled Moisture ≥ 95%
- Size = 6×12 in.
- Standard Age = 28 days

In-Place Structure

- Temperature = Varies
- Moisture for curing = Varies
- Size = Much larger
- Testing Age = > 28 days

Concrete Core Testing: AASHTO T24

1. Wipe surface and allow surface to dry and bag ≤ 60 min.
2. Keep in plastic bags for 5 to 7 days

Acknowledgements: ALDOT Prj 930-828

- **ALDOT Contributions:**
  - **Bridge Bureau:** Tim Colquett and Berhanu Woldemichael
  - **Construction Bureau:** Skip Powe, Jeff Benefield, Brad Williams, Scott Overby, Chad Harris, John Lucas, and Buddy Black
  - **Materials and Test Bureau:** Scott George, Lyndi Blackburn, Sergio Rodriguez, and Drew Waldrop
  - **Research and Development Bureau:** Michelle Owens and Ron Johnson
Concrete Core Testing: AASHTO T24

Objectives

- **Primary Objective:**
  - Develop a procedure to evaluate core strength results obtained under various conditions

- **Secondary Objectives:**
  - Determine the relationship between strengths obtained from cores and standard-cured, molded cylinders
  - Quantify the effect of significant variables on core strength

**f_{core} = ? \text{ psi}**

**Current ALDOT Practice**

- Accept with 100% pay when core strength $\geq 100\%$ of $f'_c$
- Apply price adjustment when core strength $\geq 85\%$ of $f'_c$ but $< 100\%$ of $f'_c$
- Reject in-place concrete represented by low core strength if the average core strength $< 85\%$ of $f'_c$

**ACI 318 Practice**

- ACI 318 recommends accepting in-place concrete when:
  - Average core strength is $\geq 85\%$ of $f'_c$ and
  - No single core strength (of 3 cores) is $< 75\%$ of $f'_c$

- There is thus a significant difference in the way core strength results are evaluated by ALDOT as compared to ACI 318

**Presentation Overview**

- Introduction
- **Background**
- Experimental Work and Results
- Closing Remarks

**Variables Affecting Concrete Strength**

- Concrete age
- Microcracking
- Moisture for curing
- Core orientation relative to concrete casting direction
- Core diameter
- Length-to-diameter ratio
- Concrete proportions
- Core moisture conditioning
- Temperature effects

*Not covered today*
Effect of Concrete Age

- With moisture available, hydration continues with age, so strength increases with age.
- Cores are most often extracted after low 28-day cylinder compression strengths.
- Typical core age ≈ 42 to 365 days.
  - Are cores tested at 42 and 365 days equally acceptable if they have similar strength?
- ALDOT currently uses no age adjustment factor to adjust core strengths, but other states like Florida account for age.

Effect of Concrete Age

- FDOT (2010) strength adjustment functions:
  - Obtained by testing standard-cured, molded cylinders?
  - Note: FDOT has 9 different functions for different cementitious materials (fly ash and slag cement).

Effect of Concrete Age

- ACI 209 (2008): $f_c(t) = f_{28} \left(1 + \frac{t}{a + b \cdot t}\right)$

Microcracking

- Concrete exposed to drying and thermal changes will develop many internal microcracks.
- Typical structure of the transition zone between the cement paste and aggregate:
  1) Aggregate Surface
  2) Cement Paste
  3) Voids
  4) Calcium Hydroxide
  5) Microcracks

Effect of Microcracking

- Microcracking is significantly increased in concrete that is restrained against movement.
  - Standard-cured, molded cylinders are free to contract and are moist cured → little microcracking.
  - The presence of microcracks in in-place concrete is one of the primary reasons why core strength results are generally less than results obtained from standard-cured, molded cylinders.

Effect of Availability of Curing Moisture

- The less moisture available, the lower the strength.

Effect of Availability of Curing Moisture

- The less moisture available, the lower the strength.

Microcracking

- Concrete exposed to drying and thermal changes will develop many internal microcracks.
- Typical structure of the transition zone between the cement paste and aggregate:
  1) Aggregate Surface
  2) Cement Paste
  3) Voids
  4) Calcium Hydroxide
  5) Microcracks

Effect of Microcracking

- Microcracking is significantly increased in concrete that is restrained against movement.
  - Standard-cured, molded cylinders are free to contract and are moist cured → little microcracking.
  - The presence of microcracks in in-place concrete is one of the primary reasons why core strength results are generally less than results obtained from standard-cured, molded cylinders.
Casting Direction

- Decks and drilled shafts are generally cored **parallel** (Core A) to the casting direction.
- Walls and columns are generally cored **perpendicular** (Core B) to the casting direction.

Effect of Core Orientation

**Parallel vs. Perpendicular to Casting Direction**

<table>
<thead>
<tr>
<th>Source of Data</th>
<th>Suggested Strength Difference for Perpendicular Cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bloem (1968)</td>
<td>1.18</td>
</tr>
<tr>
<td>Peterson (1964)</td>
<td>1.12</td>
</tr>
<tr>
<td>Meininger (1968)</td>
<td>1.10</td>
</tr>
<tr>
<td>Graham (1969a) and Graham (1969b)</td>
<td>1.07-1.09</td>
</tr>
<tr>
<td>Johnston (1973)</td>
<td>1.08</td>
</tr>
<tr>
<td>Munday and Dhv (1989)</td>
<td>1.08</td>
</tr>
<tr>
<td>Yip and Tam (1988)</td>
<td>1.04-1.08</td>
</tr>
<tr>
<td>Khoury (2014)</td>
<td>1.075</td>
</tr>
<tr>
<td>Bartlett and MacGregor (1994d)*</td>
<td>None</td>
</tr>
<tr>
<td>ACI 214 (2010)*</td>
<td>None</td>
</tr>
<tr>
<td>Bungey (1979)</td>
<td>None</td>
</tr>
</tbody>
</table>

*Literature states perpendicular cores may be weaker but do not specify a correction factor.

Presentation Overview

- Introduction
- Background
- **Experimental Work and Results**
- Closing Remarks

Experimental Work — Phase A: Field work

**Overview:**
- Eight full-scale slabs: 15 ft x 15 ft x 9½ in.
- Used 4 in. diameter cores with \(L/D = 2.0\)
- Compare core strengths to 6” x 12” standard-cured, molded-cylinder strengths
- Test all specimens at 28, 42, 91 and 365 days, with all cores recovered 7 days before testing
- Cores were recovered from **interior** and **exterior** zones to evaluate the effects of restraint on microcracking
Slab Elevation View

**Experimental Work — Phase A: Field work**

Effect of Restraint:

- **Exterior Zone**
- **Interior Zone**

- Least Microcracking and Highest Strength
- Most Microcracking and Lowest Strength
- Least Restraint to Movement
- Most Restraint to Movement

Full-Scale Slabs (15 ft x 15 ft x 9.5 in.):

Plan View (Not to scale)

- 28-Day Quadrant
- 42-Day Quadrant
- 91-Day Quadrant
- 365-Day Quadrant

Legend:

- ✔ Core location

**Experimental Work — Phase A: Field work**

- **6×12 in. Molded Cylinders:**
  - Made on site, and initially cured on job site in temperature controlled field-curing tanks
  - Final cure in laboratory

Initial Curing on Job Site

Transportation to Lab

**Experimental Work — Phase A: Field work**

- **Curing of Slabs**
  - **0 to 7 days:** Used wet burlap, soaker hoses with timer, and plastic sheets
  - **After 7 Days:** Concrete exposed to environment

- **Legend:**
  - ✔ Core location

**Experimental Work — Phase A: Field work**

Table: Types of Concrete Produced

<table>
<thead>
<tr>
<th>Slab Number</th>
<th>Strength</th>
<th>Type of Cementitious Material</th>
<th>Aggregate Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4,000 psi</td>
<td>100% PC</td>
<td>River Gravel</td>
</tr>
<tr>
<td>2</td>
<td>4,000 psi</td>
<td>100% PC</td>
<td>Limestone</td>
</tr>
<tr>
<td>3</td>
<td>4,000 psi</td>
<td>100% PC</td>
<td>Granite</td>
</tr>
<tr>
<td>4</td>
<td>4,000 psi</td>
<td>80% PC, and 20% Class C FA</td>
<td>River Gravel</td>
</tr>
<tr>
<td>5</td>
<td>4,000 psi</td>
<td>80% PC, and 20% Class F FA</td>
<td>River Gravel</td>
</tr>
<tr>
<td>6</td>
<td>4,000 psi</td>
<td>50% PC and 50% Slag</td>
<td>River Gravel</td>
</tr>
<tr>
<td>7</td>
<td>8,000 psi</td>
<td>100% PC</td>
<td>River Gravel</td>
</tr>
<tr>
<td>8</td>
<td>8,000 psi</td>
<td>100% PC</td>
<td>Limestone</td>
</tr>
</tbody>
</table>

Notes: PC=Portland Cement, FA=Fly Ash, and Slag = Slag Cement
All aggregates were a No. 67 gradation
Concrete was delivered to site in one 9 yd³ load per slab by ready-mixed concrete truck

**Results: Exterior versus Interior Cores**

- Level of restraint (microcracking) impacted the results

- Cores from exterior zone are stronger!
Results: Cores vs. Molded Cylinders

- Paired t-test used to determine if there is a statistical difference between interior and exterior core and cylinder strength

<table>
<thead>
<tr>
<th>Test Type</th>
<th>P-value from t-test*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior Cores vs.</td>
<td>0.002 (≤ 0.05)</td>
</tr>
<tr>
<td>6x12 in. Molded Cylinders</td>
<td></td>
</tr>
<tr>
<td>Interior Cores vs.</td>
<td>0.00004 (≤ 0.05)</td>
</tr>
<tr>
<td>6x12 in. Molded Cylinders</td>
<td></td>
</tr>
</tbody>
</table>

* At a 95% confidence level, a P-value ≤ 0.05 indicates a statistically significant difference between two variables

---

Experimental Work — Phase A: Field work

Implementation Recommendation:

- Core versus cylinder strength
  - Exterior cores were 89% of cylinder strength
  - Interior cores were 87% of cylinder strength

Use ACI 318’s standard 0.85 factor as multiplier with the specified design strength ($f'c$) to determine the average strength that cores must equal or exceed for the in-place concrete to be considered structurally adequate.

---

Effect of Concrete Age

- FDOT (2010) uses age adjustment factors based on testing standard-cured, molded cylinders:

$$ y = 0.871x \\ R^2 = 0.850 $$

**Results compare well with 0.85 of ACI 318**
Strength Gain: All Cores vs. Cylinders

Effect of age is well quantified by ACI 209

Use ACI 209 to adjust for concrete age

Effect of age is well quantified by ACI 209

A statistical analysis showed that the cementitious material type DID NOT impact the in-place strength gain

Strength Gain: Estimated with ACI 209

Experimental Work — Phase A: Field work

Implementation Recommendation:

- **Effect of concrete age on in-place strength**
  - The expression in ACI 209 provided reasonably accurate estimates of the effect of age on in-place strength development
  - ALDOT should consider using the following:

\[
 f_c(t) = f_c(28) \left( 1 + \frac{t}{t_{crit}} \right) 
\]

where, 

\[
 f_c(28) = \text{28-day core strength (psi)} \\
 f_c(t) = \text{core strength at age } t \text{ (psi)} \\
 t = \text{concrete age (days)} 
\]

Experimental Work — Phase B: Lab Work

Overview:

- Assess effect of casting direction on strength?
  - Parallel versus perpendicular
- Additional variables studied, but not covered today:
  - Assess L/D strength correction factors for concrete with strengths > 6,000psi
  - Test 6,000, 8,000, and 10,000 psi concrete
  - Effect of core diameter on strength?
    - 3 versus 4 in. diameter cores

Experimental Work — Phase B: Lab Work

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range Evaluated</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Concrete Batches</td>
<td>12 total batches</td>
</tr>
<tr>
<td>Concrete Strength</td>
<td>6,000 psi</td>
</tr>
<tr>
<td></td>
<td>8,000 psi</td>
</tr>
<tr>
<td></td>
<td>10,000 psi</td>
</tr>
<tr>
<td>Size of Coarse Aggregate</td>
<td></td>
</tr>
<tr>
<td>(Limestone)</td>
<td>No. 67 (NMSA = 0.75 in.)</td>
</tr>
<tr>
<td>Length-to-Diameter Ratio</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
</tr>
<tr>
<td>Core Diameter</td>
<td>3 in.</td>
</tr>
<tr>
<td></td>
<td>4 in.</td>
</tr>
<tr>
<td>Direction of Drilling</td>
<td>Parallel</td>
</tr>
<tr>
<td></td>
<td>Perpendicular</td>
</tr>
</tbody>
</table>

- Full-scale slab and wall specimens cast in laboratory
- 2.5 yd³ ready-mixed concrete delivered

Casting Direction

Wall (40 x 72 x 9.5 in.)
Experimental Work — Phase B: Lab Work

Coring Parallel to Casting Direction:

Coring Perpendicular to Casting Direction:

Core Drilling Orientation

Parallel vs. Perpendicular to cast direction

Parallel vs. Perpendicular

Average Strength Correction factor = 1.04

Presentation Overview

- Introduction
- Background
- Experimental Work and Results
- Closing Remarks

Recommendations

Acceptable Core Strength:

- Cores were found to be statistically weaker than molded, moist-cured cylinders
- An average equivalent 28-day core strength of 85% of the specified design strength (f') should be accepted as having adequate strength
  - This approach matches that of ACI 318
Recommendations

Effect of Core Age on Strength:

- The ACI 209 expression for Type I Cement provided reasonably accurate estimates of the effect of age on in-place strength development.
- ALDOT should consider using:

\[ f_{c,28} = f_c(t) \left( \frac{4 + 0.85t}{t} \right) \]

where, \( f_{c,28} \) = 28-day core strength (psi) 
\( f_c \) = core strength at age \( t \) (psi) 
\( t \) = concrete age (days)

Effect of Drilling Orientation on Strength:

- The apparent strength of cores recovered parallel from the casting direction is higher than those recovered perpendicular to the casting direction.
- If a core is drilled perpendicular to the casting direction, a correction factor of 1.04 is recommended.

---

Thank you for listening.
Questions are welcome!

By: Anton Schindler, PhD, PE, FACI
Co-authors:
Adam Carroll, MS Student
Aaron Grubbs, MS Student
Robert Barnes, PhD, PE, FACI

Effect of Core Age on Strength:

\[ F_{age} = \left( \frac{4.1 + 0.85t}{t} \right) \]

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>( F_{age} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>1.00</td>
</tr>
<tr>
<td>30</td>
<td>0.99</td>
</tr>
<tr>
<td>32</td>
<td>0.98</td>
</tr>
<tr>
<td>34</td>
<td>0.97</td>
</tr>
<tr>
<td>36</td>
<td>0.96</td>
</tr>
<tr>
<td>38</td>
<td>0.96</td>
</tr>
<tr>
<td>40</td>
<td>0.95</td>
</tr>
<tr>
<td>42</td>
<td>0.95</td>
</tr>
<tr>
<td>44</td>
<td>0.94</td>
</tr>
<tr>
<td>46</td>
<td>0.94</td>
</tr>
<tr>
<td>48</td>
<td>0.94</td>
</tr>
<tr>
<td>50</td>
<td>0.93</td>
</tr>
<tr>
<td>55</td>
<td>0.92</td>
</tr>
<tr>
<td>60</td>
<td>0.92</td>
</tr>
<tr>
<td>65</td>
<td>0.91</td>
</tr>
<tr>
<td>70</td>
<td>0.91</td>
</tr>
<tr>
<td>75 to 90</td>
<td>0.90</td>
</tr>
<tr>
<td>95 to 115</td>
<td>0.89</td>
</tr>
<tr>
<td>120 to 160</td>
<td>0.88</td>
</tr>
<tr>
<td>165 to 270</td>
<td>0.87</td>
</tr>
<tr>
<td>275 to 365</td>
<td>0.86</td>
</tr>
</tbody>
</table>