Code and Standards Requirements For Acceptance Testing

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Purpose of Acceptance Testing

- Concrete supplied complies with specification
- Sampling and testing should comply with standards
  - 1 cu.ft. sample represents 10 cubic yards…
  - OR 150 cubic yards (depending on frequency)
- Improper procedures generate inaccurate results
  - Will cost someone
  - Will delay project
Scope of Testing

- Samples obtained in accordance with ASTM C172
  - Point of delivery from transportation unit (or mixer)
  - Other sampling methods should be defined
- Fresh Concrete tests
  - Slump or slump flow – tolerances in ASTM C94; ACI 117
  - Air content – tolerance ±1.5%
  - Temperature – limits in specifications
  - Density – typically no limits unless its lightweight concrete
- Strength specimens
  - Average of two 6x12 in or three 4x8 in cylindrical specimens
  - Standard cured in accordance with ASTM C31
  - Tested in accordance with ASTM C39 at 28 days or as per spec
Standard Curing vs. Field Curing

- Quality control
- Developing mixture proportions for strength requirements
- Acceptance testing for specified strength

- Removal of forms or shoring
- Minimum strength for post-tensioning
- Determine if structure can be put into service
- Adequacy of curing and protection
- Compare with standard cured or with other in-place tests
ACI Strength Acceptance Criteria

Test results - Should meet both criteria

1. Average of 3 consecutive \( \geq f'_{c} \)
2. Single test \( \geq (f'_{c} - 500) \)
   - For \( f'_{c} > 5000 \) psi – Single test \( \geq 0.9f'_{c} \)

Probability of failure < 1 in 100 (1%)
ACI 318-14 for Low Strength Results

- Avg 3 consecutive - less than $f'_{\text{c}}$
  - Increase strength level

- Single test - less than $(f'_{\text{c}} - 500)$
  - Increase strength level
  - Investigate low strength - structural safety
    - Reduced load carrying capacity of structure confirmed by calculations
    - Core tests
Field Cured Cylinders

- For evaluating protection and curing of structure (ACI 318)
  - Acceptable if field cured cylinders…
    > 85% of companion lab cured
  - Or
    > \( f'_c + 500 \) psi
- Also used for formwork removal, post-tensioning
Requirements for Laboratories

ACI 318

26.12—Concrete evaluation and acceptance

26.12.1 General

(b) The testing agency performing acceptance testing shall comply with ASTM C1077.

(c) Qualified field testing technicians shall perform tests on fresh concrete at the job site, prepare specimens for standard curing, prepare specimens for field curing, if required, and record the temperature of the fresh concrete when preparing specimens for strength tests.

(d) Qualified laboratory technicians shall perform required laboratory tests.

(e) All reports of acceptance tests shall be provided to the licensed design professional, contractor, concrete producer, and, if requested, to the owner and the building official.

ACI 301

1.6.1.1 Testing agencies—Agencies that perform required tests of concrete materials shall meet the requirements of ASTM C1077. Testing agencies that test or inspect placement of reinforcement shall meet the requirements of ASTM E329. Testing agencies shall be accepted by Architect/Engineer before performing testing or inspection.

1.6.3.1(c) Owner’s testing agency will report test and inspection results of Work to Owner, Architect/Engineer, Contractor, and concrete supplier within 7 days after tests and inspections are performed. Strength test reports will include location in Work where concrete represented by each test was deposited, date and time sample was obtained, and batch ticket number. Strength test reports will include information on storage and curing of specimens before testing.
Quality Assurance

Testing Lab conducting QA testing

- Conformance to ASTM C1077
  - Inspected
  - Accredited
- Technicians Certified
  - Field Testing
  - Strength Testing
  - Lab Testing
- Testing in accordance with ASTM or AASHTO
- Timely distribution of test reports to all parties
Laboratories – ASTM C1077

Quality System
- Written manual
- Under direction of PE
- Personnel evaluation
- Equipment calibration
- Inventory control
- Participation in proficiency sample program
- Laboratory inspection and accreditation
Factors Affecting Strength

Review of Variables that Influence Measured Concrete Compressive Strength

By David N. Richardson

TABLE 1. Measured Strength Reduction by Nonstandard Conditions

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

Reason (Average strength reduction)
  • Initial curing (30%)
  • Damaging “green” specimens (18%)
  • Filling in one layer (17%)
  • From chute / no tapping (12%)
  • Top etching / no lids (11%)

Adapted from Snell
Frequent violations - Testing
Acceptance of concrete

ACI 318 Section 26.12.3.1

(a) Specimens for acceptance tests shall be in accordance with (1) and (2):

(1) Sampling of concrete for strength test specimens shall be in accordance with ASTM C172.
(2) Cylinders for strength tests shall be made and standard-cured in accordance with ASTM C31 and tested in accordance with ASTM C39.
Strength Test Specimens

Standard Curing - ASTM C31

- Maintain moisture
- Initial temperature in field
  - 60°F to 80°F
  - $f'_c > 6000$ psi - 68°F to 78°F
- Transport to lab within 48 hrs
- Transportation time 4 hrs or less
- Lab curing 73.5±3.5°F and moist
ASTM C31 Note 8 – Standard Curing

Satisfactory moisture environment

- Immerse in water
- Store in wooden boxes or structures
- Place in damp sand
- Cover with removable lids
- Place inside plastic bags
- Cover with plastic sheets or plates – with damp burlap
ASTM C31 Note 8 – Standard Curing

Satisfactory temperature environment

- Use of ventilation
- Use of ice
- Thermostatically controlled heating or cooling
- Heat, such as stoves or light bulbs

- Immersion in water may be easiest to control temperature
Violation of standard procedures

Initial Curing is most frequent problem
Field Observation

Properly stored in initial curing environment 1/3 of time

Field Examiner Summary Details
August, 2015*

<table>
<thead>
<tr>
<th>Contributing Companies</th>
<th>Number of Assessments August, 2015</th>
<th>Number of Assessments YTD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bestway Concrete</td>
<td>22</td>
<td>96</td>
</tr>
<tr>
<td>Martin Marietta</td>
<td>33</td>
<td>121</td>
</tr>
<tr>
<td>Ready Mixed Concrete Co.</td>
<td>9</td>
<td>26</td>
</tr>
<tr>
<td>Trans Colorado Concrete</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Transit Mix Concrete</td>
<td>8</td>
<td>33</td>
</tr>
<tr>
<td>United Companies</td>
<td>8</td>
<td>31</td>
</tr>
<tr>
<td>Aggregate Industries</td>
<td>7</td>
<td>18</td>
</tr>
<tr>
<td>Metro Mix Concrete</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Grand Junction Ready Mix</td>
<td>13</td>
<td>17</td>
</tr>
</tbody>
</table>

Average Score 9 (Properly stored in an initial curing environment)

34% 30%

the mixer truck discharge?
93% 81%
Initial Curing Options
Using Sand
Immerse in Water/Coolers

Add water (use ice if needed) and insert hi-low thermometer
Temperature Controlled
Effects of Initial Curing Hot Weather

Series D338 Concrete Strength - Hot Weather Exposure

- Standard Curing
- 48h out - moist
- Outside
- Avg daily temp

Age, days

Compressive Strength, psi

Avg. Daily Temp, F
Effects of Initial Curing Cold Weather

![Graph showing the effects of initial curing in cold weather.](image-url)
## Effects of Initial Curing

Importance of temperature and duration of initial curing on 28-day compressive strength

<table>
<thead>
<tr>
<th>Initial Curing (days)</th>
<th>Moist cured</th>
<th>1 day</th>
<th>3 days</th>
<th>14 days</th>
<th>28 days</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Relative Strength</strong></td>
<td>100% (5590 psi)</td>
<td>100%</td>
<td>92%</td>
<td>89%</td>
<td>73%</td>
</tr>
<tr>
<td><strong>Initial Curing Temp</strong></td>
<td></td>
<td>73°F</td>
<td>73°F</td>
<td>73°F</td>
<td>73°F</td>
</tr>
<tr>
<td>37°F</td>
<td></td>
<td>93%</td>
<td>89%</td>
<td>78%</td>
<td>73%</td>
</tr>
<tr>
<td>73°F</td>
<td></td>
<td>92%</td>
<td>89%</td>
<td>78%</td>
<td>73%</td>
</tr>
<tr>
<td>100°F</td>
<td></td>
<td>88%</td>
<td>78%</td>
<td>67%</td>
<td>62%</td>
</tr>
</tbody>
</table>

NRMCA Pub 53; Delmar L. Bloem, 1954
## Effects of Initial Curing

Importance of temperature and moisture during first 24 hours of initial curing – on 28-day compressive strength

<table>
<thead>
<tr>
<th>Condition (1 day initial curing)</th>
<th>Temp Range</th>
<th>Relative strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jobsite* – Curing box; in water</td>
<td>71 - 76°F</td>
<td>100%</td>
</tr>
<tr>
<td>Lab – immersed in water</td>
<td>73 - 82°F</td>
<td>100%</td>
</tr>
<tr>
<td>Lab – in air</td>
<td>78 - 82°F</td>
<td>88%</td>
</tr>
<tr>
<td>Jobsite* – not protected</td>
<td>71 - 107°F</td>
<td>85%</td>
</tr>
<tr>
<td>Jobsite* – covered with wet burlap</td>
<td>94 - 135°F</td>
<td>83%</td>
</tr>
</tbody>
</table>

* Cylinders were kept exposed to sunlight; thermometer shielded

Data from F. Kozeliski – New Mexico, 2016
## Effects of Initial Curing

Initial curing for 24 hours - Within limits of ASTM C31

<table>
<thead>
<tr>
<th>Condition</th>
<th>Relative Strength (28-day)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement A</td>
<td>Cement B</td>
</tr>
<tr>
<td>60°F in water</td>
<td>100% (6080 psi)</td>
<td>100% (6090 psi)</td>
</tr>
<tr>
<td>60°F in air</td>
<td>92%</td>
<td>97%</td>
</tr>
<tr>
<td>80°F in water</td>
<td>89%</td>
<td>93%</td>
</tr>
<tr>
<td>80°F in air</td>
<td>81%</td>
<td>88%</td>
</tr>
</tbody>
</table>

Both temperature limits and moisture provision matter

**Average Effect:**
- Water vs. Air: +6.6%
- 60°F vs. 80°F: +9.2%
- 60°F water vs. 80°F air: +16%

NRMCA study: Meininger, ASTM Cement Concrete & Aggregates, 1983
12. Report

12.1 Report the following information to the laboratory that will test the specimens:

12.1.1 Identification number,
12.1.2 Location of concrete represented by the samples,
12.1.3 Date, time and name of individual molding specimens,
12.1.4 Slump, air content, and concrete temperature, test results and results of any other tests on the fresh concrete and any deviations from referenced standard test methods, and
12.1.5 Curing method. For standard curing method, report the initial curing method with maximum and minimum temperatures and final curing method. For field curing method, report the location where stored, manner of protection from the elements, temperature and moisture environment, and time of removal from molds.
Statements in Laboratory Reports

- Molded to C-31 - Yes
- Initially Cured to ASTM C-31 - Unknown
- Cured & Tested in Lab to ASTM C-31 & C-39 - Yes

5. Concrete specimen cured in accordance with ASTM C-31 after being received in laboratory.

Cylinders molded to ASTM C-31 & lab cured/tested to ASTM C-31 & ASTM C-39.

2. Specimen(s) Prepared to ASTM C 31

Obtain samples of fresh concrete at the placement locations (ASTM C-172), perform required field tests and cast, cure, and test compressive strength samples (ASTM C-31, C-39, C-417).
Responsibilities for Testing

ACI 301

1.6.2 Quality control: Responsibilities of Contractor

1.6.2.2(b) Allow access to project site or to source of materials and assist Owner’s testing agency in obtaining and handling samples at project site or at source of materials.

1.6.2.2(d) Provide space and source of electrical power on project site for testing facilities acceptable to Owner’s testing agency. This is for the sole use of Owner’s quality assurance testing agency for initial curing of concrete strength test specimens as required by ASTM C31/C31M.
Responsibilities for Testing

ACI 301

1.6.3 Quality assurance: Duties and responsibilities of Owner’s testing agency

Sampled concrete used to mold strength test specimens (ASTM C31/C31M) will be tested for slump (ASTM C143/C143M), air content (ASTM C231/C231M or ASTM C173/C173M), temperature (ASTM C1064/C1064M), and density (ASTM C138/C138M).

1.6.3.2(e) Owner’s testing agency will conduct concrete strength tests by making and standard curing test specimens in accordance with ASTM C31/C31M and testing them according to ASTM C39/C39M. Unless otherwise specified, concrete strengths for acceptance shall be tested at 28 days.
Responsibilities for Testing

ACI 311.6-09 Specification for Ready Mixed Concrete Testing Services

2.5—Curing of strength test specimens

2.5.1 Initial curing—Owner or Owner’s representative will provide and maintain adequate facilities on the project site for initial storage and curing of the concrete specimens, unless otherwise specified. Specimens shall be stored under conditions that meet the requirements of ASTM C31 and shall be verified by Testing Agency. Such storage shall have temperature controls to maintain ASTM C31 temperature requirements. Calibrated temperature recording devices shall be used to record daily maximum and minimum temperatures of the initial curing environment.

2.5.2 Transportation—Testing Agency will recover and transport concrete specimens in accordance with ASTM C31.

2.5.3 Final curing—Final curing of strength test specimens shall be done in accordance with ASTM C31 and C511 until time of test.

3.3—Report information

Reports shall include accepted portions of 3.3.1 through 3.3.12, and information required by ASTM test methods referenced in Section 2.3:

3.3.1 Project name
3.3.2 Client name
3.3.3 Concrete supplier
3.3.4 Date and time of sampling and field testing
3.3.5 Dates that strength test specimens will be tested
3.3.6 Name of field and laboratory technicians and certification numbers
3.3.7 Delivery truck number, ticket, mixture designation, and locations of sampling
3.3.8 Results of air content, temperature, slump, and density (unit weight) tests
3.3.9 Specified compressive strength of concrete and the designated test age
3.3.10 Location of placement represented by the strength test specimens
3.3.11 Location of sampled concrete within the placement
3.3.12 Report maximum and minimum temperatures of the curing environment during the initial curing period
Review of a Test Report

- Reporting requirements of C31 and C39
- Dates – pour, cylinders made, rec’d at lab
- Ambient / concrete temperature
- Slump, air content, density
- Duration of initial curing
- Min / max temperatures
- Curing method
- 7 & 28 day strengths
  - Strength gain
# Compressive Strength of Concrete Test Specimens

**Project Name:**

**Project No.:**

**Project Location:**

**Client:**

**Project Contractor:**

**Concrete Supplier:**

**Cylinder Set No.:** 10938

### DESIGN DATA

- **Specified Strength:** 5000 p.s.i. @ 28 Days
- **Slump (inches):** 6
- **Air Content (percent):**
- **Mix Type:**
  - Normal w.t.
  - Lightweight
  - Mortar Mix
  - Granite
  - Grout
  - Other
- **Transit Mixed**
- **Pump Mixed**
- **Other**

### FIELD DATA

- **Date:** 9/12/13
- **Time Concrete Batched:** 11:04
- **Time Concrete Sampled:** 11:30
- **Sampled By:** DB
- **Concrete Truck No.:** 0480
- **Ticket No.:** 11043153
- **Size of Load (C.Y.):** 2
- **Slump (inches):** 5
- **Air Temperature (°F):** 89
- **Concrete Temperature (°F):** 92
- **Wet Weight (P.C.F.):**
- **Extra Water Added at Job Site:** Yes
  - If Yes, gallons To__ cy
- **Extra Water Authorized By:**
- **Weather Conditions:**

### LOCATION OF CONCRETE PLACEMENT:

- 3rd Level Column on south side of the Beam of line AY

### SPECIMEN DATA

<table>
<thead>
<tr>
<th>SPECIMEN I.D.</th>
<th>LAB NO.:</th>
<th>Date Received In Lab</th>
<th>Date Tested</th>
<th>Age (Days)</th>
<th>Test Specimen Size</th>
<th>Total Load (LBS.)</th>
<th>Test Strength (P.S.I.)</th>
<th>Type of Fracture</th>
<th>Specimen Weight (Air Dry LBS.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10938A</td>
<td></td>
<td>9/16/13</td>
<td>9/19/13</td>
<td>7</td>
<td>4.00</td>
<td>12.57</td>
<td>36400</td>
<td>2935</td>
<td></td>
</tr>
<tr>
<td>10938B</td>
<td></td>
<td>9/16/13</td>
<td>10/10/13</td>
<td>28</td>
<td>4.00</td>
<td>12.57</td>
<td></td>
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<tr>
<td>10938C</td>
<td></td>
<td>9/16/13</td>
<td>10/10/13</td>
<td>28</td>
<td>4.00</td>
<td>12.57</td>
<td></td>
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<td></td>
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<tr>
<td>10938D</td>
<td></td>
<td>9/16/13</td>
<td>11/7/13</td>
<td>56</td>
<td>4.00</td>
<td>12.57</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Transporting Hardened Cylinders

Variables:

- **Timing**
  - Up to 48 hrs, or
  - 8 hrs after final set
- **Duration of Travel**
  - 4 hours
- **Proper Cushioning**
- **Protect from Freezing**
- **Protect from Moisture Loss**
Evaluating Test Results

What do Standards Say

- Responsibilities
- Reporting
- Data evaluation
  - Precision
  - Rating test results
Testing variability (ACI 214R)

- Within-batch coefficient of Variation ($V_1$)
- Average range ($\bar{R}$) from 10 tests
- $\bar{X} =$ Average strength

$$s_1 = \frac{1}{d_2} \bar{R}$$

$$V_1 = \frac{s_1}{\bar{X}} \times 100$$

<table>
<thead>
<tr>
<th>No. Specimens</th>
<th>$d_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.128</td>
</tr>
<tr>
<td>3</td>
<td>1.693</td>
</tr>
<tr>
<td>4</td>
<td>2.059</td>
</tr>
</tbody>
</table>
## Example Calculation of $V_1$

<table>
<thead>
<tr>
<th>Cylinder 1, psi</th>
<th>Cylinder 2, psi</th>
<th>Strength Test Result, psi</th>
<th>Range, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>6740</td>
<td>7120</td>
<td>6930</td>
<td>380</td>
</tr>
<tr>
<td>7050</td>
<td>6750</td>
<td>6900</td>
<td>300</td>
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<tr>
<td>5640</td>
<td>5830</td>
<td>5735</td>
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<td>5570</td>
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<td>6030</td>
<td>5700</td>
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<td>330</td>
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<td>4650</td>
<td>5080</td>
<td>4865</td>
<td>430</td>
</tr>
<tr>
<td>5800</td>
<td>6080</td>
<td>5940</td>
<td>280</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>5837</strong></td>
<td><strong>207</strong></td>
</tr>
</tbody>
</table>

\[
s_1 = \frac{207}{1.128} = 184 \text{ psi}
\]

\[
V_1 = \frac{184}{5837} \times 100 = 3.2\%
\]
Within-batch precision

<table>
<thead>
<tr>
<th>Quality Standards (ACI 214)</th>
<th>Excellent</th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$, %</td>
<td>&lt; 3.0</td>
<td>3.0 to 4.0</td>
<td>4.0 to 5.0</td>
<td>5.0 to 6.0</td>
<td>&gt; 6.0</td>
</tr>
<tr>
<td>Average Range of 2 Companion Cylinders (assuming avg. 4800 psi)</td>
<td>&lt; 162</td>
<td>162 to 217</td>
<td>217 to 271</td>
<td>271 to 325</td>
<td>&gt; 325</td>
</tr>
</tbody>
</table>

- $V_1 > 6\%$ - reason to question testing
- $V_1$ between 4 and 6% - potential problems
- $V_1$ between 2 and 3% - C39 testing variation
- < 1.5% - likely too good to be true
ASTM C39 Single Operator precision

- Companion cylinders tested at same age
- Acceptable range should not be exceeded more often than 1 time in 20

<table>
<thead>
<tr>
<th>Cylinder Size (mm)</th>
<th>Laboratory Conditions</th>
<th>Field Conditions</th>
<th>Acceptable Range of Individual Cylinder Strengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 by 300 mm</td>
<td>2.4 %</td>
<td>2.9 %</td>
<td>6.6 %</td>
</tr>
<tr>
<td>[6 by 12 in.]</td>
<td></td>
<td></td>
<td>7.8 %</td>
</tr>
<tr>
<td>100 by 200 mm</td>
<td>3.2 %</td>
<td></td>
<td>9.0 %</td>
</tr>
<tr>
<td>[4 by 8 in.]</td>
<td></td>
<td></td>
<td>10.6 %</td>
</tr>
</tbody>
</table>
# Example Calculation within-batch Range

<table>
<thead>
<tr>
<th>Cylinder 1, psi</th>
<th>Cylinder 2, psi</th>
<th>Test Result, psi</th>
<th>Range, psi</th>
<th>Range, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>6740</td>
<td>7120</td>
<td>6930</td>
<td>380</td>
<td>5.5%</td>
</tr>
<tr>
<td>7050</td>
<td>6750</td>
<td>6900</td>
<td>300</td>
<td>4.3%</td>
</tr>
<tr>
<td>5640</td>
<td>5830</td>
<td>5735</td>
<td>190</td>
<td>3.3%</td>
</tr>
<tr>
<td>5570</td>
<td>5550</td>
<td>5560</td>
<td>20</td>
<td>0.4%</td>
</tr>
<tr>
<td>6030</td>
<td>5700</td>
<td>5865</td>
<td>330</td>
<td>5.6%</td>
</tr>
<tr>
<td>5690</td>
<td>5650</td>
<td>5670</td>
<td>40</td>
<td>0.7%</td>
</tr>
<tr>
<td>5530</td>
<td>5600</td>
<td>5565</td>
<td>70</td>
<td>1.3%</td>
</tr>
<tr>
<td>5350</td>
<td>5320</td>
<td>5335</td>
<td>30</td>
<td>0.6%</td>
</tr>
<tr>
<td>4650</td>
<td>5080</td>
<td>4865</td>
<td>430</td>
<td>8.8%</td>
</tr>
<tr>
<td>5800</td>
<td>6080</td>
<td>5940</td>
<td>280</td>
<td>4.7%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>5837</strong></td>
<td><strong>207</strong></td>
<td></td>
</tr>
</tbody>
</table>
## Example Calculation - within batch Range

<table>
<thead>
<tr>
<th>No.</th>
<th>Cylinder 1</th>
<th>Cylinder 2</th>
<th>Test Result</th>
<th>Within-batch range</th>
<th>Within-batch range, %</th>
<th>Moving Average of 10 Tests</th>
<th>Moving average of 10 Ranges</th>
<th>Moving 10 test $V_{1%}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4498</td>
<td>4254</td>
<td>4376</td>
<td>244</td>
<td>5.6%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4318</td>
<td>3842</td>
<td>4080</td>
<td>476</td>
<td>11.7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3782</td>
<td>3674</td>
<td>3728</td>
<td>108</td>
<td>2.9%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3527</td>
<td>3263</td>
<td>3395</td>
<td>264</td>
<td>7.8%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4571</td>
<td>3969</td>
<td>4270</td>
<td>602</td>
<td>14.1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>4543</td>
<td>5415</td>
<td>4979</td>
<td>872</td>
<td>17.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>3988</td>
<td>4172</td>
<td>4080</td>
<td>184</td>
<td>4.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>3361</td>
<td>3339</td>
<td>3350</td>
<td>22</td>
<td>0.7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>4831</td>
<td>4807</td>
<td>4819</td>
<td>24</td>
<td>0.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3411</td>
<td>3315</td>
<td>3363</td>
<td>96</td>
<td>2.9%</td>
<td>4044</td>
<td>289/(1.128X4044) =6.3%</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>3619</td>
<td>3913</td>
<td>3766</td>
<td>294</td>
<td>7.8%</td>
<td>3983</td>
<td>294</td>
<td>6.5%</td>
</tr>
<tr>
<td>12</td>
<td>3880</td>
<td>4082</td>
<td>3981</td>
<td>202</td>
<td>5.1%</td>
<td>3973</td>
<td>267</td>
<td>5.9%</td>
</tr>
</tbody>
</table>
Control Charts to Monitor Testing

![Graphs showing within-batch range and coefficient of variation over sample numbers.](image-url)
Evaluating Strength Data

- Poor job site curing will reduce strength
- But may not reflect within batch variation, $V_1$
ASTM C39 Multi-lab precision

- COV = 5%
- Acceptable difference between 2 = 14%
- Useful for companion testing
- Same sample tested by 2 labs at same age
  - Split samples (same wheelbarrow or same load)
Companion Tests

Company Data at plant; Lab data at jobsite

Specimens from the same sample are better to evaluate for multi-lab precision
Importance of Good Testing

Strength Standard Deviation (variability)
- Materials
- Production
- Testing

Components of variation are cumulative
Reducing Testing Variation helps isolate other causes of variation that the producer can control
What if you have Low Test Results?

NRMCA Pub 133

- Confirm likelihood of low strength
  - Verify testing accuracy
  - Non destructive tests
- Structural capacity reduced (Engineer decision)?
  - Core tests
  - Load tests
  - Corrective measures

Establish responsibility (monetary) for low strength evaluations (pre-construction)
Testing Concrete Cores

ACI 318 criteria:

• Average of 3 cores $\geq 0.85 f'_{c}$
• Individual core $\geq 0.75 f'_{c}$
Summary

- **ACI Standards (Code and Specification)**
  - Defines acceptance criteria for strength test results
  - Laboratories should conform to ASTM C1077
  - Technicians in the field and lab should be certified
  - Initial curing in accordance with ASTM C31
    - Max-min temps and curing method must be recorded (and reported)
  - Test reports should be distributed to all stakeholders
  - Criteria for core tests are defined

- **Testing variation is high when**
  - $V_1 > 4\%$ (from last 10 data points)
  - Range $> 8\%$ (or C39) more than 1-in-20

- **Responsibility for low strength evaluation should be defined**
Thank You!

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