Testing for Concrete Strength

• Quality control and acceptance testing
  - Standardized curing conditions
  - Indicator of potential strength
  - Code compliance

• In-place strength
  - Investigate low test results for standard-cured specimens (cylinders or cubes)
  - Determine if constructions loads can be applied
  - Evaluate existing structures
In-Place Strength

• Evaluation of in-place strength
  ➢ Testing cores
  ➢ Rebound hammer
  ➢ Pullout test
  ➢ Pull-off test
  ➢ Case studies
  ➢ Maturity method
Obtaining and Testing Cores
ASTM and ACI Approaches

• Planning
• Apparatus
• Core dimensions
• Moisture conditioning
• End preparation and L/D correction
• Precision
• In-place characteristic strength (ACI 214.4R)
Why Take Cores?

- Investigate low test results from standard-cured specimens
- Develop correlation with other in-place or nondestructive (NDT) tests
- Confirm interpretation of NDT methods
- Obtain samples for petrographic analysis
- Estimate the in-place “specified strength” for structural evaluations
How Many Cores?

• Will depend on the objective
• For investigating low standard-cured test results, ACI 318 (design standard) requires at least three for “area in question”
• For estimating the equivalent in-place specified strength, a larger number is required, depending on:
  - Variability of in-place strength
  - Desired confidence level
Where to Take Cores?

• Depends on objective
• For evaluating low standard-cured test results, take cores from concrete represented by the low test results
• Forensic investigations:
  - Depends on uniformity of concrete in the structure (ASTM C823/C823M)
• Avoid taking cores from top of placement (inferior properties)
Standard Practice for Examination and Sampling of Hardened Concrete in Constructions\footnote{This standard has been approved for use by agencies of the Department of Defense.}

This standard is issued under the fixed designation C823/C823M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice outlines procedures for visual examination and sampling of hardened concrete in constructions. Reference is made to the examination and sampling of concrete in prefabricated building units, precast products, and laboratory specimens.

1.2 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.
ASTM C823/C823M—Sampling

- **Concrete in structure is similar**
  - Sampling locations spread randomly or systematically over the entire structure
  - Treat data as belonging to same population
- **Concrete in two or more portions likely to have different properties**
  - Sample from each portion
  - Use statistical methods to establish if there are differences in properties
Standard Test Method for
Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

This standard is issued under the fixed designation C42/C42M; the number immediately following the designation indicates the year of

NOTE 1—Test Method C1604/C1604M is applicable for obtaining, preparing, and testing cores from shotcrete.

NOTE 2—Appendix X1 provides recommendations for obtaining and testing sawed beams for flexural performance.

1. Scope

1.1 This test method covers obtaining, preparing, and testing cores drilled from concrete for length or compressive strength or splitting tensile strength determinations. This test method is not applicable to cores from shotcrete.

NOTE 1—Test Method C1604/C1604M is applicable for obtaining, preparing, and testing cores from shotcrete.

NOTE 2—Appendix X1 provides recommendations for obtaining and testing sawed beams for flexural performance.
ACI 214.4R-10

Guide for Obtaining Cores and Interpreting Compressive Strength Results

Reported by ACI Committee 214
Many engineers have the experience of ordering the taking of cores. The operation is not difficult, usually undertaken by skilled specialist personnel. Once first place the value of the load in Newtons (or pounds), under which failure by crushing occurs, which is then to be divided by the cross-sectional area of the core in square millimeters (or square inches). Dividing the first of these by the second gives a number in megapascals (or psi); but does this number represent the compressive strength of concrete in the structure from which the core was cut?

The answer is no. Not only must the number be processed, but the resulting value of strength also must be carefully interpreted. Because cores are generally taken when there is a problem, or suspected problem, with concrete, the situation usually involves two or more parties, and they may have than specified. But there may be other reasons: the cylinders may have been incorrectly consolidated (compacted); they may have been damaged in transit, subjected to freezing at a very early age, badly cured, or incorrectly tested; or the resulting compressive strength may have been incorrectly calculated or recorded.

The contractor has reasons to suggest that it is the cylinders that are unsatisfactory, while the concrete in the structure is as specified. On the other hand, the engineer has a professional responsibility to ensure the structural adequacy of the concrete, as well as a responsibility to the client (or owner) to ascertain that the quality of concrete corresponds to
Some Factors Affecting Core Strengths

- Core size
- Location of core
- Moisture conditioning
- Length-diameter ratio
- End preparation
- Embedded steel
Review of ASTM C42/C42M

- Apparatus
- Minimum core diameter
- Moisture conditioning
- End preparation
- L/D correction factor
- Presence of reinforcement
- Precision
Apparatus for Drilling Cores

- Water-cooled, diamond-impregnated drill bit
- Stable support for drilling machine
- Low feed pressure, high speed

Traditional Coring Machine

www.penhall.com
Lightweight CORECASE
CORECASE Features

Flexible rubber coupling between drill machine and coring bit; transfers only torque

Thin walled (2 mm) diamond bit; less material is cut

Barrel is advanced in axial direction with no bending.
Benefits

- Long coring bit life (~800 cores)
- Coring with little force (fingertip pressure only)
- Straight cores
- Little space required
- Simple to core in any direction
Minimum Core Diameter

- $D_{\text{min}} = 94 \text{ mm } [3.7 \text{ in.}]$ or 2 times nominal maximum size of aggregate, whichever is larger
Length-Diameter Ratio (L/D)

• If specified strength based on cylinder
  - Preferred L/D: 1.9 to 2.1
  - L/D cannot be less than 1
  - For L/D < 1.75, strength correction required

• If specified strength based on cube
  - L/D = 1.0
Moisture Conditioning

- In the past, cores were tested after a period of air drying or after being submerged for at least 40 h
- In high w/c concrete, storage under water for 40 h resulted in saturation
- With modern concrete and lower w/c, storage under water leads to moisture gradient
Research Findings

ACI MATERIALS JOURNAL

Title no. 91-M21

ACI Materials Journal / May-June 1994

Effect of Moisture Condition on Concrete Core Strengths

by F. Michael Bartlett and James G. MacGregor

In accordance with the provisions of ASTM C 42-90 and ACI 318-89, it is current practice to either dry concrete core specimens in air for 7 days or soak them in lime-saturated water for at least 40 hr before they are tested. In this paper, the effect of moisture condition on the strengths of mature cores obtained from well-cured elements is investigated by reviewing available literature and performing regression analyses of data from tests of 727 core specimens.

It is shown that the compressive strength of a concrete specimen is...
Moisture Gradients Immediately After Wet Drilling

• Moistened concrete tends to swell
• Swelling is restrained by dry interior
• Results in internal stresses; outer region in compression
• Measured strength is reduced
Effects of Conditioning on Measured Compressive Strength of Concrete Cores

by A. E. Flocato, R. C. Burg, and R. D. Gaynor

Core conditioning involves all aspects of the storage environment: temperature, humidity, and timing.

It is common practice to extract cores from existing structures when routine quality control cylinders indicate that the concrete may not meet project specifications, or to determine in-place concrete compressive strength. When evaluating in-place concrete it is important to understand the significance of the manner in which the data were generated. If the selected or specified test methodology biases the test data low, otherwise acceptable concrete could be rejected at considerable cost to all parties. On the other hand, the test methodology biases the test data high, concrete that should be rejected, or at least further analyzed, may be accepted.
Effect of Core Conditioning on Strength

- Soak 48 hr
- Soak 7 days
- Air dry 7 day
- In bags 1 day
- In bags 7 day

Strength, MPa

Strength, psi
Moisture Conditioning
ASTM C42/C42M

• Wipe off drilling water, surface dry
• Place in watertight containers
• Wait at least 5 days between wetting due to drilling or sawing and testing
• Other procedure permitted when required by the “specifier of tests”
End Preparation

- Capping with sulfur mortar ASTM C617/C617M)
  - Ends of cores have to be relatively flat and close to perpendicular to core axis

If necessary, saw the ends of cores that will be capped so that prior to capping, the following requirements are met:

7.4.1 Projections, if any, shall not extend more than 5 mm [0.2 in.] above the end surfaces.

7.4.2 The end surfaces shall not depart from perpendicularity to the longitudinal axis by a slope of more than 1:8d or [1:0.3d] where d is the average core diameter in mm [or inches].
End Preparation

- **Grinding**
  - Ends of cores must meet ASTM C39/C39M requirements for molded cylinders
  - Plane within 0.05 mm [0.002 in.]
  - Perpendicular to within 0.5 degrees

- **Unbonded caps (ASTM C1231/C1231M)**
  - Approved in 2011 for cores
Unbonded Caps

Source: PCA
Bonded vs. Unbonded Caps

Sulfur mortar caps

Unbonded caps

Source: PCA

Test smart – Build right
Unbonded Cap

- Metal retainer
- Rubber pad
Unbonded Cap

• Pad conforms to end surface
• Retainer prevents pad from lateral flow
“Flow” of Pad During Test

Retaining ring diameter: 1.02 to 1.07 core diameter
Ends need to be $\approx$ perpendicular ($<0.5^\circ$)

No depressions $> 5$ mm

Pad hardness depends on core strength range
Testing for Compressive Strength

• Before capping and testing, measure mass of core to obtain estimate of density
  ➢ In 2011 made mandatory
• Test in accordance with ASTM C39/39M
• If L/D < 1.75, multiply the measured compressive strength by a strength correction factor
**L/D Correction Factor**

- Convert measured strength to equivalent strength for $L/D = 2$
Why Do We Need a Correction Factor?

- The apparent compressive strength of a cylindrical specimen increases as L/D decreases.
- This is due to the effect of friction between the ends of the specimens and the loading plates of the testing machine.
Effect of End Friction – Triaxial Compression
As L/D Decreases
Strength Increases
L/D Correction Factor

- Convert measured strength to equivalent strength for L/D = 2
How much embedded steel is permissible in cores?
Core with Steel Bar

Restrains lateral expansion

Causes stress concentration
Effects of Steel Bar

• Depends on:
  - Core diameter
  - Bar diameter
  - L/D
  - Bar location
  - Strength level of concrete
Limited Research

- Strength reduction due to steel varied from 0 % to >10 %
- No reliable correction factor has been developed by ASTM
Example
150 x 300 mm Molded Cylinders

A = 38 mm [1.5 in.]
B = 150 mm [6 in.]
d = 12 mm or 25 mm [#4 and #8]

How much embedded steel is permissible in cores?

5.1.2 Specimens containing embedded reinforcement shall not be used for determining compressive, splitting tensile, or flexural strength.
Cores with Steel

- Preferred approach
  - Trim core to remove steel
  - Maintain L/D ≥ 1.0

- In 2011, text was revised; permitted testing cores with steel if it can’t be avoided:

5.1.3 If it is not possible to prepare a test specimen that meets the requirements of 7.1 and 7.2 and that is free of embedded reinforcement or other metal, the specifier of the tests is permitted to allow testing of cores with embedded metal (see Note 4). If a core tested for strength contains embedded metal, the size, shape, and location of the metal within the core shall be documented in the test report.
Some Factors Affecting Core Strengths

- Core size
- Location of core
- Moisture conditioning
- Length-diameter ratio
- End preparation
- Embedded steel
Core Strength Acceptance Criteria

• In the absence of other legal requirements, specifier of tests should provide the acceptance criteria

• ACI 318 criteria is for acceptance of in-place concrete when standard-cured cylinders fail to meet requirements (ACI 318-14; 26.12.4.1(d))

\( \textit{d} \) Concrete in an area represented by core tests shall be considered structurally adequate if (1) and (2) are satisfied:

1. The average of three cores is equal to at least 85 percent of \( f_c' \).
2. No single core is less than 75 percent of \( f_c' \).
Precision Between-Laboratory

Test Results

Laboratory A  Laboratory B  Laboratory C  Laboratory D
7.11.1 The single-operator coefficient of variation on cores has been found to be $3.2\%$ for a range of compressive strength between 32.0 MPa [4500 psi] and 48.3 MPa [7000 psi]. Therefore, results of two properly conducted tests of single cores by the same operator on the same sample of material should not differ from each other by more than $9\%$ of their average.

7.11.2 The multi-laboratory coefficient of variation on cores has been found to be $4.7\%$ for a range of compressive strength between 32.0 MPa [4500 psi] and 48.3 MPa [7000 psi]. Therefore, results of two properly conducted tests on cores sampled from the same hardened concrete (where a single test is defined as the average of two observations (cores), each made on separate adjacent drilled 100 mm [4 in.] diameter cores), and tested by two different laboratories should not differ from each other by more than $13\%$ of their average.
In-Place “Specified Strength”

- In new design, engineer uses the specified strength, $f'_c$
- In a strength evaluation, need value of $f'_c$ to use in member capacity equations
ACI 214.4R

Convert core strength to in-place concrete strength.

\[ f_c = F_{\text{L/D}} F_{\text{dia}} F_{\text{mc}} F_{\text{d}} f_{\text{core}} \]

In-place strength
Core strength
Correction for L/D
Correction for "damage" due to coring
Correction for D
Correction for moisture content

Table 9.1 Provides the values of the F-factors
Table 9.1—Magnitude and accuracy of strength correction factors for converting core strengths into equivalent in-place strengths

<table>
<thead>
<tr>
<th>Factor</th>
<th>Mean value</th>
<th>Coefficient of variation V, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{ud}$: $d/d$ ratio$^4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard treatment$^4$: $1 - {0.130 - \alpha f_{core}}(2 - \frac{d}{2})^2$</td>
<td></td>
<td>$2.5(2 - \frac{d}{2})^2$</td>
</tr>
<tr>
<td>Soaked 48 hours in water:</td>
<td>$1 - {0.117 - \alpha f_{core}}(2 - \frac{d}{2})^2$</td>
<td>$2.5(2 - \frac{d}{2})^2$</td>
</tr>
<tr>
<td>Dried$^5$:</td>
<td>$1 - {0.144 - \alpha f_{core}}(2 - \frac{d}{2})^2$</td>
<td>$2.5(2 - \frac{d}{2})^2$</td>
</tr>
<tr>
<td>$F_{dia}$: core diameter</td>
<td>2 in. (50 mm)</td>
<td>1.06</td>
</tr>
<tr>
<td>4 in. (100 mm)</td>
<td>1.00</td>
<td>0.0</td>
</tr>
<tr>
<td>6 in. (150 mm)</td>
<td>0.98</td>
<td>1.8</td>
</tr>
<tr>
<td>$F_{mc}$: core moisture content</td>
<td>Standard treatment$^4$:</td>
<td>1.00</td>
</tr>
<tr>
<td>Soaked 48 hours in water:</td>
<td>1.09</td>
<td>2.5</td>
</tr>
<tr>
<td>Dried$^5$:</td>
<td>0.96</td>
<td>2.5</td>
</tr>
<tr>
<td>$F_d$: damage due to drilling</td>
<td>1.06</td>
<td>2.5</td>
</tr>
</tbody>
</table>

*To obtain equivalent in-place concrete strength, multiply the measured core strength by appropriate factor(s) in accordance with Eq. (9-1).

1. Constant $\alpha$ equals $3\times(10^{-5})$ psi for $f_{core}$ in psi, or $4.3\times(10^{-4})$ MPa for $f_{core}$ in MPa. 
2. Standard treatment specified in ASTM C42/C42M.
3. Dried in air at 60 to 70°F (16 to 21°C) and relative humidity less than 60% for 7 days.

If 4 by 8 in. core is tested in standard condition:

$$f_c = 1 \times 1 \times 1 \times 1.06 f_{core}$$
In-Place Strength

• Engineers often assume that core strength is 85% of actual in-place strength
• Or, in-place strength = core strength/0.85
• This is not a rational approach

\[ f_c \neq \frac{f_{\text{core}}}{0.85} \]
Equivalent Specified Strength

\[ f_{c,eq} = Kf_c \]

- **K** depends on:
  - Number of core tests
  - Variability of core strengths
  - Confidence level

Equivalent specified strength

Average in-place strength

Statistical factor
Summary

• Cores can be taken for different reasons
• When taking cores for evaluating in-place strength, standard procedures must be followed to obtain comparable results
  - Moisture conditioning is very important
  - End preparation in strict accordance with ASTM C42/C42M
• In the absence of governing provisions, the licensed design professional is responsible for defining acceptance criteria
Summary

• For strength evaluation of existing construction, careful planning to select location and number of cores
  - Use NDT to locate “good” and “bad” concrete
  - Number of cores depend on variability and tolerable uncertainty of population mean
• ACI 214.4R provides rigorous method to obtain equivalent specified strength