Expect Compressive Strength Test Results Less Than Specified Strength on Every Project

Use engineering judgment, test reserve cylinders, and extract cores only if evaluation is warranted

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Surprised by the title? On every project, experienced concrete industry professionals recognize that individual compressive strength test results can be lower than the specified strength, f'_c. While there are numerous reasons this might occur, one important reason is: the standards for acceptance criteria used in the United States are based on statistical concepts that permit a low test result, and it is standard practice for concrete producers to design concrete mixtures based on a probability of about 10% that an individual strength test may be less than f'_c.[1-3] This is done such that the owner benefits from an economical and sustainable concrete mixture that complies with the ACI 318-19 Code[4] and represents limited risk to structural performance considering the use of safety and resistance factors in design. When a compressive strength test result is substantially less than f'_c, engineering judgment, use of reserve cylinders, and, if necessary, evaluation of extracted cores assist in resolving the issue.

Is it Normal for a Strength Test to be Less than f'_c and How Often?

An individual compressive strength test result less than f'_c is acceptable in accordance with the Code.[3,5,6] The strength acceptance criteria in Section 26.12.3.1 of ACI 318-19 state that strength test results are acceptable if:

- The average of three consecutive tests equals or exceeds f'_c; and
- Each individual test exceeds (f'_c − 500 psi) or $0.9f'_c$, if f'_c exceeds 5000 psi.

ACI 301-20, Section 4.2.3.3,[1] establishes the process of determining the required average strength, f'_{cr}, at a 99% probability of compliance (strength tests can fail the criteria at a 1% probability).

Relative to the first criteria for acceptable strength test results, f'_{cr} should be at least $1.34s_s$ greater than f'_c, where s_s is the standard deviation of at least 30 strength tests of the same class of concrete from a previous project. In a statistical normal distribution, the factor 1.34 indicates that about 10% of individual strength tests can be less than f'_c.

ACI 318-19, Section 26.12.2.1, and ACI 301-20, Section 1.7.3.3(d), establish the same minimum frequency of compressive strength testing at one test for each 150 yd^3 of concrete. ACI 301 is usually referred to in the Project Specifications and by the AIA MasterSpec® Section 033000-Cast-in-Place Concrete.[7] Some project specifications call for tests at a higher frequency, typically at one test per 100 yd^3 of concrete. Table 1 shows how often the measured compressive strength test is likely to be below f'_c based on statistical concepts for testing frequency at one test per 100 or 150 yd^3 of concrete.

For a project with 10,000 yd^3 of concrete, expect seven to 10 tests less than f'_c. On a large project with 100,000 yd^3 of concrete, this number is 67 to 100. If this is not observed, the concrete mixture is overdesigned more than that required by ACI 301. This can be related to prescriptive requirements where a maximum water-cementitious materials ratio (*w/cm*) is not consistent with f'_c or a minimum cement content is specified. Some producers also increase strength of mixtures to avoid problems associated with testing.

Table 1:
Expected number of compressive strength test results less than f'_c

Volume of placed concrete, yd^3	Minimum number of tests		Expected number of tests less than f'_c	
	One per 150 yd^3 (ACI 318-19, ACI 301-20)	One per 100 yd^3	One per 150 yd^3 (ACI 318-19, ACI 301-20)	One per 100 yd^3
1000	7	10	1	1
10,000	70	100	7	10
50,000	334	500	34	50
100,000	667	1000	67	100

When strength test results are lower than f'_c, it is possible that the failure may be in the testing and not representative of the delivered concrete. This is especially true when the fabrication, handling, curing, and testing of the cylinders are not conducted in accordance with relevant ASTM standards. Testing issues can therefore complicate how many test results will be less than f'_c and, more importantly, if the strength test results are representative of the delivered concrete.

When strength tests fail to meet the ACI 318 acceptance criteria, steps must be taken to increase subsequent strength tests. Guidance on steps to increase future strength tests is provided in the Commentary Section R26.12.3.1(b) of ACI 318-19. A more relevant suggested sequence of evaluation is described by the National Ready Mixed Concrete Association (NRMCA).[8] If an individual strength test fails to meet the second criteria in ACI 318-19 for acceptable strength test results, then the Code requires a low-strength investigation.

Testing agencies fail to recognize that a compressive strength test can be less than f'_c and still comply with the acceptance criteria in the Code. Regretfully, the test agency marks the test report as "failed" or "rejected," both of which are inappropriate characterizations. First, the test did not fail acceptance criteria in the Code and second, the testing agency does not have the authority to accept or reject. This misleading information often creates unnecessary confusion, cost, and delays. This issue should be discussed at the preconstruction meeting. Some testing agencies believe they should alert the owner or design team if the measured strength on a single cylinder at 7 days does not achieve some assumed percentage of the specified 28-day strength. This practice could cause unnecessary panic and should be avoided because there is typically no requirement at 7 days, testing one cylinder is not a valid test, and each mixture has a unique rate of strength gain.

It Costs Less to be Less than f'_c—Owner Benefits

What is the cost if no strength tests can be less than f'_c? If f'_c is the absolute minimum strength, the mixture must be designed for a strength level at least three standard deviations greater than f'_c. This will require at least 50 lb higher cement content in each cubic yard of concrete. This could increase the concrete cost up to about $15 per cubic yard. For a project with 10,000 yd^3 of concrete, the additional concrete cost would be $150,000. And on a large project with 100,000 yd^3 of concrete, the additional concrete cost would be $1,500,000. That is the benefit the owner receives based on allowing some strength tests below f'_c. With an increased cement content, there can also be adverse performance issues such as increased potential for cracking due to higher shrinkage or thermal effects. In this era of green construction, increasing the strength of concrete also increases its carbon footprint and makes it more difficult to achieve project goals for sustainability.

Use Test Cylinders Wisely—Discuss at Preconstruction Meeting

During the preconstruction meeting, the engineer should provide direction to the testing agency regarding appropriate actions when strength test results are less than f'_c. Typically, a set of four to six cylinders are cast from a concrete sample (Fig. 1). Preferably, additional "hold" cylinders are available to test at a later age if needed (Fig. 2).

The specifics of reserve or hold cylinders are discussed in a later section. It should, however, be noted that these cylinders should be used prior to core tests because the design team felt it prudent to require reserve or hold cylinders in the project specifications and the owner felt it beneficial to pay for them. Deciding to core adds an extra cost without gaining the benefit of additional information from reserve cylinders that are already paid for.

One additional testing item should be discussed, as per NRMCA CIP 35 recommendations: "If one or both of a set of cylinders break at strength less than f'_c, evaluate the cylinders for obvious problems and hold the tested cylinders for later examination."[3] This is generally common practice at a testing agency; however, it should be discussed to make sure the cylinders are available for examination. Often, just measuring the weight of a cylinder before testing to calculate an approximate density can be useful to determine if there was improper consolidation, embedded foreign objects, or other problems.

Sometimes engineers are reluctant or refuse to consider the information provided by the reserve or hold cylinders. If that is the case, a conversation with the owner should take place

Fig. 1: **Typically, four to six 6 x 12 in. concrete cylinders are cast at the jobsite to fulfill project specification requirements** *(photo courtesy of PCA)*

FIELD AND LAB DATA				
	Date: 5/28/2010	Time Concrete Batched: 8:10 AM	Time Concrete Sampled[1]: 8:35 AM	Sampled By: KT
	Concrete Truck No: 24453	Ticket Number: 31259786	Size of Load (C.Y.): 10	Weather Conditions: Clear
	Water Added at Job Site: ☐ Yes ☒ No If Yes: Gal. To C.Y.			Extra Water Authorized By: N/A
	Slump (inches)[2]: 6	Air Temperature (° F): 78	Concrete Temperature (° F)[3]: 75	Wet Weight (P.C.F.): N/A
	Air Content (% by Vol)[4]: N/A	Molded and Cured[5] to general accordance with ASTM C-31: ☒ Yes ☐ No ☐ Unknown		Tested to ASTM C-39: ☒ Yes ☐ No
	Location of Concrete Placement: Slab on Grade at East Side of Job Site H / S Area, 100' North of Southeast Corner			

Set No. 709	Date Received In Lab	Date Tested	Age (days)	Test Specimen Size Diameter (in.)	Test Specimen Size Area (sq. in.)	Total Load Applied (lbs)	Test Strength (psi)	Type of Fracture	Specimen Weight (Air Dry-lbs)
A	06/01/10	06/04/10	7	4.04	12.82	77,000	6,010	5	
B	06/01/10	06/04/10	7	4.05	12.88	80,500	6,250	5	
C	06/01/10	06/25/10	28	4.03	12.76	97,000	7,600	5	
D	06/01/10	06/25/10	28	4.05	12.88	96,000	7,450	5	
E	06/01/10	06/25/10	28	4.03	12.76	96,500	7,560	4	
F	06/01/10		H						
G	06/01/10		H						

Fig. 2: The test agency made seven 4 x 8 in. concrete cylinders. Two cylinders were tested at 7 days, three cylinders were tested at 28 days, and two hold cylinders remained available for testing at later age if needed

prior to construction. The owner only wants to pay to receive a benefit and, if the reserve or hold cylinders do not do so, they should be removed from the testing contract.

Investigating Low Strength Test Results

ACI 318 and ACI 301 provide requirements when a low strength test must be investigated. Engineering judgment should be used to determine the scope of the investigation to verify if corrective action is necessary. First, ask yourself: if the test result is true, does it matter?

Section 26.12.6.1, Part (b), of ACI 318-19 requires the engineer to consider if "calculations indicate that structural adequacy is significantly reduced." If the low test result is adequate, why spend time and money determining the root cause? A root cause analysis should be considered, however, when there are more than the anticipated number of low strength results based on accepted statistical principles.

The engineer has tools for investigating a low strength test result, including: 1) using experienced engineering judgment; 2) assessing testing variations from standards; 3) supplementary data from reserve or hold cylinder testing; 4) nondestructive testing for a relative assessment; and 5) core testing using the criteria for core strength in ACI 318.

Engineering judgment

ACI 318-19 uses the word "judgment" 16 times in the document. The first instance included in the Introduction might be the most important: "The Code and Commentary cannot replace sound engineering knowledge, experience, and judgment." Commentary Section R26.12.6.1 in ACI 318-19 indicates that judgment should be applied as to the significance of low strength test results and whether they are a cause for concern. If further investigation is deemed necessary, such investigation may include in-place tests as described in ACI 228.1R-19[9] or, in extreme cases, the taking and testing of cores.

Engineering judgment is developed through experience. An engineer should evaluate low strength test results in view of the following observations:

- Any discrepancy or deficiency in testing provides a lower-bound value of the concrete delivered to the project. Thus, if a testing issue is suspected, the actual compressive strength is higher than the test value. Further, the most likely problem could be a lack of proper initial curing of test specimens at the jobsite;
- Concrete compressive strength increases with age. Thus, concrete strength tested at a later age is higher than the strength tested at an earlier age. The rate of strength gain is greater for mixtures containing supplementary cementitious materials such as fly ash or slag cement; and
- Compressive strength from a single cylinder tested at a later age can be used as the basis to determine if the concrete is structurally adequate. Thus, even though it is not a Code-recognized strength test, it can be used as the basis for acceptance. The engineer can consider that service and live loads on a structural member may be applied at an age later than 28 days.

Assessing testing variations from ASTM standards

It is important that procedures are conducted in accordance with ASTM standards. Deficiencies in handling and testing cylinders will result in a lower measured strength.[10] All violations add up to cause significant reductions in measured strength. Richardson[11] states that "the simplicity of the strength test is misleading because the measured results are very much dependent upon strictly adhering to standardized uniform procedures. Violation of these procedures can lead to inaccurate results. All too often, the results of strength measurements are fraught with testing errors. Most deviations from the standardized procedures for testing result in low strength results. The consequences of falsely low results can be: 1) unnecessary delays; 2) costly follow-up testing; 3) wasteful overdesign; and 4) possible rejection of concrete acceptable for the intent.[12]"

Per ACI 214R-11(19), Section 3.3: "Deviations in field sampling, specimen preparation, curing, and testing procedures may cause lower strength test results." The committee provides a list of principal sources of strength variation:

- Improper sampling from the batch;
- Variations due to fabrication techniques:
  - Substandard conditions,
  - Incorrect tools,
  - Poor quality, damaged, or distorted molds,
  - Nonstandard molding and consolidation, and
  - Incorrect handling of fresh test samples;
- Differences in curing:
  - Delays in beginning initial curing,
  - Temperature variation,
  - Variable moisture control,
  - Nonstandard initial curing,
  - Delays in bringing cylinders to the laboratory,
  - Rough handling of cylinders in transport, and
  - Improper final curing; and
- Variations in sample testing:
  - Uncertified tester,
  - Specimen surface preparation,
  - Inadequate or uncalibrated testing equipment,
  - Nonstandard loading rate, and
  - Poor recordkeeping.

Assessing testing variations can be time consuming and costly. However, a review of the strength test report can provide a preliminary assessment of the testing procedures:

- Check cylinder diameter and height. They should not all be exactly 6 x 12 in. or 4 x 8 in.;
- Check coefficient of variation between companion cylinders tested at the same age. On average, this should not exceed 3% and the difference in strength between companion cylinders should not exceed 8% more often than about 1 in 20;
- Check the 3- and 7-day strengths compared to the 28-day strength. They should have a consistent trend; and
- Other details may provide some information: truck sampled, load size, time between batching and sampling, ambient temperature and other conditions, and dates of cylinder casting and of transporting to the lab.

Supplementary data from reserve or hold cylinders

It's unclear when reserve or hold cylinders became a normal addition to project specifications for concrete testing, but it seems to date back at least 50 years. Recent project specifications we have encountered (for a hotel, medical center, transit center, and water treatment facility) included the following provision:

"Compressive strength tests: ASTM C39/C39M-12, one set for each 100 cu. yd. or fraction thereof, of each class of concrete placed in any one day or for each 5,000 sq. ft. of surface area placed: one specimen tested at 7 days, two specimens tested at 28 days and one specimen retained in reserve at the laboratory for later testing if required."

The project specification requires one extra specimen for each 100 yd^3 of concrete placed. For a project with 10,000 yd^3 of concrete, the owner pays for 100 additional reserve or hold cylinders. And on a large project with 100,000 yd^3 of concrete, the owner pays for an additional 1000 reserve or hold cylinders. The cost of making, curing, storing, and testing a cylinder varies from \$75 to \$150. The cost will be lower if the hold cylinders are not tested. For simplicity, consider the cost to be \$100, thus increasing the testing cost by as much as \$100,000. The design team and owner must believe that the increased cost is necessary and beneficial to the project. In other words, project specifications requiring reserve or hold cylinders anticipate possible issues and the need and use of additional strength data. Balance this cost with that for core tests and associated schedule delays.

The Portland Cement Association's (PCA) *Design and Control of Concrete Mixtures* recognizes the use of "hold" cylinders: "In addition to the cylinders for acceptance testing, project specifications often require one or two 7-day cylinders and one or more 'hold' cylinders. The 7-day cylinders monitor early strength gain to signal potential problems in meeting specified strength. Hold cylinders are commonly used to provide additional information in case the cylinders tested for acceptance are damaged or do not meet the required compressive strength. For low 28-day test results, the hold cylinders are typically tested at 56 days."[13] This statement was first included in 2003 in the 14th edition of this publication.[14]

In response to a question regarding the minimum number of reserve cylinders, the November 2011 Q&A in *Concrete International* stated: "It's prudent to have at least one 'hold' cylinder as a backup for a poorly fabricated or damaged cylinder (it's not acceptable to discard a cylinder break result simply because it was low—it must fall outside a range provided in the precision statement in ASTM C39, 'Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens')."[15] NRMCA CIP 35[3] also advocates for the use of additional reserve cylinders that can be tested if one cylinder of a set breaks at a lower strength.

First introduced into ACI 318-14[16] and continued in ACI 318-19, Commentary Section R26.12.1.1(a) states: "Casting and testing more than the minimum number of specimens may be desirable in case it becomes necessary to discard an outlying individual cylinder strength in accordance with ACI 214R. If individual cylinder strengths are discarded in accordance with ACI 214R, a strength test is valid provided at least two individual 6 x 12 in. cylinder strengths, or at least three 4 x 8 in. cylinder strengths, are averaged. All individual cylinder strengths that are not discarded in accordance with ACI 214R are to be used to calculate the average strength." Thus, the Code is endorsing the concept of using reserve or hold cylinders.

One cylinder strength information

The Commentary in ACI 318-63 addressed the issue of a single cylinder as a test:

"An excessive discrepancy in strength between individual cylinders constituting a test indicates either a faulty specimen or improper sampling and testing procedures. If it can be established that one of the specimens was faulty, its strength should be discarded, and the other value used as the test result. In the absence of such evidence, it may be necessary to discard the entire test since its validity as a measure of concrete quality is questionable."[17]

While the 1963 Commentary on the Code recommended that the single value be used as the test result, code commentaries following the 1963 edition indicate that one single cylinder is not a valid strength test.

PCI MNL-116-21 provides more definitive guidance on the use of one cylinder as a test: "Only one specimen may be used to determine stripping or stress transfer strength as production progresses. If any specimen shows definite evidence (other than low strength) of improper sampling, molding, handling, curing, or testing, it shall be discarded, and the strength of the remaining cylinder shall be considered the test result."[18] Note that the purpose for this is to estimate in-place strength for production of prestressed members.

Historically, engineers on many different projects have used engineering judgment to accept concrete strength at a later age based on supplemental information from one cylinder. We encourage engineers to continue to use engineering judgment and supplemental strength information in determining if the concrete is acceptable.

In-Place Concrete Strength from Core Testing

Too often, construction managers or general contractors initiate core testing without direction from the engineer when a compressive strength test is below f'_c. This is often an unnecessary expense and frequently leads to core removal and testing that is not in accordance with ASTM C42/C42M, "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete."[19] ACI 318-19, Commentary Section R26.12.6.1(c), considers the engineer as the specifier of the tests. This is an important distinction, as ASTM C42/C42M recognizes that this individual is permitted to alter default requirements and is responsible for the analysis or review and acceptance of core test results.

In addition, Commentary Section R26.12.6.1 of ACI 318-19 provides three important considerations with respect to core testing:

- Measuring compressive strength of cores should only be used in extreme cases;
- Extraction of cores and their subsequent testing is typically at an age later than specified for f'_c; and
- Core strengths need not be adjusted based on the age of the cores.

The same commentary section also states that the Code provides "conservative acceptance criteria" for cores for "virtually any type of construction." And that "Lower strength may be tolerated under many circumstances, but this is a matter of judgment on the part of the licensed design professional and building official." Per ACI 318-19, Section 26.12.6.1, Part (e): "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."

When "extreme cases" arise and cores are necessary, use the American Society of Concrete Contractors (ASCC) "Technical Checklist: Concrete Core Testing"[20] to ensure that drilled cores are obtained and tested properly.

Before commissioning expensive and possibly disruptive core tests, the project team should consider in-place testing. As stated in ACI 318-19, Commentary Section R26.12.6.1: "In-place tests of concrete, such as probe penetration (ASTM C803[21]), rebound hammer (ASTM C805[22]), or pullout test (ASTM C900[23]), may be useful in determining whether a portion of the structure actually contains low-strength concrete. Unless these in-place tests have been correlated with compressive strength using accepted procedures, such as described in ACI 228.1R, they are of value primarily for comparisons within the same structure rather than as quantitative estimates of strength."

Claims, Credits, and Damages, Oh My!

The most often cited claim is: "The 28-day cylinder strength should be at or above specified strength or the owners are not getting what they paid for. There is nothing wrong with accepting the concrete if you are satisfied that it is adequate, but perhaps there should be a financial adjustment to the benefit of the owners as they clearly did not get what they paid for."

Unfortunately, this argument assumes that f'_c is an absolute minimum. If this were true, then the Code strength acceptance criterion (1) in Section 26.12.3.1(a) of "every average of any three consecutive strength tests equals or exceeds f'_c" would have no meaning. If f'_c were a minimum, then, of course, the average of three consecutive strength tests would always exceed f'_c. Therefore, this Code criterion clearly acknowledges that some individual strength test results will be less than f'_c.

As for a financial adjustment, how would that be calculated? As stated in *Common Sense Construction Law*,[24] the requirement that financial adjustments be reasonably proportionate to actual damages stems from the fact that courts have traditionally refused to enforce what amounts to a penalty for breach of contract. One primary objection to penalties is that while the law favors reimbursement for loss, it does not approve of granting a windfall or unearned profits, even to an innocent party. To allow an injured party to recover an amount more than the actual damages it has suffered would in effect put that party in a better position that it would have had been in had the contract been performed. This result would be inconsistent with the basic theory of contract damages.

In closing, the owner is benefiting from a reduced concrete cost by allowing some test results to be below f'_c. Providing a financial credit for this issue would indeed be granting a windfall to the owner and would not be appropriate.

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Selected for reader interest by the editors.

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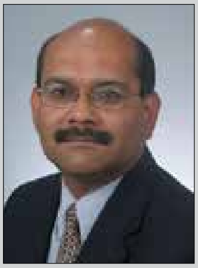

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