Section 5.6.3.3 of ACI 318-02, “Building Code Requirements for Structural Concrete,” states that the strength level of a given class of concrete is satisfactory if two requirements are met:

(a) Every arithmetic average of any three consecutive strength tests equals or exceeds \( f'_c \); and

(b) No individual strength test (average of two cylinders) falls below \( f'_c \) by more than 500 psi (4 MPa) when \( f'_c \) is 5000 psi (35 MPa) or less; or by more than 0.10 \( f'_c \) when \( f'_c \) is more than 5000 psi.

If an individual strength test doesn’t meet criterion (b), an investigation of the low-strength test result must be performed in accordance with Section 5.6.5, Investigation of low-strength test results. If an individual strength test is low (criterion (b)) or the average of three consecutive strength tests is low (criterion (a)), Section 5.6.3.4 requires that “steps shall be taken to increase the average of subsequent strength test results.” Some practical problems arise in dealing with either low individual strength tests or with a low average of three consecutive tests.

LOW INDIVIDUAL STRENGTH TEST

The Commentary for Section 5.6.5 states that “The building official should apply judgment as to the significance of low test results and whether they indicate need for concern.” Application of judgment is implied in Section 5.6.5.2: “If the likelihood of low-strength concrete is confirmed and calculations indicate that load-carrying capacity is significantly reduced, tests of cores drilled from the area in question…shall be permitted.” Confirming the likelihood of low-strength concrete probably means verifying that testing was conducted in accordance with ASTM procedures. That may be a judgment call. And the phrase “significantly reduced” also implies judgment. To avoid having to make such judgments, the local building official is more likely to accept core test results that meet the requirements of Section 5.6.5.4. Thus, when an individual strength test result doesn’t meet criterion (b), three cores are usually taken and tested to determine if the average strength of the three cores is equal to at least 85% of \( f'_c \) and no single core strength is less than 75% of \( f'_c \).

LOW AVERAGE OF THREE CONSECUTIVE TESTS

Typically, when the arithmetic average of three consecutive strength tests is low, the cement content is increased. The ACI 318-02 Commentary, however, suggests other alternatives. “The steps taken to increase the average level of test results will depend on the particular circumstances, but could include one or more of the following:

(a) An increase in cementitious content;
(b) Changes in mixture proportions;
(c) Reductions in or better control of levels of slump supplied;
(d) A reduction in delivery time;
(e) Closer control of air content;
(f) An improvement in the quality of the testing, including strict compliance with standard test procedures."

In the field, suggestions (b) through (f) are not usually considered sufficient to reduce the anxiety level. If you first increase the cement content, the other alternatives may be allowed.

**CALCULATING THE AVERAGE OF THREE CONSECUTIVE TESTS**

This seems to be an easy calculation; take each set of three consecutive strength tests and divide by three. But let’s consider some problems that arise in the field.

**Project startup.** Within each “strength level of an individual class of concrete” on the project, three consecutive strength tests won’t be available until the third test. For most experienced concrete industry professionals, this doesn’t present a problem. You can’t determine the arithmetic average of three consecutive strength tests if three tests don’t exist. For a multistory project, there might be as many as five to eight different “individual classes of concrete,” and this situation would occur for each class of concrete.

For some building officials and other people who read ACI 318-02 literally, the concrete can’t be considered satisfactory after the first two strength tests for each concrete class because ACI 318-02 requires both criteria to be met for acceptance. Fortunately, the project team usually agrees that criterion (a) makes little sense for the first two tests and waives it for concrete acceptance. ACI 318-02 concurrence, with a brief note to this effect in the Commentary, would be helpful.

**Field-cured specimens.** Occasionally, the strength test results of field-cured specimens are used to determine the arithmetic average of any three consecutive strength tests. The requirement for an arithmetic average of any three consecutive strength tests applies, however, only to laboratory-cured specimens. There is no criterion in Section 5.6.4 for the average of three consecutive field-cured specimens, or for a combination of laboratory- and field-cured cylinder test results.

**OTHER ACCEPTANCE QUESTIONS**

Consider the following situations and resulting questions about concrete acceptance that sometimes arise.

**Core tests are required.** Assume that \( f_c' \) is 4000 psi (28 MPa) and a 28-day, 3400-psi (23 MPa) individual strength test triggers the requirements of the coring and testing section of the code. The concrete is accepted when the average strength of the three cores tested exceeds 0.85\( f_c' \), and no single core strength is below 0.75\( f_c' \). But how should the three-consecutive-test average be calculated?

- Should the arithmetic average for any three consecutive tests include the original 3400-psi result?
- Should the arithmetic average for any three consecutive tests include, instead of the original 3400-psi result, the average strength of the three cores?
- Should the arithmetic average for any three consecutive tests include, instead of the original 3400-psi result, the average strength of the three cores divided by 0.85 (as an estimate of the cylinder strength represented by the cores)?

For any one of these cases, if the resulting arithmetic average is below \( f_c' \), should steps be taken to increase the average of subsequent strength test results?

**Strength test results for 56-day cylinders are used.** Assume again that \( f_c' \) is 4000 psi and a 28-day, 3400-psi...
everyday issues

individual strength test result occurs. In this case, however, sufficient cylinders were taken so that a further test result could be obtained at 56 days. The average strength of two cylinders tested at 56 days was 4200 psi (29 MPa), and the engineer was willing to accept the concrete on the basis of this 56-day strength.

Should the 3400-psi or the 4200-psi result be included in calculating the arithmetic average of any three consecutive tests? If the 3400-psi strength is included, and the average of any three consecutive tests is low, should steps be taken to increase the average of subsequent strength test results? If the 4200-psi strength is included and the averages of any three consecutive tests are equal to or above $f'_{c}$, is that sufficient?

**Results from a different test lab.** Assume again that $f'_{c}$ is 4000 psi (28 MPa) and a 28-day, 3400-psi (23 MPa) individual strength test result occurs. In this case, however, another test lab (or perhaps the concrete producer’s lab) has been doing companion testing and their strength test result from the same truck is 4350 psi (30 MPa). The engineer accepts the strength test result of the second lab, based on a belief that the lower strength from the other test is due to improper treatment of the cylinders. Should the 3400-psi or the 4350-psi result be included in the arithmetic average of any three consecutive tests?

In any of these three situations, I would not use the 3400-psi result in calculating the average of three consecutive tests because the cores used for acceptance in the first situation indicate that 3400 psi isn’t a valid number. I would also not use the average of the three core strength tests nor that value divided by 0.85. Only the strength test results from laboratory-cured specimens prepared in accordance with ASTM C 31, “Standard Practice for Making and Curing Concrete Test Specimens in the Field,” should be used in calculating the arithmetic average. Using other specimens introduces other sources of variability. Also, dividing the core strength by 0.85 does not provide an equivalent $f'_{c}$. The 0.85 factor was not developed as a means for converting a core strength to an equivalent cylinder strength.

Using the 28-day strength test results from laboratory-cured specimens from another lab—or the concrete producer’s lab—is probably reasonable. And one could argue that using either the 28-day strength test result or the 56-day strength test result might be reasonable. If the engineer, however, accepted the concrete based on cores, 56-day test results, or 28-day test results from another lab, I would not include that concrete in considering the average of any three consecutive tests. Using the higher strength tests from either the 56-day cylinders or from cylinders made and tested by a second lab is likely to artificially increase the arithmetic average of three consecutive tests. This could mask difficulties that might be occurring in the quality control of the product, delivery, or testing.

I recommend ignoring tests on the concrete represented by any of the three cases described and continuing to calculate the arithmetic average of any three consecutive tests with the strength test results for concrete made previous to and after the concrete was accepted in the special cases. This advice applies only to cases in which tests on drilled cores, 56-day laboratory-cured specimens, or specimens from a second testing lab, are the exception and not the rule. If results of tests on standard-cured cylinders regularly fail to meet the acceptance requirements, the project has more pressing problems than deciding which tests can be used to calculate the arithmetic average of any three consecutive tests.

**No Man’s Land**

There is one situation for which some disagreement may occur. Assume that $f'_{c}$ is 4000 psi, and the first five strength test results are 3600, 3700, 3800, 3900 and 4000 psi (25, 25.5, 26, 27, and 28 MPa). Because no individual strength test is below 3500 psi (24 MPa), the requirement of Section 5.6.3.3(b) is satisfied, and an investigation of low-strength test results is not required. The requirement in Section 5.6.3.3(a), however, is not satisfied because the arithmetic average of any three consecutive strength tests doesn’t equal or exceed $f'_{c}$. Steps must thus be taken to increase the average of subsequent strength test results. Because both criteria are not met, however, the strength level isn’t considered satisfactory for the concrete already in place. Is coring required?

Selected for reader interest by the editors.

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