# Technology in Practice

## What, Why & How?


# TIP 16 - Evaluating Strength Test Results

*This TIP provides guidance on evaluating strength test results used for acceptance of concrete to determine whether the testing procedures and test results indicate deficiencies in testing practices.*

## WHAT is the Purpose of Strength Testing?

One of the primary specified requirements for concrete is the compressive strength. Strength tests are typically performed by a third-party testing agency. It is imperative that the procedures for making and testing strength specimens conform to the standards. Improper testing can result in acceptable concrete being rejected, considerable cost for evaluation, and delay project schedules.

Strength tests are primarily performed to evaluate the quality of concrete supplied by a ready mixed concrete producer when strength requirements are stated in orders or specifications for ready mixed concrete. The strength test results are evaluated for compliance with the strength acceptance criteria. For this purpose cylindrical test specimens are cast from representative samples of concrete as delivered. The standard size of cylindrical strength test specimens is either 4 x 8 in. or 6 x 12 in. (100 x 200 mm or 150 x 300 mm). Strength test specimens for acceptance of concrete are subjected to standard curing, as defined in ASTM C31.

A common concern is whether strength of standard-cured cylinders represent the strength of concrete in the structure. This is not the purpose of these strength tests. Concrete structural design procedures are based on strength of standard-cured specimens with appropriate safety factors for structural capacity. Field-cured cylinders are sometimes used to estimate the in-place strength of concrete in the structure for post tensioning, formwork removal, determining adequacy of curing and protection, and for other reasons during construction. This TIP does not address results of field-cured cylinders.

## WHAT are the Requirements for Testing Agencies (Laboratories)?

A testing agency for quality assurance testing is hired by the owner of the structure or by the contractor when required in the contract. The testing agency should conform to the requirements of ASTM C1077, *Standard Practice for Agencies Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Testing Agency Evaluation*. This standard establishes a quality system for testing agencies and requires that technicians performing tests maintain certification for the tests that they perform. Certification requirements apply to field and laboratory technicians. The laboratory should be third-party inspected periodically and participate in proficiency sample testing programs. In some cases testing agencies maintain accreditation that assures compliance with this standard. The entity contracting for testing services should ensure that the agency selected has the required credentials and that they will provide reliable testing services. ACI 311.6, *Specification for Ready Mixed Concrete Testing Services*, is a good basis for this contract.

## WHAT are the Requirements for Strength Testing?

Concrete samples should be obtained in accordance with ASTM C172. The sample should be obtained after all adjustments are made to the load. The sample should not be obtained from the initial discharge. From a truck mixer, ASTM C172 requires obtaining the sample from at least two portions of the discharge stream from the middle portion of the load. The sample should be thoroughly mixed and tests should be started within specific time limits. Molding cylinders should start within 15 minutes of obtaining the sample. ASTM C94 and ACI 301 state that slump (ASTM C143), air content (ASTM C173 or ASTM C231), temperature (ASTM C1064), and density (ASTM C138) be measured when strength specimens are made. Two technicians may be required to perform these tests within the time constraints.

Making and curing specimens is addressed in ASTM C31. The standard discusses details regarding molds, casting cylinders, consolidation, transportation to the laboratory, and curing. There are two methods of curing – standard curing and field curing. Standard curing is applicable for strength tests used for acceptance of concrete.

Under standard curing, for the initial curing at the jobsite, cylinders should be maintained in a moist condition and in a temperature range of 60 to 80°F (16 to 27°C). If the specified strength of the concrete is 6000 psi (40 MPa) or greater, the temperature range should be maintained between 68 and 78°F (20 and 26°C). Specimens should be protected from sunlight and ambient conditions. Various methods for initial curing are suggested in ASTM C31. Research indicates that the best method is to immerse the cylinders in temperature controlled water (Meininger). Alternatively, curing boxes with temperature controls are commonly used. The testing agency is required to record and report the maximum and minimum temperature during initial curing at the jobsite.

Cylinders should be transported to the laboratory within about 48 hours; if the concrete setting time is retarded, then at least 8 hours after final set. Cylinders should be protected from ambient conditions and to prevent moisture loss. They should be adequately cushioned to prevent damage. Transportation time should not exceed 4 hours.

When cylinders are delivered to the lab, the molds should be removed and final curing should be initiated within 30 minutes. Cylinders should be maintained in a moist room or immersed in lime-saturated water in a temperature range of 73.5 ± 3.5°F (23.0 ± 2.0°C). Standard curing can be terminated for a maximum period of 3 hours prior to testing provided the cylinders are kept moist.

ASTM C39 covers the testing procedures. Ends of cylinders should be capped using either sulfur mortar (ASTM C617) or unbonded neoprene pad caps (ASTM C1231). ASTM C1231 indicates the durometer hardness of pad caps for different strength levels of concrete. The number of reuses of the caps is limited by the standard and the laboratory should maintain a record on this. Pad caps are not permitted for testing concrete with a specified strength that is 12,000 psi (80 MPa) or greater. Use of sulfur caps is decreasing, but there are requirements for the maximum thickness of these caps. This is especially important when testing high strength concrete (Carino et. al.). Ends of high strength concrete cylinders are sometimes ground to comply with the planeness requirements. See TIP 5 for more information on capping. ASTM C39 addresses details regarding the testing machine, calibration frequency, loading rate for strength testing and other details. Load application should be continued to complete failure of the specimen and the break type, as illustrated in C39, should be recorded.

## WHO is Responsible for Curing Facilities?

ACI 301 recognizes that the contractor maintains responsibility of the project site and states that the contractor should provide access to the site, and space and electrical power at the site for initial curing of concrete strength specimens. This presumes that the testing agency is responsible for having facilities at the jobsite that can satisfy the initial curing requirements for strength test specimens. Concrete producers and testing agencies often partner with contractors to build curing facilities at the jobsite. Maintaining proper curing facilities and ensuring that test specimens are properly protected at the jobsite should be discussed during a pre-construction meeting. The testing agency, as required in ASTM C1077, is responsible to maintain facilities for final curing of test specimens at the laboratory in accordance with ASTM C511.

## WHAT are the Reporting Requirements?

Concrete producers are often not provided all the reports of strength tests performed on their concrete mixtures. It is important that concrete producers receive these reports in a timely manner. Obtaining all reports allows the concrete producer to take corrective action if the strength results are trending lower and before a failure occurs. It also allows the concrete producer to collect data for a strength test record to develop submittals for future work. ASTM C94, ACI 318, and ACI 301 state that the concrete producer must receive test reports in a timely manner. The producer should ensure that they are on the distribution list for test reports when agreeing to supply concrete and to discuss this during the pre-construction meeting.

ASTM C31 includes the following reporting requirements:

- Identification number for the test specimens
- Location of concrete represented (in the structure)
- Date, time and name of individual molding specimens
- Results of tests performed on the sample – slump, air content, temperature, and other tests, such as density
- Deviations from the procedures in the standard test methods
- Curing method – for standard curing: method used for initial curing and a record of the maximum and minimum temperatures during this period; and final curing method (at the laboratory)

ASTM C39 includes the following reporting requirements:

- Identification number of test specimens
- Average measured diameter and length of test specimens
- Calculated cross-sectional area of test specimens
- Maximum load applied to test specimens
- Compressive strength, rounded to nearest 10 psi (0.1 MPa)– the average of two or more specimens is calculated before rounding individual cylinders
- Type of fracture – identified to 6 types illustrated in C39
- Defects in specimen or caps
- Age of specimen when tested
- If required, the density of the test specimens.

## WHAT should be Evaluated from Test Reports?

When low strength test results occur, there are several repercussions to the involved stakeholders. The evaluation process to establish the reason for low strength test results can take a considerable amount of time and delay project schedules. Ultimately, this will have financial implications to all involved parties.

There are several details involved when testing concrete. The requirements in the standards are very specific on the procedures to be followed. Most deviations from these procedures will result in low measured strength of concrete and can cause rejection of concrete that is most likely acceptable. Concrete producers commonly overdesign their concrete mixtures to avoid strength problems during a project, and this in itself represents a loss of revenue. The variables that impact the measured strength of concrete, both at the jobsite and at the laboratory, have been quantified in terms of percentage reduction in measured strength (Richardson).

Several details from test reports and the testing process should be tracked and recorded by concrete producers along with information on the mixtures supplied, even when there are no problems with testing. This can help flag a potential problem and identify the reasons for low strength problems when they occur. ASTM C94 suggests three broad reasons for low strength problems – problems with the concrete mixture, production, or testing. This TIP focuses on problems related to testing.

These are suggested items for consideration:

- Educate truck mixer drivers on the details of jobsite sampling, testing and initial curing. Improper procedures should be documented by notes on the delivery ticket and with photos. Some companies require drivers to obtain ACI certification to establish their credibility.
- A representative from the quality control department or sales representative should periodically visit the project site to observe testing and storage of test specimens. The representative should attempt to observe the precautions used when transporting test specimens from the jobsite to the laboratory.
- Record the date of the pour, plant shipped from, mixture identification, ticket number, and other details. Ensure that the test reports represent the correct project, concrete mixture, and date of pour.
- Maintain a record of test results in chronological order by date sampled. If data entry is made on spreadsheets or other software, ensure that the strength for each cylinder tested is recorded for further evaluation of data as discussed below
- Keep a record of the ambient temperature and weather conditions when tests were made. Compare these to the information on the test reports. Historical weather information can be reviewed online
- Review the fresh concrete tests performed on the concrete when strength specimens were made:
  - ◊ Variations of slump, air content, density, and temperature from what was intended will impact the strength test results.
  - ◊ Measured slump should be evaluated relative to a record or notation of jobsite added water or admixture.
  - ◊ Air content should be within the tolerances as specified. Higher air content will reduce strength.
  - ◊ Higher concrete temperature will typically result in higher early age strength but lower strength at later ages. This can impact the rate of strength gain between 7 and 28 days.
  - ◊ Density may not always be recorded, but is a useful test that can be used to identify a problem and to calculate yield. Lower density than what is expected for the mixture can indicate excess air or water.
- Review 7 and 28 day strength results and the rate of strength gain between these ages. In general, only one cylinder is tested at 7 days for information. This should not be compared to the strength acceptance criteria and should not be tagged as a failure based on an assumed 7 to 28 day strength gain. Review the trends for the 7 to 28-day strength gain and evaluate whether it is representative of the particular concrete mixture from previous laboratory or field tests. Significant changes in the 7 to 28 strength gain can point to testing problems.
- Review other information on the test report that is required by the standards
  - ◊ Test identification is related to the mixture supplied
  - ◊ Date and time cylinders were made
  - ◊ Date and time the cylinders were picked up from the jobsite – is the duration at the jobsite less than 48 hours; this might occur on weekends
  - ◊ Date and time the cylinders were delivered to the laboratory – is the duration of transportation less than 4 hours – there may be situations where a longer time is acceptable if the cylinders are properly protected.
  - ◊ Verify test date is consistent with test age required
  - ◊ It is difficult to determine if cylinders that were delivered to the laboratory were de-molded and placed in final curing from the test report, but this could be a cause for low strength results
  - ◊ A record of the maximum and minimum temperature during initial curing at the jobsite. Not conforming to the temperature limits for the initial curing represents the biggest factor that impacts strength test results. This information is required to be reported by ASTM C31, but is not typically reported on the strength test report that includes other fresh property tests. If the laboratory that made the cylinders is different from the one that tested it, this information may be difficult to obtain.

- Review details regarding the strength testing
    - ◊ Is the cylinder diameter reported – it should not be a constant value
    - ◊ Is the reported cross-sectional area consistent with the reported diameter
    - ◊ Is the reported strength consistent with the reported failure load and area
    - ◊ Is there evidence that the cylinder was not tested to complete failure – failure loads are consistently similar
    - ◊ Review break type – in general strength problems cannot be identified to reported break types. However, consistent split edge type breaks indicate a problem with machine alignment, specimen placement, or testing to complete failure. The same break type being reported for all cylinders raises a red flag
    - ◊ If reported, review whether the density of test specimens is consistent with expectations for the mixture. Lower density may indicate problems with the sample as obtained or preparation of the test specimens

Strength data tabulated in a spreadsheet can be analyzed using Control or CUSUM charts (Obla 2014).

## HOW can Strength Data be Analyzed to Identify Testing Problems?

Tabulate the data in a spreadsheet and calculate the following:

- Range of companion cylinders (difference between the maximum and minimum strength), R
- Average Range, $\overline{R}$
- The single operator (also referred to as within-batch) standard deviation, $s_1$, can be estimated from the average range, $\overline{R}$, from a minimum of 10 data sets (Section 4.3.1 in ACI 214R):

$$s_1 = \frac{\overline{R}}{d_2}$$

The single operator coefficient of variation, $V_1$, is then determined for the set of data:

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

Where: $\overline{X}$ is the average strength

$d_2$ is a factor to estimate the standard deviation from the average range

$d_2$ = 1.128 for 2 cylinders and 1.693 for 3 cylinders

The precision statement in ASTM C39 is reproduced in Table 1. It indicates that the coefficient of variation of cylinders made from the same concrete sample should have an average coefficient of variation of 2.4% for lab conditions and 2.9% for field conditions. Further, it also indicates that if two 6 x 12 in. (150 x 300 mm) cylinders are made from the same sample, they should not differ by more than 8% more often than about 1 in 20 tests for field conditions. If there are many occurrences where this range is exceeded, the quality of testing might be questioned. A slightly higher acceptable range can be expected for 4 x 8 in. cylinders, though this is not stated for field conditions in C39.

The multi-laboratory coefficient of variation for compressive strength test results of 6 by 12 in. (150 by 300 mm) cylinders is 5.0%; results of properly conducted tests by two laboratories on specimens prepared from the same sample of concrete are not expected to differ by more than 14% of the average.

The single operator coefficient of variation from a strength data set can be used to evaluate and rate the performance of a laboratory as it estimates the variation attributable to sampling, specimen preparation, curing and testing, with the assumption that proper testing procedures are used. Table 2 contains standards of concrete control related to testing for the single operator coefficient of variation.

**Table 1: Precision Statement in ASTM C39**

| | Coefficient of Variation | Acceptable Range of Individual Cylinder Strengths | |
|---|---|---|---|
| | | 2 cylinders | 3 cylinders |
| 6 by 12 in. | | | |
| Laboratory conditions | 2.4 % | 6.6 % | 7.8 % |
| Field conditions | 2.9 % | 8.0 % | 9.5 % |
| 4 by 8 in | | | |
| Laboratory conditions | 3.2% | 9.0% | 10.6% |

**Table 2: Standards for concrete control for single operator variation (related to testing variation) – ACI 214R**

| Type of testing | Coefficient of variation, % | | | | |
|---|---|---|---|---|---|
| | Excellent | Very Good | Good | Fair | Poor |
| **Field testing** | <3.0 | 3.0 to 4.0 | 4.0 to 5.0 | 5.0 to 6.0 | > 6.0 |
| **Lab trial batches** | <2.0 | 2.0 to 3.0 | 3.0 to 4.0 | 4.0 to 5.0 | > 5.0 |

The single operator coefficient of variation calculated from field test results is expected to be in the range of 2.5 to 4.0 percent for testing that is of good quality. While ACI 214R states that a coefficient of variation less than 2.0% is *excellent,* this should not be considered as typical. There should be some concern as to whether cylinders are being broken to failure or if they are being loaded to a level where strength is considered acceptable for a project. This is not appropriate, since the actual strength of concrete should be reported.

**Numerical Example**

| Date | Cylinder No. 1 | Cylinder No. 2 | Range, R | Range, % of avg. | Test result, psi |
|---|---|---|---|---|---|
| 4/24 | 3235 | 3370 | 135 | 4.1% | 3300 |
| 4/25 | 3220 | 3695 | 475 | 13.7% | 3460 |
| 4/26 | 3010 | 2960 | 50 | 1.7% | 2980 |
| 4/27 | 3135 | 3260 | 125 | 3.9% | 3200 |
| 4/30 | 3390 | 3310 | 80 | 2.4% | 3350 |
| 5/1 | 3415 | 3470 | 55 | 1.6% | 3440 |
| 5/2 | 3505 | 3480 | 25 | 0.7% | 3490 |
| 5/4 | 3530 | 3565 | 35 | 1.0% | 3550 |
| 5/7 | 3310 | 3260 | 50 | 1.5% | 3280 |
| 5/8 | 3395 | 3270 | 125 | 3.8% | 3330 |
| 5/11 | 3190 | 3230 | 40 | 1.2% | 3210 |
| 5/14 | 3215 | 3060 | 155 | 4.9% | 3140 |
| 5/15 | 3160 | 3300 | 140 | 4.3% | 3230 |
| 5/16 | 2615 | 2540 | 75 | 2.9% | 2580 |
| 5/21 | 3180 | 3095 | 85 | 2.7% | 3140 |
| 5/22 | 3090 | 3010 | 80 | 2.6% | 3050 |
| 5/23 | 3415 | 3370 | 45 | 1.3% | 3390 |
| 5/24 | 3260 | 3295 | 35 | 1.1% | 3280 |
| 5/25 | 3610 | 3555 | 55 | 1.5% | 3580 |
| 5/29 | 3570 | 3545 | 25 | 0.7% | 3610 |

Average Range, $\overline{R}$ = 95 psi

Average strength, $\overline{X}$ = 3280 psi

Estimated single operator standard deviation

$$s_1 = \frac{\overline{R}}{d_2} = \frac{95}{1.128} = 84\,\text{psi}$$

Single operator coefficient of variation

$$V_1 = \frac{s_1}{\overline{X}} \times 100 = \frac{84}{3280} \times 100 = 2.6\%$$

For this set of data, the single operator precision of 2.6% is rated as *Very Good* according to ACI 214R. The value is not too low to be concerned about.

Reviewing the data set for acceptable range of cylinders according to the precision statement of ASTM C39, only one set exceeds 8%. This difference was exceeded for the test from 4/25 at 475 psi (13.7%). The test may be considered somewhat suspect, but overall this can be expected about 1 time in 20. So the overall data set is acceptable. If the acceptable range was exceeded 3 or 4 times in this data set, there may be reason to question the testing.

1 MPa = 145 psi

## CONCLUSION

There are many factors that impact the quality of testing. Monitoring various aspects and details of testing, and recording and performing further analysis on the data can ensure that the quality of testing is at the required level. The recommendations in this TIP are intended to provide some guidance on steps that can be taken and details that can be monitored. The NRMCA has published a recommended sequence of steps to follow when low strength results occur (NRMCA Pub 133).

## References


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