Who is Watching Out for the Cylinders?

Proper initial curing of acceptance test specimens benefits all stakeholders

by Karthik H. Obla, Orville R. (Bud) Werner, John L. Hausfeld, Kevin A. MacDonald, Gregory D. Moody, and Nicholas J. Carino

ACI 318-14[1] requires that test specimens prepared for acceptance testing for specified strength shall be subject to standard curing in accordance with ASTM C31/C31M.[2] The strength of standard-cured cylinders does not represent the in-place strength of the concrete in the structure, but it serves as the basis for judging the adequacy of concrete delivered to the project. ASTM C31/C31M also includes an optional "field curing" procedure in which specimens are stored on the structure in an attempt to mimic curing of concrete in the structure. Field-cured specimens are used to determine if a structure may be put into service, evaluate the adequacy of curing and protection of the concrete in the structure, and to help determine form and shoring removal times. Field-cured specimens are not to be used as the basis for acceptance of the concrete as delivered to the project.

Standard Curing

Standard curing of test specimens consists of initial curing at the project site, transportation to the laboratory, and final curing at the testing laboratory. Conditions are specified for each phase. The initial curing portion involves storing the specimens for a period up to 48 hours in an environment that maintains a curing temperature in the range of 60 to 80°F (16 to 27°C) and controls moisture loss from the specimens. For concrete mixtures with a specified strength of 6000 psi (40 MPa) or greater, the initial curing temperature shall be between 68 and 78°F (20 and 26°C). These temperature ranges refer to the temperature of the medium surrounding the specimens, which may be air, water, or damp sand. Curing temperature does not refer to the concrete temperature. After initial curing, the specimens are transported to the testing laboratory. During transport, the specimens are to be protected from mechanical damage (Fig. 1), loss of moisture, and freezing (if applicable). Transportation time is not to exceed 4 hours. The final curing portion involves storing the specimens at a temperature of 73.5 ± 3.5°F (23.0 ± 2.0°C) in water storage tanks or moist rooms conforming to ASTM C511.[3]

An ongoing testing adherence program conducted by the Colorado Ready Mixed Concrete Association (CRMCA) showed that initial curing, as documented by qualified member representatives, was performed in accordance with ASTM C31/C31M at only about half of the project sites observed.[4] Anecdotal evidence indicates that the situation is similar or even worse in other regions (Fig. 2). Further, concrete test reports often do not provide information about initial curing of the specimens, which raises doubts whether test specimens were subjected to initial curing in accordance with ASTM C31/C31M. This article reviews the importance of adhering to the initial curing requirements mandated by ASTM C31/C31M and provides suggestions for ensuring that the responsibility for initial curing be clearly defined at the start of a project.

Fig. 1: Example of improper transportation of test specimens. Early-age specimens are fragile and susceptible to mechanical damage if not protected from jarring. In this example, the specimens are not restrained and can be affected by impact with each other and other surfaces. Lastly, the specimen molds lack covers for controlling moisture loss

Effects of Nonstandard Initial Curing

If initial curing is not in accordance with ASTM C31/C31M, there may be up to a 20% reduction in the 28-day compressive strength.[5-9] Some of the published data are summarized in Table 1 through 3. The data in Table 1 are part of a broader study[5] that involved various cementitious materials, specimen molding temperatures, initial curing conditions (durations and temperatures), and test ages. The data shown are for a concrete mixture proportioned with ordinary portland cement at 517 lb/yd^3 (307 kg/m^3), water-cement ratio (*w/c*) of 0.57, and a 3 to 4 in. (75 to 100 mm) slump. Cylindrical specimens (6 x 12 in. [152 x 305 mm]) were molded at 73°F (23°C) and subjected to initial curing temperatures of 37°F (3°C), 73°F, or 100°F (38°C) for periods of 1 or 3 days. The initial curing was in air, and the measured relative humidity (RH) was nearly 100%, 60%, and 25% for the 37, 73, and 100°F curing temperatures, respectively. At the end of the initial curing period, specimens were transferred to the standard moist room at 73°F until the test age of 28 days.

Specimens initially cured in air for 1 day at 37, 73, and 100°F achieved 100%, 92%, and 88%, respectively, of the strength of specimens that were moist cured at 73°F from the time of molding until testing (5590 psi [38.5 MPa]). Specimens initially cured in air for 3 days at 37, 73, and 100°F achieved 93%, 89%, and 78% of the strength of specimens that were moist cured at 73°F from the time of molding until testing, respectively. While there was no apparent strength reduction associated with initial curing in air at 37°F (3°C), Bloem[5] noted that low initial curing temperatures in the field could be accompanied by a lower RH than was present in the reported study, which could be expected to reduce the 28-day strength.

Table 2 shows the effect of initial curing at the extremities of the temperature and moisture ranges allowed by ASTM C31/C31M on the 28-day compressive strength.[6] The concrete mixture was proportioned with ordinary portland cement from two different sources (Cement A and B)

Fig. 2: Examples of initial curing conditions that do not comply with ASTM C31/C31M.[2] High temperature and moisture loss at the critical early age will lead to reductions in later-age strengths, even if standard curing is provided subsequently

Table 1:
Effect of nonstandard initial curing on compressive strength[5]

Initial curing conditions	Relative 28-day strength, %*		
Temperature	37°F (3°C) at 100% RH	73°F (23°C) at 60% RH	100°F (38°C) at 25% RH
1 day in air†	100	92	88
3 days in air†	93	89	78

*In comparison with compressive strength of 5590 psi (38.5 MPa) determined for specimens moist cured at 73°F and 100% RH from the time of molding until testing

†Specimens were molded at 73°F, subjected to initial curing conditions, and transferred to standard moist room at 73°F for curing until test age of 28 days

Table 2:
Compressive strength as a function of initial curing at minimum and maximum temperatures and moisture conditions allowed by ASTM C31/C31M[2,6]

Initial curing condition*	Relative 28-day strength, %	
	Cement A	Cement B
60°F (16°C) in water	100% (6080 psi [41.9 MPa])	100% (6090 psi [42 MPa])
60°F in air	92	97
80°F (27°C) in water	89	93
80°F in air*	81	88

*Specimens were molded at 73°F, subjected to initial curing condition for 22 hours, and transferred to standard moist room at 73°F for curing until test age of 28 days

Table 3:
Effect of initial curing under hot weather conditions on compressive strength[7]

Type of 1-day initial curing	Temperature range, °F (°C)	Relative strength, %
Outdoor exposure: curing box with thermostatic control; in water	71 to 76 (22 to 24)	100
Laboratory: immersed in lime water (control)	76 to 82 (24 to 28)	100
Laboratory: in air	78 to 82 (26 to 28)	88
Outdoor exposure to sunlight: not protected	71 to 107 (22 to 42)	85
Outdoor exposure: covered with wet burlap and plastic	94 to 140 (34 to 60)	83

Note: Specimens were molded at 86°F (30°C) at the jobsite and subjected to the initial curing condition for 24 hours; transferred to standard moist room at 73°F (23°C) for curing until test age of 28 days at 580 lb/yd^3 (344 kg/m^3), *w/c* of 0.51, and a 3 to 5 in. (75 to 125 mm) slump. Cylindrical specimens (6 x 12 in.) were molded at room temperature (70 to 72°F [21 to 22°C]) and initially cured at 60°F (16°C) or 80°F (27°C) and stored in air or immersed in water for 22 hours. The specimens stored in air were placed in plastic bags and sealed with rubber bands, while the water-immersed specimens were not covered. At the end of the initial curing period, specimens were transferred to a standard moist room at 73°F until the test age of 28 days. Measured strengths were compared with the strengths of the specimens immersed initially in water at 60°F. Table 2 shows that at both 60°F and 80°F, initial curing for 22 hours in air resulted in 3 to 8% lower strengths compared with initial curing under water. Initial curing at 80°F resulted in 7 to 11% lower strengths compared with initial curing at 60°F as long as the moisture conditions were not varied. Initial curing at 80°F in air resulted in 12 to 19% lower strength compared with initial curing at 60°F in water. The specimens cured initially under water had a lower temperature rise compared with the specimens stored initially in air. For specimens initially stored in air, the temperature increase for specimens made with Cement A was greater than for specimens made with Cement B. This explains the greater strength reductions in the specimens made with Cement A. Meininger[6] also found that specimens with 2 days of initial curing exhibited strength reductions that were nearly the same as specimens with 1 day of initial curing.

Table 3 shows the effect of initial curing under hot weather conditions on 28-day compressive strength.[7] Concrete was mixed in a truck and had a slump of 3-3/4 in. (95 mm), air content of 5.8%, and fresh concrete temperature of 86°F (30°C). Cylindrical specimens (6 x 12 in.) were molded and stored initially for 24 hours under five different conditions as shown in Table 3. Specimens were covered with plastic lids. Two sets of specimens were stored inside the laboratory in conditions that would be considered meeting the ASTM C31/C31M initial curing requirements. At the end of the initial curing period, specimens were transferred to a standard moist room at 73°F until the test age of 28 days. Table 3 shows that the covered specimens stored in the laboratory in air had 12% lower strength compared with specimens immersed in lime water. The results show that specimens immersed in water inside a thermostatically controlled curing box on-site attained strengths comparable to control specimens immersed in water in the laboratory (Fig. 3). They also show that specimens exposed to ambient conditions without temperature control exhibited strength reductions of 15 and 17% relative to control specimens. Montoya questioned whether any initial curing method that does not involve immersion in water would be acceptable in all RH conditions.[7]

Studies such as those discussed herein show that the initial curing requirements in ASTM C31/C31M must be followed to obtain measured strengths that represent the true strength potential of the concrete. These studies also show the benefits of placing specimens under water during initial curing.

Fig. 3: Example of a thermostatically controlled curing container with specimens stored under water. If the unit is functioning as specified, initial curing will meet the requirements of ASTM C31/C31M

The Business Case for Improving Initial Curing

In addition to reducing measured strength, inconsistent initial curing during the project is also likely to increase the variation of strength tests. To compensate for both effects and reduce the risk of failing strength tests, concrete mixtures may have to be proportioned to attain a higher average compressive strength. The effect of nonstandard initial curing on other acceptance tests, such as flexural strength in accordance with ASTM C78/C78M[10] and electrical conductance in accordance with ASTM C1202,[11] could be even more significant. Concrete mixtures may have to be designed at a considerably lower water-cementitious materials ratio (*w/cm*) or use materials that can increase the cost and negatively impact workability. Some highway departments are specifying a strength range instead of a minimum strength for acceptance. Improper curing methods make it difficult to comply with such specifications because the upper bound on strength makes it perilous to simply proportion the concrete mixture to attain a higher average compressive strength.

The benefits of proper initial curing of test specimens made at the jobsite can include:

- Concrete mixtures can be designed for lower average strengths, which will help to reduce cementitious materials contents and paste volumes. This in turn can improve concrete performance by reducing the potential for alkali-silica reaction, volume changes due to temperature rise, and drying shrinkage. Concrete mixtures will be more economical, less prone to cracking, and more sustainable; and
- The need for investigations of low strength tests will be reduced only to genuine situations. Investigations of low strength tests often require concrete cores to be taken from the structure and tested in accordance with ASTM C42/C42M[12]—these efforts are expensive and can delay a project, and often result in contentious relationships among project stakeholders. Proper curing of test specimens will reduce the occurrence of low strength tests and thus reduce unnecessary project costs and foster a better partnering environment.

Better durability, improved sustainability, reduced construction time, and reduced costs will increase confidence

Table 4:
ACI requirements regarding initial curing of test specimens

Requirement	ACI 318-14[1]	ACI 301-16[13]	ACI 311.6-09[14]
Acceptance test specimens shall be standard cured in accordance with ASTM C31/C31M	Stated	Stated	Stated
Concrete test report shall include information about the initial curing period	NA	Stated	Testing Agency to provide all project stakeholders maximum and minimum temperatures during initial curing
Provide space and electrical power for initial curing	NA	Contractor to provide	NA
Verify that standard curing is according to ASTM C31/C31M	NA	NA	Testing Agency to verify
Who is responsible for supplying the curing facility on site?	NA	Implied that Testing Agency is responsible	Owner or Owner's representative will provide this. Owner's representative is not defined explicitly

in concrete construction and maintain competitiveness with other construction materials, thus benefitting all stakeholders in a project and the concrete industry at large.

Codes and Standards Requirements

The requirements in various ACI codes and specifications related to initial curing of standard-cured specimens are summarized in Table 4. ACI 318-14, Provision 26.12.3.1; ACI 301-16, Provision 1.6.3.2(e)[13]; and ACI 311.6-09, Provision 2.5.1,[14] all require that specimens for acceptance testing be standard-cured in accordance with ASTM C31/C31M. Thus, the previously stated initial curing requirements of ASTM C31/C31M must be followed.

The reporting section of ASTM C31/C31M requires the agency making the specimens to report the maximum and minimum temperatures of the surrounding environment and the curing method used during initial curing. ACI 301, Provision 1.6.3.1(c), requires that the concrete strength test report includes information on storage and curing of specimens before testing, while ACI 311.6, Provision 3.3.12, requires the Testing Agency to report the maximum and minimum temperatures of the curing environment during the initial curing period to all the parties listed in the test report distribution list.

ACI 301, Provision 1.6.2.2(d), states that the Contractor is to: "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." This implies that the Owner's Testing Agency will be responsible for initial curing. ACI 301, Provision 1.6.2.2(b), also states that it is the Contractor's responsibility to allow the Owner's Testing Agency access to the project site for obtaining samples to make test specimens. ACI 301 defines the Contractor as "the person, firm, or entity under contract for construction of the Work."

ACI 311.6, Section 2.5.1, states that the Testing Agency is responsible for verifying that the cylinders are maintained in accordance with ASTM C31/C31M. ACI 318, ACI 301, and ACI 311.6 require that field technicians who prepare test specimens must have an ACI Field Testing Technician Grade I certification or acceptable equivalent. Thus, it is clear that the agency making test specimens is responsible for verifying conformance to the initial curing requirements.

The controversial topic is: "Who is responsible for supplying the curing facility on site?" ACI 301, Provision 1.6.3.2(e), under the duties and responsibilities of the Owner's Testing Agency, states: "Owner's Testing Agency will make and standard cure the specimens in accordance with ASTM C31/C31M…" Note that this statement is provided as information to the Contractor because ACI 301 is written to the Contractor and not the Testing Agency. This explains why the word "will" is used rather than "shall." Nevertheless, this provision implies that the Testing Agency is responsible for the initial curing and is also responsible for providing equipment needed to comply with the temperature requirements in ASTM C31/C31M. ACI 311.6, Section 2.5.1, which is written to the Testing Agency, states: "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." Unfortunately, there is ambiguity in this provision because the specification does not define the "Owner's representative." Some have interpreted the Owner's representative to be the Architect/Engineer, while others have interpreted it to include the Testing Agency. According to the International Building Code (IBC), the Owner is responsible for hiring the Testing Agency that conducts acceptance testing.[15] In many jurisdictions, it is considered a conflict of interest for the Contractor to hire the Testing Agency that conducts acceptance testing.

Implementation Challenges and Proposed Solutions

The discussion thus far can be summarized as:
- Initial curing in accordance with ASTM C31/C31M benefits all stakeholders, including the Owner; and
- ACI standards require that acceptance test specimens be subjected to standard curing in accordance with ASTM

C31/C31M, which includes initial curing at the jobsite.

Yet, too often we find that initial curing in accordance with ASTM C31/C31M does not happen.

On some projects, the Contractor does not provide space, continuous electrical power, or access to and physical protection for the curing container. Most project specifications address this implicitly by referring to ACI 301. We recommend that guide specifications such as the AIA MasterSpec[16] and project specifications explicitly state that the Contractor is responsible for providing secured space, electrical power, and access for initial curing of test specimens. This is consistent with ACI 301.

ACI 318, ACI 301, and ACI 311.6 require that field technicians be certified. As mentioned previously, ACI 311.6, Section 2.5.1, states that the Testing Agency is responsible for verifying that the cylinders are maintained in accordance with ASTM C31/C31M. Among the project stakeholders, the Testing Agency is expected to have the most knowledge of the requirements for preparing and curing test specimens. We recommend that ACI 311.6, ACI 132R-14,[17] AIA MasterSpec, and project specifications explicitly state that the Testing Agency is responsible for providing the on-site curing container and verifying that test specimens are maintained in accordance with ASTM C31/C31M at the jobsite. This will ensure an unambiguous chain of custody of standard-cured test specimens. It goes without saying that testing agencies should be duly compensated for assuming this responsibility.

We also recommend preplacement meetings be required explicitly by specifications so that on-site curing can be coordinated among the project team members. The NRMCA/ASCC preconstruction checklist for concrete acceptance testing should be used at the meeting.[18]

In some projects, the concrete producer has obtained permission to place continuous temperature monitoring devices within the on-site initial curing facility. These temperature monitoring devices are low-cost; can be reused; and allow wireless data transfer to a cell phone, tablet, or computer. Producers have reported acceptable initial curing practices on those projects.

Adopting Improved Practices

Many jobsites have a field office or a trailer thtat has power and can be maintained at a temperature between 60 and 80°F. Simply covering specimen molds with tight-fitting lids to control moisture loss and storing them inside the office or trailer may be sufficient for meeting the ASTM C31/C31M initial curing requirements, provided the specimens are protected from mechanical damage at early ages. If the trailer has no power or if there is no trailer, the best option is simply to immerse the specimens in water in 5 gal. (20 L) buckets that are capped and stored in the shade or inside a trailer if available.

In summer, ice can be added to the water. In winter, an insulated container such as a beverage cooler may be used, and the specimens can be immersed in warm water. Warm water is usually available from the concrete truck. Some trial and error may be needed to arrive at the appropriate water temperature, depending upon ambient air temperature and the insulating efficiency of the container. The aim should be that the water temperature stays between 60 and 80°F for the duration of initial curing. This may require that the initial water temperature should be about 60°F in summer and about 80°F in winter. In winter, another option is to place the cylinders inside a bucket or an insulated container containing chemical hand warmers, some of which can last up to 24 hours. However, caution should be exercised in placing cylinders in dry insulated containers—the heat of hydration can elevate the air temperature beyond 80°F. Also, handwarmers can cause localized hot spots. As has been discussed, high initial curing temperatures are detrimental to subsequent 28-day strengths, even if moisture loss is controlled.

If beverage coolers and tanks are used for initial curing on unsecured jobsites, they could be stolen. To prevent theft, on-site curing containers should be secured to immoveable objects with chains or security cables. Another option is to place the curing container inside a storage shed. Sheds are available in various sizes. Some are made from steel, are quite heavy, and would be difficult to steal. However, caution is required in summer because the internal temperature in such sheds could easily exceed 80°F. Over the years, testing agencies have also used 5 gal. buckets or beverage coolers marked with the company name and the label "Test Cylinders—Do not Disturb" (Fig. 4). As stated earlier, the party that controls the jobsite should be responsible for providing secured space for initial curing.

Documentation of Initial Curing

Both ACI 301, Provision 1.6.3.1(c) and ACI 311.6, Provision 3.3.12, require that the concrete test report include information about the initial curing period and environment. We recommend that the strength test report includes initial curing information such as maximum temperature and minimum temperature of the surrounding medium, and the method used to control moisture loss. At the very least, the strength test report should include a statement attesting that cylinders were cured in accordance with ASTM C31/C31M. If initial curing was not in compliance with ASTM C31/C31M, appropriate explanation of initial curing should be provided. This will help in any subsequent investigation of low strength tests should they occur.

We also recommend that the temperature sensor be placed in a small specimen mold filled with water or sand. This will ensure that the temperature record does not indicate large fluctuations if the curing container is opened temporarily to

Fig. 4: Example of curing in a beverage cooler: (a) a technician adds water to submerge specimens in covered molds; and (b) the cooler is marked to help mitigate disturbance during initial curing

remove or place test specimens. Requiring compressive strength test reports to include initial curing information will help ensure that the topic of the curing facility is discussed in pre-bid meetings. The use of continuous temperature monitoring devices provides a convenient means for complete documentation of the temperature history of the medium surrounding test specimens during the critical initial curing period.

Summary

ACI standards require that specimens for acceptance testing shall be subjected to standard curing in accordance with ASTM C31/C31M. Standard curing involves initial curing on-site under stipulated conditions. Field observations, however, show that on-site initial curing is often not done in accordance with ASTM C31/C31M. High temperature and moisture loss during initial curing in the field will reduce the 28-day strength, even if standard curing is provided subsequently in the laboratory.

Initial curing in accordance with ASTM C31/C31M benefits all stakeholders, including the Owner. The likelihood of low strength tests is reduced, thus avoiding unnecessary project delays and costs. Concrete mixtures can be designed to attain lower average strengths, which will lower material costs and improve durability and sustainability.

ACI 301 requires the Contractor to provide space and electrical power for initial curing by the Owner's Testing Agency. The AIA MasterSpec and project specifications should state explicitly that the Contractor is responsible for providing secured space, electrical power, and access for initial curing of test specimens.

ACI 311.6 states that the Testing Agency is responsible for verifying that the specimens are stored under conditions in accordance with ASTM C31/C31M. ACI 311.6, ACI 132R, AIA MasterSpec, and project specifications should state explicitly that the Testing Agency is responsible for providing the on-site curing facility (container). This should not preclude the Testing Agency from procuring the facility from the Contractor, but the Testing Agency is responsible for ensuring that test specimens are stored at temperatures conforming to ASTM C31/C31M. The Testing Agency's certified technicians are required to know these requirements.

A pre-placement meeting should be required explicitly by project specifications so that on-site curing can be coordinated among the project team members.

ACI 301 and ACI 311.6 require that the concrete test report includes information about the initial curing period, such as maximum and minimum temperatures of the medium surrounding the specimens. Specifiers should insist on receiving documentation of initial curing conditions. Producers can also request permission to place continuous temperature monitoring devices within the initial curing facility for independent measurements.

By implementing the aforementioned recommendations, it should be possible to improve initial curing of acceptance test specimens. This should reduce the number of low strength tests that arise because of deficient initial curing rather than deficient concrete.

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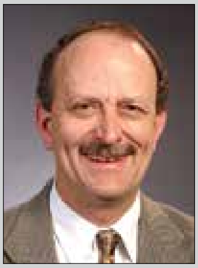

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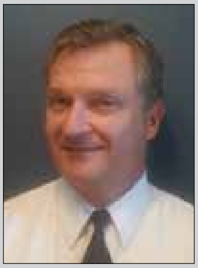

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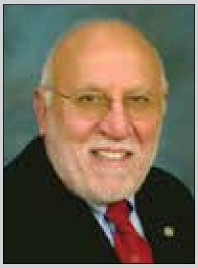

ACI Honorary Member **Nicholas J. Carino** retired from the National Institute of Standards and Technology after 25 years of service as a Structural Research Engineer. He serves on ACI Committees 228, Nondestructive Testing of Concrete; 301, Specifications for Structural Concrete; 329, Performance Criteria for Ready Mixed Concrete; 437, Strength Evaluation of Existing Concrete Structures; and ACI Subcommittee 318-A, General, Concrete, and Construction (Structural Concrete Building Code). He has been recognized by ACI for his contributions to research and standards development related to nondestructive and in-place testing of concrete. He is also a Fellow of ASTM International and served as Chair of ASTM Committee C09, Concrete and Concrete Aggregates.