Variability of 4 x 8 in. Cylinder Tests

Are three cylinders really necessary?

BY RACHEL J. DETWILER, WENDY THOMAS, THORLIEF STANGEBYE, AND MICHAEL URAHN

In November 2005, ACI Subcommittee 318-A voted to allow the use of 4 x 8 in. (100 x 200 mm) cylinders (commonly known as 4 x 8s) for acceptance testing of concrete in Section 5.6.2.4 of ACI 318-08[1] as follows:

> A strength test shall be the average of the strengths of at least two 6 by 12 in. [150 by 300 mm] cylinders or at least three 4 by 8 in. [100 by 200 mm] cylinders made from the same sample of concrete and tested at 28 days or at test age designated for determination of f_c'.

The reason behind requiring at least three 4 x 8s instead of two 6 x 12 in. (150 x 300 mm) cylinders (commonly known as 6 x 12s) is explained in the Commentary:

> Testing three 4 by 8 in. [100 by 200 mm] cylinders preserves the confidence level of the average strength because 4 by 8 in. [100 by 200 mm] cylinders tend to have approximately 20 percent higher within-test variability than 6 by 12 in. [150 by 300 mm] cylinders.

In March 2006, we began asking Engineers of Record to allow us to use 4 x 8s on a case-by-case basis. We continued to use 6 x 12s on ongoing projects, on projects in which the Engineer of Record declined to allow 4 x 8s, and whenever the nominal maximum aggregate size exceeded 1-1/4 in. (32 mm). In anticipation of the upcoming change to ACI 318, we recommended to our clients that we use sets of three 4 x 8s for concrete in buildings and sets of two 4 x 8s where ACI 318 does not apply, such as highway structures. We continued our practice of using sets of two 6 x 12s.

During 2006 and 2007, our metropolitan Minneapolis, MN, central laboratory tested more than 100,000 individual cylinders for compressive strength. These data represent a wide range of field conditions and a consistent set of laboratory conditions. That is, we used the same testing equipment and the same field and laboratory staff to cast and test specimens of both sizes. Field conditions vary with the season and also from job to job. Thus, we believe these data can provide a useful basis for comparing the precision of tests using the two cylinder sizes for acceptance testing and for determining whether there is a need to test three replicate 4 x 8s.

PAST RESEARCH

A study[2] conducted at the National Institute of Standards and Technology (NIST) is referenced in the Commentary to ACI 318-08 as the basis for the statement that 4 x 8s tend to have about 20% higher within-test variability than 6 x 12s. The NIST study included a comprehensive literature review of the factors affecting the measurement of compressive strength. As part of the review, the researchers reported a median coefficient of variation (COV) for 4 in. (100 mm) diameter cylinders that was about 20% greater than that for 6 in. (150 mm) diameter cylinders. The researchers then performed a full-factorial study of test variables on the compressive strength of concrete, including specimen size. For both 4 x 8s and 6 x 12s, the specimens were cast and rodded in three layers instead of the two layers specified for 4 x 8s in the current version of ASTM C31/C31M. The specimens were then cured under water for 2 days, stripped, and returned to the curing tanks. They found a slightly greater within-

test dispersion for the 4 x 8s, but concluded that the difference was not statistically significant.

In a 1993 study,[3] compressive strength data from 3 and 6 in. (75 and 150 mm) diameter cylinders cast under laboratory conditions were analyzed. It was found that the within-test COV for the smaller cylinders was approximately 6%, whereas it was 3 to 4% for the larger cylinders.

In a later study,[4] compressive strength data for 3, 4, and 6 in. (75, 100, and 150 mm) diameter concrete cylinders from 20 publications were analyzed. Eight of these publications also contained data pertaining to the within-laboratory standard deviations for different cylinder sizes, comprising a total of 122 data points. It was found that "[t]he coefficient of variation for strength for 100-mm [4-in.] cylinders is equivalent to that for 150-mm [6-in.] cylinders over a broad range that encompasses normal, high, and very high-strength concrete."[4] The study concluded, "Some specifications require the testing of two 150-mm [6-in.] cylinders to determine strength. Due to the equivalence of coefficients of variation, there is little justification for future specifications to require the testing of 3 rather than 2 cylinders when 100-mm [4-in.] plastic molds are used."

The majority of the data in the literature were obtained from tests of concrete cylinders cast and cured under laboratory conditions. For acceptance testing, however, it's important to examine data based on cylinders cast and cured initially under field conditions that prevail in actual acceptance testing. A previous round robin study[5] evaluated the precision of tests using 4 x 8s cast and cured initially under field conditions. The COVs obtained compared favorably with published values in ASTM C39/C39M-05 for 6 x 12s cast and cured under field conditions. That study, however, did not make any direct comparisons of the two cylinder sizes.

FIELD TESTING

Although we do test cylinders at other ages, the majority of our cylinders are broken at 28 days, and these are the only tests included in our analysis. The cylinders are cast and cured in the field in accordance with the requirements for standard curing in ASTM C31/C31M, stored in the laboratory until age 28 days, and tested in accordance with ASTM C39/C39M.

Temperatures in the Minneapolis area vary from an average low of 4 °F (–16 °C) in January to an average high of 83 °F (28 °C) in July. Because of the wide range of ambient temperatures, proper field curing of the cylinders has always been one of the most challenging aspects of ASTM C31/C31M to meet consistently and in a cost-effective manner. While it's fairly easy to control field curing temperatures where dedicated curing containers are available and properly set up, it's not always practical to provide such curing containers for every concrete placement.

On large or long-term projects we have both the lead time and the resources to provide dedicated curing containers. For winter construction we use temperature-controlled enclosures or "hot boxes" to maintain temperatures. These insulated containers are equipped with thermostatically controlled electric heaters to maintain the appropriate curing temperature.

When temperatures rise to about 75 °F (24 °C), we normally begin using water troughs or stock tanks. During warmer weather the curing temperatures are maintained through the exchange or addition of cool water, ice, or both to the tank.

On shorter or smaller projects, such as residential curbing or small foundations, we typically don't have access to power for heating curing containers, nor is it practical to deliver hot boxes or stock tanks to the site. For these projects we rely on a number of methods to maintain proper temperatures. In late fall and early spring, when temperatures can drop near freezing, we use insulated containers. Depending on the anticipated temperatures, we may provide additional insulation or put cylinder molds filled with hot water (which is generally available from the concrete truck) in with the specimens for additional warmth.

During warm weather, we've had good success with water-filled ice chests. When temperatures approach 90 °F (32 °C) or above, we may also add to the ice chests one or more 4 x 8 molds (marked for that use) filled with ice. We monitor curing temperatures using digital thermometers, predominately waterproof models, as water is often used during field curing. These thermometers record the minimum and maximum temperatures reached inside the curing container. We log these data into our Laboratory Information Management System.

LABORATORY TESTING

The Braun Intertec Materials Laboratory has been accredited by AASHTO Materials Reference Laboratory since 1990. Our concrete laboratory technicians are required to maintain ACI certification for concrete strength testing.

Cylinders arriving at the laboratory are matched to labels generated by computer based on the data entered by the technician in the field. The cylinders are stripped from the molds and labeled with sample identification information, test date, and an "X" to indicate when f_c' is greater than or equal to 6000 psi (41.5 MPa). The cylinders are then transferred to the moist room, where 100% relative humidity is maintained. The ends of cylinders with a specified strength of 6000 psi (41.5 MPa) or greater and those not meeting the criteria of Section 9.5 (finishing) of ASTM C31/C31M or Section 6.2 (perpendicularity) of ASTM C39/C39M are cut off before testing. Cylinders with a specified strength of 6000 psi (41.5 MPa) or greater

TABLE 1:
SUMMARY OF TESTS FOR EACH GROUP OF DATA

f_c', psi (MPa)	Cylinder size, in. (mm)	Specified strength range, psi (MPa)	2-cylinder tests*		3-cylinder tests*	
			Number of tests	Average COV, %	Number of tests	Average COV, %
≤5000 (34.5)	4 x 8 (100 x 200)	1500 to 5000 (10 to 34.5)	8068	2.1	3431	2.5
	6 x 12 (150 x 300)	1000 to 5000 (7 to 34.5)	10,246	2.4	0	—
>5000 (34.5)	4 x 8 (100 x 200)	5500 to 9000 (38 to 62)	2157	2.1	651	2.6
	6 x 12 (150 x 300)	5500 to 9500 (38 to 65.5)	197	2.5	0	—
Total	—	—	20,668	—	4082	—

* Each strength test involves the testing of two or three individual cylinders.

receive sulfur caps. All others are tested using neoprene caps having the appropriate strength rating. Companion 28-day cylinders are tested by the same operator using the same testing machine. Results are recorded on the daily break list and transferred to the Laboratory Information Management System for review by the senior concrete technician.

STATISTICAL ANALYSIS OF DATA

Except for the following cases, our analysis includes all sets of two or three 4 x 8s and two 6 x 12s received in 2006 and 2007 by our central laboratory for testing at an age of 28 days. Results where the technician noted some physical defect that invalidated the test (11 tests) or the cylinders were cast by the Client or the Contractor (708 tests) were not included. In these cases, we have no way of knowing whether the cylinders were cast, cured, and handled in accordance with ASTM C31/C31M. In addition, all sets of three 4 x 8s in which four or fewer cylinders were cast (50 tests) were removed because we could not consistently account for the reason behind testing three replicates when only two replicates were originally planned. All tests of three or more replicate 6 x 12s (226 tests) were also removed. Because only two replicates are required for 6 x 12s, tests of three replicates are anomalous and may indicate there was a problem—whether specifically recorded or not—with one of the first two replicates tested. The remaining data were divided into groups of tests with $f_c' \leq 5000$ psi (34.5 MPa) and $f_c' > 5000$ psi (34.5 MPa). The distribution of the 24,750 strength test results used in the analysis is shown in Table 1.

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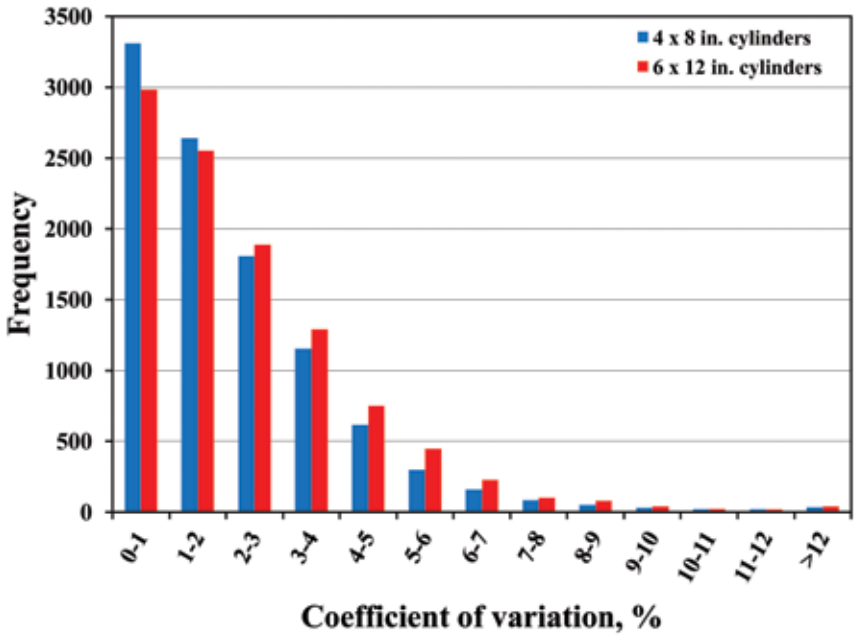

Fig. 1: Distribution of the coefficient of variation for tests of two 4 x 8 in. (100 x 200 mm) and 6 x 12 in. (150 x 300 mm) cylinders including all specified strengths. In both strength ranges, tests of two 4 x 8 in. (100 x 200 mm) cylinders have the lowest mean coefficient of variation

TABLE 2:

Comparison of within-test coefficient of variation with standards of concrete control from ACI 214R-02[6]

f_c', psi (MPa)	Type of test	Distribution of within-test variation				
		COV < 3% Excellent	3% < COV ≤ 4% Very good	4% < COV ≤ 5% Good	5% < COV ≤ 6% Fair	>6% Poor
≤5000 (34.5)	Two 4 x 8 in. (100 x 200 mm)	74%	12%	7%	3%	4%
	Two 6 x 12 in. (150 x 300 mm)	71%	12%	7%	4%	5%
	Three 4 x 8 in. (100 x 200 mm)	71%	17%	7%	3%	3%
>5000 (34.5)	Two 4 x 8 in. (100 x 200 mm)	82%	10%	3%	1%	4%
	Two 6 x 12 in. (150 x 300 mm)	66%	14%	8%	4%	8%
	Three 4 x 8 in. (100 x 200 mm)	79%	9%	4%	3%	6%

Analysis of the data focused on comparing the COVs for tests of two and three 4 x 8s with tests of two 6 x 12s within the two ranges of f_c'. The primary differences between the current study and the round robin study[5] are that all testing in the current study was done within a single laboratory and the number of tests is two orders of magnitude larger.

RESULTS AND DISCUSSION

The COV within each test was calculated using the factors for computing the within-test standard deviation from the ranges given in Table 3.1 of ACI 214R-02.[6] Table 1 provides the number of replicates and the mean COV for each cylinder size by strength range. The results indicate that the mean COV for two-replicate tests of 4 x 8s is significantly lower than either three-replicate tests of 4 x 8s or two-replicate tests of 6 x 12s regardless of the specified strength range. An analysis of variance (ANOVA) significance for the 0.95 confidence interval test is 0.000 in both cases. For cylinders with $f_c' \leq 5000$ psi (34.5 MPa), the mean COV for two-replicate tests of 4 x 8s was 12.5% lower than for 6 x 12s and 16% lower than for three-replicate tests of 4 x 8s. For cylinders with $f_c' > 5000$ psi (34.5 MPa), the mean COV for two-replicate tests of 4 x 8s was 16% lower than for 6 x 12s and 19% lower than for three-replicate tests of 4 x 8s.

As shown in Fig. 1, the distribution of COV for two-replicate tests of 4 x 8s is also similar to that of 6 x 12s.

Table 2 compares the within-test COV with the standards of concrete control given in ACI 214R Table 3.2 for $f_c' \leq 5000$ psi (34.5 MPa) and Table 3.3 for $f_c' > 5000$ psi (34.5 MPa). We see that by this measure, tests of two 4 x 8s compare favorably with tests of two 6 x 12s and with tests of three 4 x 8s. For $f_c' \leq 5000$ psi (34.5 MPa), the percentage of tests considered to have "excellent" within-test variation is about the

same for all. For $f_c' > 5000$ psi (34.5 MPa), the tests of 6 x 12s had a lower percentage of "excellent" and a higher percentage of "poor" within-test variation.

CONCLUSIONS

While these tests do not compare the mean strength obtained using 4 x 8s and 6 x 12s of the same mixture, they clearly indicate that tests of two 4 x 8s do not result in greater within-test variability than tests of two 6 x 12s cast under a wide variety of field conditions. Based on our data, we concur with previous research[4] that "there is little justification for future specifications to require the testing of 3 rather than 2 cylinders when 100-mm [4-in.] plastic molds are used."[4] We encourage other laboratories to publish their data as they make the transition to the use of 4 x 8s so this conclusion can be verified across various testing labs.

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Rachel J. Detwiler, FACI, is an Associate Principal and Senior Materials Engineer at Braun Intertec Corporation in Bloomington, MN, where she provides troubleshooting services and conducts forensic investigations. She is a member of ACI Committee 201, Durability of Concrete, and Chair of Committee 234, Silica Fume in Concrete. She is also a member of ASTM Committee C09, Concrete. She is a licensed professional engineer in Minnesota, Wisconsin, North Dakota, South Dakota, Illinois, and Hawaii.

Wendy Thomas is the Director of the Data Access Core of the Minnesota Population Center at the University of Minnesota in Minneapolis, MN, where she provides specialized access to and custom data analysis of social science data for business, government, and nonprofit agencies. In addition, she provides independent consulting services for data analysis and social science data management. She is Past President of the Association of Public Data Users and is a member of the International Association of Social Science Information Services and Technology and the International Association of Official Statistics of the International Statistical Institute.

Thorlief Stangebye is an Associate Principal and the Laboratory Manager of the Braun Intertec Materials Laboratory at its Bloomington, MN, facility. As Laboratory Manager, he oversees the day-to-day operation of construction materials laboratory testing as well as special testing of products and materials. He is a member of ASTM International, the Society of American Military Engineers, and the American Society for Quality.

Michael Urahn is Corporate Quality Assurance Manager at Braun Intertec. He monitors compliance with quality management system processes and procedures. He is also responsible for reporting and advising senior management on any issues related to the quality management system. He is a member of ASTM International.