Using Historical Cylinder Strength Data for Structural Evaluation

F. Michael Bartlett

Synopsis: Section 20.2 of ACI 318-08 gives provisions for determining required dimensions and material properties for the strength evaluation of an existing concrete structure. Subsection 20.2.3 states "If required, concrete strength shall be based on results of cylinder tests from the original construction or tests of cores removed from the part of the structure where the strength is in question. For strength evaluation of an existing structure, cylinder or core test data shall be used to estimate an equivalent f_c'." The commentary cites two methods presented in ACI 214.4R for determining an equivalent-to-specified f_c' using cores from an existing structure. There are no criteria provided or references cited, however, suggesting how to compute an equivalent f_c' based on cylinder strength data. The paper first identifies necessary conditions for using original cylinder test data to determine a concrete compressive strength for structural evaluation. To investigate strength compliance during initial construction, methods to compute an equivalent-to-specified f_c' value are presented that are based on inverting the conventional acceptance criteria given in ACI 318-08 Section 5.6.3.3. To evaluate an older structure, a method to determine an equivalent-to-specified strength based on the lower-bound fractile of the concrete strength represented by f_c' is presented.

Keywords: concrete cylinder tests, equivalent specified concrete strength, specified concrete compressive strength, strength evaluation, structural concrete

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INTRODUCTION

Section 20.2 of ACI 318-08 gives provisions for determining required dimensions and material properties for the strength evaluation of an existing concrete structure. Subsection 20.2.3 states "If required, concrete strength shall be based on results of cylinder tests from the original construction or tests of cores removed from the part of the structure where the strength is in question. For strength evaluation of an existing structure, cylinder or core test data shall be used to estimate an equivalent $f_c^{'}$. The method for obtaining and testing the cores shall be in accordance with ASTM C42." The commentary to this subsection draws the user's attention to two methods developed by ACI Committee 214 for determining $f_c^{'}$ from cores taken from an existing structure. There are no criteria provided or references cited, however, concerning the computation of an equivalent $f_c^{'}$ based on cylinder strength data.

This paper is intended to rectify this deficiency. It starts with a brief discussion of potential pitfalls that can occur when using original cylinder test data for strength evaluation of an existing structure, and identifies conditions necessary to follow this procedure. Then, paralleling the structure of ACI 214.4R-10 (ACI 214, 2010), it offers two procedures: one applicable for investigating low cylinder strength test results in new construction, based on the provisions of ACI 318-08 (ACI 318, 2008) Section 5.6.3.3, and the other applicable for the strength evaluation of an existing structure based on determining a lower-bound estimate of the fractile of the concrete strength represented by $f_c^{'}$ as derived from the cylinder strength data. A brief comparison of the results obtained using these two methods is then presented and discussed.

RESEARCH SIGNIFICANCE

The provisions in Section 20.2 of ACI 318-08 permit the determination of the compressive strength of concrete in an existing structure using the original cylinder strength test results. Although this procedure may be flawed because it does not directly measure the in-place strength of concrete in a structure, it provides a low-cost approach that is clearly welcome in practice. Current design criteria, including particularly the calibration of strength reduction factors used to verify structural safety under ultimate loading conditions, recognize that the specified compressive strength of concrete is a lower bound on the cylinder strength. This paper therefore proposes two procedures for the computation of an equivalent $f_c^{'}$ based on cylinder strength data for two extremely common circumstances: (1) when low strength test results occur during construction of a structure; and, (2) when an equivalent-to-specified strength is sought for the strength evaluation of an existing structure after it has been occupied.

NECESSARY CONDITIONS TO USE CYLINDER STRENGTH DATA

The use of cylinder data to assess the strength of concrete in an existing structure is potentially deceiving because cylinders give no direct indication of actual in-place strengths. If the concrete was improperly cured or has deteriorated over time, the actual in-place strength could be markedly less than the strengths obtained by testing the original cylinders. Conversely the actual in-place strengths could be markedly greater than the original strengths, as cement continues to hydrate over time, particularly for coarse-ground cements produced before the 1970s. For example, 40-year old cores from the main foundations of Lions' Gate Bridge in Vancouver indicated compressive strengths between 39 and 86 MPa, even though the original specified strength was believed to be 21 MPa (Buckland, 1981).

Thus a decision to determine the concrete strength in an existing structure from the original cylinder test results would be appropriate only if the following conditions are satisfied:

1. Complete cylinder test records from a reputable testing company are available. The reports should include the test specification adopted, typically ASTM C39/C39M (ASTM, 2010 or earlier), and details including the type of fracture, if different from the typical cone failure, and the presence of any defects in the specimen or caps.
2. Visual inspection indicates no evidence that the concrete has deteriorated from its original as-placed condition.
3. If there is more than one concrete strength class in the structure – footings, columns and slabs in a building often have unique specified strengths, for example – the reported cylinder test results can readily be classified according to the strength classes.

It is further assumed in this paper that the strength evaluation being conducted is to assess the safety of the structure when subjected to load combinations that do not involve earthquake loads, so it is appropriate to obtain a lower-bound estimate of the concrete compressive strength. If developing a model for analysis of the structure, or checking serviceability limit states, it is usually more appropriate to use the estimated mean concrete strength instead of a lower bound value. It is often unsafe to use a lower-bound estimate of concrete strength when assessing the probable seismic performance of an existing structure because this causes the capacity of concrete components to be underestimated, and so may underestimate the demands on the energy-dissipating elements of the structure (e.g., Sezen et al, 2011)

METHOD 1: ASSESSMENT OF STRENGTH AT TIME OF CONSTRUCTION

Section 5.6.3.3 of ACI 318-08 provides the following acceptance criteria for concrete, based on the results of compressive cylinder tests:

1. The average of any set of three consecutive strength tests must exceed f_c', and
2. For f_c' < 5000 psi (35 MPa), no individual strength test may fall by more than 500 psi (3.5 MPa) below f_c', or
3. For f_c' > 5000 psi (35 MPa), no individual strength test may fall by more than 0.10 f_c' below f_c'.

A strength "test", in the context of these criteria, is the average of two or more cylinder breaks observed when the concrete has a specified age, typically 28 days.

These acceptance criteria have remained unchanged since the 1971 edition of ACI 318 (ACI 318, 1971). They are intended to balance the risks of the consumer, who doesn't want to accept inferior quality concrete in the structure, and the producer, who doesn't want to see concrete of acceptable quality rejected. Both the consumer's risk and the producer's risk can be reduced by testing larger numbers of specimens, so these acceptance criteria also implicitly represent a further optimization balancing the expected costs of a faulty outcome with the costs of testing additional specimens. The method based on these criteria may therefore not be appropriate for assessing older structures, when the producer is no longer a major stakeholder and the consequences of overestimating the strength on the structural safety may be more severe, but are potentially useful when assessing new construction, where the producer is a major stakeholder.

If low-strength concrete test results occur during construction, Section 5.6.5.2 of ACI 318-08 makes provision for investigating the in-place concrete strength by tests of cores drilled from the area in question if "calculations indicate that load-carrying capacity is significantly reduced". ACI 318-08 does not provide guidance on how to compute a value of specified compressive strength to be used in such calculations, but in this circumstance it is credible simply to invert the traditional concrete-strength-acceptance criteria. Thus the equivalent-to-specified f_c' is taken as the lesser of:

1. Every arithmetic average of any three consecutive strength tests, and
2. For all single strength test strengths less than 4500 psi (31.5 MPa), the test strength plus 500 psi (3.5 MPa), or
3. For all single test strengths greater than 4500 psi (31.5 MPa), the test strength multiplied by (1/0.9).

This approach can be used to determine the equivalent-to-specified strength for a class of concrete used in a specific project. If the construction records are detailed, it may be possible to assign unique equivalent-to-specified strengths to specific components in a structure to assess their structural adequacy, as illustrated in the example below.

Example Application of Method 1

Table 1 summarizes cylinder strength data from a series of consecutive concrete placements during the construction of a concrete high-rise building. The data have been generated by numerical simulation but are based on a real project where the specified 28-day concrete compressive strength was 12000 psi (82.7 MPa). None of the 28-day test results, shown in the fourth column, satisfy this requirement.

Table 1 — Data for Example Illustrating Method 1

Test	Placement Date	Location	28-day Test (psi)	Min. Avg. of 3 (psi)	Test/0.9 (psi)	Equiv. f_c' (psi)
1	24-Oct-10	Cols B1 &B2	10540	10490	11711	10490
2	30-Oct-10	Cols C1 & C2	11160	10367	12400	10367
3	12-Nov-10	Bases D8 & E7	9770	10073	10856	10073
4	14-Nov-10	Cols C6 & C7	10170	9993	11300	9993
5	19-Nov-10	Cols B6 & B7	10280	9913	11422	9913
6	20-Nov-10	Cols E3 & E4	9530	9763	10589	9763
7	25-Nov-10	Cols C3 & C4	9930	9723	11033	9723
8	26-Nov-10	Cols B3 & B4	9830	9523	10922	9523
9	8-Dec-10	Cols B5 & E5	9410	9107	10456	9107
10	9-Dec-10	Cols D4 & D5	9330	9107	10367	9107
11	10-Dec-10	Cols F1 & F2	8580	9107	9533	9107
12	12-Dec-10	Cols D1 & D2	9600	9170	10667	9170
13	15-Dec-10	Cols E6 & F6	9450	9210	10500	9210
14	16-Dec-10	Cols C5 & F5	10020	9537	11133	9537
15	17-Dec-10	Bases G8 & H7	9140	9360	10156	9360
16	18-Dec-10	Cols F3 & F4	9940	9360	11044	9360
17	21-Dec-10	Cols D8 & E7	9000	9000	10000	9000

The analysis using Method 1 is also presented in Table 1. The computed values are not rounded to the nearest 10 psi (0.05 MPa), as is usual practice, to expose the calculation procedures. The "Minimum Average of 3" is the minimum value obtained by inverting the first acceptance criterion assuming the test result is the first, the second, or the third value in the set of three used to compute the average. For example, the three averages involving the Test 3 result are for: Tests 1, 2 and 3; 2, 3 and 4; and 3, 4, and 5. They equal 10490, 10367 and 10073 psi (72.3, 71.5 and 69.4 MPa), respectively, so the minimum value of 10073 psi is shown. Values shown for the first two tests and last two tests involve the averaging of three or fewer specimens in the set: for example, for Test 1, the minimum average is the minimum of: the Test 1 result; the Test 1 and 2 results averaged; or, the Test 1, 2 and 3 results averaged. The "Test/0.9" value is obtained by inverting the second acceptance criterion for the case where the test strengths exceed 4500 psi (31.5 MPa). The equivalent f_c' value shown in the right column is the lesser of the "Minimum Average of 3" and the "Test/0.9" values.

The range of equivalent f_c' values obtained using the method may be practically useful in resolving the strength compliance issue. For example, elements cast on or before November 14th have equivalent f_c' values above 10000 psi (69. MPa) and so may be sufficient given the factored demands. The elements cast between December 8th and 12th with equivalent f_c' values less than 9200 psi (63.4 MPa) are more likely to be insufficient, however, and so more likely to require remedial measures.

METHOD 2: POST-CONSTRUCTION STRENGTH ASSESSMENT

While Method 1 has potential for assessing new construction, it may not be appropriate for assessing an older structure, when the producer is no longer a major stakeholder and the consequences of overestimating the strength on the structural safety may be more severe. In this instance it is appropriate to develop a method to compute a suitable lower-bound exclusion fractile as ACI 214.R4-10 (ACI 214, 2010) does for cores. This requires two steps: determining what fractile of the concrete cylinder strength corresponds to f_c', and then, knowing that fractile, determining how to compute the equivalent specified strength that corresponds to a lower-bound (i.e., safe) estimate of that fractile.

Fractile of Cylinder Strength Represented by f_c'

The definition of a fractile is illustrated using the probability density function of cylinder test strengths shown in Figure 1. Cylinder strengths are typically assumed to be normally distributed, as shown (e.g., ACI 214, 2002). The "fractile represented by f_c'" is the area under the probability density function to the left of f_c', shown shaded and denoted A in the figure. It represents the probability that a test cylinder strength will be less than or equal to f_c'. Typically the average cylinder strength is much greater than the specified strength f_c', because Section 5.3 of ACI 318 requires the concrete producer to achieve a required average strength so that the likelihood of not passing the strength acceptance criteria, as shown above, is in the order of 1%. This overstrength is reflected in the reliability analyses used to compute the strength reduction factors in Section 9.3.2 of ACI 318-08 and so must be accounted for in any calculation of an equivalent-to-specified strength that will be used with these resistance factors.

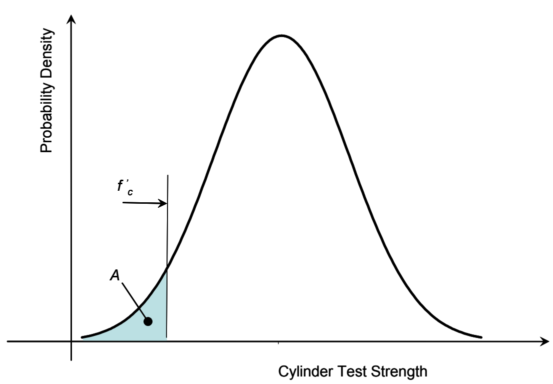

Figure 1 — Fractile of cylinder strength represented by f_c'.

Two approaches to determine this fractile are as follows:

1. Compute fractile values that are consistent with the bias coefficients and coefficients of variation of concrete cylinder strength data for ordinary ready-mix concretes reported by Nowak et al. (2005), which were "analysed" to determine the statistical parameters used for calibration of ACI 318-08.

2. Compute fractile values that are consistent with the required average compressive strengths, f_{cr}', specified in Clause 5.3.2.1 of ACI 318-08.

Fractile Based on Statistical Parameters for Cylinder Strength Data Reported by Nowak et al. (2005)

Nowak et al. (2005) collected a significant quantity of concrete cylinder strength data to derive the strength reduction factors now presented in Section 9.3.2 of ACI 318-08. The actual calibration was based on parameters obtained by "analysis" of the raw strength data. The bias coefficient, representing the ratio of the mean value to the nominal value, was assumed to vary from 1.31 to 1.08 as the specified strength increases from 3000 psi to 12000 psi (20.7 MPa to 82.7 MPa) as shown in Figure 2(a). The coefficient of variation, which is the ratio of the standard deviation to the mean, was deemed to reduce from 0.15 to 0.11 over this range as shown in Figure 2(b). The fractile represented by $f_c^{'}$ therefore increases as the specified strength increases: assuming concrete strengths to be normally distributed, the probability of the actual cylinder strength being less than a specified value of 3000 psi (20.7 MPa) is 8.2% while the probability of the actual cylinder strength being less that a specified value of 12000 psi (82.7 MPa) is 25%, as shown in Figure 2(b).

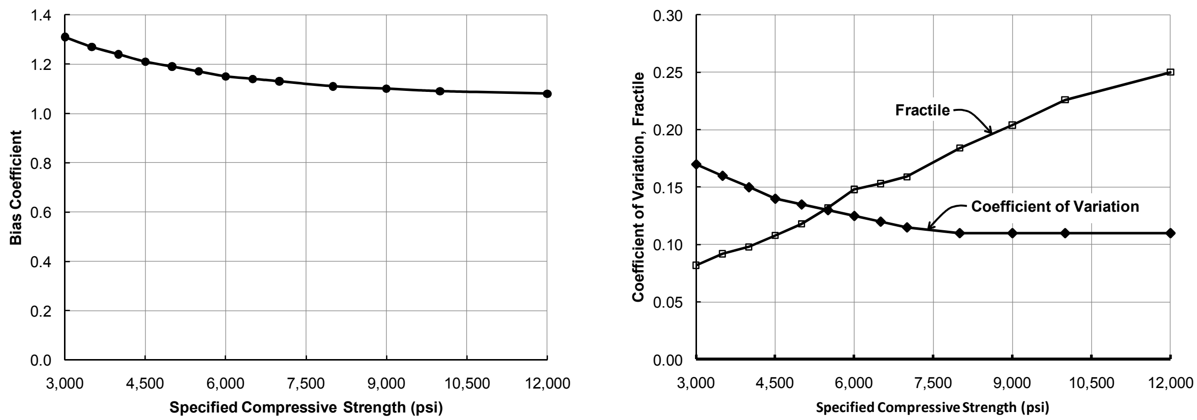

Figure 2 — Statistical Parameters for cylinder strength assumed by Nowak et al (2005) for resistance factor derivation: (a) Bias coefficient; (b) Coefficient of variation and associated fractile value.

It is more realistic to determine fractiles based on the actual data, which don't particularly follow the derived parameters shown in Figure 2. The statistical parameters for ordinary strength concretes shown in Table 2, taken from Table 5-2 of Nowak et al., are based on over 11,000 standard cylinder tests. The bias coefficients are relatively constant for specified strengths between 3500 and 5000 psi, and there is no clear relationship between the specified strength and the coefficient of variation or standard deviation. The fractile represented by $f_c^{'}$ ranges from 4.4% to 15.9%. For specified strengths between 3000 and 5000 psi (20.7 and 35 MPa), the average fractile is 9.1%.

Table 2 — Fractiles Consistent with Ordinary Strength Concrete Data Reported by Nowak et al (2005)

$f_c^{'}$ (psi)	n	Bias	CoV	Std dev	fractile
3000	4016	1.33	0.145	0.193	0.044
3500	527	1.24	0.115	0.143	0.046
4000	2784	1.21	0.155	0.188	0.131
4500	1919	1.19	0.160	0.190	0.159
5000	1722	1.22	0.125	0.153	0.075
6000	130	1.22	0.075	0.092	0.008
Total	11098				

1000 psi = 6.985 MPa

The statistical parameters shown in Table 3, taken from Table 5-4 of Nowak et al. (2005), are for high-strength concretes. The numbers of tests for each specified strength, n, are typically smaller than those for the ordinary concrete strength data shown in Table 2. The bias coefficients do not display a consistent trend with increasing $f_c^{'}$ and the value shown for the specified strength of 12000 psi (84.7 MPa) is quite low. The standard deviations and coefficients of variation are quite consistent, irrespective of the specified concrete strength. The fractiles represented by $f_c^{'}$ range from 8.4% to 36.2%, and the average for specified strengths between 7000 and 10000 psi (48.3 and 69 MPa) is 12.5%.

Table 3 — Fractiles Consistent with High Strength Concrete Data Reported by Nowak et al (2005)

f_c' (psi)	n	Bias	CoV	Std dev	fractile
7000	210	1.19	0.116	0.138	0.084
8000	753	1.09	0.088	0.096	0.174
9000	73	1.16	0.100	0.116	0.084
10000	635	1.13	0.115	0.130	0.159
12000	381	1.04	0.109	0.113	0.362
Total	2052				

1000 psi = 6.985 MPa

The statistical parameters shown in Table 4, taken from Table 5-3 of Nowak et al. (2005), are for plant-cast concretes used for precast concrete construction. The number of test results for a specified strength of 5500 psi (37.9 MPa) is very small, which may explain the low coefficient of variation and very low fractile for that strength category. The average fractile represented by f_c' for the other three strength categories is 6.6%.

Table 4 — Fractiles Consistent with Plant-Cast Concrete Data Reported by Nowak et al (2005)

f_c' (psi)	n	Bias	CoV	Std dev	fractile
5000	330	1.32	0.105	0.139	0.010
5500	26	1.20	0.045	0.054	0.000
6000	493	1.16	0.080	0.093	0.042
6500	325	1.08	0.070	0.076	0.145
Total	1174				

1000 psi = 6.985 MPa

Thus the fractile of the compressive cylinder strengths represented by f_c' typically varies between 4% and 17% according to the data collected by Nowak et al (2005).

Fractile Consistent with the Required Average Compressive Strength Specified in ACI 318-08

Clause 5.3.2.1 of ACI 318-08 specifies a required average compressive strength f_{cr}' to be used as the basis for proportioning the concrete mixture that is intended to ensure that the likelihood of failing each of the concrete acceptance criteria, described in the previous section, is in the order of 1%. For $f_c' \leq 5000$ psi (35 MPa), equations presented in Table 5.3.2.1 require that the required average compressive strength be the larger of:

$f_{cr}' = f_c' + 1.34\, s_s$ (ACI 318 Eq. 5-1)

or

$f_{cr}' = f_c' + 2.33\, s_s - 500$ psi (ACI 318 Eq. 5-2)

where s_s is the sample standard deviation of cylinder strengths obtained from test batches. ACI 318 Eq. 5-1 governs for s_s <505 psi, and implies that the specified strength f_c' represents the 9% fractile of the cylinder strength distribution, irrespective of the magnitude of f_c'. ACI 318 Eq. 5-2 governs for larger sample standard deviations and implies the specified strength represents a fractile that is constant for a given standard deviation, irrespective of f_c', but reduces from 9% as s_s increases.

For f_c' > 5000 psi (35 MPa), equations presented in Table 5.3.2.1 require that the required average compressive strength be the larger of:

$f_{cr}' = f_c' + 1.34\, s_s$ (ACI 318 Eq. 5-1) or

$f_{cr}' = 0.9 f_c' + 2.33\, s_s$ (ACI 318 Eq. 5-3)

ACI 318 Eq. 5-1 governs for $s_s < 0.101\, f_c'$ and again implies that the specified strength f_c' represents the 9% fractile of the cylinder strength distribution, irrespective of the magnitude of f_c'. ACI 318 Eq. 5-3 governs for larger sample standard deviations and implies the specified strength represents a fractile that is constant for a coefficient of variation of the cylinder strength, irrespective of f_c', but reduces from 9% as s_s increases.

It has been shown (Bartlett and MacGregor, 1996) that the actual mean strength of concrete mixes with a given standard deviation does not correspond particularly well to the required strengths computed using ACI 318 Eqs. 5-1 to 5-3. This is also apparent from the values shown in Tables 3, 4 and 5: while the overall average fractile based on 14,324 cylinder tests is approximately 9%, the individual average fractiles can be either markedly lower or markedly higher than 9%.

Practically, the procedure to determine an equivalent specified strength should be based on a single value for the fractile representing the percentage of cylinder tests less than f_c'. Based primarily on the data presented in Tables 3, 4 and 5, the most suitable single value is the 9-10% fractile. This is consistent with the fractile implicit in ACI 318 Eq. 5-1, which often governs the required average compressive strength for a given specified strength.

Procedure for Computing an Equivalent-to-specified Compressive Strength

With the target fractile defined as 9-10%, it remains only to develop a procedure to determine the associated equivalent specified strength. The conventional approach to estimate a fractile value (e.g., ACI 214.4-R10) is the Tolerance Factor Approach involving a tolerance factor, *K*, that accommodates the uncertainties of both the sample mean and the sample standard deviation caused by smaller sample sizes:

$f_c' = \bar{f}_c - K\, s_c$ (1)

where $\bar{f}_c$ is the mean and s_c is the sample standard deviation of the cylinder strengths. Table 5 presents suitable values of *K* for a known sample size *n* that correspond to a 75% confidence level and have been normalized to eliminate the sample size effect for more than 30 specimens. The values shown correspond to a fractile of 10%, which is sufficiently close to the target 9-10% fractile.

Table 5 — Tolerance Factors *K* for Use in Eq. (1)

n	3	4	5	6	8	10	12	15	18	21	24	≥ 30
K	2.16	1.84	1.70	1.61	1.51	1.45	1.40	1.37	1.33	1.32	1.30	1.28

ACI 214.4-R10 (2010) provides a procedure to modify Equation (1) to account for the uncertainty of strength correction factors, which does not diminish as the sample size increases. There are no strength correction factors involved with the interpretation of concrete cylinder strength data, so this modification is unnecessary.

ACI 214.4-R10 (2010) also provides an alternate procedure to determine the equivalent specified strength that generally gives greater values than the Tolerance Factor Approach because core strengths tend to be more variable than the actual in-place strength. While it would be possible to devise a similar alternative procedure, based on the precision statements for cylinder testing given in ASTM C39, this seems unwarranted.

Example Application of Method 2

Original construction records give the following eight cylinder strength test results for a class of concrete in a structure: 6030, 5460, 6500, 6190, 6570, 5030, 5260, and 5720 psi (note 1000 psi = 6.895 MPa). The original records are complete and indicate that the testing was done in accordance with ASTM C39. Visual inspection indicates no evidence that the concrete has deteriorated from its original as-placed condition.

To determine an equivalent specified strength value from these data to use for strength evaluation of the structure using Method 2:

- The mean and standard deviation of the cylinder strengths are computed to be 5845 psi and 570 psi, respectively
- From Table 5, for n = 8, K = 1.51
- The equivalent specified strength, from Equation (1), is (5485 – 1.55x570 =) 4984 psi, say 4980 psi.

If these data are analysed using Method 1, the minimum equivalent specified strength is 5337 psi, say 5340 psi. In this case, the additional safety margin provided using Method 2 corresponds to an equivalent specified strength value that is 6.7% less than the minimum specified strength value obtained using Method 1.

COMPARISON OF RESULTS OBTAINED USING METHODS 1 AND 2

Figure 3 shows a comparison of results obtained using Methods 1 and 2. The data shown are derived by simulation: cylinder strengths were generated assuming the cylinder strength population has a mean value of 5870 psi (40.5 MPa) and a standard deviation of 587 psi (4.05 MPa). For the assumed standard deviation, the mean strength is equal to the required target strength of a mixture with f_c' specified to be 5000 psi (35 MPa) in accordance with ACI 318 Eq. 5-1. The mean strength predicted using Method 1 reduces as the sample size increases as shown in Figure 3(a) because the equivalent-to-specified strength is based on the minimum average of three consecutive tests, or the minimum test strength, and lower realizations of these minima are likely to be realized as the sample size increases. This may not in practice be a serious issue because, as demonstrated in the example involving Method 1, the equivalent-to-specified strength can be computed uniquely for each individual cylinder strength test result, so the minimum value shown in Figure 3(a) need not be applied to the entire data set. The mean strength predicted using Method 2 increases as the sample size increases, particularly for relatively small sample sizes, because the Tolerance Factors, K, shown in Table 5 reduce as the sample size increases. The standard deviation of the predicted strength, shown in Figure 3(b), is a measure of the accuracy of the predicted strength and reduces as the sample size increases for both Methods 1 and 2. This reduction is particularly apparent when Method 2 is used because the larger sample sizes decrease the variability of the sample mean and sample standard deviation of the cylinder strengths, $\bar{f}_c$ and s_c, respectively.

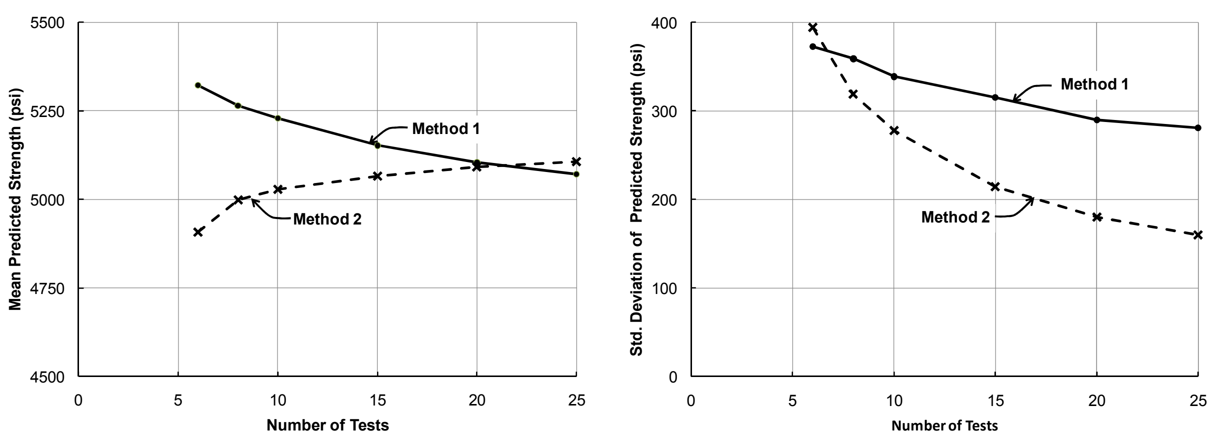

Figure 3 — Comparison of results obtained using Methods 1 and 2: (a) Mean predicted strength; (b) Standard deviation of predicted strength.

SUMMARY

This paper has presented two approaches for determining an equivalent-to-specified strength from original cylinder strength test data for the strength evaluation of a concrete structure. Although permitted by Section 20.2 of ACI 318-08, this procedure creates potential pitfalls because cylinders give no direct indication of actual in-place strengths. It is not recommended that either approach be considered unless: (1) complete cylinder test records are available; (2) visual inspection indicates no evidence that the concrete has deteriorated from its original as-placed condition; and, (3) the available cylinder strength data can be readily classified according to the concrete strength classes present in the structure.

The first method proposed simply inverts the strength acceptance criteria given in Section 5.6.3.3 of ACI 318-08 to compute an equivalent specified strength. It is recommended for evaluating components of an existing structure when these strength acceptance criteria are not met. It has the potential advantage of allowing unique equivalent specified strength values to be computed for each available cylinder strength test result, and so may facilitate distinguishing regions of the structure where the concrete strength, although less than specified, is sufficient to resist the design loadings.

The second method proposed involves computation of a suitable lower-bound of the fractile of the cylinder strength probability distribution represented by the specified cylinder strength $f_c^{'}$. Cylinder test data reported by Nowak et al (2005), gathered as part of the calibration that derived the strength reduction factors in ACI 318-08, suggest that the specified strength represents approximately the 9-10% fractile of the cylinder strength distribution. A tolerance factor approach is proposed to determine the 75% confidence limit on the 10% fractile value. This approach gives equivalent specified strengths that are less than those obtained using the first method, and so is recommended for the strength evaluation of an existing structure after construction and occupancy, when the original ready-mix concrete producer is no longer a significant stakeholder.

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