Excessive Overdesign of Concrete Mixtures for Strength—Causes and Solutions

by Luke M. Snell, Karthik H. Obla, and Nicholas J. Carino

Recently, there have been a lot of discussions about concrete mixtures being overdesigned for compressive strength. Many instances have occurred where concrete mixtures with a 28-day specified strength of 4000 psi have exceeded 7000 psi in measured average strength. These strengths greatly exceed the required average strengths given in ACI SPEC-301-20.[1] This results in an increased carbon footprint due to much higher cementitious materials used and added construction costs. The mixtures also have higher paste contents that can lead to other performance problems, such as cracking, higher in-place concrete temperatures, excessive shrinkage and creep, and alkali-silica reaction. In this article, we discuss some of the reasons why concrete mixtures are overdesigned and offer solutions to reduce this issue.

Concrete Test Results

The making and testing of concrete specimens to determine compliance with project requirements should be in accordance with the practices and test methods specified in the contract documents, such as ASTM C31/C31M and ASTM C39/C39M. These tests are also referred to as acceptance tests. A compressive strength test is the average strength of two 6 x 12 in. or three 4 x 8 in. concrete cylinders.[2]

Compressive strength test results for a given class of concrete are assumed to follow a normal distribution, often called a "bell curve." This assumption is appropriate in most cases if concrete strength does not exceed 10,000 psi.[3] Figure 1 shows a typical normal frequency distribution curve, which indicates the frequency of test results with different strength values.

The normal distribution is mathematically defined completely by two statistical parameters: the population mean $\overline{X}$ and the sample standard deviation s, which is a measure of the variability of test results. The standard deviation depends on the material, manufacturing, and testing variations.

ACI CODE-318 Strength Acceptance Criteria

The ACI Building Code, Section 26.12.3.1,[2] states that the strength level of a concrete mixture shall be acceptable if the following requirements are satisfied:

- Every average of any three consecutive strength tests equals or exceeds the specified strength f_c'; and
- No strength test falls below f_c' by more than 500 psi if f_c' is 5000 psi or less; or by more than $0.10f_c'$ if f_c' exceeds 5000 psi.

If either of these two requirements is not satisfied, steps need to be taken to increase strength test results. If the second requirement is not met, the low-strength test result needs to be investigated.

What is overdesign?

Investigations of low-strength test results typically lead to considerable expense and delays in project schedules. These problems can be reduced by ensuring that the average strength is greater than the specified strength. ACI SPEC-301-20,

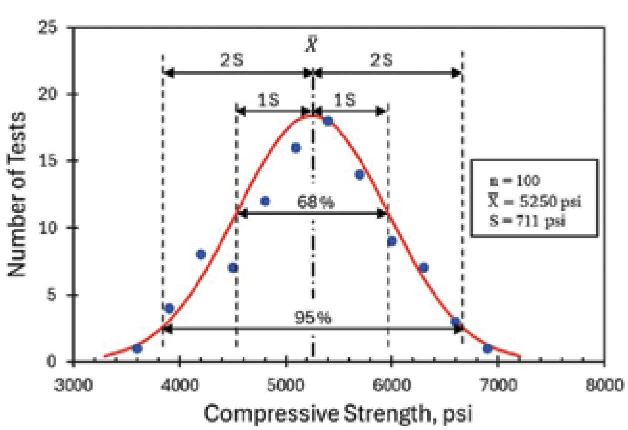

Fig. 1: Normal distribution curve for strength test results

Table 4.2.3.3(a)1, provides a way to calculate the required average strength so there is a high likelihood of meeting the acceptance criteria. It states that the proposed concrete mixture should be proportioned to produce an average strength that is greater than the values calculated by the following equations:

$$f'_{cr} = f'_c + 1.34ks \quad (1)$$

$$f'_{cr} = f'_c + 2.33ks - 500 \text{ (if } f'_c \leq 5000 \text{ psi)} \quad (2a)$$

or

$$f'_{cr} = 0.90 f'_c + 2.33ks \text{ (if } f'_c > 5000 \text{ psi)} \quad (2b)$$

where f'_{cr} is the required average strength for the mixture; f'_c is the specified strength given in the specifications; and k is the factor for increasing the sample standard deviation s, if less than 30 test results are considered in calculating the standard deviation. The k values are provided in Table 4.2.3.3(a)2 of ACI SPEC-301-20.

The standard deviation is determined from strength test results obtained in past projects for similar concrete mixtures. ACI SPEC-301-20, Sections 4.2.3.4(a) and 4.2.3.4(b), provide requirements for past strength records. In the absence of past records, the required average strength must be greater than f'_c by a fixed value that depends on f'_c. This is provided in Table 4.2.3.3(b) of ACI SPEC-301-20.

The ACI SPEC-301-20 equations have been developed statistically to ensure that the likelihood of failing to meet the Code strength acceptance criteria is not greater than one in 100.

In summary, in industry parlance, overdesign is the difference between f'_c and the average strength that is attained in the project. This is shown in Fig. 2. As will be explained, the problem is that $\bar{X}$ is often much greater than f'_{cr}. Also, there will always be a fraction of test results below the specified strength.

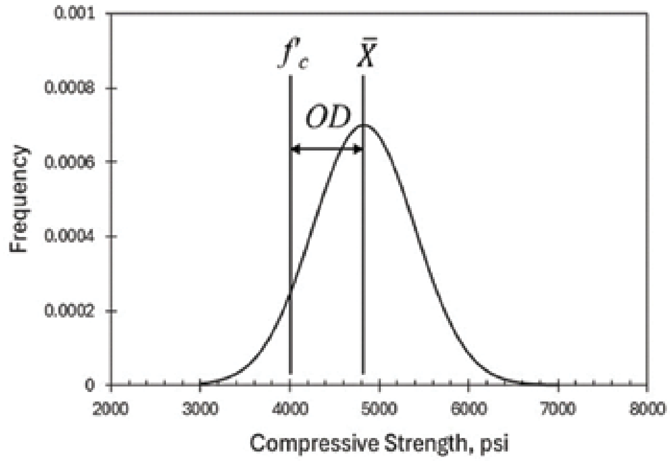

Fig. 2: Overdesign (OD) strength shown as the difference between the specified strength and the average strength attained in the project

Design Example

f'_c = 4000 psi (from the project's specification)

s = 412 psi (calculated from 30 test results from recent production by the batch plant for this or similar mixture proportions)

k = 1.0 (from ACI SPEC-301-20, Table 4.2.3.3(a)2)

Calculation of the required average strength of the mixture using Eq. (1) and (2a):

$f'_{cr} = 4000 + (1.34 \times 1.0 \times 412) = 4550$ psi

$f'_{cr} = 4000 + (2.33 \times 1.0 \times 412) - 500 = 4460$ psi

The higher value is to be selected. Therefore, the required average strength for the mixture would be 4550 psi. The mixture submittal should document that the proposed concrete mixture proportions will produce an average compressive strength equal to or greater than 4550 psi. So, the overdesign for compliance with ACI SPEC-301-20 is 550 psi. This ensures a 99% likelihood that the ACI CODE-318-19(22) acceptance criteria will be satisfied.

As stated earlier, there have been instances of overdesigns exceeding 3000 psi. It can be calculated that every 100 psi increase in average strength would contribute about a 2% increase in embodied carbon. This calculation is based on the National Ready Mixed Concrete Association (NRMCA) industry-wide life-cycle assessment for ready mixed concrete.[4] So, reducing excessive overdesign values is desirable and beneficial for several reasons, as mentioned in the introduction.

On a given project, four separate entities affect the average strength of concrete. These are the licensed design professional (LDP) that develops the specifications, the concrete supplier that produces the concrete to the required specifications, the contractor that buys and places the concrete, and the testing agency that samples and tests the concrete delivered to the jobsite. Each of these entities has to play their part if unnecessarily high overdesigns are to be avoided.

Can We Reduce Overdesign?

Licensed design professional

The LDP determines the specified strength of the concrete based on the structural design requirements. The LDP also ensures that the concrete has sufficient durability. The durability requirements of the concrete are covered in Chapter 19 of ACI CODE-318-19(22). This chapter defines four exposure categories (freezing and thawing, sulfate exposure, contact with water, and corrosion protection of reinforcement) and various exposure classes based on the severity of each exposure category. It also defines the concrete requirements for each exposure class. The primary intent of these requirements is to provide sufficient resistance to penetration by water and dissolved chemicals that can cause durability failures. This is addressed by stipulating a maximum water-cementitious materials ratio (w/cm) and a minimum f'_c. Because w/cm cannot easily be verified during construction, the strength requirement serves as an acceptance criterion. As listed in Table 19.3.2.1 of ACI CODE-318-19(22), the paired *w/cm* and strength requirements for different exposure classes are: 0.40 and 5000 psi; 0.45 and 4500 psi; 0.50 and 4000 psi; and 0.55 and 3500 psi. To summarize, the LDP selects a f_c' that satisfies structural design requirements as well as durability requirements.

In addition to strength and *w/cm*, ACI CODE-318-19(22) requires the LDP to specify an air content based on the nominal maximum aggregate size and the freezing-and-thawing exposure class (Table 19.3.3.1). The specified air contents can be reduced by 1% if f_c' equals or exceeds 5000 psi (Section 19.3.3.6).

Frequently, the LDP specifies additional requirements over and above the ACI CODE-318 requirements. Some of these and their implications on the overdesign are discussed herein.

Minimum cementitious materials requirements: Some LDPs will specify a minimum cementitious materials content. For example, a specification that requires a minimum cementitious materials content of 700 lb/yd^3 and a specified compressive strength of 4000 psi can result in an average strength of over 7000 psi, that is, an overdesign of about 3000 psi. The implication of minimum cementitious materials content requirement discussed in ACI PRC-329.1T-18 concludes that there are numerous benefits associated with eliminating requirements for minimum cementitious materials content and adopting performance-based alternatives in specifications.[5]

Overly conservative interpretation of Code requirements: ACI CODE-318-19(22) stipulates a maximum *w/cm* only for concrete durability exposure classes F1 to F3, S1 to S3, W2, and C2. Requiring a low *w/cm* for concrete that is not subject to such durability exposure classes or requiring a lower *w/cm* than that warranted by the durability exposure class will result in higher average strengths. For example, for concrete without any durability exposure requirements, it is not uncommon to see a f_c' of 4000 psi, a maximum *w/cm* of 0.40, and no air entrainment. The average compressive strength for such a mixture is likely to be over 7500 psi, that is, an overdesign of 3500 psi. This is roughly three to five times the overdesign needed to have a high likelihood of meeting the strength acceptance criteria, depending on production variability.

ACI CODE-318-19(22) requires entrained air content only for concrete durability Exposure Classes F1 to F3. A column subject to Exposure Class F1 requires an air content between 3.5 and 6.0%, depending on the aggregate size (Table 19.3.3.1). If the LDP wants to be conservative and selects a target air content of 6.5%, there can be about a 10 to 30% loss in strength, with a higher percentage strength loss for higher-strength concretes.[6] Specifying air contents that exceed the Code requirement results in mixtures with a higher carbon footprint. Researchers are conflicted about the need for air entrainment for high-strength concrete.[6] Because strength loss is greater for high-strength concrete, the air content required by the Code should not be exceeded for high-strength concrete columns.

In the event of a low-strength investigation, ACI CODE-318-19(22) requires that if coring is necessary, three cores are to be taken from the area of the suspected low-strength concrete. The average strength of the three cores needs to be at least 85% of f_c' with no single core strength below 75% of the f_c' (Section 26.12.6.1). The authors have seen project specifications requiring concrete cores to exceed 100% of the specified strength. Such specifications tend to increase the overdesign so that the likelihood of having to conduct low-strength investigations is reduced. ACI E702.8-22 provides guidance for evaluating concrete test results according to the Code through three case studies.[7]

Lack of knowledge about ACI acceptance criteria for specimens: As stated earlier, according to ACI CODE-318-19(22), Section 26.12.3.1, low-strength investigations are required only if a single test result falls below f_c' by 500 psi for f_c' less than 5000 psi or $0.10f_c'$ if f_c' exceeds 5000 psi. Recall that a strength test result is the average strength of two 6 x 12 in. or three 4 x 8 in. cylinders.

One of the authors was contacted by an LDP about doing a low-strength investigation when one cylinder from a test result was below the f_c' or when a strength test result was below f_c', but not 500 psi below f_c'. These misinterpretations of Code requirements invariably lead to project delays, increased costs, and disputes. To reduce the chance of such unnecessary disputes, the concrete producer may choose to use a higher overdesign than is necessary.

Not designing structural members for actual concrete strength: Sometimes the LDP may reduce the number of strength classes to avoid complexity. This results in some parts of the structure having a compressive strength that is much higher than that required for safety. Alternatively, the compressive strength required to meet the Code exposure classes for durability may be higher than the compressive strength used for structural design. In such situations, the structural elements should be designed to take advantage of the higher strength needed for durability. This may result in reduced member sizes, which in turn will lead to reduced dead load and a lower carbon footprint.

Some structural elements, such as foundations, may not have to resist design loads for several months after they are built. In such situations, it may be prudent to specify strength at 56 days. Alternatively, a strength versus age relationship can be developed and a lower 28-day strength can be accepted if curing is adequate to ensure the required strength development.

Some LDPs determine the required average strengths in accordance with Table 4.2.3.3(b) of ACI SPEC-301-20, even if past strength test data are available. This requires an overdesign of 1200 psi for f_c' of 4000 psi, which in most instances will be higher than the overdesign calculated if past data are available.

NRMCA Publication 2PE004-21[8] provides several suggestions on how LDPs can improve specifications and ensure better performance and sustainability.

Contractor

Requiring high early strength: For rapid scheduling of construction operations such as formwork release or application of prestressing, high-early-age strengths may be required. An arbitrary strength requirement of 75% of f_c' at 2 or 3 days may translate to a strength well over 7000 psi at 28 days, even though only 4000 psi may be required by the structural design. Thus, the unintended consequence of requiring an arbitrary high-early-age strength will result in excessive overdesign of the concrete mixture. The early-strength requirements should be based on actual early design loads instead of an arbitrary requirement such as 75% of f_c' at 3 days.

Testing agency

Initial curing at the jobsite: ACI CODE-318-19(22), Section 26.12.1.1, requires that test specimens prepared for acceptance testing for f_c' shall be subject to standard curing in accordance with ASTM C31/C31M. 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. Standard curing of test specimens consists of initial curing at the project site, transportation to the laboratory, and final curing at the testing agency. Acceptable conditions are specified for each phase. The initial curing portion involves storing the specimens for a period of up to 48 hours in an environment that maintains a curing temperature in the range of 60 to 80°F and controls moisture loss from the specimens. For concrete mixtures with f_c' of 6000 psi or greater, the initial curing temperature shall be between 68 and 78°F.

ACI SPEC-301-20, Section 1.7.2.2(c), requires the contractor to supply electricity and space to store the cylinders while they are on the construction site. ACI PRC-132-14 states that the LDP should define the responsibilities for initial curing in the construction documents, and the testing agency should include the cost of the initial curing in the bid for testing services.[9] In a majority of projects, however, cylinders are not subject to initial curing in accordance with ASTM C31/31M.[10] In too many projects, we have observed cylinders left unprotected in temperatures exceeding 90°F or in freezing weather. Several studies have shown that if cylinders are not subject to proper initial curing, the strength loss can be about 20% compared with cylinders subject to standard curing.[11,12] An added problem is that many jobsites are secured and closed on the weekends. Concrete cylinders cast on Friday cannot be picked up until Monday (if Monday is a holiday, they would be picked up on Tuesday). This results in cylinders being on the jobsite for more than the allocated 48 hours.

Because the jobsite conditions are likely unknown when the mixture proportions are being developed, the concrete producer may increase the overdesign to compensate for possible lapses in following standard procedures for curing the specimens.

Lack of enforcement of testing standards: Some stakeholders (this could be the owners, LDPs, or contractors) view testing only from a cost viewpoint and not as a professional service. Even though ACI CODE-318-19(22), Section 26.12.1.1, states that certified testing agencies and certified technicians are needed to test the concrete, this is not always enforced on projects. The selection of the testing agency is often based on a low bid rather than qualifications. There is little or no monitoring of the testing services as long as no issues are identified. When we do seminars throughout the country, we hear complaints that there is a testing agency in the area that is a high-volume, low-quality company. In many cases, contractors and concrete producers do not confront these problematic testing agencies because they may have to work with them on future projects. If the entity that hires the testing agency does not ensure the quality of the testing, the producer may choose to excessively overdesign the concrete to account for the possibility of poor testing.

Inability of the concrete producer to obtain test results: Concrete test results are often not routinely sent to concrete producers unless there are low-strength results. Concrete producers are unable to see how the strength test results are trending and make mixture adjustments to avoid excessive overdesign or low-strength investigations. Concrete producers are left "flying in the dark," and to protect themselves, they overdesign the concrete mixtures.

ACI SPEC-301-20, ACI SPEC-311.6-18,[13] and the AIA MasterSpec[14] state that the concrete producer is entitled to receive strength test reports in a timely manner. While testing agencies have a contract to send test reports to the people identified in their contracts, they have a responsibility to inform their clients about the ACI requirements to share test reports with the producer.

Concrete producer

Rational Code interpretations: Because concrete strength test data typically follow a normal distribution, there is always a probability of a failing test result regardless of the average strength. However, the higher the average strength, the lower the probability of a failing test result. Because a typical concrete company has its concrete tested thousands of times every year, a chance of one test result in 100 failing guarantees multiple low test results in a year. This could be an expensive problem that the concrete producer would rather avoid, leading to the production of concrete with an excess overdesign so that the chance of having failing test results is much lower than one in 100 tests.

The ACI SPEC-301-20 equations to calculate the required average strength are based on a probability that one test in 100 will fail the acceptance criteria. Yet, ACI CODE-318-19(22), Section 26.12.3.1, requires a low-strength investigation if the second acceptance criterion (Eq. (2a) and (2b)) is not met. However, given that some low test results are inevitable, the LDP should use engineering judgment. The LDP should determine if there is an actual strength deficiency before launching into a coring program. If the likelihood of low-strength concrete is confirmed and calculations indicate that structural adequacy is significantly reduced, then core tests can be considered. NRMCA Publication No. 133 provides a stepwise approach for conducting investigations of low-strength test results.[15] It discusses steps the project team can undertake before taking cores from the structure.

Inability to change mixture proportions: Once a proposed mixture has gone through the multistep process of approval, it can be difficult to get approval to make a change. Usually, an approved mixture will be used throughout the project. This means that in a long-term project, the concrete producer would need to design for the worst-case conditions when it comes to the quality of the materials, manufacturing, and testing. Thus, in most situations, the mixture will be overdesigned except if the worst-case conditions occur.

Commentary Section R26.12.3.1(b) of ACI CODE-318-19(22) lists several reasons why it may be necessary or beneficial to adjust concrete mixtures during the course of a project. The Code states that evidence acceptable to the LDP shall be submitted to demonstrate that the modified mixture complies with the requirements in the construction documents. Industry practice is to calculate a psi/lb value (compressive strength per lb of cementitious material) and adjust cementitious materials contents to accommodate small changes in strength. This approach can work only if the material sources are not changed. Some agencies may permit small changes to mixtures without requiring a submittal. For example, the Florida Department of Transportation allows the cementitious materials content to vary ±6.5% without a submittal.[16] Admixture dosages can also be varied. This allows the concrete producer to adjust mixtures as job conditions change and avoid proportioning for the worst-case condition.

Quality control issues: The mixing water content in a batch can vary due to an unknown amount of wash water present in the mixer drum before batching, incorrect aggregate moisture determinations, incorrect amount of batch water, and water added at the wash rack and the jobsite. For these reasons, the exact amount of water is not known, and the *w/cm* cannot be calculated accurately. A variable *w/cm* can lead to variability in concrete strength.

In addition to the mixing water variation, there can be variability due to materials, manufacturing, and testing. On long-term projects, there can be different personnel performing these functions, which adds to the variability.

Table 1 shows the calculated overdesigns for various standards of concrete control from ACI PRC-214-11(19) for concrete with $f_c' = 4000$ psi.[17]

By reducing the standard deviation from 1500 to 450 psi, the overdesign can be reduced from 3000 to 600 psi. Interestingly, if a producer wants to be conservative and design the mixtures for a one in 1000 failure probability (10 times less risky than ACI SPEC-301-20), they will have to raise the overdesign by just 290 psi if the standard deviation is 450 psi, but raise the overdesign by 1140 psi if the standard deviation is 1500 psi. So, attaining a lower standard deviation will provide a substantial increase in risk reduction for a smaller increase in overdesign, which is in the best interest of all stakeholders including the owner.

Some producers may choose to use an excessive overdesign instead of improving concrete quality practices. This approach can be discouraged by requiring producers to have personnel, plants, and trucks that are qualified according to local Department of Transportation (DOT) or NRMCA requirements. Improved quality practices targeting a lower standard deviation and lower overdesign are penalized by concrete specifications that have minimum cementitious materials, or unnecessary maximum *w/cm* requirements, or both.

Conclusions

Overdesign of concrete mixtures is a necessary part of producing quality concrete that will comply with acceptance criteria. The average strength requirements in ACI SPEC-301-20 provide acceptable values of overdesign. But as discussed in this article, there are many reasons why higher overdesigns are common. However, excessive overdesign leads to higher costs, poor concrete durability, and is not good for the environment. To avoid unnecessarily high overdesigns, we provide the following recommendations:

- Avoid specifying minimum cementitious materials contents in project specifications;
- Specify the maximum *w/cm* that ACI CODE-318 requires for the applicable exposure classes. Do not specify a lower maximum *w/cm*;
- Specify air content only if the ACI CODE-318 exposure classes require it, and do not specify a higher air content than the Code requirement. This is particularly true for high-strength concrete;
- Be clear in the specifications that different ACI CODE-318

Table 1:
Calculated overdesigns for various standards of concrete control for f_c' of 4000 psi

Quality standards (ACI PRC-214-11(19))	Excellent	Very good	Good	Fair	Poor	Poor	Poor
s, psi	350	450	550	650	750	1200	1500
f_c' (ACI SPEC-301-20), psi	4470	4600	4780	5020	5250	6300	7000
Overdesign, psi	470	600	780	1020	1250	2300	3000

strength acceptance criteria apply for cylinder and core strengths. Arbitrary, unclear, or more stringent requirements result in high overdesigns;
- Use field strength test records if available to calculate the required average strength;
- Require high early strength only if needed. The early-strength requirements should be based on early design loads instead of arbitrary requirements such as 75% of f_c' at 3 days. If the 28-day strength will be higher because of high-early-age strength requirements or durability exposure considerations, take advantage of the higher strength in the structural design;
- Make sure concrete test specimens are cured and tested in accordance with the applicable standards, particularly their initial curing, which is often overlooked. Ensure inspectors enforce initial curing of specimens on the jobsite;
- Ensure testing agencies performing acceptance testing conform to ASTM C1077 and technicians testing concrete have ACI field or laboratory certifications;
- Ensure all stakeholders, particularly concrete producers, receive concrete acceptance test results in a timely manner;
- There is always the possibility of a small number of test results not meeting the ACI CODE-318 acceptance criteria even if the overdesign meets project requirements. The LDP should use engineering judgment in evaluating the significance of low-strength test results;
- Allow the cementitious materials contents and admixture dosages to vary over a specified range without requiring a new mixture submittal; and
- Concrete producers should follow good quality control practices and strive for a low standard deviation and a low overdesign. Ensure producers have personnel, plants, and trucks that are qualified according to local DOT or NRMCA requirements.

While we have identified many approaches for reducing the overdesign of concrete, implementing just a few of them can result in substantial reductions. In some ways, the approaches go hand in hand. For example, performance-based specifications (first two bullets) and testing in accordance with standards (the seventh bullet) will motivate producers to improve quality control and attain a lower standard deviation, thereby permitting a lower overdesign. If many of the steps suggested above are undertaken, a reasonable overdesign can be around 800 psi for concrete with a f_c' below 5000 psi, rather than the 1500 to 3000 psi used currently in many projects.

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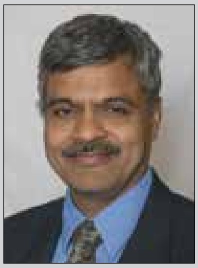
Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

Selected for reader interest by the editors.

ACI Honorary Member **Luke M. Snell** is a Concrete Consultant and a Professor Emeritus at Southern Illinois University Edwardsville, Edwardsville, IL, USA. He is a member and past Chair of ACI Committees 120, History of Concrete, and E702, Designing Concrete Structures. Snell is also a member of ACI Committees C630, Construction Inspector Certification, and S801, Student Competitions. He is a licensed professional engineer in Missouri.



Karthik H. Obla, FACI, is Senior Vice President of Technical Services at the National Ready Mixed Concrete Association (NRMCA), Alexandria, VA, USA. He is Chair of ACI Committee 214, Evaluation of Results of Tests Used to Determine the Strength of Concrete, a member and past Chair of ACI Committee 232, Fly Ash and Bottom Ash in Concrete; and a member of ACI Committees C690, Concrete Quality Technical Manager Certification; 201, Durability of Concrete; 211, Proportioning Concrete Mixtures; 236, Material Science of Concrete; 240, Pozzolans; 329, Performance Criteria for Ready Mixed Concrete; 365, Service Life Prediction; and 555, Concrete with Recycled Materials. He has served as Chair of ASTM Subcommittee C09.49, Pervious Concrete. He received his BTech in civil engineering from the Indian Institute of Technology (IIT BHU) Varanasi, Varanasi, Uttar Pradesh, India, and his MS and PhD in civil engineering from the University of Michigan, Ann Arbor, MI, USA. Obla is a licensed professional engineer in Maryland.

ACI Honorary Member **Nicholas J. Carino** retired from the National Institute of Standards and Technology after 25 years of service as a Research Structural Engineer. He serves on several ACI committees, including E707, Specification Education; 228, Nondestructive Testing of Concrete; 301, Specifications for Concrete Construction; 329, Performance Criteria for Ready Mixed Concrete; 437, Strength Evaluation of Existing Concrete Structures; and 562, Evaluation, Repair and Rehabilitation of Concrete Structures; and ACI Subcommittee 318-A, General, Concrete, and Construction. Carino is also a Fellow of ASTM International and served as Chair of ASTM Committee C09, Concrete and Concrete Aggregates.