Expected compressive strength in precast, prestressed concrete design: A methodology to analyze regional strength results

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- A methodology was proposed for generating expected concrete strength prediction models using regional strength test data.
- The proposed methodology was implemented for a data set representing approximately 1900 Alabama bridge girder production events that took place at four precast, prestressed concrete plants in the southeastern United States.
- The resulting strength prediction models were compared with empirical prediction models published by others.

Concrete production relies on a combination of equipment, materials, methods, and labor, each with its own associated variability. As a result, inherent statistical variability is expected in measured concrete strength results. Appropriate characterization of expected concrete strength is critical to ensure structural reliability[1] of precast concrete components as well as to ensure that designers can predict deformational behavior (for example, camber and deflection) with sufficient accuracy to avoid fit or functional use issues. Producers often rely on American Concrete Institute (ACI) design guidance[1,2] to help select appropriate mixture proportions to meet the specified compressive strength requirements; however, failure to concurrently account for the expected modulus of elasticity in serviceability design may lead to undesirable service limit state behavior.[3] Camber, deflections, and prestress losses in precast, prestressed concrete elements can differ greatly from predicted values calculated using specified material properties. As an example, the significant differences in measured versus predicted camber and effective prestress are evident in **Fig. 1** for actual prestressed concrete bulb-tee bridge girders.[4] To address this design challenge, previous researchers[5–8] have reviewed historical strength test records for precast, prestressed concrete girders for selected U.S. regions and proposed single-factor empirical expressions enabling designers to predict expected concrete compressive strength as a function of specified strength.

In a previous paper,[9] the authors demonstrated the limitation of relying on a single-factor approach for developing

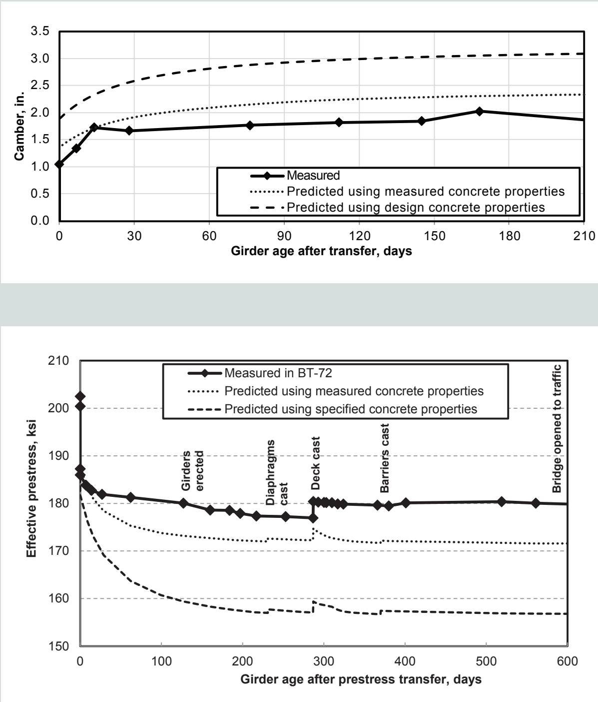

Figure 1. Camber and effective prestress in precast, prestressed concrete bridge girders. Note: BT-72 = PCI bulb-tee girder with 72 in. height. 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

strength prediction models and outlined a potential approach to generate a strength prediction model based on ACI 214R.[1] It was observed that for high-strength concretes, the average difference between measured and specified strength is less than the average difference for moderate-strength concretes and the data tend to be less dispersed as specified concrete strength increases. In the previous paper,[9] the ACI 214R equations were treated as fixed-form equations with a standard deviation *s* determined to obtain the best-fit match to the measured strength results. Although such a calibration of the ACI 214 strength evaluation equations may provide satisfactory estimates of particular regional strength results, this approach does not satisfy the requirements that ACI 214 imposes on the data set to allow computation of the standard deviation *s*. To date, there has not been research aimed at developing a methodology to analyze precast, prestressed concrete component regional strength test results in a manner fully compatible with ACI 214.

In this paper, a methodology is outlined for generating expected concrete strength prediction models using regional strength test data. The proposed methodology is implemented for a data set representing approximately 1900 Alabama bridge girder production events that took place at four precast, prestressed concrete plants in the southeastern United States. The resulting strength prediction models are compared with models published by others. Design application of representative relationships for expected strength—at prestress transfer and at 28 days—is discussed.

Methodology for developing strength prediction models

The proposed methodology for developing concrete strength prediction models based on available historical strength test results is outlined in **Fig. 2**. The strength prediction at time of prestress transfer is obtained by organizing a strength data set for direct implementation within the strength evaluation procedures of ACI 214R[1] and ACI 301[2] and also by empirical models of fixed predictive equations (similar to previous work by others). For 28-day concrete strength prediction, the proposed methodology implements multiple model formulations based on a reasonable assumption of regional concrete strength-growth properties.

For the ACI 214–based strength prediction equations at prestress transfer, a common metric of dispersion is the standard deviation of strength test results determined from 30 batches of the same concrete class within 1000 psi (6895 kPa) of the specified concrete strength.[1] Its stated purpose is to ensure that past strength test results "represent materials, mixture proportions, quality control procedures, and climatic conditions similar to those expected" in the project.[2] A small sample standard deviation indicates better quality control of concrete production, placement, and testing.

In the precast, prestressed concrete industry, a standard deviation computed from a collection of available strength test records representing various projects and producers often contains strengths outside of that applicable range in the ACI 214 data set.[9] For example, the historical data set compiled from four plants of precast, prestressed concrete girders in Alabama exhibits a range of specified concrete transfer strength f'_{ci} from 4000 to 9000 psi (27,580 to 62,055 kPa).[9] Because the data from typical historical precast, prestressed concrete girder strengths do not meet the ACI 214 data analysis requirements, it is proposed herein that the ACI 214 analysis approach be used with an analysis technique, the strength-difference approach, as described and implemented in the subsequent section.

In this study, five empirical equations were also considered for predicting expected transfer strengths to allow the comparison of prediction accuracy with models published by others.[5–8] The empirical models consist of one- and two-parameter functions and two-part piecewise functions. The calibration parameters were determined by minimizing the sum of the squares of the error between the measured and predicted values.

For 28-day compressive strength prediction, a calibrated regional strength-growth model was implemented, as outlined in a previous work.[9] For Alabama concrete mixtures containing Type III cement, a ratio of 1.44 multiplied by the expected concrete strength at prestress transfer satisfactorily predicted the expected 28-day compressive strength.[9] In the proposed methodology, this strength-growth ratio was also

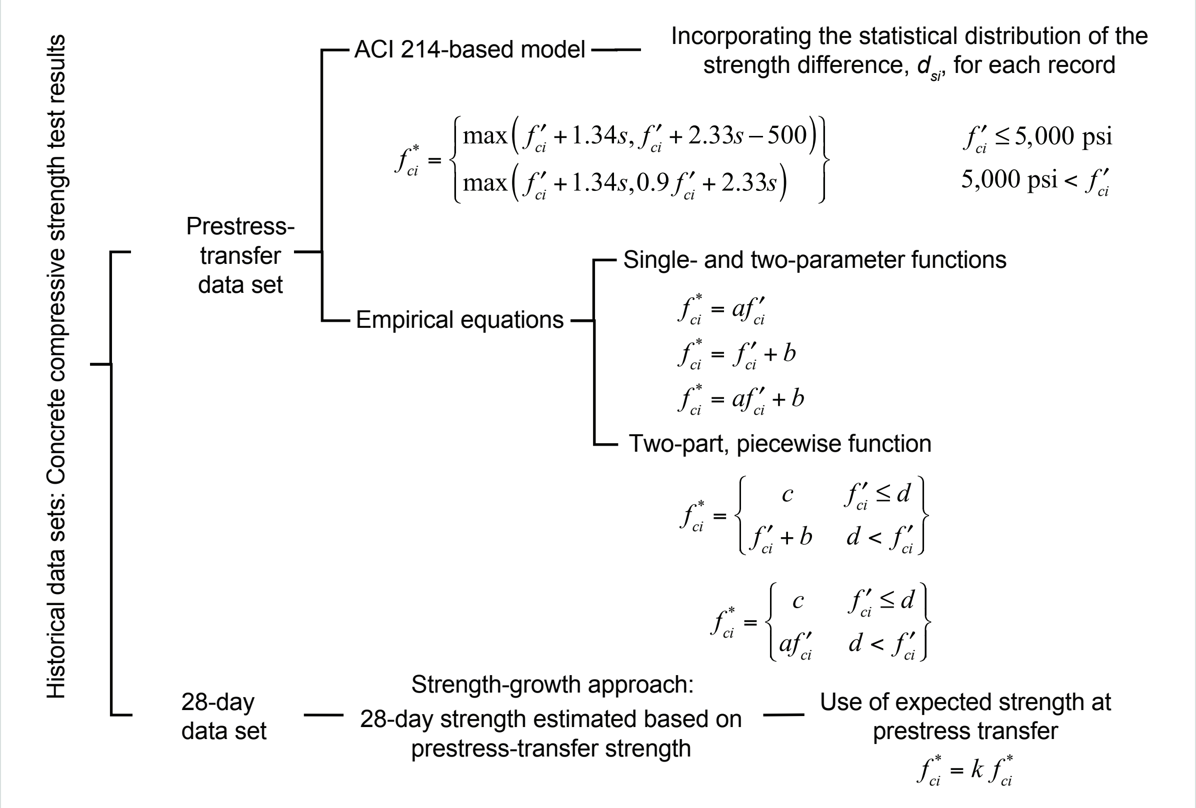

Figure 2. Methodology for development of expected strength prediction models. Note: a = prediction model calibration parameter; ACI = American Concrete Institute; b = prediction model calibration parameter; c = prediction model calibration parameter; d = prediction model calibration parameter; f^*_c = expected concrete strength at 28 days; f'_{ci} = specified concrete strength at time of prestress transfer; f^*_{ci} = expected concrete strength at prestress transfer; k = prediction model calibration parameter; s = sample standard deviation from historical strength test data. 1 psi = 6.895 kPa.

applied to the specified prestress-transfer strength for comparison. Empirical equations based solely on the specified 28-day strength were not used because the measured 28-day compressive strengths for typical precast, prestressed concrete girders were shown to be much more accurately predicted based on the prestress-transfer strength than based on the specified 28-day strength.[9]

Strength-difference approach

A data analysis procedure is proposed to facilitate the use of the strength evaluation equations of ACI 214 and ACI 301 with a typical data set from the precast, prestressed concrete industry. This proposed approach relies on isolating the difference between the specified and measured strengths for each test record, combining these differences to form a new data set, and then examining the dispersion of the combined data set. As defined in Eq. (1) and (2), the strength difference d_s computed for each measurement age represents the difference between the measured and specified strength, denoted as d_{si} at the time of prestress transfer and d_{s28} at 28 days.

$$d_{si} = f_{ci} - f'_{ci} \tag{1}$$

$$d_{s28} = f_c - f'_c \tag{2}$$

where

f_c = measured concrete strength at 28 days

f'_c = specified concrete strength at 28 day

f_{ci} = measured concrete strength at time of prestress transfer

f'_{ci} = measured concrete strength at time of prestress transfer

Three sample cases were examined to illustrate the functionality of the proposed strength-difference approach for the time of prestress transfer (**Fig. 3**). The first part of Fig. 3 demonstrates that for a single strength test data set that meets the requirements for implementation of the ACI 214 and ACI 301 strength evaluation equations, the standard deviation of the strength test results f_{ci} and the strength differences d_{si} are identical. The second part of Fig. 3 illustrates a similar analysis for two distinct strength test data sets with identical sample sizes n and standard deviations s that, when combined, do not satisfy the requirements to use the ACI 214 and ACI 301 equations. Direct superposition of the two distinct distributions of strengths causes a bimodal distribution that fails to

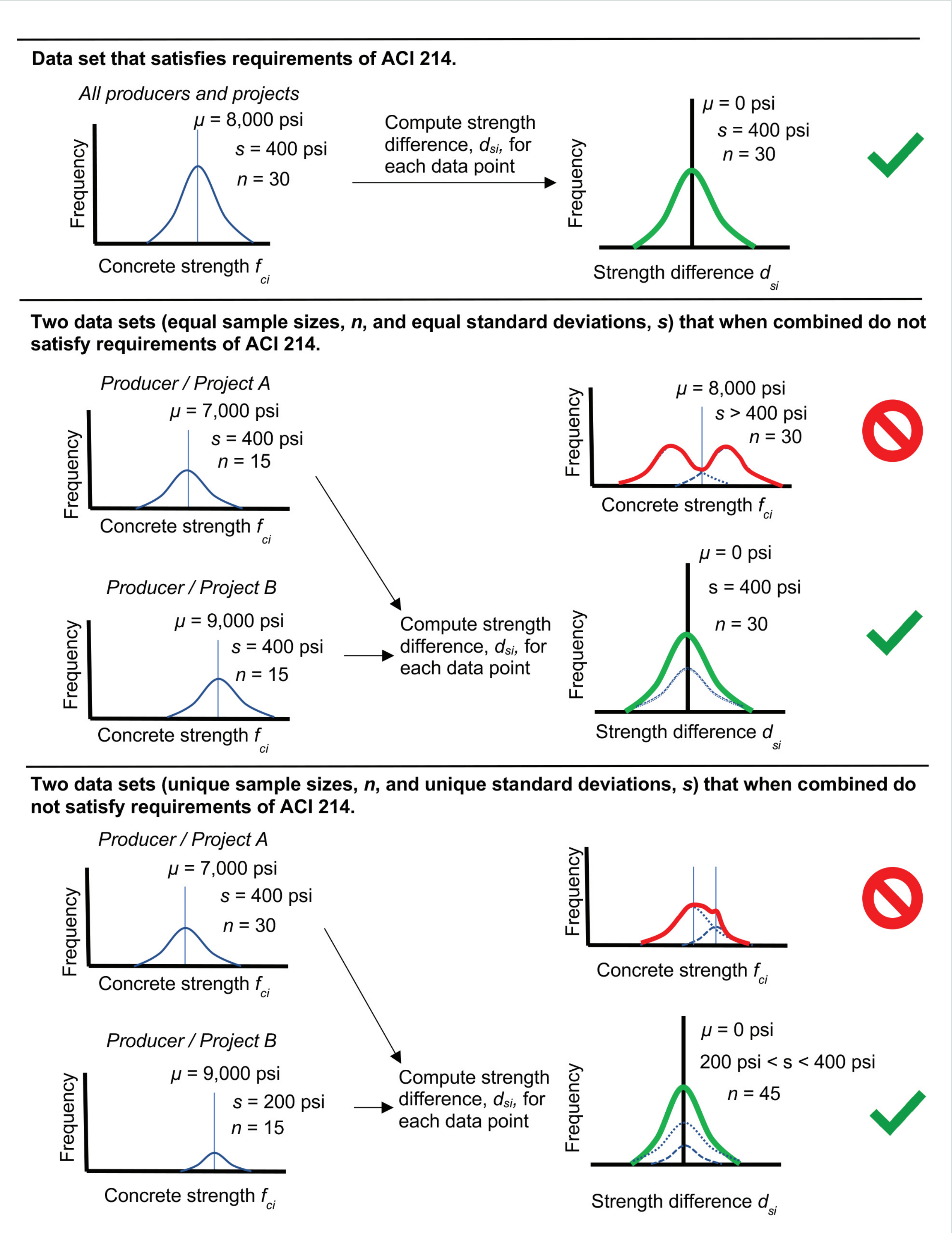

Figure 3: Conceptual illustration of the strength-difference approach for prestress transfer strength test data. Note: ACI = American Concrete Institute; d_{si} = strength difference at time of prestress transfer; f_{ci} = measured concrete strength at time of prestress transfer; n = sample size; s = standard deviation of distribution; μ = mean of distribution. Note: 1 psi = 6.895 kPa.

adequately characterize the standard deviation of the manipulated data set. The d_{si} data set is generated by computing d_{si} for each strength test record and superimposing the results to generate the manipulated data set. The strength-difference approach centers the peaks of distributions of two distinct data sets and accurately reflects the dispersion of strength test data relative to specified strengths. It also overcomes the problem of bimodal distribution.

The third part of Fig. 3 describes the more realistic case of two distinct strength test data sets with different sample sizes and standard deviations that when combined do not satisfy the requirements to use the ACI 214 and ACI 301 strength evaluation equations. The distribution that results from the direct superposition of two strength test distributions does not meet the intent of the ACI equation use. The manipulated distribution of d_{si} results from the superposition of the computed d_{si} for each strength test record. The resulting combined distribution of d_{si} represents a weighted average of the available strength test data that is proportionally affected by the relative size and dispersion of each data set.

Because the proposed analysis methodology directly implements the strength evaluation procedures of ACI 214R[1] and ACI 301[2] for the manipulated data set, the standard deviation *s* computed from the manipulated data set represents the standard of quality control used to produce the concrete, a parameter associated with the repeatability of production procedures for similar precast products within a region. The standard of concrete control computed from data within one region is expected to be similar to the standard from other regions that rely on similar "materials, mixture proportions, quality control procedures, and climatic conditions."[1]

The strength-difference approach can be applied to all available strength results for a given region or to a selected subset of data (for example, by producer or specified strength range) depending on the desired prediction model. Because the prediction model developed in this paper was aimed to help bridge designers predict expected concrete strength for Alabama bridge girders, all of the approximately 1900 available strength test results for this region were included. The same methodology could also be applied by a single producer or for a single concrete mixture if the quantity of available strength test results is at least 30.

For data sets with a disproportionate amount of data within certain strength ranges, the distribution of d_{si} may be skewed in the direction of the dispersion of the highly populated strength ranges. For instance, because the dispersion of strength test results has been observed to decrease as specified concrete strength increases,[9] a sample group containing more test data from lower strength ranges is expected to result in a greater dispersion of d_{si} compared with a group with a uniform amount of data from each strength range. This larger estimate of dispersion, in turn, could result in overprediction of concrete strengths in higher specified concrete strength ranges.

Implementation of the strength-difference approach for historical Alabama strength data

As an example, the proposed analysis methodology was implemented for a previously presented data set[9] that reported concrete strength at prestress transfer for approximately 1900 Alabama bridge girder production events from four independent bridge girder producers. The distributions for the strength difference d_{si}, computed using Eq. (1), are visualized for each producer at point (a) in **Fig. 4**, each specified prestress-transfer strength range at point (b), each transfer age range at point (c), and the entire data set at point (d). Histograms for the strength differences for the entire strength data set at prestress transfer and 28 days are given in the lower portion of Fig. 4.

For the entire data set, d_{si} has a mean of 1840 psi (12,687 kPa) and a standard deviation of 1064 psi (7336 kPa). At point (a) of Fig. 4, the mean of the d_{si} distribution is biased by producer practices and not necessarily expected to be uniform when comparing data within this grouping. Despite the means of d_{si} distributions varying between 1109 and 2078 psi (7646 and 14,328 kPa) for each producer at the time of prestress transfer, relative consistency is observed in the dispersion of the strength difference regardless of producer. Production practices for producers A, B, and C, which rely on accelerated curing, are characterized by a standard deviation of d_{si} ranging from 891 to 1003 psi (6143 to 6916 kPa), whereas producer D did not rely on accelerated curing and exhibited a greater standard deviation of 1262 psi (8701 kPa). At point (b) of Fig. 4, an increase in specified strength at prestress transfer is accompanied by a decrease in the mean and standard deviation of d_{si}. Although it is difficult to evaluate the potential relationship between specified strength at prestress transfer and the standard deviation of d_{si} due to varying sample sizes ($97 \le n \le 1085$), the dispersion of d_{si} (measured by the standard deviation) ranges from 655 to 1175 psi (4516 to 8102 kPa). When grouped by age at prestress transfer at point (c) of Fig. 4, the group of typical transfer ages (with a mean at approximately 18 hours) exhibited a reduced mean and standard deviation of d_{si} compared with the group representing delayed prestress transfer. At point (e) of Fig. 4, the dispersion of the strength difference at prestress transfer is characterized by a standard deviation of 1064 psi (7336 kPa). Although a detailed analysis is not shown for the available 28-day strength test data, a summary distribution of d_{s28}, computed by Eq. (2), for these same production events is shown for reference at point (e).

An F-test for equal variances (significance level α of 0.05) was used to evaluate the dependency of distributions on each producer. The following was concluded:

- The distribution of d_{si} for each producer is not substantially different regardless of the strength measurement age.
- The distribution of d_{si} for producers A, B, and C are

n	1,147	421	118	201	293	1,085	412	97	1,602	285	1,887
μ_{dsi}, psi	2,078	1,489	1,109	1,649	2,585	1,868	1,486	782	1,681	2,739	1,840
σ_{dsi}, psi	1,003	951	891	1,262	1,175	990	858	655	918	1,347	1,064

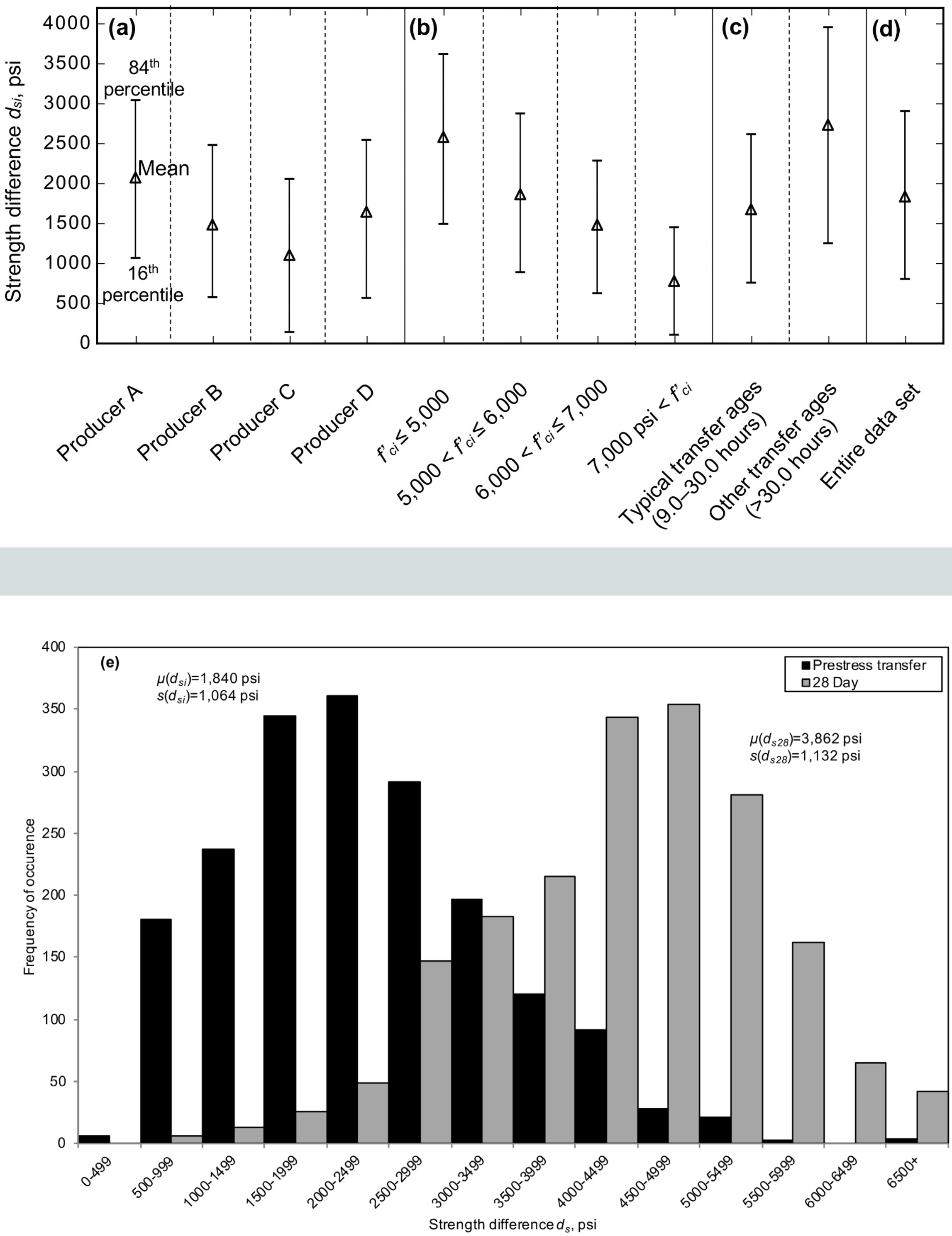

Figure 4. Distributions of strength difference of data set for prestress transfer. Note: d_{si} = strength difference at time of prestress transfer; f'_{ci} = specified concrete strength at time of prestress transfer; n = sample size; s = standard deviation; μ = mean of distribution. 1 psi = 6.895 kPa.

similar but substantially different from the distribution of producer D.

When considering a grouping of data (not shown in Fig. 4) including only those producers relying on accelerated curing in Alabama, the standard deviations s of d_{si} and d_{s28} distributions were computed as 1039 and 1126 psi (7194 and 7764 kPa), respectively.

Model performance for prestress-transfer strength prediction

The methodology for the development of expected strength prediction models was implemented for the prediction of prestress transfer concrete strength for the Alabama girder data set (Fig. 2). The implementation included an ACI 214–based model with the standard deviation s computed using the strength-difference approach as well as five empirical prediction equations. Based on the strength-difference analysis of the Alabama girder data set in the previous section, the computed standard deviation value s of 1039 psi (7164 kPa) for prestress transfer was rounded to a value of 1050 psi (7240 kPa) for implementation within the proposed ACI 214–based model. This value exceeds the typical range of standards of quality control recommended by ACI 214R-11 (between 400 and 700 psi [2758 and 4827 kPa]) for conventional concrete work; however, it is not unexpected given the causes of variability for concrete strength at the time of prestress transfer in the precast, prestressed concrete industry.[9] The ACI 214–based expressions for expected prestress-transfer strength f_{ci}^* with a standard deviation s of 1050 psi are presented as follows:

$$f_{ci}^* = \begin{Bmatrix} f'_{ci} + 1950 & f'_{ci} \le 5000 \\ 0.90 f'_{ci} + 2450 & 5000 < f'_{ci} \le 9000 \end{Bmatrix} \text{psi} \quad (3)$$

Equation (3) is bounded by the extreme limits of specified prestress-transfer strength in the Alabama historical data set.

In addition to the ACI 214–based prediction model shown in Eq. (3), five empirical models (**Table 1**) were also explored for predicting f_{ci}^* to facilitate comparison with previous empirical design recommendations for other regions.[5–7] These five empirical models are denoted as E-1 through E-5 (Eq. [4] through [8], respectively, as shown in **Table 1**. Models E-1 through E-3 are characterized by a single prediction equation within the prediction range, whereas models E-4 and E-5 provide a piecewise prediction equation within the prediction range.

The optimization of the calibration parameters was conducted by minimizing the sum of the squares of the errors between the data and each model form. The calibration parameter values are reported in Table 1. Piecewise models E-4 and E-5 were intended to reflect the potential tendency of producers to set a baseline (minimum) preferred strength level. When certain water–cementitious material ratios *w/cm* are targeted to achieve improved surface finish characteristics, it will likely result in an expected actual strength (calibration parameter c in Table 1) significantly greater than f'_{ci} for specified strengths less than or equal to the threshold strength (calibration parameter d in Table 1). The resulting equations developed for the expected concrete strength at time of prestress transfer are plotted with the collected Alabama strength data (**Fig. 5**).

Table 1. Empirical equations to predict compressive strength at prestress transfer

Model designation	Model form	Equation number	Calibration parameter, psi
E-1	$f_{ci}^* = af'_{ci}$	4	a = 1.30
E-2	$f_{ci}^* = f'_{ci} + b$	5	b = 1840
E-3	$f_{ci}^* = af'_{ci} + b$	6	a = 0.34 b = 5660
E-4	$f_{ci}^* = \begin{Bmatrix} c & f'_{ci} \le d \\ f'_{ci} + b & d < f'_{ci} \end{Bmatrix}$	7	b = 1300 c = 7500 d = 6200
E-5	$f_{ci}^* = \begin{Bmatrix} c & f'_{ci} \le d \\ af'_{ci} & d < f'_{ci} \end{Bmatrix}$	8	a = 1.18 c = 7500 d = 6360

Note: a = calibration parameter; b = calibration parameter; c = calibration parameter; d = calibration parameter; E-1 = empirical prediction model 1; E-2 = empirical prediction model 2; E-3 = empirical prediction model 3; E-4 = empirical prediction model 4; E-5 = empirical prediction model 5; f'_{ci} = specified concrete strength at time of prestress transfer; f_{ci}^* = expected concrete compressive strength at time of prestress transfer. 1 psi = 6.895 kPa.

The line of equality represents the line where the measured transfer strength is equal to the specified strength. Model E-3, represented by Eq. (6), predicts a transfer strength less than the specified transfer strength for specified strengths greater than 8500 psi (58,608 kPa), a trend that is not evident in the actual data in this range; however, because the sample of historical measurements within this data range was limited, this model was kept in the comparison.

The mean squared error (MSE) expressed as a percentage shown in Eq. (9), as defined by ACI 209,[10] was used to evaluate the goodness of fit of the proposed models for concrete strength at prestress transfer.

$$\text{MSE} = \sqrt{\frac{\sum\left(\left[\frac{100\left(f_{ci}^* - f_{ci}\right)}{f_{ci}}\right]^2\right)}{n-1}} \quad (9)$$

where

f_{ci}^{*} = expected concrete compressive strength as predicted by a given model at prestress transfer

MSE values for each of the models considered in this paper, computed by Eq. (9), are tabulated in **Table 2**.

All models considered in Table 2, including previously proposed models,[5–7] represent an improvement in accuracy compared with the current design practice (that is, neglecting the difference between specified and expected strength). As expected, when more parameters are introduced, the two-parameter combination of multiplier and constant offset formulation in E-3 tends to be more accurate than the single-parameter models defined by E-1 and E-2. The ACI 214 recommendations for concrete strengths exceeding 5000 psi (34.47 MPa) also employ the multiplier and constant offset formulation. The introduction of the piecewise formulation in the empirical models of E-4 and E-5 does not significantly increase the accuracy of the prediction models when compared with the historical data set. The empirical recommendations of previous researchers[5–7] for other regions generate less-accurate predictions of the Alabama compressive strength at prestress transfer compared with the empirical models calibrated directly to the Alabama data set. The proposed ACI 214–based model of Eq. (3) provides predictions of the same approximate accuracy as the empirical models and a reduction of the mean squared error MSE by 12.3% compared with current practice.

Model performance for 28-day strength prediction

Previous work[9] demonstrated that efforts to estimate expected 28-day compressive strength as a function of specified 28-day strength do not provide the best accuracy. Instead, the most accurate predictions of 28-day compressive strength were achieved by applying a growth factor to the concrete strength expected at prestress transfer. This strength-growth approach[9] was applied to the specified strength at prestress transfer and expected strength at prestress transfer according to the ACI 214–based model. The expected concrete strength at 28 days f_c^* was rewritten by multiplying the ACI 214–based model in Eq. (3) by a strength-growth factor of 1.44:[9]

$$f_c^* = \begin{Bmatrix} 1.44 f'_{ci} + 2800 & f'_{ci} \le 5000 \\ 1.30 f'_{ci} + 3500 & 5000 < f'_{ci} \le 9000 \end{Bmatrix} \text{ psi} \quad (10)$$

Table 2. Effectiveness of strength-prediction equations at time of prestress transfer

Model reference	Model form	Equation number	MSE, %
Current practice, Mante et al. (2020)	$f_{ci}^* = f'_{ci}$	n/a	25.8
ACI 214 (s = 1050 psi)	$f_{ci}^* = \begin{Bmatrix} f'_{ci} + 1950 & f'_{ci} \le 5000 \\ 0.90 f'_{ci} + 2450 & 5000 < f'_{ci} \le 9000 \end{Bmatrix}$	3	13.5
E-1	$f_{ci}^* = af'_{ci}$	4	14.9
E-2	$f_{ci}^* = f'_{ci} + b$	5	13.7
E-3	$f_{ci}^* = af'_{ci} + b$	6	12.6
E-4	$f_{ci}^* = \begin{Bmatrix} c & f'_{ci} \le d \\ f'_{ci} + b & d < f'_{ci} \end{Bmatrix}$	7	12.5
E-5	$f_{ci}^* = \begin{Bmatrix} c & f'_{ci} \le d \\ af'_{ci} & d < f'_{ci} \end{Bmatrix}$	8	12.5
French and O'Neill (2012)	$f_{ci}^* = 1.16 f'_{ci}$	n/a	17.2
Storm et al. (2013)	$f_{ci}^* = 1.24 f'_{ci}$	n/a	15.0
Rosa et al. (2007)	$f_{ci}^* = 1.11 f'_{ci}$	n/a	19.4

Note: a = calibration parameter; b = calibration parameter; c = calibration parameter; d = calibration parameter; E-1 = empirical prediction model 1; E-2 = empirical prediction model 2; E-3 = empirical prediction model 3; E-4 = empirical prediction model 4; E-5 = empirical prediction model 5; f'_{ci} = specified concrete strength at time of prestress transfer; f_{ci}^* = expected concrete compressive strength at time of prestress transfer; MSE = mean squared error; s = standard deviation. 1 psi = 6.895 kPa.

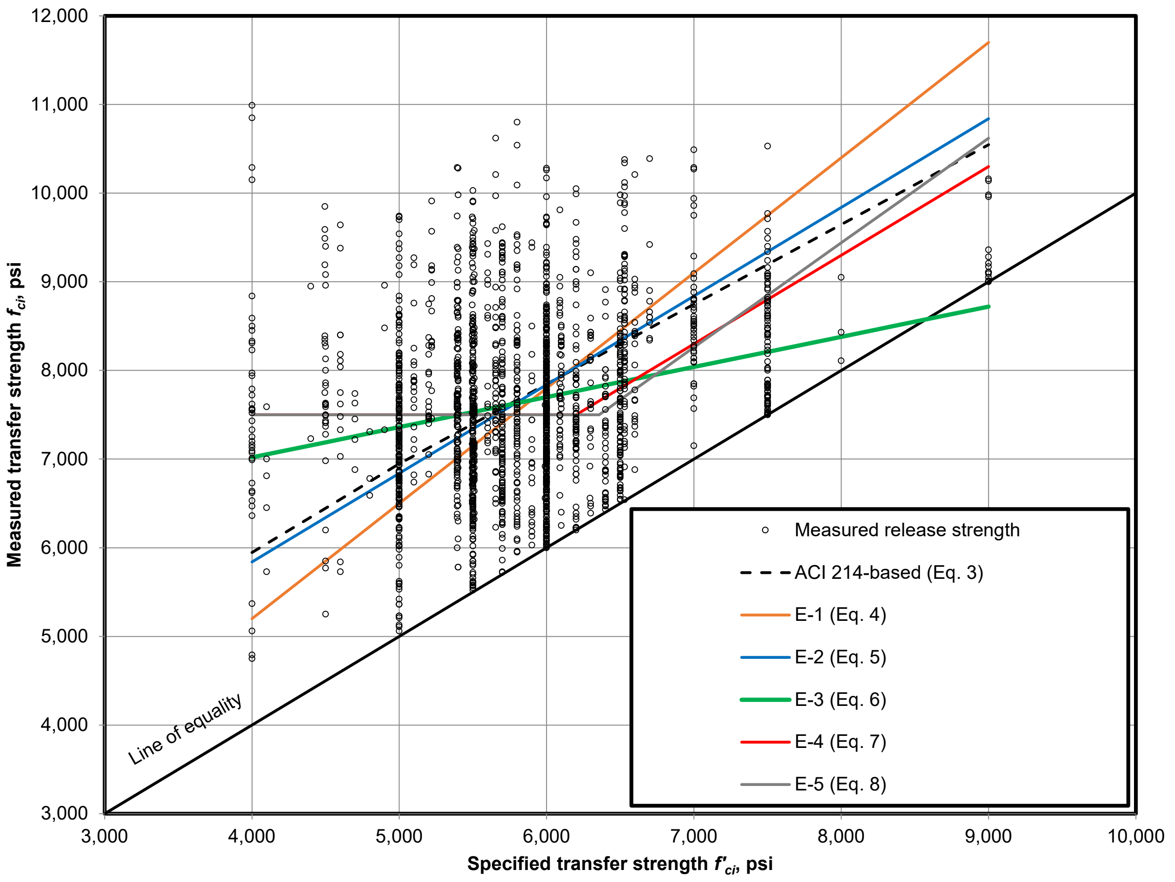

Figure 5. Trial prediction models for expected concrete strength at prestress transfer. Note: ACI = American Concrete Institute; E-1 = empirical prediction model 1; E-2 = empirical prediction model 2; E-3 = empirical prediction model 3; E-4 = empirical prediction model 4; E-5 = empirical prediction model 5. 1 psi = 6.895 kPa.

Table 3. Model definition and effectiveness of strength-prediction equations at 28 days

Model reference		Model definition	Equation number	MSE, %
Current practice		$f_c^* = f'_c$	11	37.0
Strength-growth approach	Based on specified prestress transfer strength	$f_c^* = 1.44f'_{ci}$	12	23.5
	ACI 214-based model (s = 1050 psi)	$f_c^* = \begin{cases} 1.44f'_{ci} + 2800 & f'_{ci} \le 5000 \\ 1.30f'_{ci} + 3500 & 5000 < f'_{ci} \le 9000 \end{cases}$	10	14.0
Storm et al. (2013)		$f_c^* = 1.45f'_c$	n/a	14.5
Rosa et al. (2007)		$f_c^* = 1.25f'_c$	n/a	22.7

Note: f'_c = specified concrete strength at 28 days; f_c^* = expected concrete compressive strength at 28 days; f'_{ci} = specified concrete strength at prestress transfer; MSE = mean squared error; n/a = not applicable; s = standard deviation. 1 psi = 6.895 kPa.

A summary of the 28-day compressive strength prediction model definitions assessed against the methodology proposed in this paper is shown in **Table 3**. Note that the 28-day compressive strength prediction models generated by the recommended strength-growth methodology are fundamentally functions of the specified transfer strength, whereas current practice and the recommendations by others[5,7] are functions of specified 28-day strength. Eq. (11) and (12) are identified within Table 3 and reflect current practice and an intermediate permutation of the Eq. (10) prediction model.

The model 28-day strength predictions are plotted in **Fig. 6** against the measured Alabama 28-day strength results. Prediction model accuracy is graphically illustrated by lines representing the percentage over- or underestimate relative to the measured 28-day strength and also by the MSE noted in Fig. 6 and Table 3. In this case, the MSE for a data point at 28 days is computed using Eq. (9), substituting variables f'_c and f^*_c for f'_{ci} and f^*_{ci}, respectively.

In the top graph of Fig. 6, the current design practice of assuming the expected strength will be equal to the specified 28-day compressive strength results in a large (MSE of 37.0%) and systematic underestimate of the actual 28-day compressive strength. This consistent and large underestimate of the actual concrete strength will result in a systematic overprediction of service limit state deflections of precast, prestressed concrete members.[3] By comparison, the middle graph of Fig. 6 indicates that prediction of the expected 28-day strength using the strength-growth approach on the basis of the specified prestress-transfer strength results in improved accuracy (MSE of 23.5%); however, a bias is evident because a large, consistent underestimate of the actual concrete strength occurs when using the equation $f^*_c = 1.44 f'_{ci}$. A further reduction in the MSE (MSE of 14.0%) is observed for prediction of the expected 28-day strength using the strength-growth approach on the basis of the expected prestress-transfer strength (that is, when using Eq. [10]). A marked decrease in systematic bias is apparent. These results reaffirm that most accurate predictions of expected 28-day strength result from models relying on the prestress-transfer strength rather than the specified 28-day strength.[9]

Application to design

Previous similar efforts by others[5–8] reported the ratio of expected-to-specified strength at prestress transfer $(E/S)_i$ and at 28 days $(E/S)_{28}$. The results reported herein indicate that these ratios are not constant; rather, they vary across the range of practical specified strengths. Nonetheless, these ratios may be computed if desired for comparison to previous work or to generate implementation tools. Based on the relationship given in Eq. (3), the expected-to-specified strength ratio at prestress transfer generated by the methodology proposed in this paper is a function solely of specified transfer strength, and for the Alabama data is computed as follows:

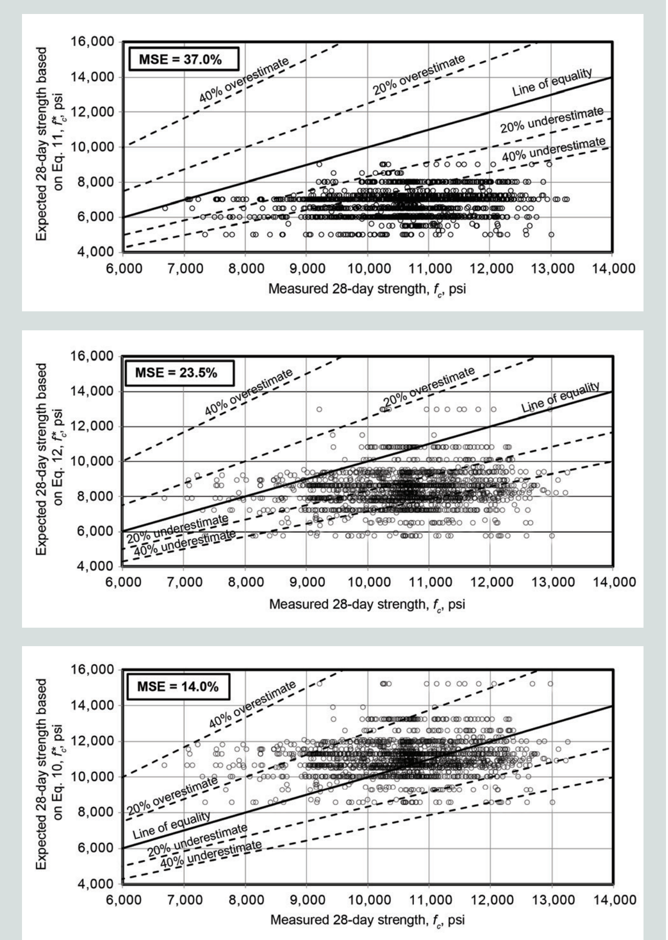

Figure 6. Comparison of expected 28-day strength predictions. Note: MSE = mean squared error. 1 psi= 6.895 kPa.

$$\left(E/S\right)_i = \frac{f^*_{ci}}{f'_{ci}} = \begin{cases} 1.00 + \dfrac{1950}{f'_{ci}} & f'_{ci} \le 5000 \\ 0.90 + \dfrac{2450}{f'_{ci}} & 5000 < f'_{ci} \le 9000 \end{cases} \tag{13}$$

Based on the relationship given in Eq. (10), $(E/S)_{28}$ is a function of specified transfer strength and specified 28-day strength and for the Alabama data is computed as follows:

$$\left(E/S\right)_{28} = \frac{f^*_c}{f'_c} = \begin{cases} 1.44\dfrac{f'_{ci}}{f'_c} + \dfrac{2800}{f'_c} & f'_{ci} \le 5000 \\ 1.30\dfrac{f'_{ci}}{f'_c} + \dfrac{3500}{f'_c} & 5000 < f'_{ci} \le 9000 \end{cases} \tag{14}$$

The ratios resulting from Eq. (13) and Eq. (14) are shown in tabulated form in **Table 4**.

Table 4 can serve as a design aid for regions where Type III cement mixtures relying on materials, mixture proportions, quality control procedures, and climatic conditions are similar to those of Alabama.[9] A designer of precast, prestressed

Table 4. Expected-to-specified strength ratios at prestress transfer and 28 days for Alabama Type III cement mixtures

Specified concrete strength at prestress transfer f'_{ci}, psi	$(E/S)_i$	$(E/S)_{28}$								
		Specified concrete strength at 28 days f'_c, psi								
		4000	5000	6000	7000	8000	9000	10,000	11,000	12,000
4000	1.49	2.14	1.71	1.45	1.24	1.07	n/a*	n/a*	n/a*	n/a*
4500	1.43	n/a†	1.86	1.56	1.34	1.16	1.04	n/a*	n/a*	n/a*
5000	1.39	n/a†	2.00	1.67	1.43	1.25	1.11	1.00	n/a*	n/a*
5500	1.35	n/a†	n/a†	1.78	1.52	1.33	1.18	1.07	n/a*	n/a*
6000	1.31	n/a†	n/a†	1.88	1.61	1.41	1.26	1.13	1.03	n/a*
6500	1.28	n/a†	n/a†	n/a†	1.71	1.49	1.33	1.20	1.09	1.00
7000	1.25	n/a†	n/a†	n/a†	1.80	1.58	1.40	1.26	1.15	1.05
7500	1.23	n/a†	n/a†	n/a†	n/a†	1.66	1.47	1.33	1.20	1.10
8000	1.21	n/a†	n/a†	n/a†	n/a†	1.74	1.54	1.39	1.26	1.16
8500	1.19	n/a†	n/a†	n/a†	n/a†	n/a†	1.62	1.46	1.32	1.21
9000	1.17	n/a†	n/a†	n/a†	n/a†	n/a†	1.69	1.52	1.38	1.27

Note: Intermediate values can be interpolated. $(E/S)_i$ = ratio between the measured concrete strength and specified concrete strength at prestress transfer; $(E/S)_{28}$ = ratio between the measured concrete strength and specified concrete strength at 28 days; n/a = not available. 1 psi = 6.895 kPa.

* Combinations of specified strength that result in $(E/S)_{28}$ values less than 1.0 are atypical and indicate that mixture selection is likely to be controlled by 28-day compressive strength requirements.

† Combinations of specified strength where f'_{ci} exceeds f'_c are not feasible.

concrete elements would first complete strength and transfer limit state design calculations and then reference Table 4 to estimate the expected-to-specified strength ratios from which the expected strength and modulus of elasticity values can be determined to use in the associated camber and deflection calculations. For instance, a designer specifying a transfer strength of 6000 psi (41.37 MPa) and a 28-day strength of 8000 psi (55.16 MPa) might expect the strength at prestress transfer for Alabama Type III cement mixtures to exceed the specified transfer strength by approximately 31% and expect the strength at 28 days to exceed the specified 28-day strength by approximately 41%.

More directly, designers can compute the expected values of strength f^*_{ci} and f^*_c as a function of f'_{ci} using Eq. (3) and Eq. (10), respectively. The resulting expected values (rounded to the nearest 50 psi [345 kPa]) that represent Alabama Type III cement mixtures are reported in **Table 5**.

The ACI 214–based strength prediction model implemented in Tables 4 and 5 reflects the best calibration to the Alabama data set, but it is subject to potential bias from disproportionate sample sizes within certain strength ranges of the data set. The bottom graph in Fig. 6 indicates overestimation of 28-day strength for f^*_c values exceeding about 12,000 psi (82.74 MPa) when using Eq. (10). This corresponds to f'_{ci} values exceeding 6500 psi (44.8 MPa) in Tables 4 and 5. In this case, only 12.2% (230 results) of the approximately 1900 Alabama test results represent specified prestress-transfer strengths exceeding 6500 psi. Only 7.3% (137 results) of the Alabama test results represent 28-day strengths exceeding 12,000 psi. Designers implementing the Alabama prediction model generated in this study should use caution when predicting the expected 28-day strength for designs with specified prestress-transfer strengths exceeding 6500 psi. If feasible, the proposed methodology could be applied to a refined sample of regional strength test results that is more representative of the probable strength range for a given project.

Conclusion

The use of accurately predicted expected concrete compressive strength at prestress transfer and 28 days results in more-accurate design-phase predictions of service limit state deflections (for example, effective prestress or camber) than the use of the specified concrete strength.

Key conclusions and design recommendations supported

Table 5. Expected concrete strength at prestress transfer and 28 days for Alabama Type III cement mixtures

Specified concrete strength at prestress transfer f'_{ci}, psi	Expected concrete strength at prestress transfer f^*_{ci}, psi	Expected concrete strength at 28 days f^*_c, psi
4000	5950	8550
4500	6450	9300
5000	6950	10,000
5500	7400	10,650
6000	7850	11,300
6500	8300	11,950
7000	8750	12,600
7500	9200	13,250
8000	9650	13,900
8500	10,100	14,550
9000	10,550	15,200

Note: 1 psi = 6.895 kPa.

by the implementation described in this paper include the following:

- Regardless of the range of strengths within a representative data set, the strength evaluation procedures of ACI 214R-11 and ACI 301 can be adapted to formulate expected strengths of similar precast concrete components. Rather than focusing on the dispersion of the strength results, this adaptation is accomplished by determining the difference between the specified and measured strength for each test and then quantifying the dispersion of these strength differences.

- The standard deviation of the strength differences computed from the Alabama precast, prestressed bridge girder data set is approximately 1050 psi (7240 kPa). For regions where Type III cement mixtures rely on materials, mixture proportions, quality control procedures, and climatic conditions similar to those of Alabama,[8] the expected compressive strength at the time of prestress transfer f^*_{ci} can be predicted from Eq. (3).

- For prediction of prestress transfer strength for the Alabama bridge girder data set, the proposed ACI 214–based strength prediction model decreased the mean squared error from 25.8% to 13.5% compared with current practice.

- Among implemented empirical models to estimate the concrete strength at prestress transfer, fixed-form models with a two-parameter combination (multiplier and constant offset) tended to generate the most accurate predictions.

- The expected 28-day strength can be obtained by using the strength-growth approach on the basis of the expected prestress-transfer strength. For Type III cement mixtures relying on materials, mixture proportions, quality control procedures, and climatic conditions similar to those of Alabama,[9] the expected compressive strength at 28 days f^*_c can be predicted from Eq. (10).

- Designers implementing the 28-day strength prediction model shown in Eq. (10) should use caution for specified prestress-transfer strengths exceeding 6500 psi (44.8 MPa).

- For prediction of 28-day strength for the Alabama bridge girder data set, the proposed ACI 214–based strength prediction model decreased the mean squared error from 37.0% to 14.0% compared with current practice.

- The proposed ACI 214–based data analysis procedures can be applied to any selected grouping of available data (by state, by producer, by project, by strength range, and so forth) depending on the intended use of the resulting strength prediction equation. Most accurate predictions are likely to be generated from data representing a narrow range of specified strengths with a relatively uniform distribution of data throughout the range.

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References

1. ACI (American Concrete Institute) Committee 214. 2011. *Guide to Evaluation of Strength Test Results of Concrete*. ACI 214R-11. Farmington Hills, MI: ACI.

2. ACI Committee 301. 2016. *Specifications for Structural Concrete*. ACI 301-16. Farmington Hills, MI: ACI.

3. Mante, D. M., R. W. Barnes, L. Isbiliroglu, A. Hofrichter, and A. K. Schindler. 2019. "Effective Strategies for Improving Camber Predictions in Precast, Prestressed Concrete Bridge Girders." *Transportation Research Record* 2673 (3): 342–354.

4. Keske, S. D., R. W. Barnes, A. K. Schindler, B. R.

Johnson, M. A. Ellis, D. E. Miller, and T. L. Neal. 2015. *Self-Consolidating Concrete for Prestressed Applications—Phase II: Bridge Construction and In-Place Performance*. Research report FHWA/ALDOT 930-799. Auburn, AL: Auburn University Highway Research Center.

5. Rosa, M. A., J. F. Stanton, and M. O. Eberhard. 2007. *Improving Predictions for Camber in Precast, Prestressed Concrete Bridge Girders*. Research report, University of Washington, Seattle, WA, Washington State Transportation Center (TRAC).

6. French, C. E., and C. O'Neill. 2012. *Validation of Prestressed Concrete I-Beam Deflection and Camber Estimates*. Final report, University of Minnesota, St. Paul, MN: Minnesota Department of Transportation.

7. Storm, T. K., S. H. Rizkalla, and P. Z. Zia. 2013. "Effects of Production Practices on Camber of Prestressed Concrete Bridge Girders." *PCI Journal* 58 (1): 96–111. https://doi.org/10.15554/pcij.01012013.96.111.

8. Nervig, J. 2014. *Improving Predictions of Instantaneous Camber for Prestressed Concrete Bridge Girders*. Paper 13817, MS thesis. Iowa State University, Ames, IA.

9. Mante, D. M., L. Isbiliroglu, A. Hofrichter, R. W. Barnes, and A. K. Schindler. "Expected Compressive Strength in Precast, Prestressed Concrete Design—Review and Discussion of Current Practice." *PCI Journal* 67 (3): 53–70. https://doi.org/10.15554/pcij67.3-02.

10. ACI Committee 209. 2008. *Guide for Modeling and Calculating Shrinkage and Creep of Concrete*. ACI 209.2R-08. Farmington Hills, MI: American Concrete Institute.

Notation

a = calibration parameter

b = calibration parameter

c = calibration parameter

d = calibration parameter

d_s = strength difference at a given age

d_{si} = strength difference at time of prestress transfer

d_{s28} = strength difference at 28 days

$(E/S)_i$ = ratio of expected-to-specified strength at time of prestress transfer

$(E/S)_{28}$ = ratio of expected-to-specified strength at 28 days

f_c = measured concrete strength at 28 days

f'_c = specified concrete strength at 28 days

f^*_c = expected concrete strength at 28 days

f_{ci} = measured concrete strength at time of prestress transfer

f'_{ci} = specified concrete strength at time of prestress transfer

f^*_{ci} = expected concrete strength at time of prestress transfer

k = calibration parameters

n = sample size

s = sample standard deviation from historical strength test data or distribution

α = significance level

μ = mean of distribution

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Abstract

Accurate predictions of concrete compressive strength are critical for designers to effectively estimate the camber, deflections, and prestress losses of precast, prestressed concrete elements. A methodology that relies on regional concrete bridge girder strength test results is proposed for predicting expected concrete compressive strength. Strength data collected from precast, prestressed concrete plants were manipulated by the use of a strength-difference approach to facilitate American Concrete Institute 214R-11 analysis methods. The data set was used to evaluate five other empirical prediction model forms. When implemented using an Alabama regional data set, the methodology resulted in markedly more accurate predictions of expected concrete strength at prestress transfer and at 28 days compared with current practice.

Keywords

Camber, concrete compressive strength, deflection, expected strength, historical review, serviceability, specified strength, strength prediction.

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