# Expected compressive strength in precast, prestressed concrete design: Review and discussion of regional practice

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- Historical concrete strength results were compiled from archived records of 1887 girder concrete placements by four producers in the southeastern United States, accounting for nearly 5000 Alabama girders. The data set consisted of specified concrete compressive strength, measured concrete strength, chronological age of the girders at the time of prestress transfer concrete strength test, and measured air content.

- The data set was then compared with available empirical strength prediction methods derived from other regions in the United States. These empirical results did not accurately represent the Alabama data. The most promising candidates for prediction methodologies for expected compressive strength were models based on guidance from American Concrete Institute Committee 214 for prediction of expected strength at prestress transfer and models based on concrete strength-growth modeling to predict 28-day strength.


Concrete production involves a combination of tools, materials, methods, and labor to produce a measurable output; therefore, statistical variability is expected in concrete strength parameters. To safeguard against failure, it is essential that structural designs account for concrete strength uncertainty to ensure a sufficient level of structural reliability.[1] American Concrete Institute (ACI) guidance[1,2] helps concrete producers target a required concrete strength during mixture proportioning to ensure that the average measured concrete strength meets or exceeds the specified strength by acceptable, statistically determined margins. Appropriate characterization of concrete strength is also critical for designers to accurately predict the deformational behavior of reinforced and prestressed concrete elements. In the precast, prestressed concrete industry, accurate predictions of deflections (such as camber [**Fig. 1**]) at various ages are required to ensure proper girder fit, proper function, and timely installation.

Measured and predicted camber values for a previously studied Alabama bridge girder (Fig. 1) demonstrate how camber predictions based on measured material properties can be much more accurate than those based on the specified (design) concrete strength.[3] U.S. engineers customarily rely on specified concrete compressive strength when performing design tasks related to both strength and serviceability limit states. Because the concrete strength typically exceeds the specified strength, this practice may result in inaccurate deflection estimates for concrete bridge girders.[4–8] The American Association of State Highway and Transportation

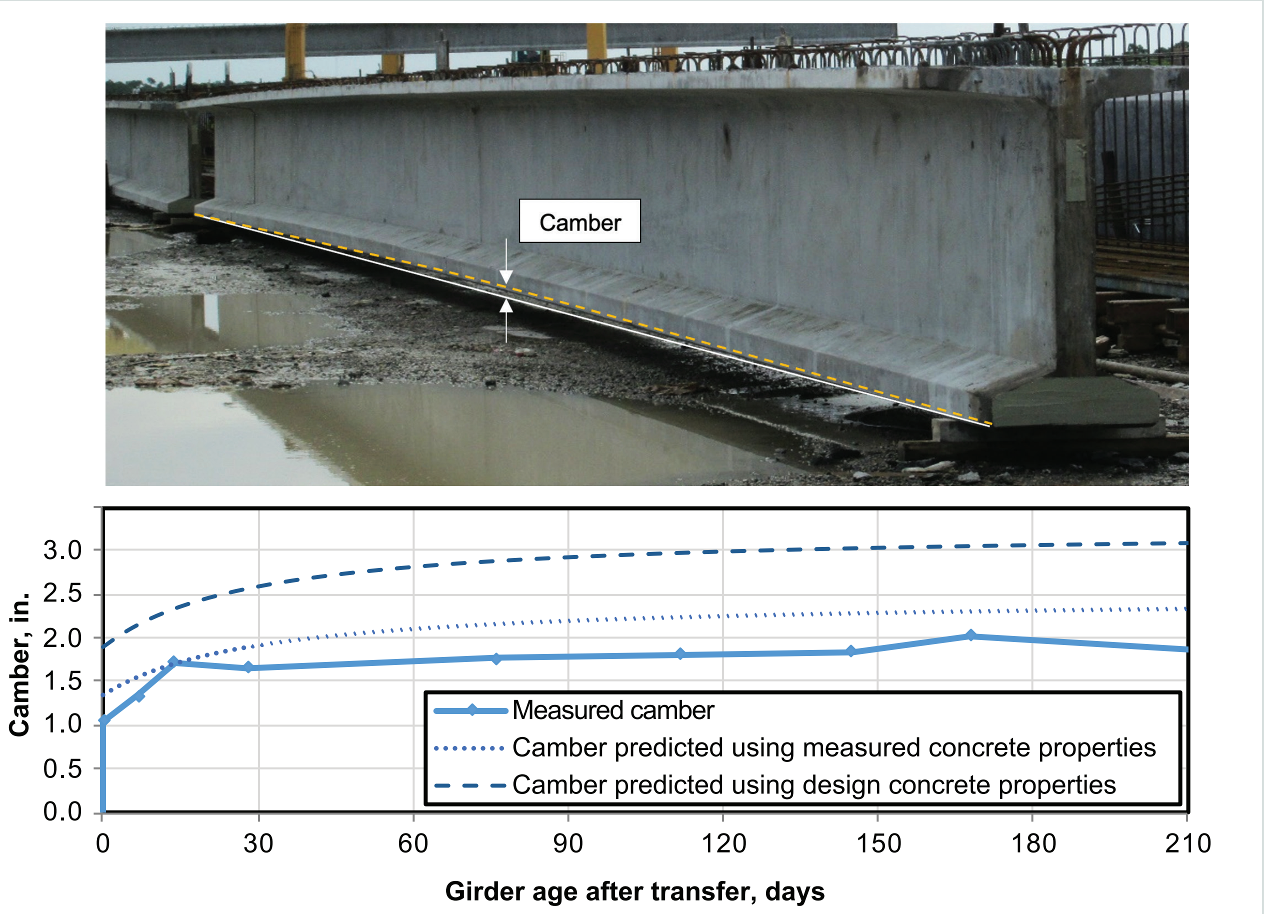


**Figure 1.** Camber of a precast, prestressed concrete bridge girder. Note: 1 in. = 2.54 cm.

Officials' *AASHTO LRFD Bridge Design Specifications*[9] does not offer a standardized approach to include the difference between expected strength and specified strength within serviceability design.

When accurate prediction of deformations (such as camber) is critical, it is important to account for the difference between expected concrete strength and specified strength. Previous work related to precast, prestressed concrete includes historical reviews of regionally available strength test records and recommendations for empirical relationships that correlate specified concrete strength to expected concrete strength (**Table 1**).[4–8] To compare these empirical models, the notation $M/S$ is introduced to define the ratio of the measured concrete strength $M$ to the specified concrete strength $S$ at common concrete acceptance ages: at prestress transfer $M/S_i$ and at 28 days $M/S_{28}$. Table 1 indicates large differences between reported measured strength and specified strength. The different mean values of the ratio of the measured concrete strength to the specified concrete strength $M/S$ at prestress transfer and 28 days from each study reflect regional variations in concrete composition, design practices, and specifications pertaining to concrete strength.

The objective of this paper is to review approaches and models used to predict expected concrete strength during precast, prestressed concrete design within different regions of the United States, identify practices that contribute to variations between predicted and measured concrete strength, and evaluate the appropriateness of implementing available strength prediction approaches for Alabama girder design and fabrication practices. In a companion paper,[10] the authors rely on the background given in this paper to propose a strength prediction methodology that is in better theoretical alignment with the statistical approaches most commonly used for concrete strength evaluation.

## Existing provisions for interpretation of concrete compressive strength

A sample of compressive strength test results may be characterized by its statistical mean and some associated metric of dispersion (for example, sample standard deviation or coefficient of variation). Design codes rely on this metric of dispersion, which is a function of a concrete producer's ability to consistently replicate a single concrete mixture or class of concrete mixtures.[1,2] Four defined types of strength are

**Table 1.** Summary of previous studies on ratio of measured to specified concrete strength *M/S*

| Model reference | State department of transportation studied | Girder sample size $n$ | At time of prestress transfer $t = i$ | | At 28 days $t = 28$ | |
|---|---|---|---|---|---|---|
| | | | Strength range, psi | Mean ratio of measured to specified concrete strength at prestress transfer $M/S_i$, psi | Strength range, psi | Mean ratio of measured to specified concrete strength at 28 days $M/S_{28}$, psi |
| French and O'Neill (2012) | Minnesota | 1067 | $S_i$: n/a<br>$M_i$: n/a | 1.16 | n.d.<br>n.d. | n.d. |
| Storm et al. (2013) | North Carolina | 382 | $S_i$: n/a<br>$M_i$: n/a | 1.24 | $S_{28}$: n/a<br>$M_{28}$: n/a | 1.45 |
| Rosa et al. (2007) | Washington | 146 | $S_i$: 5000 to 8050<br>$M_i$: 5440 to 10,395 | 1.11 | $S_{28}$: 7000 to 10,000<br>$M_{28}$: 8325 to 12,930 | 1.25 |
| Nervig (2014) | Illinois | 105 | $S_i$: 4500 to 8000<br>$M_i$: 4890 to 10,360 | 1.40 for $4500 \le f'_{ci} \le 5500$, 1.12 for $6000 \le f'_{ci} \le 8000$ | n.d.<br>n.d. | n.d. |

Note :$i$ = time of prestress transfer $M_i$ = measured concrete strength at prestress transfer; $M_{28}$ = measured concrete strength at 28 days; n/a = not applicable; n.d. = no data; $S_i$ = specified concrete strength at prestress transfer; $S_{28}$ = specified concrete strength at 28 days; $t$ = time after girder production. 1 psi = 6.895 kPa.

relevant to a discussion on how to evaluate a large data set of compressive strength results:

- the strength *specified* by the design engineer for a specific age (for example, 28 days) $f'_c$
- the strength *measured* using standardized cylinder testing (in accordance with ASTM C39[11]) at any age $f_c$
- the *required* average strength $f'_{cr}$ as defined in *Guide to Evaluation of Strength Test Results of Concrete*, ACI PRC-214-11,[1] intended for concrete producers to ensure that the average strength at 28 days $f_c$ meets or exceeds the specified strength $f'_c$, by a statistically required margin to ensure adequate structural reliability
- the strength *expected* at any age based on a prediction model $f^*_c$ (that is, if the prediction model is accurate, $f^*_c$ will be equal to the average strength at 28 days $f_c$)

For precast, prestressed concrete fabrication, the primary concrete ages of relevance are usually the age at the time of transfer of the prestressing force and 28 days. The previously identified variables with no secondary subscript ($f'_c$, $f_c$, $f'_{cr}$, and $f^*_c$) denote compressive strengths at a chronological age of 28 days, while the addition of subscript $i$ denotes the corresponding value at the time of prestress transfer:

- the strength *specified* by the design engineer at the time of prestress transfer $f'_{ci}$
- the strength *measured* using standardized cylinder testing (in accordance with ASTM C39[11]) at prestress transfer $f_{ci}$
- the *required* average strength at prestress transfer $f'_{cri}$ as defined in ACI PRC-214-11[1]
- the strength *expected* at any age based on some prediction model at prestress transfer $f^*_{ci}$

To ensure a sufficiently low probability of a single strength test result failing to reach the specified strength, the dispersion of concrete strength test results is used to dictate the relationship between the mixture required average strength $f'_{cr}$ and the specified design strength $f'_c$. This process is guided deterministically by the *AASHTO LRFD Bridge Construction Specifications*[12] and probabilistically by ACI PRC-214-11,[1] as reflected in ACI SPEC-301-16, *Specifications for Structural Concrete*.[2]

ACI PRC-214-11[1] provides statistical background and best practices to ensure that the average of any three consecutive strength tests exceed the specified strength $f'_c$ 99% of the time. These guidelines are implemented in ACI SPEC-301-16[2] with two criteria:

- Every average of three consecutive tests equals or exceeds the specified compressive strength $f'_c$.

- No strength test result falls below the specified compressive strength $f'_c$ by more than a specified value.

In the AASHTO LRFD specifications,[12] the average of at least two 6 × 12 in. (152 × 305 mm) or at least three 4 × 8 in. (102 × 203 mm) cylinders is used for the compressive strength test. Concretes other than AASHTO Class P(HPC) and Class A(HPC) are rejected if any cylinder test result is below the specified strength by more than 500 psi (3.45 MPa). AASHTO Class P(HPC) and Class A(HPC) are rejected if a single-test result indicates a strength less than the specified compressive strength.

To help producers select an appropriate required average strength $f'_{cr}$, ACI SPEC-301-16[2] offers two approaches: using a metric of dispersion computed from available historical strength test data or using a conservative approximate metric of dispersion when there is an absence of available strength data. **Table 2** summarizes the various ACI SPEC-301-16 provisions. The metric of dispersion considered is the sample standard deviation $s$ of a particular set of historical strength data containing 30 or more strength test results.

The data set used to compute the sample standard deviation (Table 2) shall contain at least 30 consecutive compressive strength tests of concrete produced to meet a specified concrete strength within 1000 psi (6.89 MPa) of the specified strength for the project at hand. These past strength test results should "represent materials, mixture proportions, quality control procedures, and climatic conditions similar to those expected" in the project.[2] As discussed later in this paper, strength test data compiled from precast, prestressed concrete girder production for the purpose of predicting future concrete strength rarely meet this requirement because different projects use specified strengths exceeding a range of 1000 psi.

**Table 2.** Required average compressive strength when historical data are available to establish a standard deviation (adapted from ACI SPEC-301-16)

| Specified concrete strength $f'_c$, psi | $f'_{cr}$, psi |
|---|---|
| 5000 or less | Use the larger of $f'_{cr} = f'_c + 1.34s$ or $f'_{cr} = f'_c + 2.33s - 500$ |
| Greater than 5000 | Use the larger of $f'_{cr} = f'_c + 1.34s$ or $f'_{cr} = 0.9 f'_c + 2.33s$ |

Note: ACI = American Concrete Institute; $s$ = standard deviation of a sample of strength test data. 1 psi = 6.895 kPa.

A small sample standard deviation indicates little dispersion of the strength results and is generally correlated with better quality control during concrete production, placement, and testing. ACI PRC-214-11[1] offers guidance on the interpretation of computed sample standard deviations (among other metrics of dispersion) and correlates ranges of computed standard deviation with standards of concrete control for general construction (**Table 3**).

In the absence of strength test data satisfying the requirements to use the expressions given in Table 2, ACI SPEC-301-16[2] offers a more conservative alternative form of these equations with the implicit assumption that the sample standard deviation ranges from 730 to 1330 psi (5.0 to 9.2 MPa) as a function of specified concrete strength $f'_c$.

By relying on the provisions of ACI PRC-214-11 and ACI SPEC-301-16, the concrete producer will target an average compressive strength greater than the specified strength, which introduces a margin of safety when proportioning and producing concrete. Therefore, the required average strength $f'_{cr}$ likely serves as the best available estimate of the expected strength $f^*_c$ in the absence of more accurate information during the design stage before the producer and mixture proportions are established. An understanding of typical precast, prestressed concrete production practice is essential to developing a procedure to determine expected compressive strengths by employing existing strength requirements. The next section reviews relevant plant production practices.

## Production practices

Regional design practices throughout the United States can indirectly affect the absolute and relative magnitudes of specified and measured compressive strengths. Structural design of precast, prestressed concrete bridge girders is typically constrained by specific state design requirements, such as the Alabama Department of Transportation (ALDOT) *Structural Design Manual*.[13] Concrete mixtures typically used in the precast, prestressed concrete industry are characterized by low water–cementitious material ratios *w/cm*, relatively high total paste content, use of Type III cement and supplementary cementing materials, and medium to high dosages of chemical

**Table 3.** Standards of concrete control for general construction (adapted from ACI PRC-214-11)

| | Concrete compressive strength | Excellent | Very good | Good | Fair | Poor |
|---|---|---|---|---|---|---|
| Standard deviation for different control standards, psi | $f'_c < 5000$ psi | Below 400 | 400 to 500 | 500 to 600 | 600 to 700 | Above 700 |
| Coefficient of variation for different control standards, % | $f'_c \geq 5000$ psi | Below 7.0 | 7.0 to 9.0 | 9.0 to 11.0 | 11.0 to 14.0 | Above 14.0 |

Note: ACI = American Concrete Institute; $f'_c$ = specified concrete strength. 1 psi = 6.895 kPa.

admixtures.[13] Concrete mixture design for precast, prestressed concrete bridges is usually governed by a rigorous mixture approval process, such as ALDOT 170-82.[14]

The provisions for concrete strength testing are intended for general concrete construction and their use in the precast, prestressed concrete industry does not account for the effects of industry-specific factors.[1,2] The precast, prestressed concrete industry is unique in that concrete is typically evaluated for acceptance at two ages: immediately before prestress transfer (to ensure successful, safe, and predictable transfer of the prestressing force into the concrete) and at an age of 28 days (to ensure performance as designed for both strength and deflections). While the latter strength test $f_c$ occurs at a specified age (28 days), the measurement of $f_{ci}$ may be made at any age after the concrete is predicted to exceed the specified concrete transfer strength $f'_{ci}$. Measurement of $f_{ci}$ occurs before prestress transfer, typically 0.5 to 2.0 days after concrete placement.

A failure to achieve the specified 28-day compressive strength $f'_c$ is expected to result in the rejection of the product, while a failure to achieve the specified transfer strength $f'_{ci}$ usually merely results in a delay until another round of testing and postponement of prestress transfer. As a result, these two acceptance scenarios are characterized by distinct permissible probabilities of failure, which are expected to manifest as two distinct dispersions of concrete strength test results at the two ages of evaluation. The prediction models and standards of concrete control presented in ACI 301-16[2] and Table 3 (adapted from ACI PRC-214-11), respectively, are intended for evaluation of a data set of strength test results measured at a specific quality assurance testing age (for example, 28 days) and do not offer sufficient guidance for application of these provisions to concrete governed by both an acceptance age (28 days) and an age at which nonacceptance causes temporary production delays (prestress transfer).

The production cycle of precast, prestressed concrete components is unique because producers attempt to employ mixture designs and curing practices that balance the available raw materials and girder labor costs by minimizing time to prestress transfer, while satisfying all construction specification requirements to ensure a high-quality completed component. The following characteristics may have an impact on the deviation of measured strength $f'_{ci}$ from the specified concrete strength $f'_c$:

- the practice of selecting from a few preapproved mixtures rather than developing more mixtures across the full spectrum of the specified strengths required for different girders
- the tendency of producers to deliberately select a higher compressive strength to accelerate construction and minimize the likelihood of delayed production
- the tendency of some producers to prefer mixtures with an increased paste content to facilitate improved girder surface finish
- the presence of additional production events, each with associated variability (for example, detensioning of strands, steam curing, or different form removal times)

Often, rigorous mixture approval specifications that require months of testing to obtain owner approval are imposed on producers of precast, prestressed concrete, thereby implicitly encouraging producers to maintain only a limited inventory of concrete mixtures suitable for a wide variety of projects. Because of this limited inventory, the expected concrete strength at prestress transfer $f^*_{ci}$ may result in a strength well in excess of the specified prestress transfer strength $f'_{ci}$ for many products. Experienced producers realize this tendency and aim to capitalize on the reduced curing time necessary before prestress transfer. In this way, they can maximize productivity or minimize energy-intensive curing conditions (for example, steam curing) to minimize the production cycle in their plants. Most of the producers participating in field aspects of this research study reported a preference for high-performance concrete mixtures with an increased paste content (similar to self-consolidating concrete). This paste content increase was motivated by a desire to improve concrete workability, improve surface finish characteristics, ease placement of inserts into fresh concrete, and decrease placement labor needs.

## Historical production data for Alabama bridge girders

Historical concrete strength results were compiled from archived records of 1887 Alabama girder concrete placements by four producers (referred to as producers A, B, C, and D) in the southeastern United States during the six-year period preceding 2013. Because multiple girders are often manufactured simultaneously, the 1887 concrete placements produced nearly 5000 total girders. Of the prestressed concrete girders produced within the six-year evaluation period, approximately 65% were PCI bulb-tee shapes (predominately BT-54 and BT-72 girders), with the remainder primarily distributed among AASHTO Type I, II, and III girders.

The Alabama data set consisted of specified concrete compressive strengths (at the time of prestress transfer and at an age of 28 days after production), measured concrete strengths (at the same ages), the chronological age of the girders at the time of prestress transfer concrete strength test, and measured air content. On average, concrete mixtures used in the production of precast, prestressed concrete bridge girders during this study were characterized by a water–cementitious material ratio *w/cm* of 0.31; average cementitious material content of 881 lb/yd$^3$ (523 kg/m$^3$); average sand–to–total aggregate ratio of 0.42; binary or ternary blends including combinations of slag cement, fly ash, or silica fume in varying percentages; relatively low dosages of air-entraining admixture; and medium to high dosages of high-range water-reducing admixtures. For conventional-slump concrete, producers tended to target the maximum permissible slump limit of 9 in. (229 mm) with an average air content of 3.3%.

## Strength at time of prestress transfer

The time to prestress transfer is one of the most influential variables affecting concrete compressive strength at prestress transfer. **Figure 2** shows the distribution of the chronological concrete ages at prestress transfer for the 1887 girder concrete production events.

The first and primary peak occurs at the age of approximately 18 hours. Concrete is most often placed in the late morning or early afternoon, with the intent to transfer the prestressing force early the next morning to facilitate reuse of the formwork on a 24-hour cycle. Other non-primary peaks (for example, 40 to 48 hours and 60 to 72 hours) represent nonstandard events typically beginning with concrete placement on Friday afternoon and then extended curing over the weekend. Isolating the primary peak (83.6% of data) as a representation of typical plant practices, the mean chronological age at prestress transfer for the girder production events included in this study was 17.7 hours with a standard deviation of 2.2 hours.

The curing temperature histories were not available for all 1887 girder production events; therefore, a subset of 435 production events was selected to estimate the average concrete maturity at the time of prestress transfer in accordance with ASTM C1074.[15] For this equivalent-age analysis, a reference temperature of 72.5°F (22.5°C) and activation energy of 45,000 J/mol were used in accordance with the recommendations of Carino and Tank.[16] The mean equivalent age at prestress transfer from the considered data set was 65.0 hours (2.71 days) with a sample standard deviation of 24.4 hours (1.02 days).

**Figure 3** shows the full data set of concrete strength results immediately before prestress transfer for all 1887 girder production events. Efforts to adjust concrete strengths to a single benchmark air content had an insignificant effect on the data distribution; therefore, the adjusted data are not reported here.[17,18]

The specified strength functions as the lower bound of the measured strength results. The measured strengths at prestress transfer range up to 11,000 psi (75.9 MPa), even for specified strengths as low as 4000 psi (27.6 MPa). It is clear that transfer of prestress was not permitted for any girder until the measured strength exceeded the specified strength, and, in some instances, the measured strength exceeds the specified

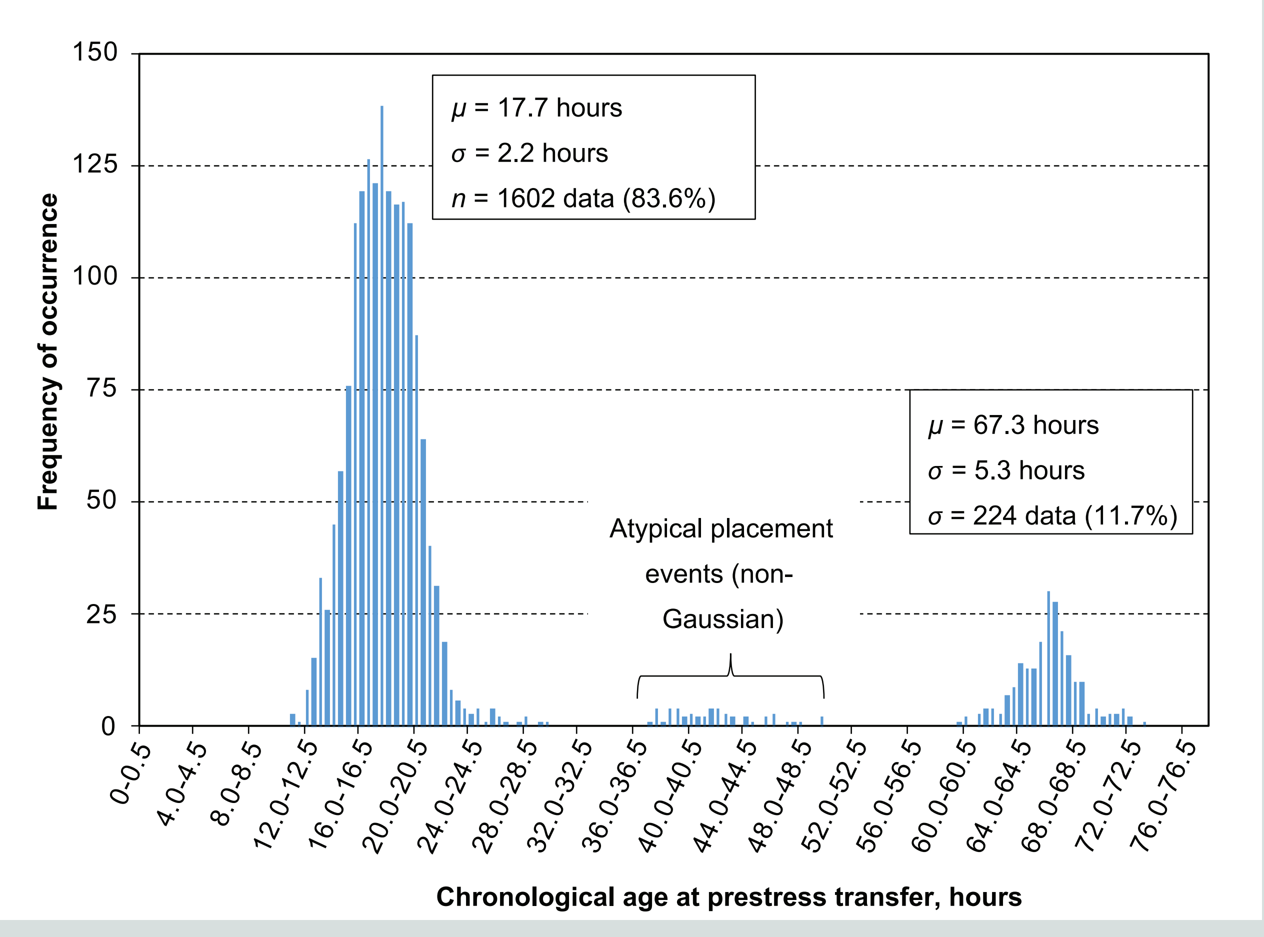


**Figure 2.** Concrete age at prestress transfer of 1887 events. Note: $n$ = sample size; $\mu$ = mean of the distribution; $\sigma$ = standard deviation of the distribution.

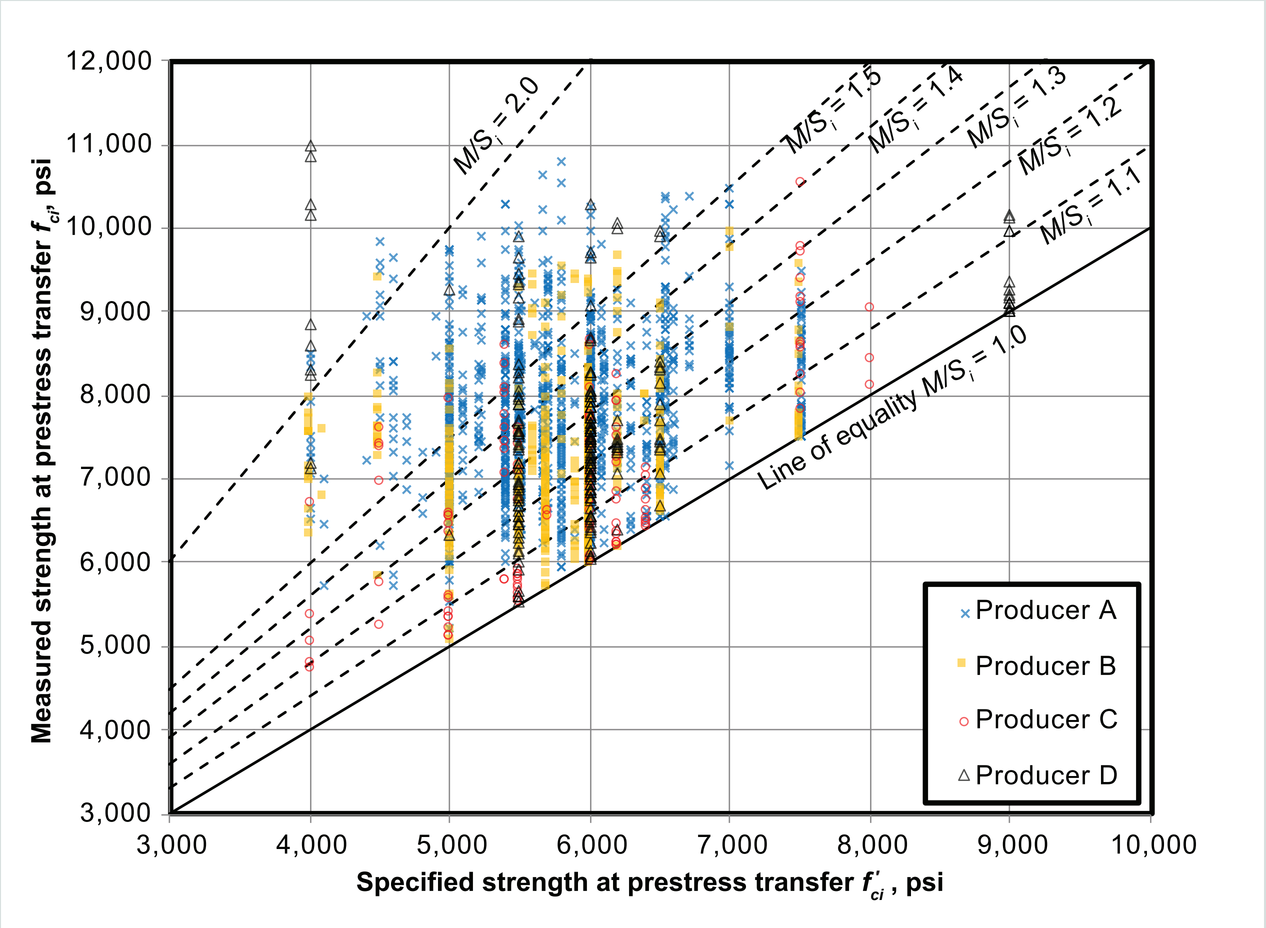


**Figure 3.** Specified versus measured concrete strength at prestress transfer. Note: $M/S_i$ = ratio of measured to specified concrete strength at transfer. 1 psi = 6.895 kPa.

strength by more than 100%. At greater specified strengths, the measured strengths tend to decrease relative to the specified strengths. In other words, the measured strength is closer to the specified strength for high-strength concretes.

The ratios of measured concrete strength to specified concrete strength are calculated at prestress transfer as $M/S_i$ and at 28 days as $M/S_{28}$:

$$M/S_i = f_{ci}/f'_{ci} \tag{1}$$

$$M/S_{28} = f_c/f'_c \tag{2}$$

**Table 4** presents the ratio of measured to specified concrete strength at prestress transfer $M/S_i$ summary statistics grouped by producer, range of prestress transfer age, and specified strength level. The "typical" range of ages at prestress transfer represents the primary grouping (from 9.0 to 30.0 hours), with the "other" group having the nonstandard and extended curing times.

The ratio of measured to specified concrete strength at prestress transfer $M/S_i$ has a mean of 1.33 and a standard deviation of 0.22 for the entire data set. This confirms the observation that producers tend to target sufficiently high strength to minimize the duration of time a product occupies the fabrication line. The standard deviation of the ratio of measured to specified concrete strength at prestress transfer $M/S_i$ represents how precisely the producers achieved the same level of concrete strength for a given specified strength. Such variability in concrete strength can be explained by the usual factors, such as variations in the composition and proportions of the raw materials and differences in sampling procedures and specimen curing and testing, as well as factors unique to the precast, prestressed concrete industry, such as varying prestress transfer age and curing temperature. Producers A, B, and D show similar ratio of measured concrete strength to specified concrete strength $M/S_i$ means of between 1.27 and 1.37. Producer C produced concrete with the strength closest to the specified prestress transfer strength, but producer C had the fewest events in the data set. When compared with the typical age at transfer, the mean ratio of measured to specified concrete strength at prestress transfer $M/S_i$ tends to increase from 1.30 to 1.50 for the group of nonstandard time (> 30.0 hours) of prestress transfer. However, the data with nonstandard ages has only

**Table 4.** Ratio of measured to specified concrete strength at prestress transfer $M/S_i$ computed by Eq. (1)

| Characteristic | Group | Sample size $n$ | $M/S_i$ $\mu \pm \sigma$ |
|---|---|---|---|
| None | Entire data set | 1887 | 1.33 ± 0.22 |
| Producer | Producer A | 1147 | 1.37 ± 0.20 |
| | Producer B | 421 | 1.27 ± 0.20 |
| | Producer C | 118 | 1.20 ± 0.17 |
| | Producer D | 201 | 1.30 ± 0.29 |
| Concrete age at prestress transfer | Typical (9.0 to 30.0 hours) | 1602 | 1.30 ± 0.19 |
| | Other (> 30.0 hours) | 285 | 1.50 ± 0.29 |
| Specified concrete strength at prestress transfer, $f'_{ci}$ | $f'_{ci} \leq 5000$ psi | 293 | 1.56 ± 0.28 |
| | 5000 psi < $f'_{ci} \leq 6000$ psi | 1085 | 1.33 ± 0.18 |
| | 6000 psi $f'_{ci} \leq 7000$ psi | 412 | 1.23 ± 0.13 |
| | 7000 psi < $f'_{ci} \leq 8000$ psi | 82 | 1.11 ± 0.09 |
| | $f'_{ci}$ > 8000 psi | 15 | 1.04 ± 0.05 |

Note: $\mu$ = sample mean; $\sigma$ = standard deviation of the distribution. 1 psi = 6.895 kPa.

a small influence on the ratio of measured to specified concrete strength at prestress transfer $M/S_i$ for the entire data set because these data represent only about 15% of the production events. Based on the evident decrease in mean ratio of measured to specified concrete strength at prestress transfer $M/S_i$ as the specified strength increases, it is clear that a single correction factor (ratio) cannot be used to effectively predict the expected concrete strength over a wide range of specified strengths. This is consistent with the findings of Nervig.[8]

## Strength at concrete age of 28 days

**Figure 4** shows the compiled 28-day concrete compressive strengths for the 1887 girder production events. As with the results at prestress transfer, efforts to correct for measured air content did not result in significant changes to the data set.[17,18]

The measured 28-day concrete strengths are highly dispersed, varying from nearly equal to the specified strength to above 13,000 psi (89.6 MPa) regardless of the specified 28-day strength.

To quantify the dispersion between the measured and specified concrete strength at 28 days, Eq. (2) was used to obtain the ratio of measured to specified concrete strength at 28 days $M/S_{28}$ for each producer, each prestress transfer age grouping, and each strength level range. **Table 5** summarizes the results.

The ratios of measured to specified concrete strength at 28 days $M/S_{28}$ have a mean of 1.59 and a standard deviation of 0.21 for the entire data set. The mean ratios of measured to specified concrete strength at 28 days $M/S_{28}$ are greater than the corresponding mean ratios of measured to specified concrete strength at prestress transfer $M/S_i$, indicating that the discrepancy between measured and specified strength is quite large at 28 days. The standard deviations are similar to the corresponding values at prestress transfer. Producers A and B experienced similar mean ratios of measured to specified concrete strength at 28 days $M/S_{28}$ and associated standard deviations. Producers C and D, which had fewer samples (Table 4), produced concrete with 28-day strengths closer to the specified value. The time of prestress transfer had minimal influence on the ratios of measured to specified concrete strength at 28 days $M/S_{28}$. As seen with the strengths at prestress transfer, the mean ratios of measured to specified concrete strength at 28 days $M/S_{28}$ and the corresponding dispersion decreased with increasing specified strength. Therefore, it would be inappropriate to apply a single, uniform correction factor across all strength ranges when converting a specified 28-day strength to an expected strength for serviceability calculations.

## Prediction of expected concrete strength

In the Alabama data set, a significant difference between the specified and measured concrete compressive strengths was observed. The existence of such excess strength over the specified strength signifies the necessity of a concrete strength prediction model that can appropriately capture the trends relating to producer practices as well as industry-specific trends to help designers effectively predict the expected concrete compressive strength as a function of the specified compressive strength.

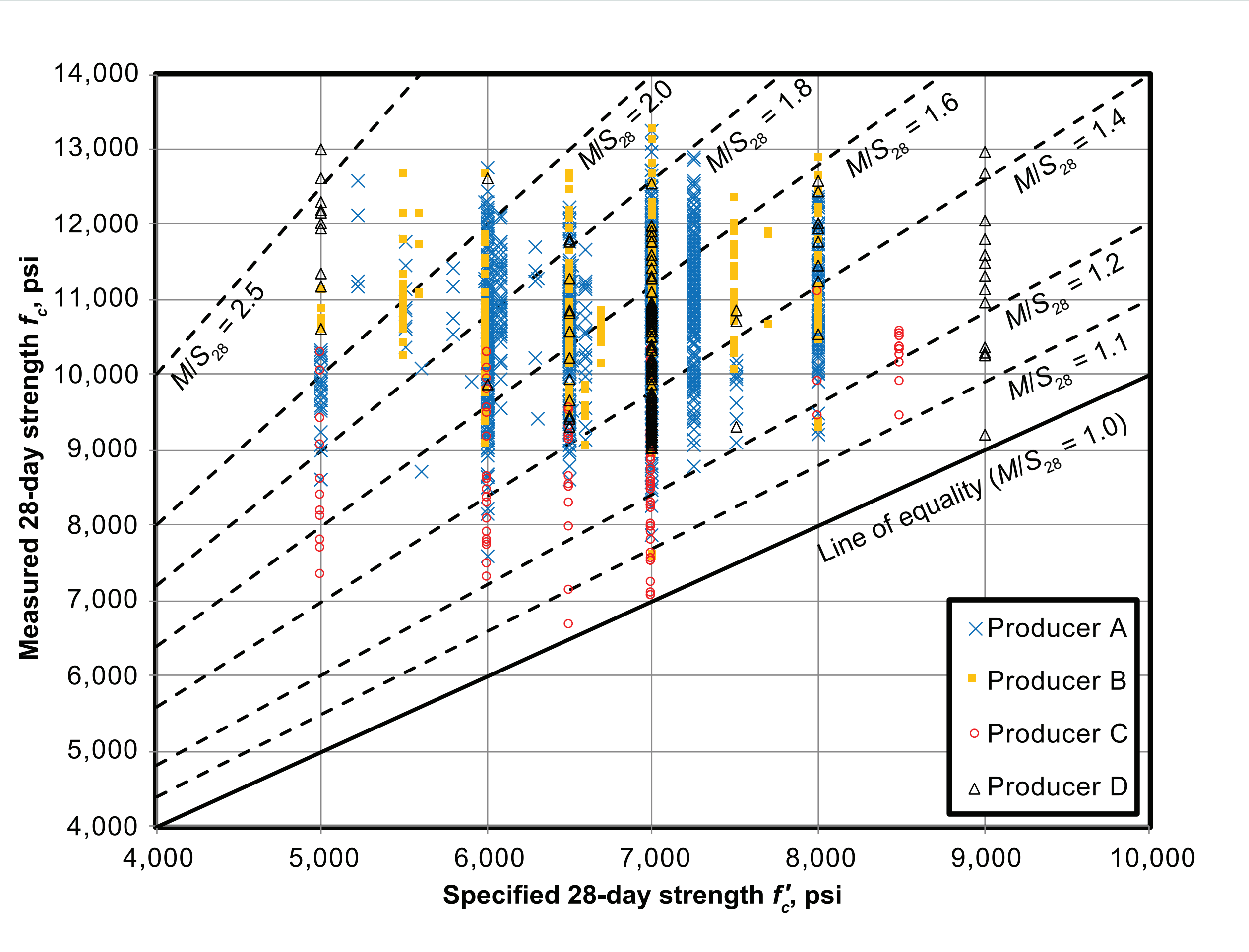


**Figure 4.** Specified versus measured 28-day concrete strength. Note: $M/S_{28}$ = ratio between the measured concrete strength and specified strength at 28 days. 1 psi = 6.895 kPa.

**Table 5.** Ratio of measured to specified concrete strength at 28 days $M/S_{28}$ computed by Eq. (2)

| Grouping | Category | Sample size $n$ | $M/S_{28}$ $\mu \pm \sigma$ |
|---|---|---|---|
| None | Entire data set | 1887 | 1.59 ± 0.21 |
| Producer | Producer A | 1147 | 1.62 ± 0.19 |
| | Producer B | 421 | 1.64 ± 0.20 |
| | Producer C | 118 | 1.33 ± 0.20 |
| | Producer D | 201 | 1.48 ± 0.25 |
| Concrete age at prestress transfer | Typical (9.0 to 30.0 hours) | 1602 | 1.59 ± 0.21 |
| | Other (> 30.0 hours) | 285 | 1.57 ± 0.26 |
| Specified strength at 28 days, $f'_c$ | $f'_c \le 6000$ psi | 520 | 1.80 ± 0.20 |
| | 6000 psi $< f'_c \le 7000$ psi | 927 | 1.55 ± 0.17 |
| | 7000 psi $< f'_c \le 8000$ psi | 413 | 1.45 ± 0.12 |
| | $f'_c > 8000$ psi | 27 | 1.22 ± 0.09 |

Note: $\mu$ = sample mean; $\sigma$ = standard deviation of the distribution. 1 psi = 6.895 kPa.

## Predicted strength at time of prestress transfer

Previous researchers[5–8] reviewed historical testing data from different regions within the United States and each determined a single strength multiplier that could be used to compute the expected strength at the time of prestress transfer as a function of the specified strength (Table 1). **Figure 5** plots these suggested prediction relationships with the Alabama data set. Where explicit bounds of applicability were not provided for these recommendations, a range of 4000 to 9000 psi (27.6 to 62.1 MPa) for specified concrete strength at time of prestress transfer $f'_{ci}$ was assumed. The recommendation of Nervig[8] is undefined for specified strengths between 5500 and 6000 psi (37.9 and 41.4 MPa). The ACI PRC-214-11–based prediction models (Table 2) are shown on the plot with four trial standard deviations *s* with the values of 400, 600, 800, and 1000 psi (2.76, 4.14, 5.52, and 6.89 MPa) representing standards of concrete control ranging from excellent to poor, respectively. More rigorous statistical calibration of the ACI PRC-214-11–based prediction models to match the Alabama data set is not feasible due to incompatibilities between the particular ACI PRC-214-11 historical data set requirements and the Alabama data set (for example, the Alabama data set does not meet the requirement for 30 consecutive tests representing a range of 1000 psi). In addition, it is unclear how the ACI PRC-214-11 provisions might best be applied to the precast, prestressed concrete field that is characterized by dual ages of strength acceptance testing for a single produced component. Figure 5 shows that the single coefficient approaches used by other authors tend to predict an increased offset between specified and predicted strength as concrete strength increases, whereas the two-coefficient approach of ACI PRC-214-11 (slope and offset) tends to generate predictions that more closely mimic the observed trend (Table 4) that the ratio of measured to specified concrete strength at prestress transfer $M/S_i$ decreases as concrete strength increases.

The ACI PRC-214-11–based prediction equations demonstrate varying levels of dispersion with banding that largely overlaps the recommendations of previous researchers. For specified strengths in the lower range, the factor suggested by Nervig[8] provides similar expected transfer strengths with the most dispersed option (a standard deviation *s* of 1000 psi

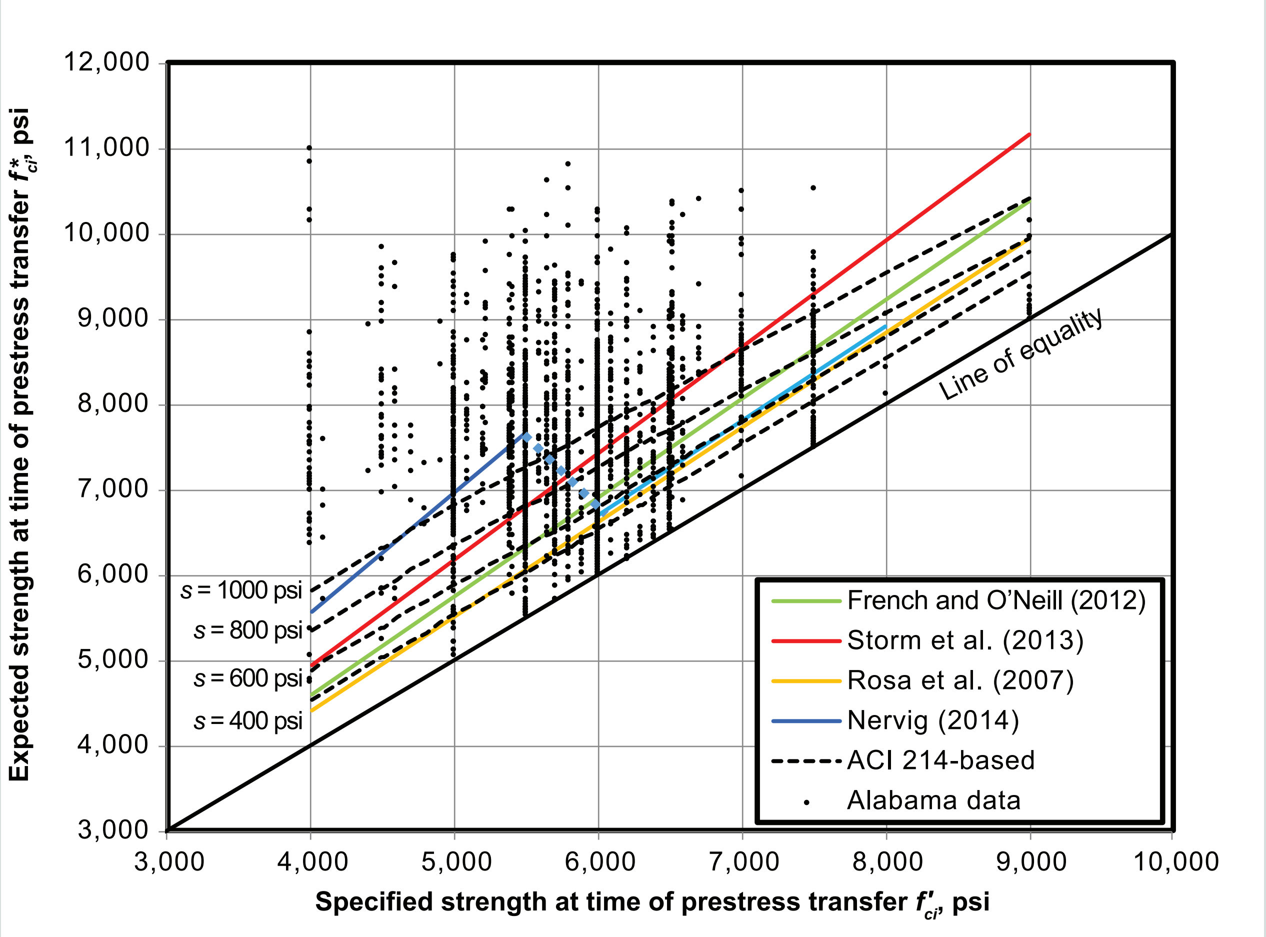


**Figure 5.** Comparison of previous studies and ACI PRC-214-11–based prediction equation with Alabama data at time of prestress transfer. Note: *s* = standard deviation of sample of strength test data. 1 psi = 6.895 kPa.

[6.89 MPa]) of the ACI PRC-214-11–based prediction equations, while the factor suggested by Rosa et al.[5] demonstrates expected transfer strengths similar to the least dispersed alternative (a standard deviation $s$ of 400 psi [2.76 MPa]). For high specified strengths, the Storm et al.[7] factor yields results even larger than the most dispersed option (a standard deviation $s$ of 1000 psi) of the ACI PRC-214-11–based prediction equations. Nervig[8] and Rosa et al.[5] produce expected strengths similar to the ACI PRC-214-11–based prediction equation with a standard deviation of 600 psi (4.14 MPa). In general, the differences in these empirical relationships underline the effect of region-based study. To compare the accuracy of the empirical models with the Alabama data set, the relative goodness of fit was evaluated using the mean squared error (MSE) (expressed as a percent) as defined by ACI 209:[19]

$$MSE = \sqrt{\frac{\sum\left(\left[\frac{100\left(f_c^* - f_c\right)}{f_c}\right]\right)}{n-1}} \tag{3}$$

**Table 6** gives the MSE value for each existing model at the time of prestress transfer.

Expected strength at the time of prestress transfer is best predicted using the ACI PRC-214-11–based prediction method with an assumed standard deviation $s$ of 1000 psi (6.89 MPa). Prediction models proposed by previous researchers correspond to improved predictions compared with current practice but are likely most effective for the specific geographical region in which they were calibrated. Efforts to reconcile the incompatibilities of the Alabama data set (data representing multiple projects with specified strengths exceeding a range of 1000 psi) with the requirements for analysis with ACI PRC-214-11 are justified to provide less regionally biased recommendations when compared to empirical prediction models. Techniques for direct calibration of ACI PRC-214-11 provisions to such historical data are presented in a forthcoming paper.[10]

## Predicted strength at concrete age of 28 days

Accurate prediction of expected strength at 28 days is less important for predicting camber and prestress losses than accurate prediction of expected strength at the time of prestress transfer; however, expected 28-day strength is needed for long-term deflection calculations and necessary for designers to understand long-term properties of concrete as compared to specified.[4,17,18] The previous studies by Storm et al.[7] and Rosa et al.[5] predict strength at 28 days simply as a multiplier of the specified 28-day strength. **Figure 6** compares the expected 28-day strength based on these predictions with the Alabama data set. It also shows the ACI PRC-214-11–based prediction models with the four trial standard deviation values for excellent to poor standards of concrete control.

The expected 28-day strength curve of Storm et al.[7] appears to be nearest to the average of the measured strength particu-

**Table 6.** Effectiveness of various prediction equations for data collected from Alabama projects at time of prestress transfer

| Model reference | Model definition | Mean squared error, % |
|---|---|---|
| Current practice | $f_{ci}^* = f'_{ci}$ | 25.8 |
| French and O'Neill (2012) | $f_{ci}^* = 1.16f'_{ci}$ | 17.2 |
| Storm et al. (2013) | $f_{ci}^* = 1.24f'_{ci}$ | 15.0 |
| Rosa et al. (2013) | $f_{ci}^* = 1.11f'_{ci}$ | 19.4 |
| Nervig (2014) | $f_{ci}^* = \begin{cases} 1.40f'_{ci} & 4500 \le f'_{ci} \le 5500 \\ 1.12f'_{ci} & 6000 \le f'_{ci} \le 8000 \end{cases}$ | n/a |
| ACI PRC-214-11 with $s$ = 400 psi | $f_{ci}^* = f'_{ci} + 536$ | 20.0 |
| ACI PRC-214-11 with $s$ = 600 psi | $f_{ci}^* = \begin{cases} f'_{ci} + 898 & f'_{ci} \le 5000 \\ 0.9f'_{ci} + 1398 & 5000 \le f'_{ci} \le 5940 \\ f'_{ci} + 804 & 5940 \le f'_{ci} \end{cases}$ | 17.2 |
| ACI PRC-214-11 with $s$ = 800 psi | $f_{ci}^* = \begin{cases} f'_{ci} + 1364 & f'_{ci} \le 5000 \\ 0.9f'_{ci} + 1864 & 5000 \le f'_{ci} \le 7920 \\ f'_{ci} + 1072 & 7920 \le f'_{ci} \end{cases}$ | 14.0 |
| ACI PRC-214-11 with $s$ = 1000 psi | $f_{ci}^* = \begin{cases} f'_{ci} + 1830 & f'_{ci} \le 5500 \\ 0.9f'_{ci} + 2330 & 5000 \le f'_{ci} \le 9900 \end{cases}$ | 13.3 |

Note: ACI = American Concrete Institute; $f'_{ci}$ = specified concrete strength at time of prestress transfer; $f_{ci}^*$ = the expected concrete compressive strength at time of prestress transfer; $s$ = standard deviation of strength test data. 1 psi = 6.895 kPa.

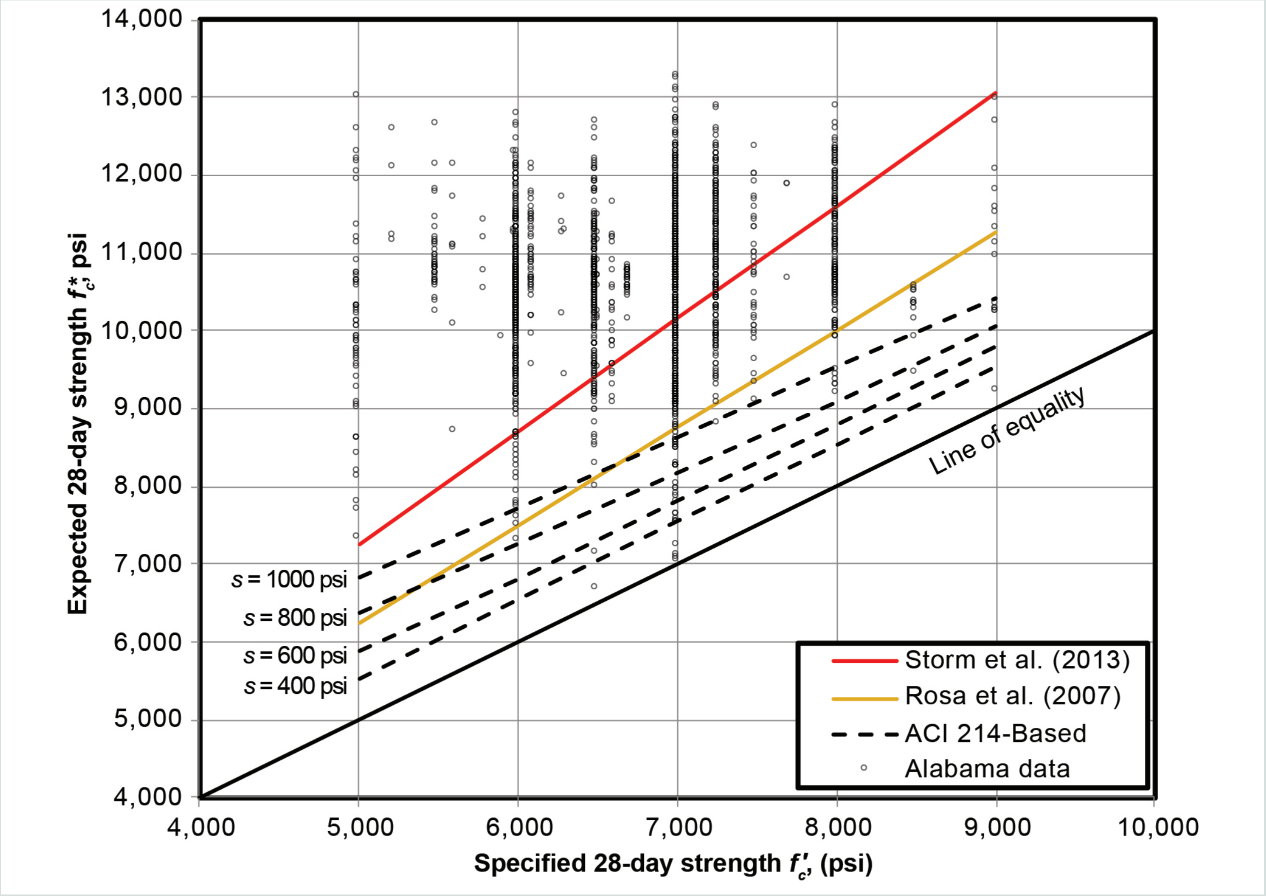


**Figure 6.** Comparison of previous studies and ACI PRC-214-11–based prediction equation with Alabama data at 28 days. Note: 1 psi = 6.895 kPa.

larly for a specified strength between 7000 and 8000 psi (48.3 and 55.2 MPa). The recommendation of Rosa et al.[5] and the ACI PRC-214-11–based prediction methods mostly produce expected 28-day strengths that are less than the measured strengths. Both single-factor prediction methods suggested by previous researchers imply that the difference in measured and specified strength increases with increasing strength; however, the opposite trend is apparent in the measured results. In other words, the idea of a uniform characteristic ratio of measured to specified concrete strength at 28 days $M/S_{28}$ that is effective over a range of concrete strengths is not supported by the data.

To quantify the effectiveness of these approaches relative to the Alabama data set, the MSE values for the concrete strength at 28 days were determined according to Eq. (3) (**Table 7**).

For the Alabama data set, the recommendation of Storm et al.[7] corresponded to significant improvements in the prediction of expected 28-day compressive strength as compared to current practice. The expected 28-day strengths obtained by using the Rosa et al.[5] and the ACI PRC-214-11–based prediction methods were less accurate: MSE for these methods ranges from 22.3% to 32.2%. The significant difference in the $f'_c$ multiplier (1.45 compared with 1.25) in the models by Storm et al.[7] and Rosa et al.[5] suggests that the practice of extending regionally determined calibrations to geographic areas other than those used for calibration is questionable. The trial ACI PRC-214-11–based models tend to demonstrate improved fit to experimental data as the trial standard deviation increases, but even at $s$ of 1000 psi (6.89 MPa), this model form does not approach the prediction accuracy of the other models.

In these cases, predicting the expected 28-day strength by simply applying a multiplier to the specified 28-day strength can be expected to exhibit substantial error. Even if this multiplier was determined based on regional research results, it is difficult to reliably extend its application accurately to other regions or other types of pretensioned elements. Furthermore, as noted previously, the use of a single multiplier over a wide range of specified strengths is not justified. Because precast, prestressed concrete production practices focus on achieving strength at the time of prestress transfer, a more reliable approach for predicting the 28-day compressive strength $f_c^*$ is to apply a strength-growth model based on $f_{ci}^*$ and the expected strength-growth properties as outlined in the next section.

**Table 7.** Effectiveness of previous studies and ACI PRC-214-11-based prediction equation on Alabama strength data at 28 days

| Model reference | Model definition | Mean squared error, % |
|---|---|---|
| Current practice | $f_{ci}^{*} = f_c'$ | 37.0 |
| Storm et al. (2013) | $f_{ci}^{*} = 1.45 f_c'$ | 14.5 |
| Rosa et al. (2007) | $f_{ci}^{*} = 1.25 f_c'$ | 22.7 |
| ACI PRC-214-11–based with s = 400 psi | $f_{ci}^{*} = f_c' + 536$ | 32.2 |
| ACI PRC-214-11–based with s = 600 psi | $f_{ci}^{*} = \begin{cases} f_c' + 898 & f_c' \le 5000 \\ 0.9f_c' + 1398 & 5000 \le f_c' \le 5940 \\ f_c' + 804 & 5940 \le f_c' \end{cases}$ | 29.7 |
| ACI PRC-214-11–based with s = 800 psi | $f_{ci}^{*} = \begin{cases} f_c' + 1364 & f_c' \le 5000 \\ 0.9f_c' + 1864 & 5000 \le f_c' \le 7290 \\ f_c' + 1072 & 7290 \le f_c' \end{cases}$ | 26.2 |
| ACI PRC-214-11–based with s = 1000 psi | $f_{ci}^{*} = \begin{cases} f_c' + 1830 & f_c' \le 5500 \\ 0.9f_c' + 2330 & 5000 \le f_c' \le 9900 \end{cases}$ | 22.3 |

Note: ACI = American Concrete Institute; $f_c'$ = specified concrete strength at 28 days; $f_c^{*}$ = expected concrete strength at 28 days; $s$ = standard deviation of strength test data. 1 psi = 6.895 kPa.

## Strength-growth model

Comparing the relative goodness of fit for current practice at the time of prestress transfer (MSE of 25.8%) with that at 28 days (MSE of 37.0%), it is evident that measured compressive strength in the Alabama region tends to, on average, more reliably approach the specified compressive strength at prestress transfer $f_{ci}'$ than the specified compressive strength at 28 days $f_c'$. When concrete mixture selection prioritizes achieving $f_{ci}'$ without delay, the strength-growth characteristics of typical precast, prestressed concrete mixtures will ensure, in the vast majority of cases, that the specified 28-day compressive strength is exceeded. This observation serves as the basis of the strength-growth approach presented herein for the prediction of expected 28-day compressive strength $f_c^{*}$, based on expected compressive strength at prestress transfer $f_{ci}^{*}$.

A well-established strength-growth relationship is proposed by ACI 209:[19]

$$f_c(t) = f_c\left[\frac{t}{\alpha + \beta t}\right] \quad (4)$$

where

$f_c(t)$ = concrete strength at any concrete age

$t$ = time after girder production

$\alpha$ = regression constant

$\beta$ = regression constant

While Eq. (4) allows a user to predict the expected concrete strength at any age of interest on the basis of a 28-day strength, a more useful expression for the precast, prestressed concrete community is a similar equation that predicts the concrete strength at later ages based on a known or assumed strength at prestress transfer. As detailed by Hofrichter,[20] constants $\alpha$ and $\beta$ were calibrated based on historical testing data representing 435 prestressed girder production events in Alabama and Mississippi, a subset of the same data set presented herein. For typical accelerated-cured, Type III cement concretes, this analysis supports the use of a regression constant $\alpha$ of 0.34 days and $\beta$ of 0.98. By combining these constants with a mean concrete age at transfer of 18 hours (0.75 days), Eq. (5) was developed for computing the expected 28-day concrete compressive strength $f_c^{*}$ as a function of the concrete strength measured at transfer $f_{ci}$:

$$f_c^{*} = 1.44 f_{ci} \quad (5)$$

**Figure 7** shows the use of Eq. (5) within a prediction model, referred to as the strength-growth approach.

The two projected concrete strength development curves shown in Fig. 7 represent the shape of expected concrete strength development curves based on differing initial strength metrics at the time of prestress transfer ($f_{ci}'$ and $f_{ci}$). Point A represents the overall best estimate of 28-day compressive strength $f_c^{*}$ based on the measured strength at prestress transfer $f_{ci}$ and expected strength-growth parameters, while point B represents a less accurate estimate of the 28-day compressive strength $f_c^{*}$ based only on expected strength-growth rates and neglecting the discrepancy between the specified and measured transfer strength ($f_{ci} - f_{ci}'$).

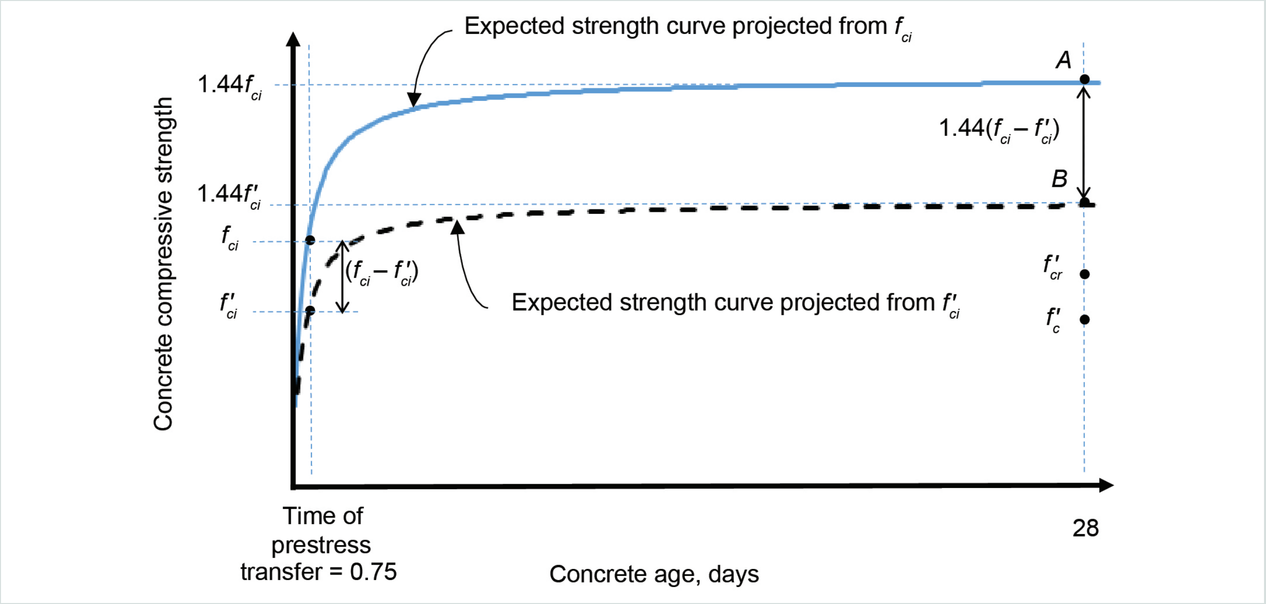


**Figure 7.** Strength-growth approach incorporating regional concrete strength development recommendations by Hofrichter (2014). Note: $f'_c$ = specified concrete strength at 28 days; $f_{ci}$ = measured concrete strength at prestress transfer; $f'_{ci}$ = specified concrete strength at prestress transfer; $f'_{cr}$ = required average concrete strength.

**Figure 8** shows the predictions of 28-day compressive strength resulting from applying the strength-growth approach on the basis of measured compressive strength at time of prestress transfer for each production event. Prediction model accuracy is illustrated by lines representing the percent above or below the expected 28-day strength that was computed as the ratio of the difference divided by the measured 28-day strength. MSE is calculated according to Eq. (3) and the results are provided in the figure.

In Fig. 8, 88.4% of the expected 28-day strengths obtained by the strength-growth approach fall within ±20% error lines. When compared with the MSE of the other models summarized in Table 7, the MSE of 12.6% obtained for the strength-growth approach makes it the most accurate approach among the 28-day prediction models. Even though the measured strength at time of prestress transfer is not available at the design stage, this indicates that efforts to better predict transfer strength can improve the accuracy of expected 28-day strength when using the strength-growth approach.

## Conclusion

The use of accurately predicted expected concrete compressive strength results in more accurate design-phase predictions of service limit state deflections than the use of the specified concrete strength. The research described in this paper supports the following conclusions related to accurately predicting the expected strength of precast, prestressed concrete components:

- The average measured concrete compressive strength for a sampling of Alabama precast, prestressed concrete girders was 33% greater than the specified strength at prestress transfer and 59% greater than the specified strength at 28 days.

- Empirical expected strength prediction equations that are based on practices and materials in only one region of the United States may not be reliable in other regions.

- Single-factor approaches for predicting the expected concrete strength as a simple multiple of the specified strength are not accurate over a wide range of specified strengths. There is also less dispersion of measured strengths in higher-strength concretes.

- For predicting expected concrete strength at prestress transfer ACI PRC-214-11 equations are promising tools to predict expected concrete strength as a function of specified strength, but ACI PRC-214-11 requirements for calibrating ACI PRC-214-11 equations from regional strength test results are not compatible with bridge girder data sets that typically contain different specified strengths among projects.

- The expected concrete strength at 28 days in precast, prestressed concrete components is better predicted based on extrapolating growth from the specified strength at transfer than based on the specified strength at 28 days. A suitable strength-growth approach is outlined in this paper.

In a companion paper,[10] the authors leverage the findings reported here and propose an ACI PRC-214-11–based methodology to analyze regional strength test results to generate expected strength prediction models for use in precast, prestressed concrete design. In that forthcoming work, the authors propose

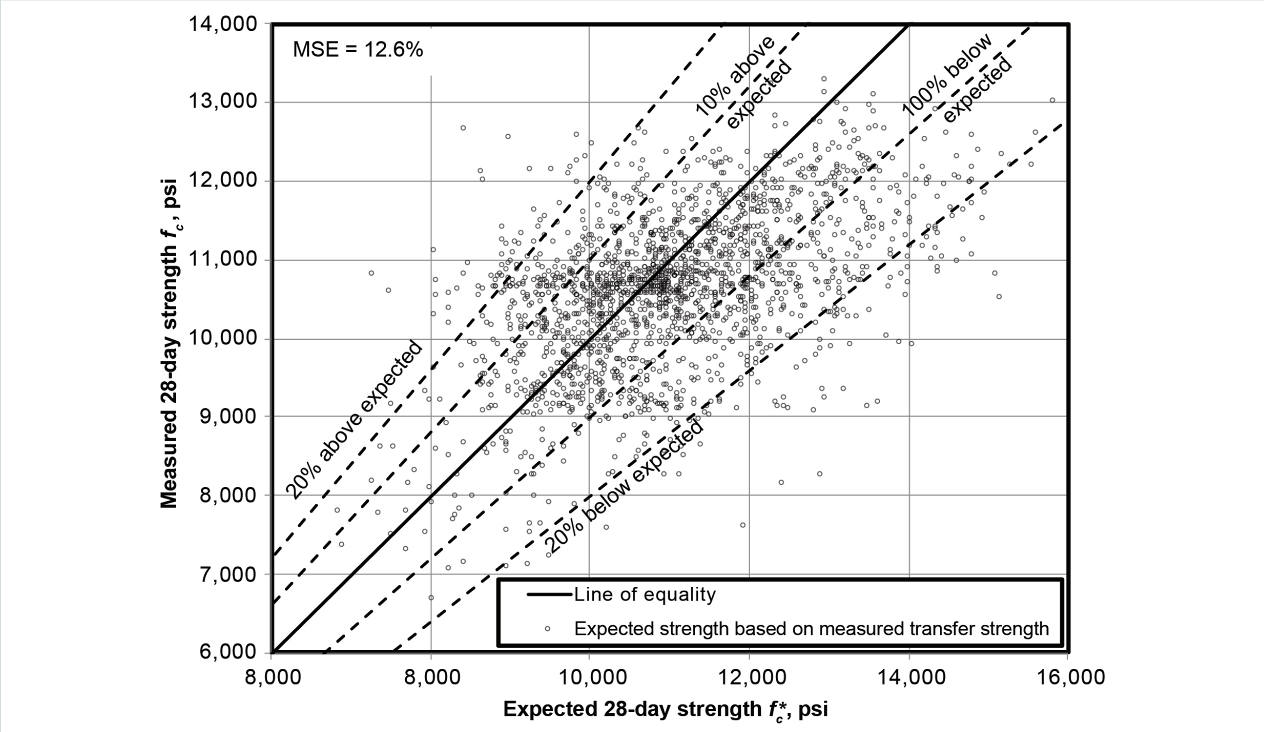


**Figure 8.** Expected 28-day strength with strength-growth approach. Note: MSE = mean squared error. 1 psi = 6.895 kPa.

an analysis technique that addresses the thus unresolved challenge of relying on archived regional strength test data containing a range of specified strengths exceeding 1000 psi.

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## Notation

$f_c$ = strength measured using standardized cylinder testing at 28 days

$f'_c$ = strength specified by design engineer at 28 days

$f_c^*$ = strength expected at 28 days based on some prediction model

$f_{ci}$ = strength measured using standardized cylinder testing at prestress transfer

$f'_{ci}$ = strength specified by design engineer at prestress transfer

$f_{ci}^*$ = strength expected at prestress transfer based on some prediction model

$f'_{cr}$ = required average strength at 28 days

$f'_{cri}$ = required average strength at prestress transfer

$f_c(t)$ = strength measured at any concrete age

$i$ = time of prestress transfer

$M$ = measured concrete strength

$M_i$ = measured concrete strength at prestress transfer

$M_{28}$ = measured concrete strength at 28 days

$n$ = sample size

$s$ = standard deviation of strength test data

$S$ = specified concrete strength

$S_i$ = specified concrete strength at prestress transfer

$S_{28}$ = specified concrete strength at 28 days

$t$ = time after girder production

$w/cm$ = water–cementitious material ratio

$\alpha$ = regression constant

$\beta$ = regression constant

$\mu$ = mean of the distribution

$\sigma$ = standard deviation of the distribution

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## Abstract

Accurate estimates of expected concrete compressive strength are critical for designers to predict the deformational behavior of precast, prestressed concrete elements such as camber, deflections, and prestress losses. To explore the difference between specified and expected concrete compressive strength for Alabama bridge girders, a compressive strength data set representing 1887 girder production events was collected. The average measured concrete compressive strength for Alabama girders was 33% greater than the specified strength at prestress transfer and 59% greater than the specified 28-day strength. Available empirical strength prediction methods derived for other U.S. regions did not accurately represent the Alabama data. The most promising candidates for prediction methodologies for expected compressive strength were models based on guidance from the American Concrete Institute Committee 214 for the prediction of expected strength at prestress transfer and models based on concrete strength-growth modeling to predict 28-day strength.

## Keywords

Compressive strength, deflection, expected strength, historical review, serviceability, specified strength, strength prediction.

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