CHARACTERIZATION OF MECHANICAL PROPERTIES AND VARIABILITY OF PCC MATERIALS FOR RIGID PAVEMENT DESIGN

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The FHWA-supervised Long-Term Pavement Performance (LTPP) project includes many experimental Special Pavement Studies (SPS) pavements from which concrete materials were sampled and tested for a variety of concrete mechanical properties. The materials and techniques used in constructing the SPS test pavements represent modern concrete pavement construction practices. The information collected includes compressive strength, flexural strength, split tensile strength, and static elastic modulus. The ages at which the specimens were tested for the various strength parameters ranged from 14 to 500 days.

This paper describes an analysis of strength data from the LTPP SPS-2 experiment. The authors studied the rate of strength gain under the varied influences of climate/curing conditions, specimen type, and cement type. The variability of strength data obtained from a given project and the differences between "as-specified" and "as-built" strengths were also investigated. Both strength development and variability are important input parameters for pavement design and reliability analysis. Finally, commonly cited relationships between the various strength parameters were also analyzed. This paper provides typical concrete material inputs to the rigid pavement mechanistic-empirical design process.

INTRODUCTION

Mechanical properties of concrete, including compressive strength, flexural strength (or the modulus of rupture), modulus of elasticity, and tensile strength important inputs to the pavement design process. Also, the variability of the mechanical properties of concrete is an important input for reliability analysis. For example, the concrete modulus of rupture is one of the most sensitive inputs in determining rigid pavement thickness using the AASHTO design procedure (1). Likewise, in many mechanistic-empirical design procedures, the modulus of rupture is a key input in estimating the fatigue life of the pavement. A small change in the modulus of rupture can have a huge impact on the fatigue calculations.

The mechanical properties of concrete are typically characterized in pavement design using a single value (e.g., 28-day mean flexural strength or a 28-day mean elastic modulus). However, concrete materials continue to gain strength almost indefinitely over time due to the continued hydration of the portland cement. Significant factors affecting the development of strength with time include the cement type, initial water-cement ratio, and curing conditions. Several studies

conducted to study the impact of each of these parameters on the strength development are reported in the literature (2, 3). In recognition of this fact, some pavement design methodologies, such as the Portland Cement Association procedure (4), account for strength gain beyond 28 days. The 2002 Design Guide, currently being developed under NCHRP Project 1-37A, utilizes the incremental damage concept to predict pavement performance. This approach also requires concrete strength and modulus information from the time the pavement is opened to traffic to the end of its design life.

Obtaining long-term material properties over the entire design life of the pavement for use in design cannot be based entirely on laboratory testing, for obvious reasons. Guidance will need to be sought from available concrete material databases to help estimate long-term properties based on short-term testing.

REVIEW OF PAST STRENGTH CHARACTERIZATION STUDIES

Several studies have been conducted to characterize PCC strength development.

PCA Study (5, 6)

A PCA study conducted by Wood analyzed data compiled from tests of 5000 concrete prisms and 1500 concrete cylinders representing nearly 300 combinations of cement type, mix proportions, and curing conditions. The data included specimens tested from 1 day to 34 years for compressive strength, flexural strength, and dynamic modulus of elasticity. Among other interesting findings, the study presented the variation of normalized concrete compressive strength with age (1 day to 20+years) for a variety of cement types and curing conditions. Data was normalized using the 28-day strength values.

Zero Maintenance Study (7)

Darter and Barenberg developed the following equation during the Zero Maintenance study for use in characterizing Portland Cement Concrete flexural strength. The equation was as follows:

$$STRRATIO = 1.22 + 0.17\log_{10}(AGE) - 0.05[\log_{10}(AGE)]^2 \qquad (1)$$

where

STRRATIO	=	ratio of M_R at a given age to M_R at 28 days
AGE	=	specimen age in years

M_R for a given age is obtained by multiplying the predicted strength ratio by the 28-day M_R (user input). A summary of the strength development ratios for compressive and flexural strengths is presented below.

Table 1. Strength development ratios for PCC.(5, 6, 7)

Specimen Age	PCA Study (Type I Cement- Compressive Strength)			Zero Maintenance (Type I Cement- Flexural Strength)		
	Moist Curing	Air Curing	Outside Exposure	Moist Curing	Air Curing	Outside Exposure
1 day	0.18	0.16	—	—	0.47	—
3 day	0.46	0.44	0.53	—	0.67	—
7 day	0.7	0.67	0.78	—	0.81	—
28 day	1	1	1	—	1.00	—
90 day	1.14	1.08	1.09	—	1.13	—
1 yr	1.22	1.02	1.19	—	1.26	—
3 yr	1.28	1.02	1.23	—	1.33	—
5 yr	1.33	1.02	1.37	—	1.36	—
10 yr	1.33	1.11	1.39	—	1.38	—
20 yr	1.44	1.34	1.42	—	1.40	—

Others

Several agencies have developed relationships between the four main PCC strength parameters, namely compressive, flexural, tensile, and elastic modulus. The relationships are summarized below.

Tensile Strength (2, 3)

Tensile strength measured from split tensile tests tend to be less than that measured form the third point loading—flexural strength. The ratio between the two typically ranges from 0.6 to 0.7.

Models for Relating Compressive to Elastic Modulus (2, 3)

Table 2 presents a summary of models available for relating PCC elastic modulus to compressive strength.

Table 2. Summary of models available for relating PCC elastic modulus to compressive strength.

Model	Source
$E_c = 0.043\rho^{3/2}(f'_c)^{1/2}$	American Concrete Institute (ACI)
$E_c = 9.1(\rho/2300)(f'_c)^{0.33}$	British Standards Institution (BSI)
$E_c = 9.5(\rho/2400)^2(f'_c + 8)^{0.33}$	Comite Europeen du Beton (CEB)

E_c is the PCC secant elastic modulus in GPa, ρ is the PCC unit weight in kg/m^3, and f'_c is the PCC compressive strength of a standard 150 x 300 mm cylinder in MPa.

Models for Relating Compressive to Flexural Strength (2, 3)

Table 3 presents a summary of models available for relating PCC flexural strength to compressive strength.

Table 3. Summary of models available for relating PCC flexural strength to compressive strength.

Model	Source
$M_R = 9.5 (f_c)^{0.5}$ (stress in psi)	PCA Model
$M_R = 0.62 (f_c)^{0.5}$ (stress in MPa)	ACI
$M_R = 8.3 (f_c)^{0.5}$ (stress in psi)	Teychenne
$M_R = 0.3 (f_c)^{0.66}$ (stress in MPa)	Comite Europeen du Beton
$M_R = k_2 (f_c)^{k1}$ (k_2 ranges from 3 to 6, k_1 from 0.3 to 0.8, stress in psi)	Neville
$M_R = 8.3 / (4 + 12000/f_c)$ (stress in psi)	Sozen, et al.

M_R is the PCC flexural strength in MPa or psi and f_C is the PCC compressive strength in MPa or psi.

In applying the findings from these studies to develop guidance on long-term strength development of concrete for pavement design purposes, the following issues came to the fore:

- The concrete specimens analyzed by Wood were made from cements manufactured in the 1940s and 1950s and may not accurately represent the early strength development of modern cements.
- Data for outdoor curing was obtained from only two locations (Skokie, Illinois and Dallas, Texas).
- All the pavement concrete specimens were cast; no cores were obtained and tested. These factors need to be further investigated, along with the effects of modern materials production and construction practices on the strength development before generalized guidance on strength can be developed.
- There were several models available for relating strength parameters with no guidance on their suitability.
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STUDY OBJECTIVES AND SCOPE

The specific research objectives considered in this study were:

- Investigation of PCC strength development over time for modern pavement concretes.
- Characterization of "within project" or "along project" variability of concrete strength parameters.
- Assessment of the relationship between material strength variability and the mean strength.
- Verification of the relationships between compressive strength, flexural strength, split tensile strength, and elastic modulus.

The stated objectives were investigated using data from the FHWA Long Term Pavement Performance (LTPP) Special Pavement Studies Experiment 2 (SPS-2) projects. The pavement sections under the SPS-2 experiment were constructed in the 1990s and reflect modern materials production and pavement construction practices. The rate of strength development was studied for PCC compressive, flexural, and split tensile strength. A similar study was not possible for the static elastic modulus due to lack of sufficient time-series data. The time-series information in the LTPP Information Management System (IMS) ranged from 14 days to 450 days; therefore, the strength development could be studied only up to these ages. A part of the data presented

here was analyzed under an ongoing LTPP data analysis contract sponsored by the FHWA (7). The scope of the present investigation was limited to data from test sections pertaining to the SPS-2 primary experiment (section numbers 201 to 224), which had the most substantial information on concrete materials of all the SPS experiments.

DATA AVAILABLE FROM LTPP SPS PROJECTS

The LTPP SPS-2 test sites or projects are spread across several States and climatic regions. Each SPS-2 project (typically one in every State) includes a series of side-by-side test sections that are 152 m (500 ft) long. Each test section within a project is constructed as uniformly as practical in order to avoid excessive variability in the materials and construction practices and to facilitate direct comparisons of performance.

Materials Specifications for SPS-2 Project Construction

The SPS-2 test sections are constructed at two levels of target flexural strength—3.8 MPa (550 psi) and 6.2 MPa (900 psi)—as determined from third-point loading at 14 days. The higher target strengths were usually achieved by adjusting the water-cement ratio (increased cement factor). The as-delivered slump (not to exceed 62.5 mm [2.5 in]) and air content (6.5 $\pm$ 1.5% for freeze-thaw areas) were monitored to ensure consistency with the specifications. A majority of the projects (95 percent) were built with Type I (62 percent) and Type II cements (33 percent) with a possibility of up to 15 percent substitution of Class F fly ash by weight (although this was rarely observed in practice). The cements used were specified to meet the requirements of AASHTO M85 specification. The fine aggregates used were required to meet the quality guidelines specified in AASHTO M6, and the coarse aggregates were specified to meet the AASHTO M80 requirements. Special emphasis was placed on ensuring that the aggregates met the highest standards of durability.

Sampling and Testing

Two types of samples—bulk samples as the concrete was being delivered during construction and cored samples of hardened in-place concrete— were collected as part the materials testing program under the SPS-2 experiment. The bulk samples were molded into test specimens (cylinders for compressive and split tensile strength and beams for flexural strength), moist cured, and tested at various ages to determine the mechanical properties. Prior to testing the PCC cylinders were moist cured at 23 $\pm$ 1.7^{o}C (73.4 $\pm$ 1°F) in a room meeting AASHTO specification M201. Core samples were also obtained from the test sections at various pavement ages and were tested. Thus, strength data from the cylinder or beam specimens reflect the effect of indoor curing conditions and that from cores reflect the effect of outdoor curing conditions. Testing of the PCC cores, cylinders, and beams was accomplished by the State/Province/Agency laboratory (or designee) where the SPS-2 project was located. The following protocols were followed for testing the concrete samples in the LTPP program:

- Compressive strength — SHRP P61 (ASTM C39).
- Flexural strength — SHRP P69 (ASTM C78).
- Split tensile strength — SHRP P62 (ASTM C496).
- Static elastic modulus — SHRP P64 (ASTM C469).

Further details of the sampling and testing procedures can be obtained from the SPS-2 Materials Sampling and Testing Guidelines (8).

Summary of the Available Data

Table 4 lists the number of specimens for which data was available for compressive, flexural, tensile, and elastic modulus material properties. The data are arranged by climatic zones, specimen types, and specimen age at testing. The following rules were applied in interpreting the age at testing for each specimen for which data was available in the LTPP IMS:

Actual Specimen Age at Test	Assigned Specimen Age
Between 13 to 15 days	14 days
Between 26 to 30 days	28 days
Between 320 to 400 days	365 days

These rules were necessitated to consolidate samples with varying ages under the three distinct categories noted in table 1 to form the basis for generalized conclusions.

Table 4. Summary of the PCC materials data in the LTPP IMS.

LTPP Climatic Zone	Target Flexural Strength, MPa (psi)	Specimen Type	No.of Comp. Str. Specimens 14/28/365	No. of Flex. Str. Specimens 14/28/365	No. of Split Tensile Str. Specimens 14/28/365	No. of Elastic Mod. Specimens 14/28/365
DF	3.8 (550)	Core	17/17/16	N/A*	21/20/20	0/14/18
		Cylinder/Beam	12/12/12	13/13/12	16/16/16	0/12/18
	6.2 (900)	Core	15/16/16	N/A	20/19/20	N/A
		Cylinder/Beam	12/12/12	12/12/12	15/15/15	N/A
DNF	3.8 (550)	Core	5/6/6	N/A	6/6/5	0/6/6
		Cylinder/Beam	3/3/3	3/3/3	3/3/3	0/5/5
	6.2 (900)	Core	5/5/5	N/A	6/7/6	N/A
		Cylinder/Beam	3/3/3	6/6/6	3/3/3	N/A
WF	3.8 (550)	Core	16/17/16	N/A	18/20/14	0/7/14
		Cylinder/Beam	15/16/14	18/18/15	15/16/15	0/10/14
	6.2 (900)	Core	14/17/15	N/A	18/17/14	N/A
		Cylinder/Beam	15/15/13	16/16/12	17/18/10	N/A
WNF	3.8 (550)	Core	0/0/0	N/A	3/6/3	0/5/6
		Cylinder/Beam	2/2/2	7/7/7	3/3/3	0/5/6
	6.2 (900)	Core	0	N/A	2/5/6	N/A
		Cylinder/Beam	3/3/2	2/4/4	3/3/4	N/A

* These specimens were not intended to be collected and tested according to the original LTPP program.

The percentage of samples to which these rules had to be applied was a very small fraction of the total number of samples, as the age at testing for most specimens fell under the pre-selected categories. Specimens outside the age ranges indicated above were not considered in this analysis.

The following conclusions can be drawn from table 4:

- Companion data from cylinder and core specimens are available for compressive strength and split tensile strength facilitating the comparison of strength development under moist curing (indoor) versus outdoor curing.
- Data from multiple specimens are available from within the same project, enabling conclusions to be drawn on "within project" variability for all the strength parameters investigated.
- Time-series information is available for all the strength parameters, which facilitates the investigation of strength development with time.
- Data required for the validation of commonly cited strength-strength and strength-modulus interrelationships exists.

In all, data from 416 compressive strength, 229 flexural strength, 503 split tensile strength, and 151 elastic modulus specimens were used in the analysis. These data represented 4 climatic zones, 13 projects located in as many States, 2 specimen types, 2 target strengths, and 3 specimen ages at testing.

STRENGTH DEVELOPMENT AND VARIABILITY ANALYSIS

As mentioned earlier, the primary objective of this study was to determine the rate of strength gain of PCC. The three strength types analyzed were compressive, flexural, and split tensile strengths. Strength development is a complicated process that could be significantly affected by factors such as climate/curing conditions, cement type, and water-cement ratio. The effect of each of these factors on strength development was investigated as part of the procedure for characterizing PCC. For the purposes of this study, water-cement ratio was substituted by target flexural strength at which the SPS-2 sections were constructed since these two variables were strongly correlated. The procedure is summarized as follows:

1. Determine if the following factors affect strength gain for the SPS-2 data:
   - Climate/curing conditions.
   - Specimen type (core or cylinder/beam).
   - Target strength.
   - Cement type.
2. Based on the results from step 1, compute strength ratio for subgroups with significantly different strength ratios (e.g., if there is a significant different between the strength ratios for cores and cylinders, then two different strength ratios must be computed to characterize their rate of strength development).

Strength gain ratios are calculated as follows:

$$\mathrm{STRGAIN}_X = \frac{\mathrm{STR}_X}{\mathrm{STR}_{28}} \qquad (2)$$

where $STRGAIN_X$ is the ratio of the strength at age X to the given reference age strength. The reference strength used in computing the strength ratios is the 28-day strength, as shown in equation 2. $STRGAIN_{28}$ will therefore always have a value of 1.0, so the analysis was limited to the effect of climate and other factors listed previously on $STRGAIN_{14}$ and $STRGAIN_{365}$.

Statistical Procedures Used in Data Analysis

Analysis of variance (ANOVA) was used to investigate the main and interaction effects of the categorical factors (independent variables such as climate and specimen type) on strength gain. Interaction effect is defined as the joint effect of two or more independent variables on the dependent variable (strength). The key test used in ANOVA was the F-test. It was to used to test if the means of the groups formed by values of the independent variables (or combinations of values of multiple independent variables) were different enough not to have occurred by chance.

If the group means do not differ significantly, then it was inferred that the independent variables did not have an effect on the dependent variable. If the F-test shows that overall the independent variables are related to the dependent variable, then *multiple comparison tests* of significance were used to explore which value groups of the independent variables had the most effect on the dependent variable. The multiple comparison test of significance used for data analysis was the Scheffé test. The Scheffé test is a widely used method for testing of differences in group means. It is a conservative test and is more appropriate for situations where some variability is expected due to the experimental design set up.

Summary of Factors that Influence PCC Compressive Strength Gain

The effect of the independent factors listed in table 5 on compressive strength development was investigated.

Table 5. Independent factors considered in the compressive strength means comparisons.

Factor	Number of Levels	Values
Climate*	4	Dry-freeze, Wet-freeze, Dry-nofreeze, Wet-nofreeze
Specimen type	2	Core, cylinder
Mean strength, MPa	2	Target flexural strength = 3.8 MPa (550 psi) or 6.2 MPa (900 psi)
Cement type	2	Type I, Type II

* Based on LTPP definitions.

The results for $STRGAIN_{14}$ and $STRGAIN_{365}$ are summarized in table 6.

Table 6. Summary of Scheffé multiple range test results for compressive strength.

Strength Ratio	Factor	Level	N	Mean Ratio	Scheffé Grouping*
$STRGAIN_{14}$	Climate	Wet freeze	60	0.918	A
		Dry freeze	56	0.871	A
		Wet nofreeze	5	0.897	A
		Dry nofreeze	16	0.907	A
	Specimen type	Core	72	0.919	A
		Cylinder	65	0.873	B
	Target flexural strength	3.8 MPa (550 psi)	60	0.889	A
		6.2 MPa (900 psi)	77	0.905	A
	Cement type	Type I	68	0.904	A
		Type II	45	0.878	A
$STRGAIN_{365}$	Climate	Wet freeze	58	1.285	A
		Dry freeze	56	1.393	A
		Wet nofreeze	4	1.391	A
		Dry nofreeze	17	1.289	A
	Specimen type	Core	74	1.405	A
		Cylinder	61	1.247	B
	Target flexural strength	3.8 MPa (550 psi)	30	1.349	A
		6.2 MPa (900 psi)	105	1.329	A
	Cement type	Type I	66	1.370	A
		Type II	44	1.219	A

* Levels, within a given factor, represented by different letters (e.g., Scheffé groupings = A or B) are significantly different.

The results presented in table 6 suggest the following:

- Climate/curing does not significantly affect compressive strength development as much as would normally be expected.
- Specimen type does significantly affect 14- and 365-day strength development ratios.
- Mean target strength does affect compressive strength development.
- Cement type (Type I or II) does not affect strength development.

Compressive Strength Development Ratios

Based on the results presented above, the strength ratios at 14 and 365 days were computed as a function of the mean 28-day strength and presented in table 7.

Table 7. Strength ratios for compressive strength development.

Specimen Type	$STRGAIN_{14}$ (Variability)	$STRGAIN_{365}$ (Variability)
Core	0.919 (0.109)	1.405 (0.264)
Cylinder	0.873 (0.065)	1.247 (0.179)

Typical Within-Project Compressive Strength Variability

The second objective of the study was to characterize typical "within project" compressive strength variability which is a key input for M-E design. Typical variability was defined as the variability corresponding to the 90th percentile of all the individual test sites evaluated within the

SPS-2 experiment. The effect of mean strength on variability was also evaluated. Figures 1 and 2 present the distribution of variability for the SPS-2 experiments evaluated and the plot of mean strength and computed variability. Figure 1 shows that typical variability was 14.1 MPa (2044.5 psi). Figure 2 shows that mean strength had no obvious effect on variability.

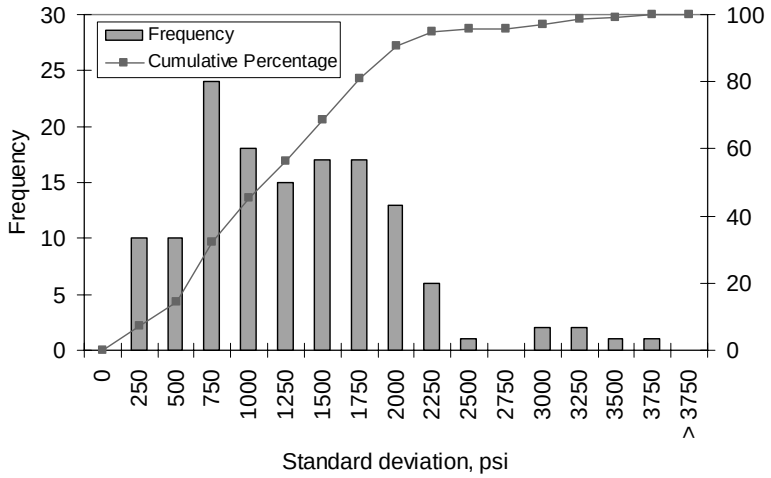

Figure 1. Distribution of within-project variability (measured as standard deviation) for PCC compressive strength.

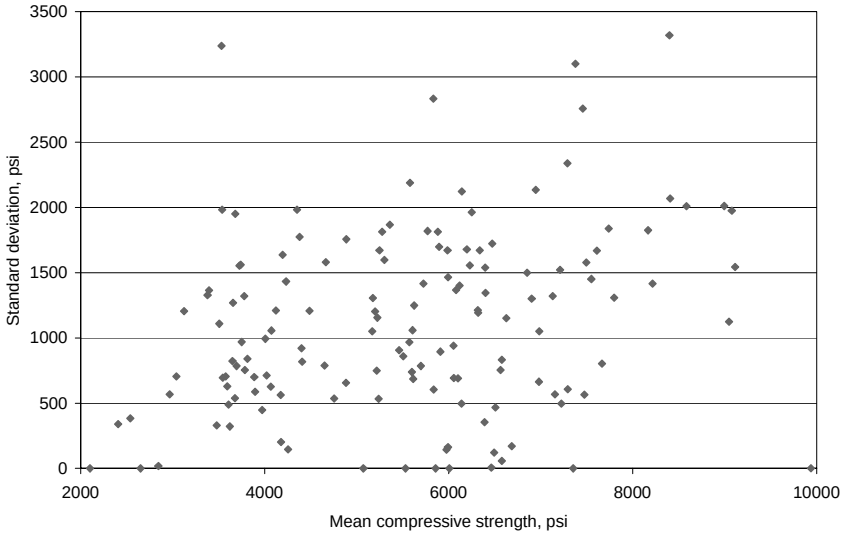

Figure 2. Plot of variability (measured as standard deviation) versus PCC compressive strength.

Summary of Factors that Influence PCC Flexural Strength Development

The effect of the independent factors listed in table 8 on flexural strength development was investigated.

Table 8. Independent factors considered in the flexural strength means comparisons.

Factor*	Number of Levels	Values
Climate	4	Laboratory cured
Specimen type	2	Beam
Target flexural strength, MPa (psi)	2	3.8 (550), 6.2 (900)
Cement type	2	Type I, Type II

* Climate and specimen type were not evaluated because all data was available only for laboratory-cured beams.

The results for $STRGAIN_{14}$ and $STRGAIN_{365}$ are summarized in table 9. The results presented in table 9 suggest the following:

- Climate/curing does not significantly affect flexural strength development as much as would normally be expected.
- Specimen type does significantly affect 14- and 365-day flexural strength development ratios.
- Mean target strength does not affect flexural strength development ratios.
- Cement type (Type I or II) does not affect flexural strength development.

Table 9. Summary of Scheffé multiple range test results for flexural strength development.

Strength Ratio	Factor	Level	N	Mean Ratio	Scheffé Grouping*
$STRGAIN_{14}$	Target flexural strength	3.8 MPa (550 psi)	12	0.923	A
		6.2 MPa (900 psi)	8	0.912	A
	Cement type	Type I	12	0.924	A
		Type II	6	0.893	A
$STRGAIN_{365}$	Target flexural strength	3.8 MPa (550 psi)	5	1.172	A
		6.2 MPa (900 psi)	15	1.109	A
	Cement type	Type I	12	1.153	A
		Type II	6	1.107	A

* Levels, within a given factor, represented by different letters (e.g., Scheffé groupings = A or B) are significantly different.

Flexural Strength Development Ratios

Based on the results presented in table 9, the strength ratios were computed as presented in table 10.

Table 10. Strength ratios for compressive strength development.

Specimen Type	$STRGAIN_{14}$ (Variability)	$STRGAIN_{365}$ (Variability)
Beam	0.916 (0.095)	1.125 (0.139)

Typical Within-Project Flexural Strength Variability

The typical within-project flexural strength variability, which is a key input for mechanistic-empirical (M-E) design, was also characterized. Typical variability was defined as the variability corresponding to the 90 percentile of all the individual test sites within the SPS-2 projects evaluated. The effect of mean strength on variability was also evaluated. Figures 3 and 4

present the distribution of variability for the SPS-2 experiments evaluated and the plot of mean strength and computed variability. Figure 3 shows that typical variability was 1.1 MPa (159.5 psi). Figure 4 shows that mean strength had no obvious effect on variability.

Summary of Factors that Influence PCC Split Tensile Strength Development

The effect of the independent factors listed in table 11 on tensile strength development was investigated. The results for $STRGAIN_{14}$ and $STRGAIN_{365}$ are summarized in table 12. The results presented in table 12 suggest the following:

- Climate/curing does not significantly affect tensile strength development.
- Specimen type does significantly affect 14- and 365-day tensile strength development ratios.
- Mean target strength does not affect early tensile strength development ratios.
- Cement type (Type I or II) does not affect tensile strength development.

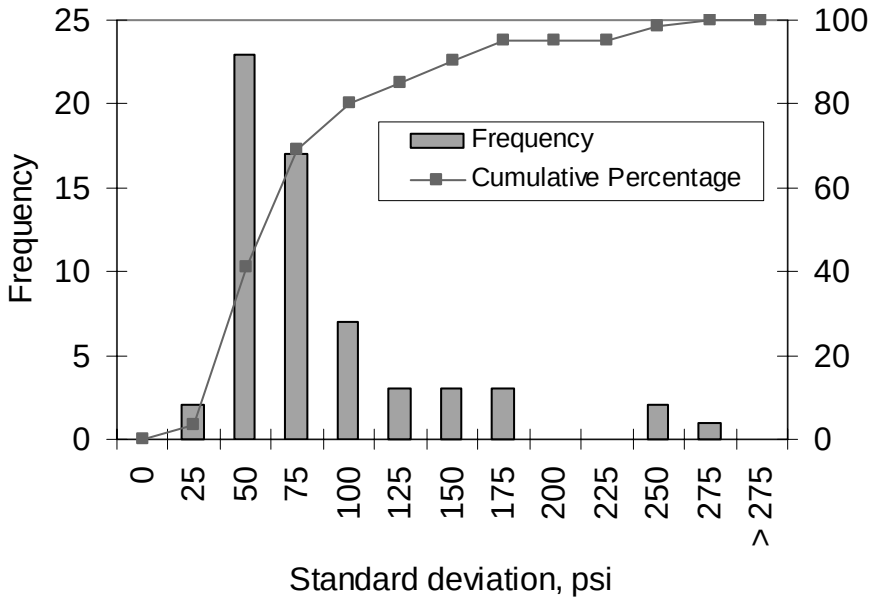

Figure 3. Distribution of within-project variability (measured as standard deviation) for PCC flexural strength.

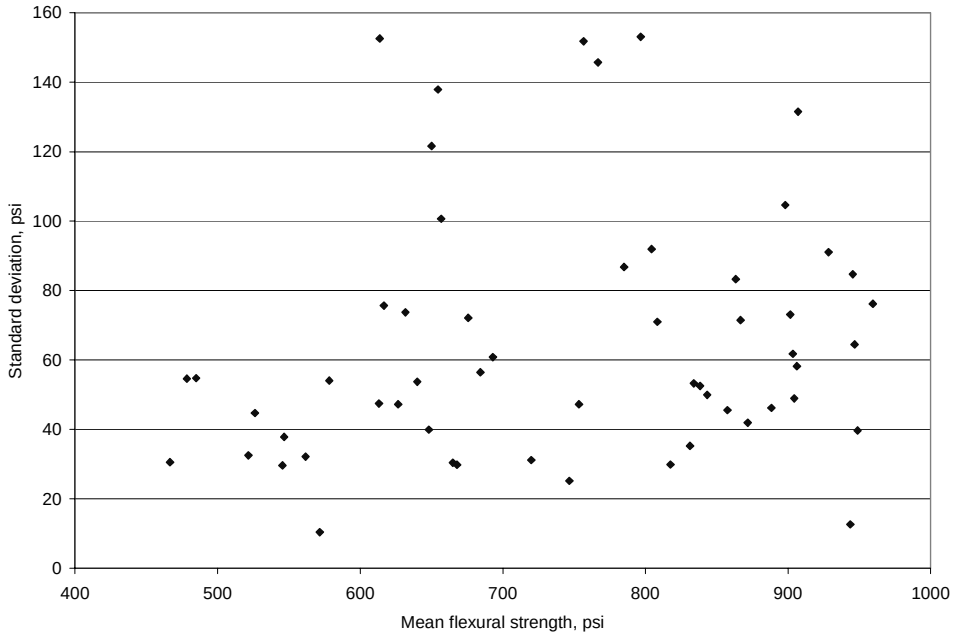

Figure 4. Plot of variability (measured as standard deviation) versus PCC flexural strength.

Table 11. Independent factors considered in the split tensile strength means comparisons.

Factor	Number of Levels	Values
Climate*	4	Dry-freeze, Wet-freeze, Dry-nofreeze, Wet-nofreeze
Specimen type	2	Core, cylinder
Target flexural strength, MPa (psi)	2	3.8 (550), 6.2 (900)
Cement type	2	Type I, Type II

* Based on LTPP definitions.

Table 12. Summary of Scheffé multiple range test results for tensile strength development.

Strength Ratio	Factor	Level	N	Mean Ratio	Scheffé Grouping
$STRGAIN_{14}$	Climate	Wet freeze	31	0.857	A
		Dry freeze	48	0.870	A
		Wet nofreeze	9	0.830	A
		Dry nofreeze	8	0.925	A
	Specimen type	Core	52	0.862	A
		Cylinder	44	0.872	A
	Target flexural strength	3.8 MPa (550 psi)	49	0.856	A
		6.2 MPa (900 psi)	47	0.878	A
	Cement type	Type I	46	0.872	A
		Type II	21	0.907	A
$STRGAIN_{365}$	Climate	Wet freeze	26	1.375	A
		Dry freeze	52	1.282	A
		Wet nofreeze	11	1.333	A
		Dry nofreeze	16	1.430	A
	Specimen type	Core	63	1.326	A
		Cylinder	42	1.343	A
	Target flexural strength	3.8 MPa (550 psi)	56	1.409	A
		6.2 MPa (900 psi)	49	1.246	A
	Cement type	Type I	54	1.347	A
		Type II	31	1.308	A

* Levels, within a given factor, represented by different letters (e.g., Scheffé groupings = A or B) are significantly different.

Split Tensile Strength Development Ratios

Based on the results, the strength ratios were computed as presented in table 13.

Table 13. Strength ratios for tensile strength development.

Specimen Type	$STRGAIN_{14}$ (Variability)	$STRGAIN_{365}$ (Variability)
Core/Cylinder	0.867 (0.092)	1.324 (0.300)

Typical Within-Project Split Tensile Strength Variability

The second objective was to characterize typical within-project tensile strength variability that is a key input for M-E design. Typical variability was defined as the variability corresponding to the 90th percentile of all the individual experiments within the SPS-2 projects evaluated. The effect of mean strength on variability was also evaluated. Figures 5 and 6 present the distribution of variability for the SPS-2 experiments evaluated and the plot of mean strength and computed variability. Figure 5 shows that typical variability was 1.1 MPa (159.5 psi). Figure 6 shows that mean strength had no obvious effect on variability.

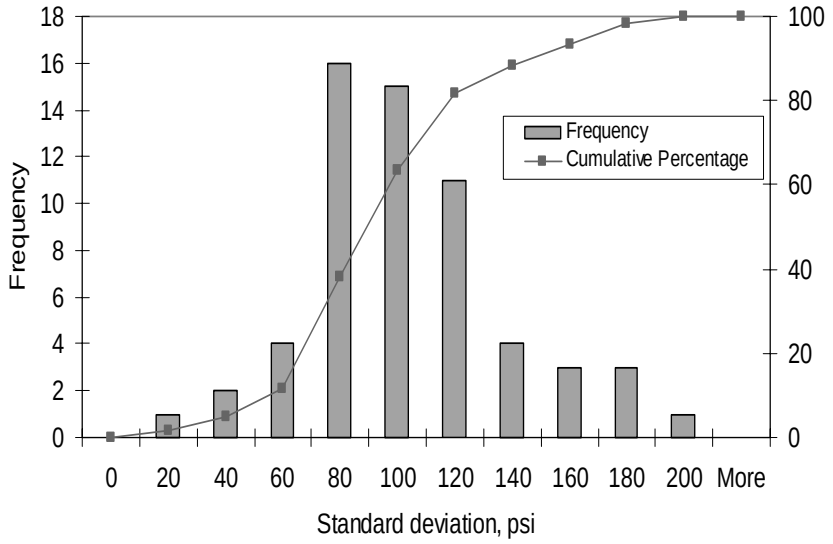

Figure 5. Distribution of within-project variability (measured as standard deviation) for PCC tensile strength.

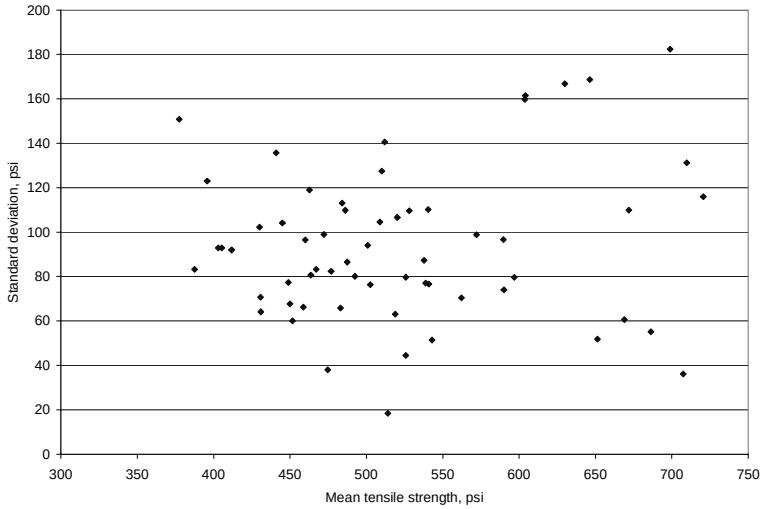

Figure 6. Plot of variability (measured as standard deviation) versus PCC tensile strength.

VERFICATION OF STRENGTH CORRELATIONS

Although there are no unique relationships between the various measures of concrete strength, some simplified correlations do exist. Among the most commonly used correlations are those between PCC compressive strength and tensile strength, as well as compressive strength and elastic modulus. Since compressive strength is one the easiest strength tests to be performed in a laboratory, these correlations assume significance in obviating the need to run more complicated and expensive tests. They also facilitate quick and expeditious estimation of material properties based on simpler tests. In this section, the applicability of these correlations to the LTPP data is discussed. Specifically, the following correlations were studied:

- Compressive strength versus flexural strength.
- Flexural strength versus split tensile strength.
- Compressive strength versus static modulus of elasticity.

Comparison of Compressive Strength and Flexural Strength

The flexural strength test is a common way of approximating the tensile strength of concrete. In many applications the flexural strength is not monitored during construction (5). Instead, the compressive strength is used along with standard correlations to estimate the flexural strength. Several formulae have been proposed to relate flexural strength to the compressive strength of concrete. The general form of this correlation is expressed in equation 3 below:

$$MR = K\sqrt{f_c'} \qquad (3)$$

where

MR = modulus of rupture, psi
f'c = compressive strength, psi
K = coefficient ranging from 8 to 10

The commonly used coefficients with equation 3 are 7.5 suggested by the ACI Committee 318 (10), 9.0 suggested by PCA (11), and 9.5 suggested by the European Concrete Committee (CEB) (12). The reasonableness of these models in predicting PCC flexural strength was evaluated using the LTPP data.

Figure 7 presents a plot of the mean compressive strength data from LTPP sections against corresponding mean flexural strength from the same projects at various ages. The mean strengths were computed by averaging data from multiple specimens for each age category within each SPS-2 project (typically there is one project per State). It should be noted that only compressive strength data from lab-cured cylinder specimens were used in the comparisons presented in figure 7 to ensure compatibility with the flexural strength data, which are also obtained from lab-cured beam specimens. In all, 8 LTPP projects with approximately 181 compressive strength specimens and 243 flexural strength specimens were used in the comparisons presented in figure 7. Also plotted in figure 7 are the three aforementioned theoretical correlations between compressive strength and flexural strength, for comparison.

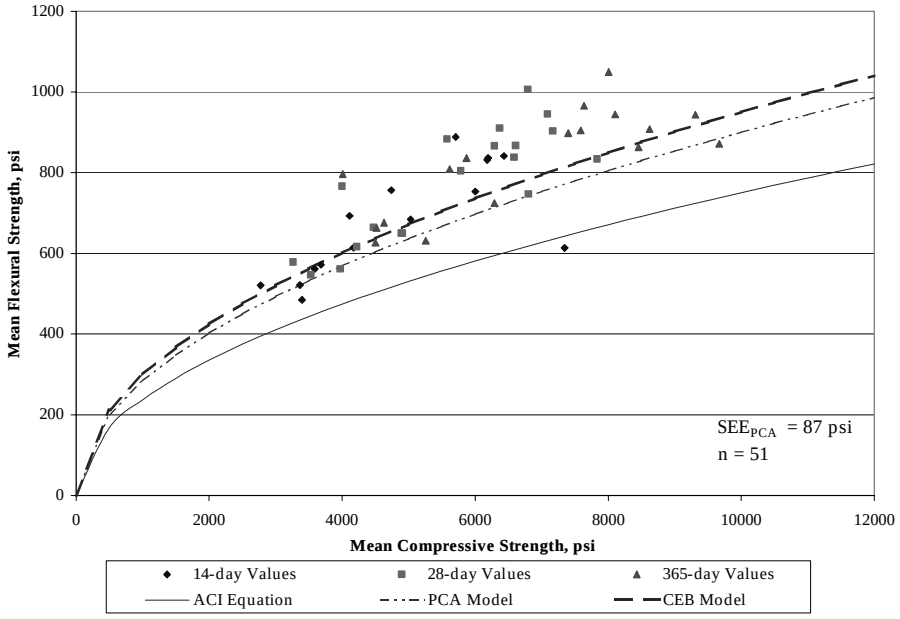

Figure 7. Comparison of LTPP SPS-2 compressive and flexural strength data.

The following conclusions can be drawn from the figure:

- The square-root relationship between the flexural and compressive strengths seems to adequately characterize the general trend of the data.
- All the three theoretical equations under-predict the actual flexural strength development, especially at the higher compressive strengths, with the ACI model being the most conservative and the European Concrete Committee model being the least conservative.
- Although the theoretical relationships were primarily based on the 28-day flexural strength data, they seem to be holding for all other ages as well.
- The LTPP materials strength data seems to be of adequate quality despite being collected and tested under a wide variety of conditions.
- The trends observed in this chart agree well with the earlier findings of Wood (5, 6) for moist-cured specimens.

Comparison of Flexural Strength and Split Tensile Strength

The tensile strength of concrete is important in the design of continuously reinforced concrete pavements. Although flexural strength testing is the most common way of estimating tensile strength of concrete, other loading modes (such as the direct tension and splitting tensile strength) are also used to characterize this parameter. The split tensile strength of concrete is commonly approximated as being two-thirds of its flexural strength (3). This approximation was examined using the LTPP data.

As a first step in setting up the comparisons between measured and predicted split tensile strengths, the data was processed to yield a one-to-one comparison between the flexural strength and tensile strength data sets contained in the LTPP IMS. Subsequently, the splitting tensile

strength was estimated using the simple approximation noted above. Figure 8 compares the predicted tensile strength with the measured value. Approximately 181 tensile strength specimens and 192 flexural strength specimens were used in developing the plot. These specimens were located across 10 different States. The following observations can be made from the figure:

- The simple correlation used does a reasonable job in approximating the split tensile strength from flexural strength.
- The standard error of the estimate of the predicted flexural strength is approximately 0.67 MPa (97.1 psi).
- The LTPP split tensile strength data is of good quality, with the exception of a few possible outliers seen in figure 8.

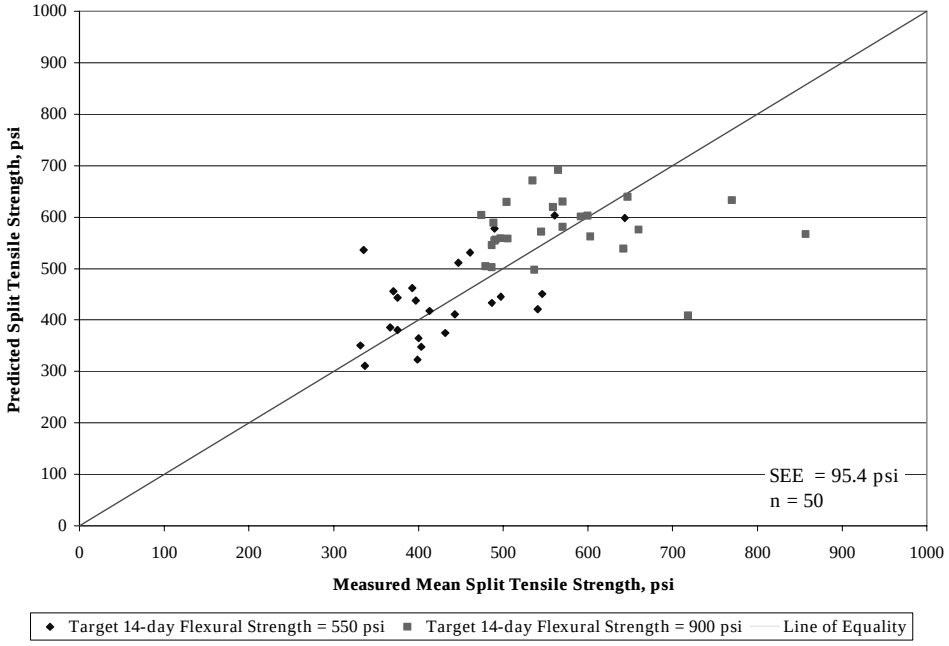

Figure 8. Comparison of measured versus predicted PCC split tensile strength.

Comparison of Compressive Strength and Static Elastic Modulus

The modulus of elasticity used in concrete pavement design is seldom determined by direct test. It is generally estimated from the empirical relationship suggested by ACI committee 318 and presented in equation 4. This equation was used to examine the relationship between the compressive strength and modulus data in the LTPP IMS database.

$$E_c = 57000\sqrt{f_c'} \qquad (4)$$

where

E_c = PCC static modulus of elasticity, psi
f_c' = PCC compressive strength, psi

Figure 9 presents a comparison between the companion sets of mean compressive strength and mean static modulus data. Data processing to obtain the respective strength and modulus values was performed as noted in the previous sections. There is a wide scatter of the data points about the theoretical prediction computed from equation 4. However, the data appears to be equally scattered on either side of the theoretical prediction. The standard error of the estimate between the measured modulus and the theoretical values is approximately 8451 MPa (1,200,000 psi). This is quite high; however, given the fact that most pavement design procedures are not very sensitive to the modulus of elasticity, it may be considered within reason. An important factor that may explain the variability of the data is that the type and nature of the coarse aggregate, which have a significant influence on the elastic modulus (3), may have varied considerably from project to project. This aspect will need further investigation.

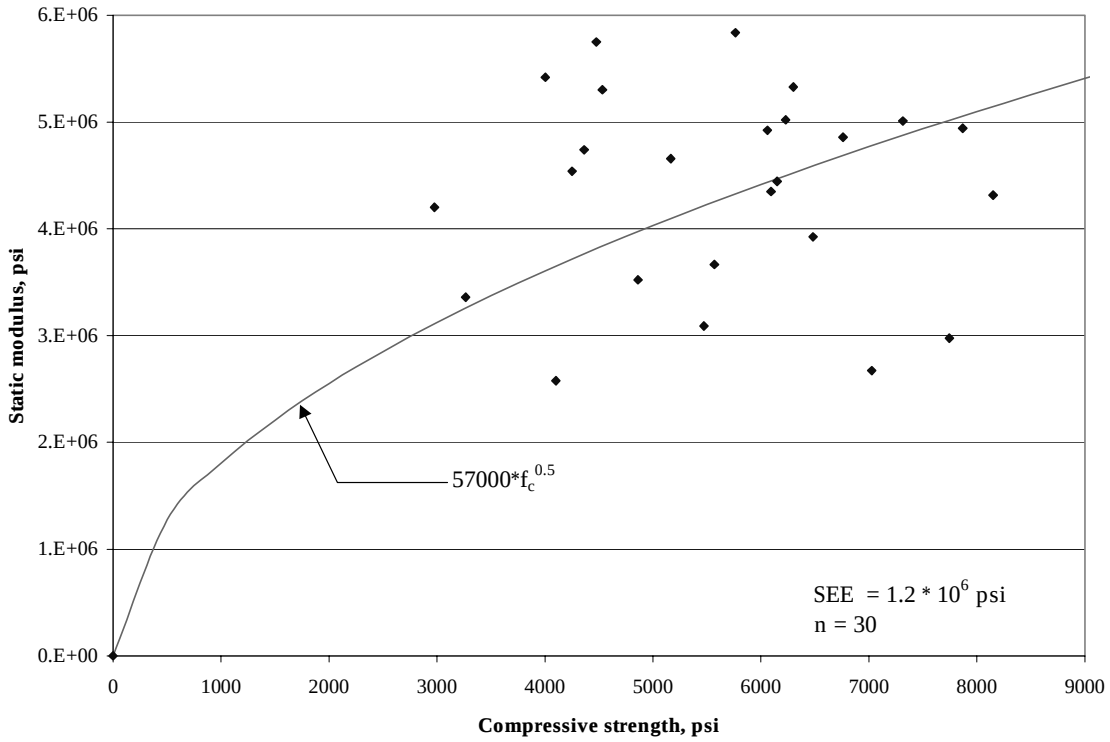

Figure 9. Comparison of LTPP SPS-2 measured and predicted split tensile strength data.

SUMMARY AND CONCLUSIONS

The research presented in this paper shows that strength development is not affected by outside climatic conditions so far as standard curing specifications are applied to the cast-in-place PCC or to specimens in the laboratory. Also, the PCC mixes target strength, and cement Types I or II had no significant effect on strength development. However, for PCC compressive strength, the specimen type—cored from the in-place pavement or cylinder cast from fresh PCC and cured in the laboratory—experienced significantly different rates of strength development. The rates of strength development are summarized throughout this paper and presented in figure 10.

The results also show that most of the current correlation's used to estimate PCC strength parameters are reasonable with the exception of PCC elastic modulus. They mostly compute conservative estimates of strength or are on target. A summary of the capabilities of the models evaluated is presented below:

- Compressive/flexural strength relationships—produced conservative estimates.
- Tensile/flexural strength relationships—on target.
- Compressive strength/static elastic modulus relationships—produced no consistent relationship.

Both the ratios developed and the existing strength relationships are reasonable and may be used for material characterization for pavement design.

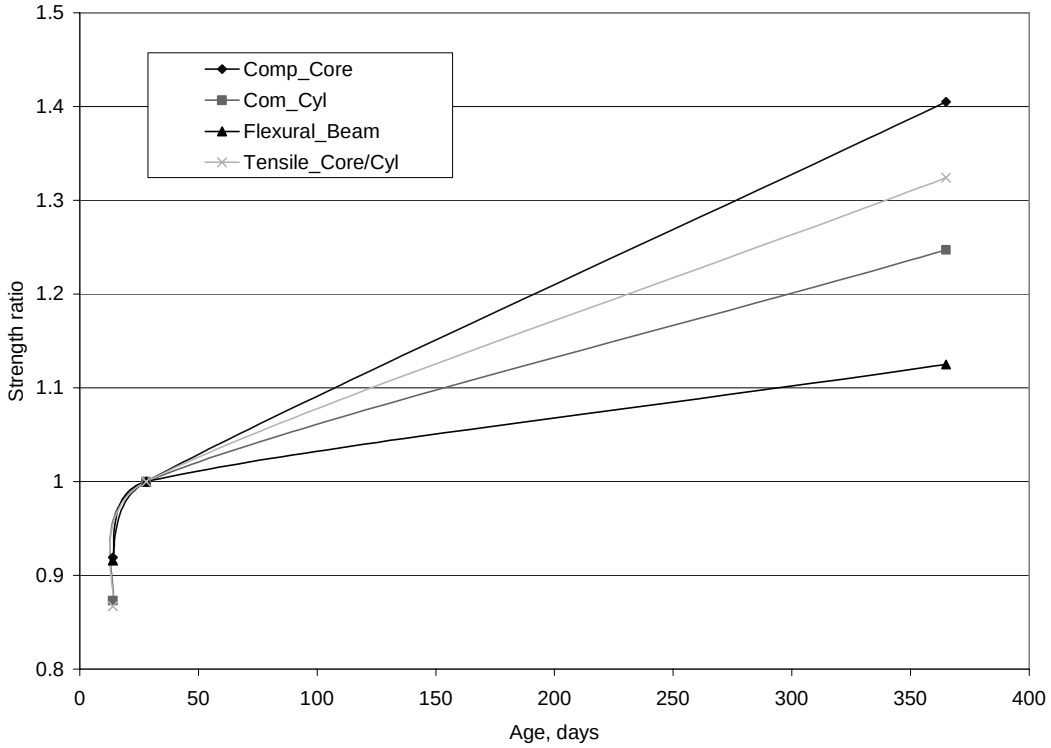

Figure 10. Strength development curves for PCC.

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