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Lesson 5:

Factors Affecting the Accuracy of Maturity Predictions

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Introduction

The recent TDOT/TRMCA/ACPA Evaluation of New PCC Maturity Technology Project generated a large quantity of data. The data generated can be analyzed to provide valuable lessons about PCC behavior. This is the fifth and final paper in a series of technology transfer articles. The authors appreciate the financial support of TDOT and TRMCA. We hope you find the information presented helpful in better understanding PCC behavior. In the final article, factors affecting the accuracy of maturity predictions of compressive strength are discussed.

New Maturity Technology Measurements and Assumptions

The new maturity technology only measures time and temperature. The new maturity technology assumes:

1. Maturity loggers are embedded in PCC of the same mixture design as the correlation mixture.
2. Moisture is adequate for continued curing.
3. Consolidation of the PCC is similar to the consolidation of the correlation mixture.

4. Temperature remains within the range in which the maturity relationship is valid.
5. The relationship between compressive strength and area under the temperature-time curve is constant for a particular PCC mixture design.

These assumptions will be examined separately to determine their effect on maturity prediction accuracy.

Statistical Implications on Maturity Accuracy

Compressive strengths for PCC mixtures are ranges rather than points. Small differences in component material proportions or qualities as well as mixing, transportation, placement, consolidation, and testing lead to differences in compressive strengths. If a plot of the number of results versus the compressive strength range is constructed with a large enough number of data points, a column graph similar to Figure 1 typically results. Connecting the tops of the columns with a smooth curve yields the familiar normal distribution curve (Figure 2). Three observations about the normal distribution curve can be made:

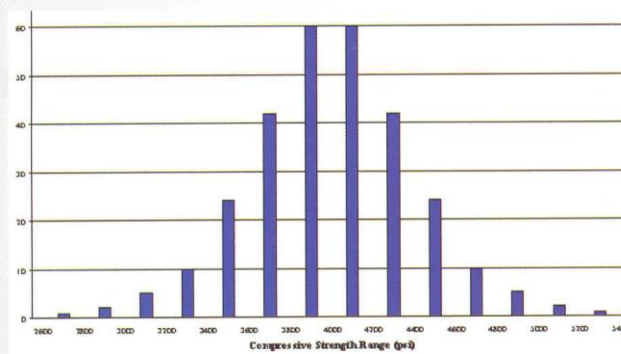


Figure 1. Distribution of Compressive Strength Results

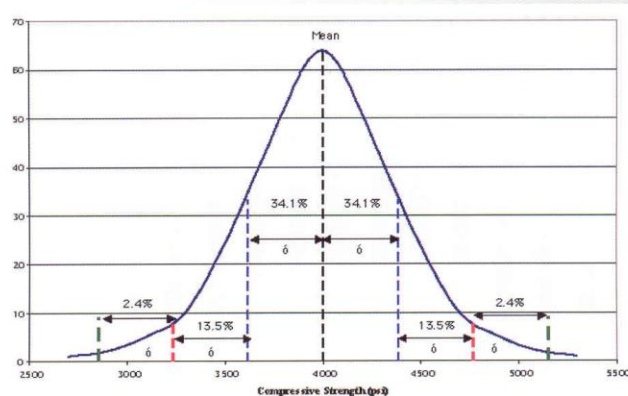


Figure 2. Normal Distribution of Compressive Strength Results

1. The curve is symmetrical about the mean of the data.
2. The curve is peaked at the mean.
3. The area under the curve is proportional to probability.

The standard deviation is a measure of how "peaked" the curve is. A low standard deviation indicates low variability (data grouped tightly about the mean). As the standard deviation increases the curve becomes less peaked and data is spread further from the mean. Probability computations show that about 68.2 percent of the data lies within \pm one standard deviation of the mean. Further, 95.2 percent of the data lies within \pm two standard deviations of the mean [1]. The normal distribution curve (shown in Figure 2) has a standard deviation slightly below 400-psi. ACI 214R-02 [1] provides guidance on the degree of control for compressive strength distributions. A standard deviation below 400-psi is rated "Excellent" (lowest variability that can be reasonably expected in field operations). Even in the excellent rating, the range of compressive strength results is over 2000-psi for a 3000-psi PCC mixture design with a 4000-psi mean compressive strength.

Is the Logger Embedded in the "Same" PCC Used in the Correlation Plot?

Defining "same" PCC is very difficult. For the purposes of maturity predictions, "same" refers to the relationship between compressive strength development and area under the temperature-time curve. Differences in plastic properties can be used as clues. Large differences in plastic properties (especially air content) would certainly have an effect on compressive strength development. However, the only way to determine with a high level of confidence if the compressive strength development of several batches of PCC is the same is to compare them statistically.

Probability can be used to determine if compressive strength data points are from the same mixture. For example, if the I-65 Nashville correlation and verification 28-day lab-cured compressive strengths are plotted together as one data set (see Figure 3), it is clear that the correlation batches are far weaker than the verification batches. The standard deviation of the combined correlation and verification data set is 555-psi. Both correlation batches (compressive strength results of 5919 and 5892-psi) have compressive strengths less than the mean compressive strength of the combined data set (7066-psi) minus two standard deviations (5956-psi). Either both correlation mixtures were highly unlikely statistical anomalies (probability of occurrence less than 2.5 percent) or the correlation batches were from a different mixture design. Unfortunately, mixture design differences cannot be positively detected in the plastic state in the field. Plastic properties and experience can provide some evidence but not a definitive determination. The inability to determine if the mixture design has been altered is an inherent weakness of the new maturity technology.

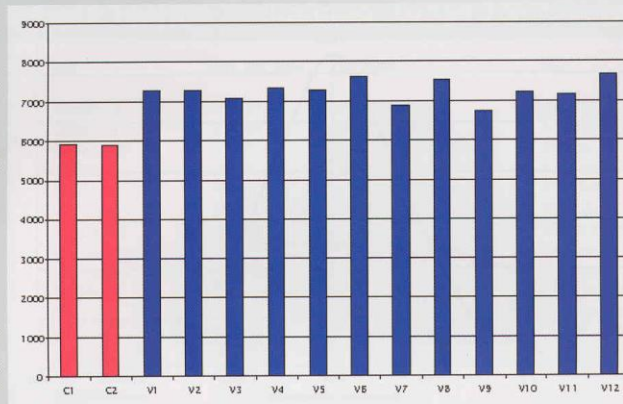


Figure 3. Compressive Strength Results I-65 Nashville Correlation and Verification Batches

Are Maturity Predictions Conservative or Optimistic?

The location of the correlation batch in the range of compressive strength results of the "same" PCC mixture can have a large effect on prediction accuracy even when variability is relatively low. The probability of high or low compressive strength results is the same since the normal distribution curve is symmetrical about the mean. Therefore, there is the same probability that a batch of the PCC mixture used to fabricate the compressive strength-maturity correlation curve will be above or below the mean compressive strength. If the batch used to fabricate the compressive strength-maturity correlation curve is low in the range of compressive strengths for the

mixture, maturity predictions will be conservative (predicted less than measured). If however, the batch used to fabricate the maturity-compressive strength correlation curve is high in the range of compressive strengths for the mixture, maturity predictions will be optimistic (predicted greater than measured). Table 1 shows the effect of relative location of the correlation mixture for a 3000-psi PCC mixture design with a 4000-psi mean and a 395-psi standard deviation. Fortunately, there is a 68.2 percent probability that a batch used to fabricate the compressive strength-maturity correlation curve will be within \pm one standard deviation of the mean compressive strength for the mixture.

Table 1. Effect of relative location of the correlation mixture for a PCC mixture with a 4000-psi mean and a 395-psi standard deviation

Location of Correlation Mixture	Location of Mixture Whose Compressive Strength is being Predicted	Prediction as a percent of measured compressive strength
- 2 standard deviations	- 2 standard deviations	100
- 2 standard deviations	Near the mean	80.3
- 2 standard deviations	+ 2 standard deviations	67.0
Near the mean	- 2 standard deviations	124.6
Near the mean	Near the mean	100
Near the mean	+ 2 standard deviations	83.5
+ 2 standard deviations	- 2 standard deviations	149.2
+ 2 standard deviations	Near the mean	119.8
+ 2 standard deviation	+ 2 standard deviations	100

The Effect of Batch-to-Batch Variability

The previous section showed that the location of the correlation mixture has a substantial effect on prediction accuracy even when the standard deviation is relatively low. What is the effect of increasing the standard deviation (increasing batch-to-batch variability)? Predictions of compressive strength from the new maturity technology are points. That is, on the compressive strength-maturity correlation curve there is only one compressive strength value

corresponding to each maturity index. However, as previously pointed out, compressive strength of a PCC mixture at any time (or maturity) is a range of values not a point. The extent of the range is a function of batch-to-batch variability. Table 2 shows the effect of variability (as characterized by ACI 214R-02 Control Ratings) on compressive strength range. Table 3 shows the possible effects of ACI 214R-02 Control Rating on maturity prediction accuracy for a 3000-psi PCC mixture design with a 4000-psi mean compressive strength.

Table 2. Compressive Strength Range for Each ACI 214R-02 Control Rating [1]

ACI 214R-02 Standard of Control Rating	Standard Deviation Requirement (psi)	Range from - 1 to + 1 standard deviation (psi)	Range from - 2 to + 2 standard deviation (psi)
Excellent	< 400	< 800	< 1600
Very Good	400 – 500	800 – 1000	1600 – 2000
Good	500 – 600	1000 – 1200	2000 – 2400
Fair	600 – 700	1200 – 1400	2400 – 2800
Poor	> 700	> 1400	> 2800

Table 3. Possible Effects of Control Rating on Maturity Prediction Accuracy for a 3000-psi PCC Mixture Design with a Mean Compressive Strength of 4000-psi

ACI Standard of Control Rating	Probable Range of Predictions (± 1 Standard Deviation) in pounds-per-square-inch	Possible Range of Predictions (± 2 Standard Deviation) in pounds-per-square-inch
Excellent	81.8 – 122.2	66.7 – 149.2
Very Good	77.8 – 128.6	60 – 166.7
Good	73.9 – 135.3	53.8 – 185.7
Fair	70.2 – 142.4	48.1 – 207.7
Poor	< 70.2 - > 142.4	< 48.1 - > 207.7

Table 3 shows that users requiring the majority of maturity predictions within ± 22.2 percent of the measured compressive strength will need to work with only very low variability PCC (ACI 214R-02 Excellent Rating). The use of maturity predictions for PCC with ACI 214R-02 ratings other than “Excellent” or “Very Good” is not recommended by the authors.

Effect of Adequate Moisture

The compressive strength-maturity correlation is

developed using laboratory-cured cylinders. Fog curing or lime-water immersion curing provide ample moisture for the continuation of hydration reactions. The Portland Cement Association [2] indicates that drying of PCC reduces compressive strength development. Maturity should over predict the compressive strength of PCC which has not received adequate moisture. No data are currently available to quantify this effect. The inability to determine whether adequate moisture is available is another inherent weakness of the new maturity technology.

Effect of Consolidation

The compressive strength-maturity correlation is developed using standard AASHTO T 23 or T 126 [3, 4] consolidation of the compressive strength cylinders. Although no data are available to characterize the strength loss of structures due to inadequate consolidation, Richardson [5] indicates the insufficient consolidation can reduce the compressive strength of 6 x 12 cylinders up to 61 percent. Maturity should over predict the compressive strength of PCC which has received substandard consolidation. The new maturity technology, which measures only time and temperature, can not detect whether consolidation is adequate.

Effect of Temperature Range

The central concept of the maturity method is that the area under the temperature-time curve is proportional to the compressive strength of a particular PCC mixture. Reviewing the Nurse and Saul [6] equation below, it is apparent that an M value can be achieved with infinite number of combinations of T and Δt values for a given T_0 .

$$M = \sum_0^t (T - T_0) \Delta t$$

Where:

- M = maturity index
- T = average concrete temperature during time Δt
- T_0 = datum temperature
- T = elapsed time hours
- Δt = time interval (hours)

Lesson 3 showed that the maturity concept is valid for curing temperatures between 45 and 90°F at M values greater than or equal to 2400°C-hours (equivalent to curing 72.75 hours at 73°F). However, at low temperatures, the choice of the datum temperature becomes critical. The datum temperature is the threshold where the hydration reaction ceases. At the datum temperature, compressive strength gain is negligible. AASHTO T 276-97 [7] recommends a datum temperature of -10°C (14°F), which was used in the TDOT/TRMCA/ACPA research. The manufacturer recommends using 0 or 5°C (32 or 41°F), but stresses that the datum temperature used in the correlation must be used for the verification [8]. However, if 5°C (41°F) is selected as the datum temperature, compressive strength can increase considerably for $\Delta M = 0$. The increase in compressive strength in the field with no corresponding increase in maturity would result in under prediction of measured compressive strength. Further, the threshold temperature for hydration cessation is a function of mixture components and proportions. The effects of high temperatures and the order of temperature application will be discussed in the next section.

Is the Relationship between Compressive Strength and Area under the Temperature-time Curve Constant for a Particular PCC Mixture Design?

Lesson 1 showed that:

1. High early mean curing temperatures (> 73 and < 100° F) result in rapid early compressive strength development and lower 28-day compressive strengths.
2. Low early mean curing temperatures (> 60 and < 73° F) result in slower early compressive strength development and higher 28-day compressive strengths.

Clearly, the relationship between compressive strength and area under the temperature-time curve is not constant for a particular PCC mixture design: the order of application and the magnitude of the temperature are important factors. Low early mean curing temperatures would lead to a conservative (under) prediction of 28-day compressive strengths while high early mean curing temperatures would lead to an optimistic (over) prediction of 28-day compressive strengths.

What is Considered an Accurate Maturity Prediction?

TRMCA and TTU conducted a maturity short course at TDOT Materials and Tests Division Headquarters on March 27, 2000. A phone and e-mail survey of several state departments of transportation indicated that a maturity prediction within ± 10 percent of the measured strength was considered very accurate. Constantino and Carrasquillo [9], who conducted maturity research for the Texas Department of Transportation, concur with the limit.

How Accurate were the Predictions in the TDOT/TRMCA/ACPA Research?

Table 4 shows the maturity prediction accuracy obtained for I-65 Nashville and I-75 Chattanooga in the recent project. The mean maturity predictions as a percentage of the mean core compressive strength for I-65 Nashville at both times are in the ± 10 range considered very accurate. Neither I-75 Chattanooga mean maturity prediction as a percentage of the mean core compressive strength was in the ± 10 range, but mean predictions at both times were close to the very accurate range. The following paragraphs show possible explanations for the accuracy of the predictions.

For I-65 Nashville, correlation batch compressive strengths were very low (< mean minus 2 standard deviations) in the range of compressive strengths for the mixture (if the correlation batches were of the same mixture design), which led to predictions at both times being conservative.

For I-75 Chattanooga:

1. High early mean curing temperatures (94 to 98°F) led to conservative predictions at 4 days (higher than expected early compressive strength development in the field) and optimistic predictions (lower compressive strengths than expected) at 28 days.
2. Higher variability at 28 days (ACI 214R-02 "Good" Rating) for core compressive strengths accounts for the 28 day I-75 Chattanooga predictions having the largest range of maturity predicted strength as a percentage of core strength.

Table 4. Maturity Predicted Strength as a Percentage of Core Compressive Strength

Location	Age (days)	Range of Maturity Predicted Strength as a Percentage of Core Strength	Mean Maturity Predicted Strength as a Percentage of Mean Core Strength
I-65 Nashville	4	74.5 – 112.7	91.8
	28	79.9 – 105.0	91.8
I-75 Chattanooga	4	72.7 – 108.5	89.5
	28	94.3 – 145.1	112.1

Lesson Summary / Recommendations

The new maturity technology makes many assumptions and actually only measures time and temperature. Understanding the impact of these assumptions on prediction accuracy is essential to knowing when the use of the new maturity technology is appropriate. Due to the cumulative nature of the factors, the use of the new maturity technology is **not** recommended if any of the following apply:

1. Compressive strength-maturity correlation batch does not produce 28-day compressive strength within ± 1 standard deviation the mean 28-day compressive strength for the PCC mixture.

2. PCC mixture design requires frequent changes or adjustments.
3. ACI 214R-02 Standard of Control Rating is not "Excellent" or "Very Good".
4. Adequate moisture for curing is not available.
5. Consolidation is substandard compared to AASHTO T 23 or T 126.

In situations 1, 2, and 3 described above, the authors recommend the use of field-cured 6 x 12 cylinders cured in close proximity to the structure for characterizing in-place PCC compressive strength. In situations 4 and 5, the authors recommend that curing and/or consolidation procedures be improved. ■

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