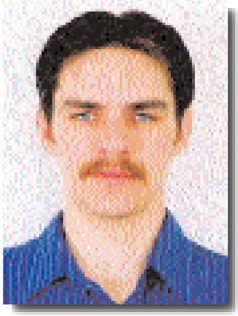
Implementation of the Maturity Method for Zero-Slump Concrete Products

Alvin Olar, P.Eng.
Design Engineer
M.R. Wright and Associates Co. Ltd.
Sault Ste. Marie, Ontario, Canada



Nataliya Hearn, Ph.D., P.Eng.
Associate Professor
Department of Civil and Environmental Engineering
University of Windsor
Windsor, Ontario, Canada

Dale Wannamaker, P.Eng.
Project Manager
Halsall Associates Limited
Windsor, Ontario, Canada

The maturity method has been proven effective in determining the compressive strength of concrete as it hydrates; however, the method has seen little use in the precast concrete industry. This paper describes the implementation of the maturity method in a precast concrete hollow-core plant. The results indicated that the method was reliable in measuring concrete compressive release strength and the time to detension the prestressing strands. The number of precast concrete hollow-core slabs with out-of-tolerance strand slippage was significantly reduced after the introduction of the maturity method. Furthermore, the study revealed that by providing real-time information in a precast concrete manufacturing setting, the maturity method could lower production costs with respect to mixture design, labor, and curing energy.

The personnel at Prestressed Systems Incorporated (PSI) in Windsor, Ontario, suspected that using zero-slump test cylinders to measure the compressive strength of hollow-core slab concrete was not reliable. If a test cylinder failed due only to the occurrence of a chipped edge while being tested for compressive strength, the specimen was useless for determining the time at which the prestressing force in the tendons could be transferred to the slab.

For this reason, a more reliable method was sought to quantify the compressive strength of zero-slump concrete at the time of tendon release. The method should also provide real-time information on the progress of concrete strength development and result in production optimization associated with the concrete mixture design, labor, and accelerated curing energy.

This paper describes the implementation of the maturity method at PSI's precast concrete hollow-core plant. To gain a further understanding of the theory of maturity and how it may be utilized in the precast concrete industry, particularly in the production of hollow-core slabs, the objectives of this investigation were as follows:

1. Investigate the methods and materials used to produce precast concrete hollow-core slabs.
2. Evaluate the practice of making, curing, and testing zero-slump concrete test cylinders.
3. Review the history and theory of maturity to help explain the concept of cement hydration and how the maturity method parameters may be altered to fit specific applications such as the production of hollow-core slabs.
4. Determine the appropriate maturity functions for zero-slump concrete.
5. Correlate the maturity method with measured compressive strength to calculate required maturity values that equate to specified hollow-core concrete compressive release strengths.

The authors discuss the evaluation of the maturity method as it is used at PSI. Strand slippage data were used to measure the reliability and performance of the new method. The optimization results in the hollow-core manufacturing process with respect to mixture design, labor, and accelerated curing energy are also presented.

Fig. 1. Stacks of precast hollow-core concrete slabs in storage at PSI, Windsor, Ontario, Canada.

BACKGROUND

Hollow-Core Production

At PSI, hollow-core concrete slabs are produced by casting zero-slump concrete with power extruders to make 4.0 ft (1.2 m) wide sections of various depths (see Fig. 1). Continuous production requires the hollow-core to be cast and removed within a limited time frame. Determining the time by which the hollow-core can be removed from the casting beds is governed by the minimum concrete compressive release strength. An established minimum strength level ensures that there is sufficient bond between concrete and prestressing strands to resist strand slippage, as well as the forces associated with the stripping and handling of the individual slab.

Hollow-Core Optimization

Maintaining an efficient and cost-effective operation demands that optimization be considered at every step of production. In the manufacture of hollow-core concrete components, cost depends on three main parameters: the concrete mixture design, the labor needed to produce the desired daily precast quantities, and the accelerated curing cycle. Any action that can increase the efficiencies of any of these parameters is good for business.

Because the reliability of required testing can be directly related to a producer's cost optimization, a study was initiated to evaluate the benefits of replacing the existing zero-slump cylinder method with a more reliable concrete compressive release strength test.

Compressive Strength Determination

Some acceptable methods for evaluating compressive strength of zero-slump concrete are outlined in CSA A23.4-00 Section 17.8.1.[1] Typically, the compressive strength of precast concrete is quantified by using test cylinders. The typical method by which zero-slump specimen cylinders are made, cured, and tested conforms to the practice established by CSA A23.2-00 Test No. 12C. This method includes the use of a modified Proctor hammer to compact the concrete into steel molds to produce a specimen of the same density as the product represented. The molds are then placed at the head of the casting bed during the curing cycle and tested for compressive strength before tendon release.

The CSA A23.2-12C test procedure is time consuming, and it is debatable whether the cured specimens are truly representative of the extruded hollow-core concrete, as the cylinder compaction procedure may not replicate the results of production methods.

The method of producing test cylinders of zero-slump concrete is shown in Fig. 2. The appearance of a typical wet-cast cylinder is compared to a typical zero-slump cylinder in Fig. 3. There is a considerable difference between the surface appearance of the two cylinders. The wet-cast cylinder concrete is smooth and uniform throughout, whereas the concrete ends of the zero-slump cylinder are visibly porous and non-uniform. The disparity between the conditions of the two specimens raises concern about the reliability of strength test results produced from these cylinders.

PSI believes that the porous ends of a typical test specimen can lead to low

Fig. 2. Modified Proctor hammer used to compact zero-slump concrete into steel molds.

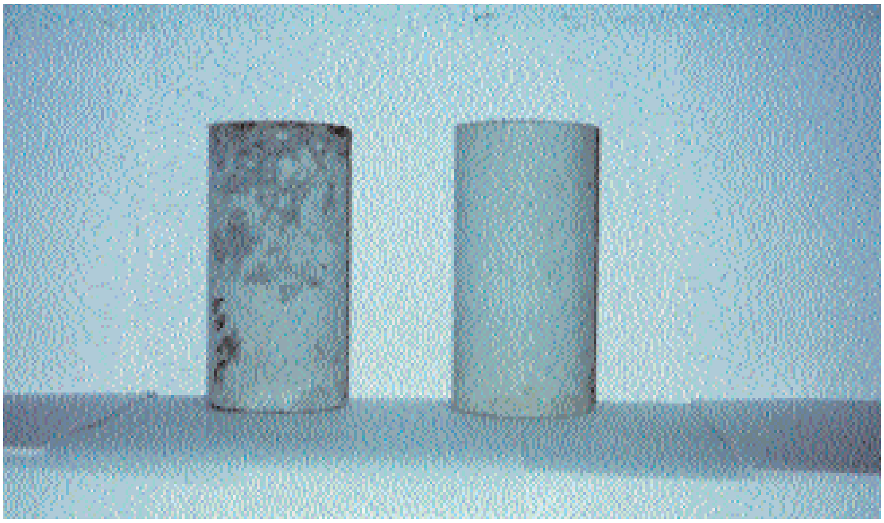


Fig. 3. On the left, a zero-slump test cylinder after stripping from the mold; on the right, a wet-cast test cylinder after stripping from the mold. Note the irregularity in appearance and voids in the zero-slump cylinder in comparison to the uniform appearance of the wet-cast cylinder.

apparent cylinder strengths and great variability in the compressive strength data. Concrete cylinders with porous ends frequently fail because of edge chipping during testing; this mode of failure renders specimens useless in predicting the release strength. Drilled concrete cores are considered a good representation of the final product because cores are extracted from the hollow-core piece itself to determine concrete compressive strength. Although drilled core test results are reliable, drilling cores consumes too much time during the manufacturing process.

CSA A23.4-00 states in Section 17.8.2: "…other nondestructive testing, calibrated to a test specified in Clause 17.8.1 (drilled cores for example), [may be used to determine] intermediate strength levels, such as handling or transfer of the prestress force." Also, PCI's Manual for Quality Control[2] states in Division 6-2: "[Non-destructive tests] may serve to determine stripping, transfer, or shipping strengths …" Based on these guidelines, the maturity method was envisioned as a possible replacement for zero-slump test cylinders.

LITERATURE REVIEW

According to Adam Neville,[3] "the fact that the strength of concrete increases with the progress of hydration of cement, coupled with the fact that the rate of hydration of cement increases with an increase in temperature, leads to the proposition that strength can be expressed as a function of the time-temperature combination."

This premise was first developed in the early 1950s when an approach was proposed to account for the combined effects of time and temperature on the strength development of concrete. It was postulated that a single numerical value could be computed from a measured temperature history during a curing period, and this value could be related to the concrete compressive strength. This value was called *maturity* by A. G. Saul,[4] who created the maturity rule "Concrete of the same mix at the same maturity has approximately the same strength whatever the combination of temperature and time go to make up that maturity."[5,6] Based on this concept, the American Society for Testing and Materials (ASTM) developed "Standard Practice for Estimating Concrete Strength by the Maturity Method" (ASTM C 1074).[7]

Briefly, ASTM C 1074 suggests two alternative maturity functions: *temperature-time factor* and *equivalent age*. Both the temperature-time factor and the equivalent age maturity functions have been used in other studies[5,6,8-11] to calculate the maturity index of a given concrete from its temperature history. The most appropriate maturity function should be determined through experiment using samples of concrete similar to that which is to be evaluated by means of the maturity and compressive strength estimations.

By isothermally curing concrete samples at different temperatures, plots of compressive strength versus age are obtained. A linear hyperbolic model, as suggested by ASTM,[7] or a parabolic-hyperbolic model[8] can be curve fit to the data with a computer program, and the rate constants at each temperature can be determined from the regression analysis. A plot of rate constant-versus-temperature can then be created and used to decide if there is a linear or nonlinear relationship between the rate constant and temperature.

This enables the user to (1) choose which maturity function to use – temperature-time factor or equivalent age, and (2) evaluate the mixture-specific parameters of that chosen maturity function, i.e., datum temperature, T_o, for temperature-time factor, or activation energy, E, for equivalent age.

A plot of relative strength versus temperature-time factor or equivalent age can be created to determine the applicability of the maturity method to the particular mixture design being evaluated. At this point, if the user has a unique relative strength-maturity curve for their mixture design, the curve can be used to solve for values of required maturity that correspond to any desired value of compressive strength.

The use of the maturity method in precast concrete production has been limited in both theory and practice. In order to expand existing maturity knowledge to precast applications, both time and temperature parameters had to be revisited. The age at which the strength of hollow-core concrete needs to be estimated is about 5 to 7 hours after casting. Previous studies have only investigated maturity at later ages, typically after 24 hours. The curing temperature of hollow-core concrete is about 60° to 65°C (140° to 150°F), but temperatures in previous studies did not typically exceed 50°C (122°F). Furthermore, the combination of raw materials used to manufacture hollow-core elements such as cement type and manufacturer, aggregate types, admixture type and dosage, and *w/cm* was not previously investigated.[5,8-13]

EXPERIMENTAL PROCEDURE AND RESULTS

Normally, the designer of a prestressed concrete slab or beam will specify the minimum concrete compressive strength that is required before strand release. To estimate the minimum strength with the maturity method, a correlation study is required and may be obtained by testing actual concrete mixes.

Table 1. Cementitious material quantities for 2.0 cu yds of concrete.

Mix design	Type III (CSA Type 30), lb	Type I (CSA Type 10), lb	Fly ash, lb
A	1300	—	—
B	1200	—	—
C	300	900	—
D	300	700	200

Note: 1 lb = 0.454 kg; 1 cu yd = 0.76 m^3.

Concrete Mixes

The four most common zero-slump concrete mixture designs used for all depths of hollow-core slabs were chosen. The only difference among the mixtures was the combination of cementitious materials, which were changed to accommodate stripping schedules. Table 1 outlines the amount of cementitious material for each mixture design, and quantities are listed for one batch of 2.0 cu yds (1.53 m^3) of concrete.

Rate Constant Versus Temperature

To determine how the rate constant of the hydration of the cement varies with curing temperature and ultimately deciding which maturity function to use, procedures in the Annex (A1) of ASTM C 1074 were followed for this testing, with any deviations being noted.

ASTM C 1074 suggests using mortar cubes having a fine aggregate-to-cement ratio (by mass) that is the same as the coarse aggregate-to-cement ratio of the concrete mixture under investigation. Since mortar of such a mixture for zero-slump concrete could not be effectively compacted into molds, actual concrete samples were used for this testing.

Samples of concrete from 8.0 in. (203 mm) thick hollow-core slabs were extracted during normal production immediately after being extruded. The samples were in the form of 10.0 in. (254 mm) long elements (see Figs. 4 and 5). Equal numbers of samples were placed into three different curing baths once they achieved enough stiffness to keep them from falling apart, usually at an age of 1.5 hours. The baths were heated, covered, and saturated with lime, and the temperature was monitored with a thermocouple.

All baths were held at constant temperature (isothermal curing) as follows: one at the minimum expected hollow-core curing temperature of 20°C (68°F), one at the maximum expected curing temperature of 65°C (150°F), and one midway between the extremes, 40°C (104°F). ASTM suggests testing the first specimen at an age of two times the final set time and the remaining specimens at twice the age of the previous test.

In this experiment, as the strength was estimated within the first 12 hours of accelerated curing, it was desirable to obtain a larger number of data points at earlier rather than later ages. Seven- and 28-day ages were chosen to remain consistent with most standards, specifications, and previous studies. Specified ages of approximately 5, 8, 12, 24, 72, 168, and 672 hours (28 days) were used.

The average strength-versus-age data were plotted with a program called KaleidaGraph.[14] Eq. (A1.1), $S = S_u k(t - t_o)/[1 + k(t - t_o)]$, from ASTM C 1074, was curve fit, where S is the compressive strength (psi), S_u is the ultimate compressive strength (psi), k is the rate constant (hr^{-1}), t is the test age (hr), and t_o is the age when strength development is assumed to begin (hr). The constants k, S_u, and t_o were obtained from the best-fit regression analysis. The values of k obtained from the regression analyses were plotted versus bath temperature shown in Fig. 6.

Previous studies have shown that when concrete is cured at temperatures up to 40°C (104°F), there is a distinct *exponential* relationship between curing temperature and rate constant.[5,6,8,11,13] Results of those studies allowed for the use of the equivalent age technique based on the Arrhenius equation.

From Fig. 6, it is not obvious that the rate constant has an exponential

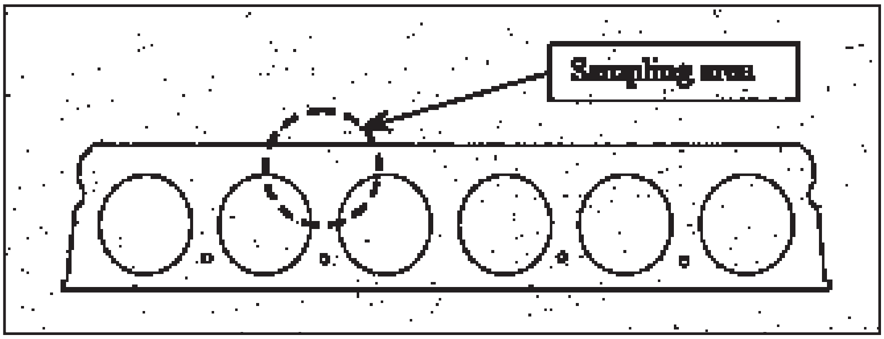


Fig. 4. Sampling area shown on typical hollow-core slab cross section.

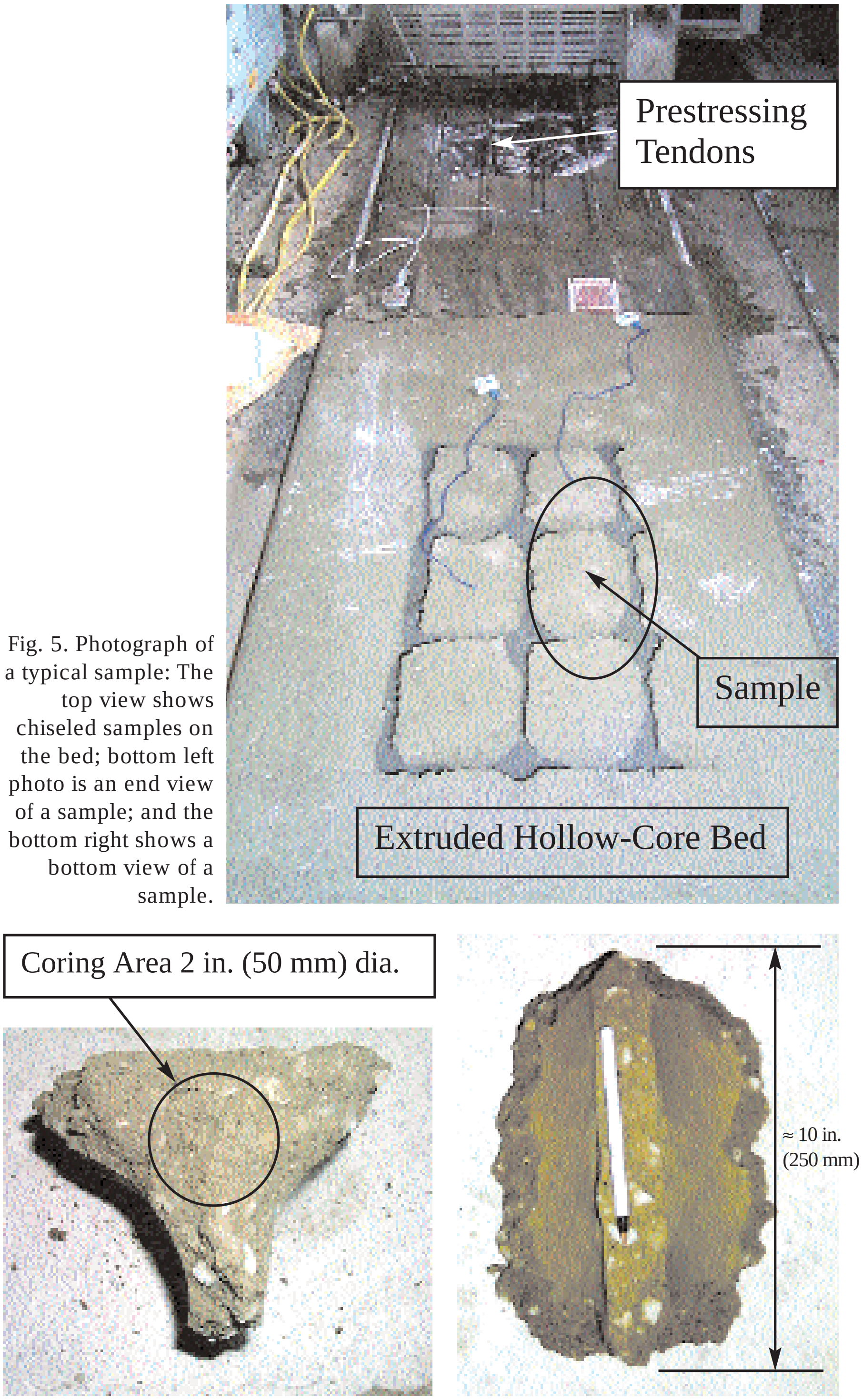


Fig. 5. Photograph of a typical sample: The top view shows chiseled samples on the bed; bottom left photo is an end view of a sample; and the bottom right shows a bottom view of a sample.

relationship with curing temperature through the range of temperatures used to cure the hollow-core concrete [20° to 65°C (68° to 150°F)]. If the results of this testing are assumed to be concurrent with other studies, and there is an exponential relationship between curing temperature and rate constant between 0° and 40°C (32° and 104°F), there is then insufficient data to determine a relationship.

Furthermore, at curing temperatures beyond 40°C (104°F) (previously uncharted territory), the current results show a leveling-off effect. The leveling off of the data indicates that the rate constant for the hollow-core mixtures is reaching the maximum value as the temperature exceeds 40°C (104°F).

By fitting a bilinear relationship to the data,[6] the authors decided to use the temperature-time factor, Eq. (1) of ASTM C 1074, $M(t) = \Sigma(T - T_o)\Delta t$, to calculate a maturity index, where T is the concrete temperature (°C), T_o is the datum temperature (°C), and Δt is the time interval (hr).

Maturity Function Parameters

Once the maturity function is selected, the parameters of that function were required for each hollow-core mixture design. The only constant or parameter needed for the temperature-time factor maturity function was the datum temperature, T_o.

Traditionally, a datum temperature of –10°C (14°F) has been used; however, it was shown that it may not be the best value.[5,13] Appendix X1, Section X1.2 of ASTM C 1074 recommends a datum temperature of 0°C (32°F) for Type I (CSA Type 10) cement with no admixtures, cured between 0° and 40°C (32° and 104°F). Since hollow-core concrete is produced with Type III (CSA Type 30) cement with a plasticizing admixture and cured between 20° and 65°C (68° and 150°F), Fig. 6 was used to determine an appropriate datum temperature.

The first portion of the bilinear curve yields a datum temperature of 0°C (32°F), and that value was accepted for all four hollow-core mixtures. With the maturity function chosen and the parameters of that function determined for the selected hollow-core mixture designs, strength-maturity relationships were needed to estimate strength by measuring maturity.

Strength Maturity Relationships

Section 8 of ASTM C 1074 outlines the procedure for developing the strength-maturity relationships. ASTM specifies the preparation of concrete cylinders for each mixture design. The cylinders must be moist cured at 23°C (73°F) and tested at ages of 1, 3, 7, 14, and 28 days. Thermocouples embedded in at least two cylinders are suggested for calculating maturity at each test age.

Instead of 23°C (73°F) moist curing (as per ASTM C 1074), a complete set of strength-versus-maturity relationships was obtained for all four hollow-core mixtures used under normal manufacturing conditions at PSI. The samples were outlined with a chisel just prior to tarping but left on the beds, exposing the specimens to the same initial curing conditions as the production concrete (see Fig. 5). Specimens were extracted, cored to 2.0 in. (51 mm) diameter by 4.0 in. (102 mm) length, and tested at specified ages of 5, 6, 7, 12, 24, 72, 168, and 672 hours (28 days).

In addition, two samples were extracted immediately and cured under standard 23°C (73°F) conditions for the entire 672 hours (referred to as S_{S28}) to determine the effect of high early-age temperatures on long-term compressive strengths. Thermocouples embedded in two samples on the bed were used to calculate maturity.

A summary of the 28-day compressive strength results is given in Table 2. As expected, the standard cured 28-day strengths, S_{S28}, were significantly higher than the 28-day strengths, S_{28}, for specimens exposed to high early age temperatures (see Fig. 7). The strength reduction observed was concurrent with other studies and standards.[1,15] Values of reduced standard cured 28-day strength, S_{S28R}, were calculated using the correlation plot of Fig. 7 and shown in Table 2.

Strength maturity results were plotted with a KaleidaGraph and a parabolic-hyperbolic function[8] (S/S_u =

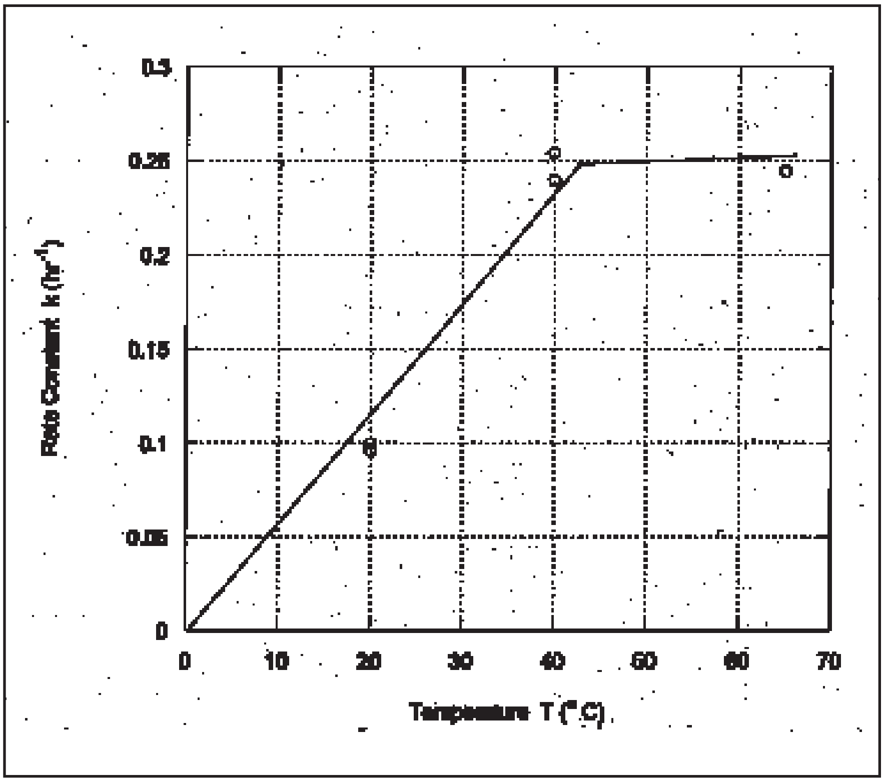


Fig. 6. Rate constant versus temperature for Mixture B.

Table 2. Ultimate strengths and 28-day compressive strength results.

Trial	Ultimate strength S_u (psi)	28-day strength S_{28} (psi)	Standard cured 28-day strength S_{S28} (psi)	Reduced standard cured 28-day strength S_{28R} (psi)	Correlation reduction
Mix A				$S_{S28R} = 0.982 * S_{S28} - 653$	
1	9355	9130	10292		
2	9358	9101	9925		
3	9925	9461	9949		
4	9250	9013	9496		
Average			9916	9084	8.4 percent
Mix B					
1	9529	9353	9666		
2	9424	8652	9629		
3	9822	8608	8459*		
Average			9648	8821	8.6 percent
Mix C					
1	8507	7843	8079		
2	7244	6839	8006		
3	8161	7521	8477		
Average			8187	7387	9.8 percent
Mix D					
1	8860	8204	8790		
2	9125	8148	7928†		
3	7689	7085	8040		
Average			8415	7610	9.6 percent

Note: 1 psi = 0.0069 MPa.
* Not included in average – S_{S28} was less than S_{28} – Likely caused by high curing tank temperature at age of 3 days.
† Not included in average – S_{S28} was less than S_{28} – Unexplained result.

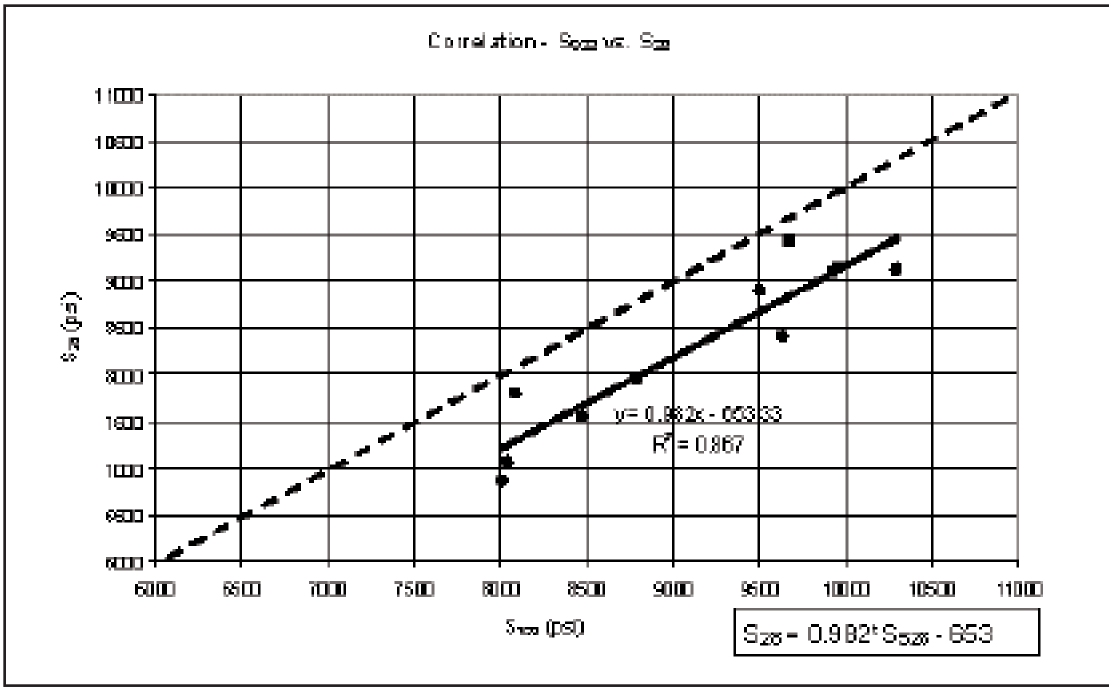


Fig. 7. Compressive strength correlation (S_{S28} versus S_{28}).

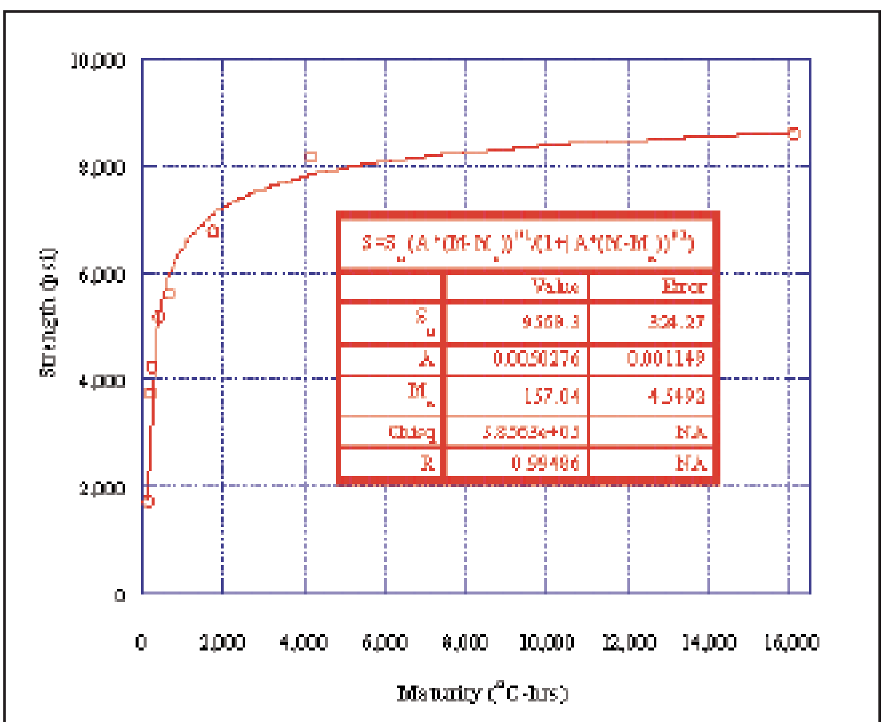


Fig. 8. Strength versus maturity for Mixture B, Trial No. 3.

$[A(M - M_o)]^{1/2}/\{1 + [A(M - M_o)]^{1/2}\})$ was fit to the data, where S is the compressive strength (psi), S_u is the ultimate compressive strength (the upper asymptote of the parabolic curve) (psi), A is a constant (°C·hr)$^{-1}$, M is the accumulated maturity index (°C·hr), and M_o is the maturity index at t_o (°C·hr). A regression analysis was used to determine S_u for each trial for each mixture. The strength-versus-maturity plot for Mixture B (Trial No. 3) is presented in Fig. 8.

Relative strengths were obtained by dividing the strength at each age by the associated ultimate strength (S/S_u). Relative strength versus maturity was plotted for each mixture, combining all trials into one plot, and the parabolic hyperbolic equation was fitted to the data (see Fig. 9).

Required Maturity

Once the relative strength-maturity relationships were created, the maturity required to reach the desired release strengths could be calculated. Two release strengths are commonly required, 3500 or 4000 psi (24 or 28 MPa), depending on the hollow-core design requirements. To satisfy the requirements of the PCI Manual for Quality Control, Division 6, Section 6.2.3-2,[2] a statistical approach was used to calculate the required maturity values.

Fig. 10 contains the plot of relative strength versus maturity at values less than 800°C·hrs, the area of the curve used in this application. Also shown in Fig. 10 are the best-fit regression model and the associated regression output. The regression values of A and M_o are tabulated in Table 3. *Chisq* is defined by KaleidaGraph[14] as the sum of the squared residuals, $\Sigma(y_i - \hat{y})^2$, where $\hat{y}$ is the predicted value on the regression curve. The residual standard deviations (RSD) were calculated by taking the square root of *Chisq* divided by $(n - 2)$ degrees of freedom $[\Sigma(y_i - \hat{y})^2/(n - 2)]^{1/2}$.

A lower 99 percent confidence limit

was created by assuming a normal probability distribution and subtracting $[t_{\alpha/2} * RSD/(n-2)^{1/2}]$ from the modeled curve fit, where $t_{\alpha/2}$ is a tabulated critical value of the t-distribution at the 99 percent confidence level.[16] The lower confidence limit curve and the associated regression outputs are shown in Fig. 10. Tabulated values of the statistical regression fit are listed in Table 4.

Conservatively, the values of α were taken as the ratio of required release strength to the reduced standard cured 28-day strength $(S_{release}/S_{S28R})$ as opposed to $(S_{release}/S_u)$, since S_{S28R} is the maximum strength that any particular mixture design can realize in an actual production cycle. The resulting values of α can be found in Table 3. Therefore, by using the parabolic hyperbolic equation and the necessary data in Tables 3 and 4, the values of required maturity for each mixture design and both release strengths were calculated (see Table 5).

Maturity System Implementation

The maturity system was installed in PSI's hollow-core plant during the summer of 2002 and was operational by September 2002. During the first two weeks of September, the system was used in conjunction with the zero-slump cylinder method. After a two-week trial period, sufficient confidence in the new system led to the discontinuation of cylinder testing.

Since the second week of September 2002, the maturity method has been used exclusively at PSI to measure the concrete compressive strength at transfer, enabling the production department to determine when to cut prestressing strands. Fig. 11 depicts the temperature sensor on a freshly cast bed of hollow-core concrete. Fig. 12 illustrates the signaling system used in the plant to notify the production personnel of the proper time for detensioning the precast beds.

RESULTS AND DISCUSSION

Slippage Study

The best way to gauge the effectiveness of the installed maturity system is

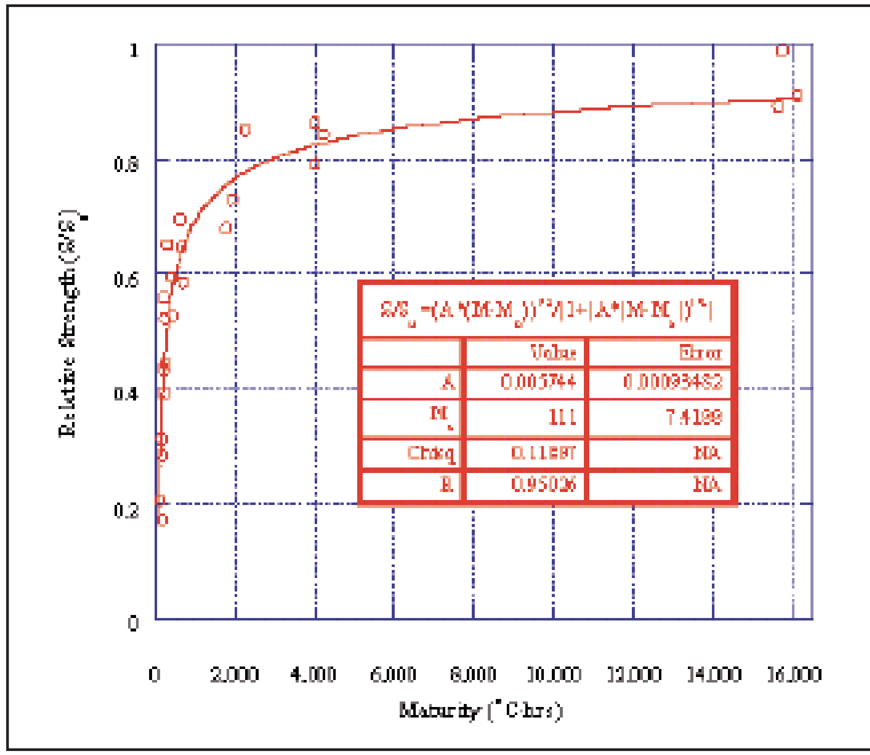
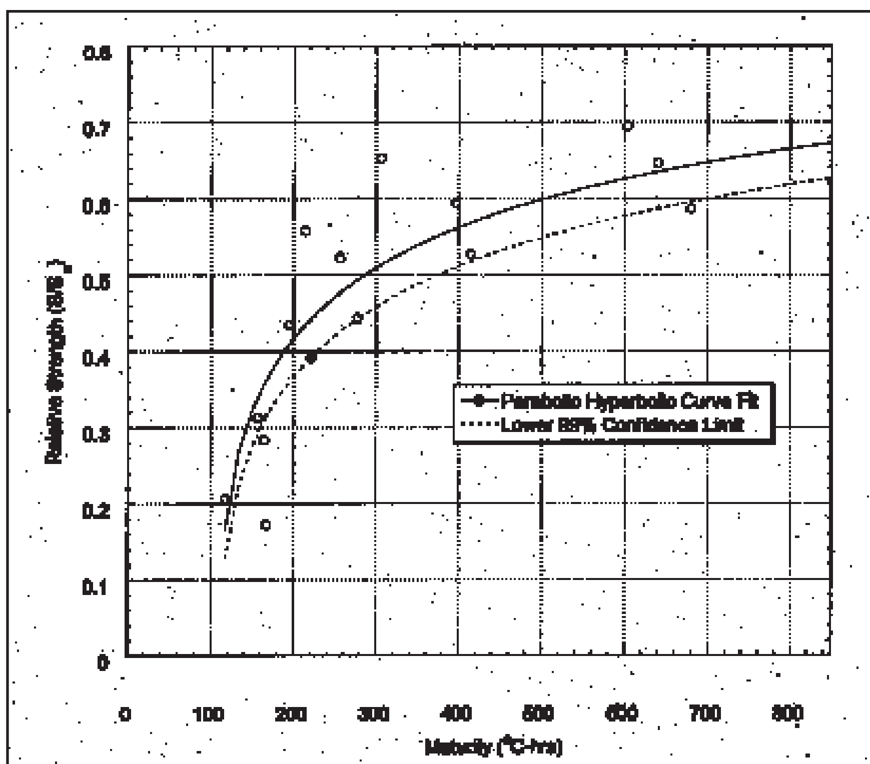


Fig. 9. Relative strength versus maturity for Mixture B, all trials.



$S/S_u = (A*(M-M_o))^{1/2}/(1+(A*(M-M_o))^{1/2})$		
Regression Output	Value	Error
A	0.005744	0.00093452
M_o	111	7.4188
Chisq	0.11697	NA
R	0.95026	NA

$S/S_u = (A*(M-M_o))^{1/2}/(1+(A*(M-M_o))^{1/2})$		
Lower 99% Limit	Value	Error
A	0.0039942	9.5300e-05
M_o	112.23	1.1698
Chisq	0.0029544	NA
R	0.99954	NA

Fig. 10. Relative strength versus maturity for Mixture B, all trials.

Table 3. Results of regression analyses (A, M_o) and α values.

Mix	S_{S28R} (psi)	*A* (°C·hr)$^{-1}$	M_o (°C·hr)	α (3500 psi)	α (4000 psi)
A	9084	0.006580	106.6	0.385	0.440
B	8820	0.005744	111.0	0.397	0.454
C	7386	0.005606	183.4	0.474	0.542
D	7610	0.003061	162.1	0.460	0.526

Note: 1 psi = 0.0069 MPa.

Table 4. Regression analysis results from statistical analysis.

Best fit regression values			99 percent confidence limit values[16]			
Chisq	*n*	RSD	$t_{\alpha/2}$	$t_{\alpha/2}$*RSD/$(n-2)^{1/2}$	*A* (°C·hr)$^{-1}$	M_o (°C·hr)
0.1423	32	0.0689	2.741	0.03446	0.00478	107.35
0.1190	24	0.0735	2.797	0.04385	0.00383	112.23
0.0495	22	0.0498	2.819	0.03136	0.00417	184.16
0.0460	23	0.0468	2.807	0.02866	0.00235	164.05

Table 5. Required maturity values.

	Maturity required (°C·hr)	
Mix	3500 psi	4000 psi
A	190	237
B	225	292
C	379	519
D	472	686

Note: 1 psi = 0.0069 MPa.

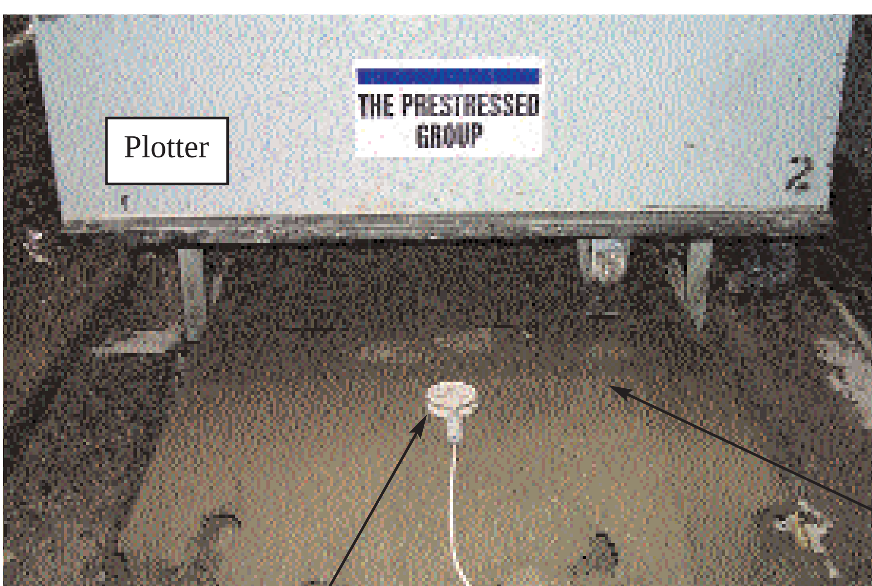
to analyze its ability to predict the compressive strength of hollow-core concrete at the time of release in a production setting. This is determined by evaluating the amount of strand slippage before and after the implementation of the new method.

In the precast hollow-core industry, two types of strand slippage are of concern. *Initial slippage* occurs when the prestressing strands are initially cut (released) at the very ends of the hollow-core bed with an oxy-acetylene torch. *Final slippage* occurs when the strands slip inward from the sawn face, as the 400 ft (122 m) long hollow-core bed is cut into individual slabs with a crosscut saw.

Both types of slippage can affect the performance of the slabs. Any slab that has slippage greater than the specified tolerance of $^1/_4$ in. (6.4 mm) initial slippage or $^1/_8$ in. (3.2 mm) final slippage must be reviewed by the design engineer, according to CSA A23.4-00 Section 26.2.7.2.[1] It is not uncommon that slabs are rejected for not meeting the specified tolerance, requiring new slabs to be produced.

Slippage data taken from the monthly quality control reports at PSI are provided in Table 6. The results clearly show a decrease in slippage after implementation of the maturity method. The statistical data in Table 7 indicate that the average number of slabs requiring review dropped from 14 to 2 per month based on initial slippage. For final slippage, the review average dropped from 119 to 5 per month.

A t-test was conducted on the initial and final slippage data to evaluate the effects of the maturity method, and the results are recorded in Table 7. The t-test compared the mean values of initial and final slippage for the months of February to August 2002 to the



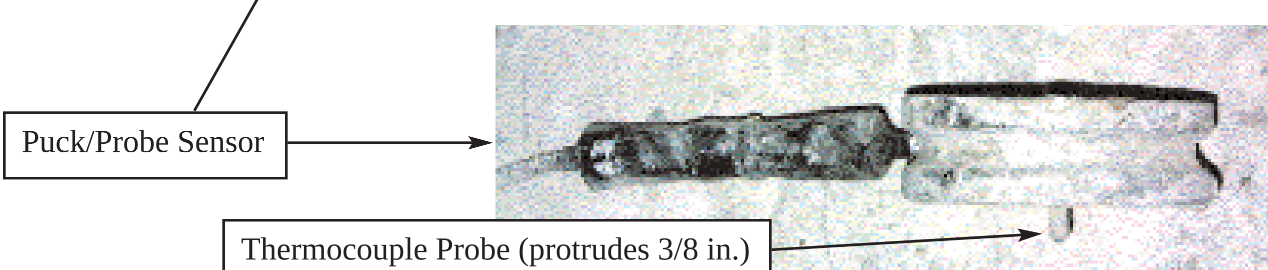


Fig. 11. Temperature measuring sensor on bed.

mean values of initial and final slippage for the months of September to December 2002.

In order to determine whether the maturity method would increase or decrease the amount of slippage, the results of the two-sided test were examined. Data indicate the probability of reduction in out-of-tolerance slippage due to the implementation of the maturity method alone (assuming no other steps are taken to reduce slippage) is 96 percent for initial slippage and 98 percent for final slippage.

The results of this study strongly suggest that the maturity method is providing valid measurements of the concrete compressive strength at release and is indicating the proper time to detension the strands. It is concluded, therefore, that the maturity method is a significantly more reliable method of strength measurement in the production plant setting than the zero-slump cylinder method.

These results also confirm that the temperature-time factor maturity function, with a 0°C (32°F) datum temperature, can be used successfully to calculate maturity and subsequently determine the compressive strength of zero-slump concrete at early ages.

Fig. 12. Bed ready light system in operation.

Manufacturing Hollow-Core Slabs Using Maturity Method

The goal of this research was to determine whether cost savings with respect to mixture design, labor, and curing energy could be realized if the cylinder method was replaced with the maturity method. A discussion of plant production efficiencies resulting from the study results follows.

Maturity method and mixture design selection — If a precast concrete production department is provided with accurate and timely information, staff can make well-informed decisions. By using actual average curing cycle lengths, production staff can choose the appropriate mixture design to match productivity requirements and vice versa, thereby scheduling labor according to the mixture design and the availability of casting beds.

Prior to the introduction of the maturity method, the PSI production department was relying on incomplete and unreliable information, which often led mix designers to proportion mixes that were either too rich or too lean, causing problematic scheduling. For example, if a mix was too rich with a large quantity of cement, the mixture would likely achieve the specified strength early, before the start of the subsequent production shift. If a mix was too lean and the concrete took longer to reach specified strength, the casting bed would often not be ready until well after commencement of the next shift.

Maturity method and labor scheduling — Since the maturity method has the capacity to calculate and display real-time results, production staff can be continuously well informed of curing status to effectively schedule labor. For example, assume a mechanical breakdown delays the day shift beds from being completed on schedule. When the night shift crew arrives, it will know precisely how long to wait before detensioning the strands and stripping the beds. If the wait is only ten minutes, the crew can prepare the beds immediately; if the wait is one hour, the workers can initiate required maintenance or other preparatory work.

Maturity method and slippage — As discussed earlier, every slab that exhibits out-of-tolerance slippage must be reported by quality control and reviewed by the design engineer. In March 2002, 5 percent of total PSI hollow-core production exhibited slippage, and by December 2002 that number was below 1 percent. That was and continues to be a production quality improvement resulting in substantial time and cost savings for the design engineer as well as the quality control department.

Table 6. Number of slabs with out-of-tolerance initial and final slippage from PSI.

Month	Number of slabs with initial slippage	Number of slabs with final slippage	Total number of slabs
Pre-maturity			
February 2002			
Total	19	143	4792
percent	0.40 percent	2.98 percent	
March 2002			
Total	29	234	4301
percent	0.67 percent	5.44 percent	
April 2002			
Total	23	159	4337
percent	0.53 percent	3.67 percent	
May 2002			
Total	9	86	4177
percent	0.22 percent	2.06 percent	
June 2002			
Total	9	47	2674
percent	0.34 percent	1.76 percent	
July 2002			
Total	6	64	3237
percent	0.19 percent	1.98 percent	
August 2002			
Total	3	98	3203
percent	0.09 percent	3.06 percent	
Post-maturity			
September 2002			
Total	3	19	2919
percent	0.09 percent	1.00 percent	
October 2002			
Total	2	9	4200
percent	0.05 percent	0.21 percent	
November 2002			
Total	1	5	4973
percent	0.02 percent	0.10 percent	
December 2002			
Total	1	28	3135
percent	0.03 percent	0.89 percent	

Maturity method and curing energy — There is one area of cost optimization that has not yet been discussed, and that is the energy associated with accelerated curing. By installing electrically controlled modulating valves in the pipeline manifold, the maturity system is able to interact with the accelerated curing system. This system interaction allows more or less steam to be pumped to a given bed, depending on the rate of strength development in relation to the available curing time. Once the system indicates that a bed has achieved the required maturity, the steam is then ramped down, minimizing excess heat and energy cost, and increasing production efficiencies.

CONCLUSIONS

The maturity method has demonstrated excellent performance in precast concrete applications:

1. The system is reliable and easy to use in a precast plant environment.

2. Implementation of the maturity method has resulted in an order-of-magnitude reduction in out-of-tolerance slippage, and produced immediate savings in engineering time and recasting costs.

3. Real-time monitoring of the strength evolution of the precast elements allows effective use of curing energy, labor, and mixture proportioning, and results in substantial economic benefits.

The maturity method does require, however, repeating the correlation testing of strength versus maturity at least annually, and after any substan-

Table 7. Results of the t-test on the slippage data.

t-Test: Two-sample assuming equal variances	Initial slippage February-August 2002	Initial slippage September-December 2002	Final slippage February-August 2002	Final slippage September-December 2002
Mean	14.00	1.75	118.71	15.25
Variance	94.33	0.92	4189.90	106.92
Observations	7.00	4.00	7.00	4.00
Pooled variance	63.19	—	2828.91	—
Hypothesized mean difference	0.00	—	0.00	—
df	9.00	—	9.00	—
t Stat	2.46	—	3.10	—
$P(T \leq t)$ one-tail	0.02	—	0.01	—
t Critical one-tail	1.83	—	1.83	—
$P(T \leq t)$ two-tail	0.04	—	0.01	—
t Critical two-tail	2.26	—	2.26	—

tial mixture design change, including a change in cement type, cement supplier, admixture supplier or dosage. Since the datum temperature value of 0°C (32°F) should be applicable to most zero-slump concrete mixtures, the datum temperature experiments would likely not need to be repeated.

It should be noted that there have been challenges in the plant environment since adopting the maturity system; for example, damage to thermocouple wires due to handling and nearby equipment operation has occurred. An upgrade to a wireless maturity probe would be advantageous in a typical precast plant setting.

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