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The Use of the Concrete Maturity Method In the Construction of Industrial Facilities: A Case Study

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Executive Summary

The pilot project described in this report was a field trial of recent technology that predicts in-situ strength of concrete using the concrete maturity method. The pilot was conducted in realistic field conditions by Fluor Corp. personnel over two months during the main concrete placement phases of the Amgen Opus Program Project in Puerto Rico. This report reviews the concrete maturity method, describes the technology, and describes field experience in trials of that technology.

The concrete maturity method determines concrete strength in real-time based on the actual thermal history of the concrete. While it has been in existence for over fifty years, the technology to implement it accurately and efficiently has not been economically available and the maturity method has not been widely used in industrial construction. The technology used in this study employs a sacrificial data logger that is embedded in wet concrete at placement. The logger contains temperature sensors and a memory device that periodically record the temperature of concrete as it cures, and calculates the maturity index on the sensor itself. Readings from this system can be taken and strength determined as frequently as the user wishes. This allows earlier confirmation of strength necessary to support successor construction activities (e.g. form removal and load setting) than was feasible using traditional strength determination methods.

Results of the pilot program indicate that the in-situ concrete strength can be more accurately and consistently determined by the concrete maturity method than with other conventional methods. Furthermore, the field experiences with this technology indicate a significant potential for improvement in project cost and schedule performance.

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1 Introduction

1.1 Concrete strength determination method and technology

Determination of the in-situ strength of concrete is an important step in the quality assurance of an industrial construction project. Typically, cylinder or beam specimens, cast from the same batch of concrete as that used in the construction project, are tested for the in-place strength as they cure. The hydration of concrete, which controls strength development, is primarily affected by two factors: time and the temperature of hydration. Due to the difference in placement conditions and the thermal history between test specimens and the actual structure, specimens cast and aged in separate test cylinders can sometimes inaccurately reflect the actual concrete strength within the structure at a given time.

The maturity method is an alternative non-destructive testing technology of in-situ concrete. The maturity method is not a revolutionary method of measuring concrete strength. Its origins can be traced back to work in England by McIntosh (1949), Nurse (1949), and Saul (1951). Their work formulated an attempt to better understand the influence of the various factors affecting concrete curing. From their efforts, the principle that concrete's change in temperature and time can be correlated with concrete's strength, hence the concrete maturity method was derived. A 1978 construction failure of a cooling tower during cold weather indirectly spurred the development of the ASTM C 1074.[1,3]

Interest in the maturity method has been revived due in part to the technology transfer efforts of the Federal Highway Administration (Carino and Lew 2001).[3] As a result, new technologies that enable the use of the maturity method have been developed. One type of recently developed technology is the use of sacrificial sensors designed to be embedded in concrete placement to record a time series of temperature readings during curing.

1.2 Brief Description of potential benefits of the concrete maturity method

The Maturity method provides a relatively simple, efficient and effective approach for making reliable determinations of in-place concrete strength during construction. When applied, the method allows earlier determination of when formwork can be removed, post-tensioning applied, or a concrete placement can be exposed to live loads thereby resulting in accelerated construction and cost savings. In many cases, using concrete maturity in conjunction with, or instead of, testing separately cast specimens to measure the concrete strength can improve quality control, because the strength estimates from the maturity method are based on data from the actual structure instead of separate specimens. In addition, extreme temperatures or thermal gradients within a concrete structure that may affect quality can be remedied or documented when the maturity method is used.

1.3 Report objectives:

The primary objective of this report is to describe the results of FIATCH's pilot efforts using data loggers that enabled the use of the maturity method on a construction jobsite. In addition, the report is intended to:

- Provide designers and contractors with a background of the concrete maturity method using sacrificial sensors;
- Describe lessons learned from using the technology under field conditions.
- Describe the potential impact of the use of the concrete maturity method using sacrificial sensors on project QA/QC, cost, and schedule.

2 Description of the Concrete Maturity Method

The *maturity method* is a technique for predicting concrete strength in real-time based on the actual thermal history of the concrete. There are three steps required to carry out the maturity method: 1) Establish the strength-maturity relationship for the specific mix that will be used in construction; 2) Estimate the in-situ strength of the concrete using the maturity index; and 3) Verify the strength-maturity relationship. A brief discussion of each of these steps follows.

1). Establish the strength-maturity relationship,

Using the same concrete mix design that will be used in construction, test cylinders are cast in accordance with normal ASTM procedures. Sensors are embedded in at least two cylinders when the cylinders are molded. The sensors are used to record the temperature of concrete hydration. Using the temperature data, the maturity-time factor or maturity index is calculated. Next, the maturity index is correlated with results of the compression test to develop the calibration curve, which is unique to the mix-design.

The most common expression used to calculate the maturity index is the *Nurse-Saul Material Function* (Equation 2-1). Figure 2-1 illustrates a schematic temperature history and the maturity index computed according to Equation 2-1.

$$M(t) = \sum \left(T_a - T_0\right)\Delta t \qquad \textbf{(2-1)}$$

where:

$M(t)$ =maturity index, $°C - days$ (or $°C - hours$)
T_a =average concrete temperature during each time interval
T_0 =datum temperature, temperature below which cement hydration is assumed to cease
Δt =time intervals, days or hours
Σ =summation of all the intervals of time multiplied by temperature.

A key variable in equation 2-1 is the datum temperature. Approximate values for the datum temperature are provided in ASTM C 1074. However, the datum temperature is affected by parameters such as cement fineness, particle size distribution, water-to-cement ratio, cement composition, admixtures, and initial temperature. Consequently, the accuracy of the strength estimation can be improved by measuring the datum temperature for the concrete mixture that is used on the construction project as described in ASTM C 1074.

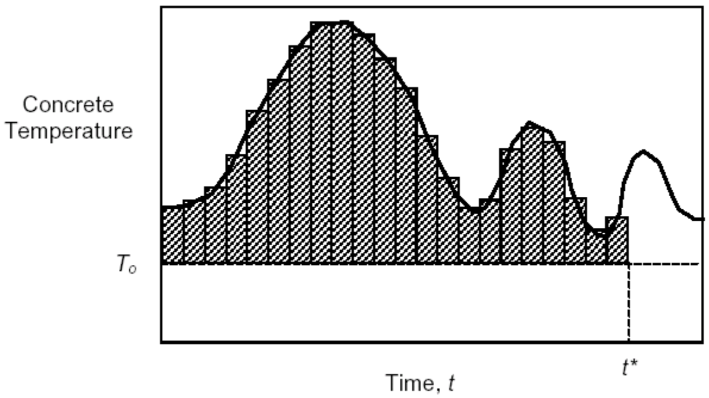

Figure 2-1: *Schematic of temperature history and temperature-time factor compute according to equation 2-1[3]*

Commercial maturity sensors are available to monitor the temperature and calculate the maturity index. There have been several significant changes in maturity techniques in recent years, with options ranging from simple thermometers placed in the concrete to microprocessor-controlled data loggers to wireless transmission of the data directly to construction staff.

Commonly at ages 1, 2, 5, 7, 14 and 28 days, compressive test are performed on at least two cylinders. The break points can be earlier for high-early mixes and later for slower strength gain mixes. The most valuable data is typically in the early-age data and more points are taken during the early-age portion of the strength-maturity relationship cure. At the same time of compressive testing, the average maturity value of instrumented cylinders is recorded. Next, a plot of the average maturity versus the average compressive strength of the test cylinders is made. A best-fit curve is then drawn through the data or regression analysis is used to determine strength maturity relations (Figure 2-2).

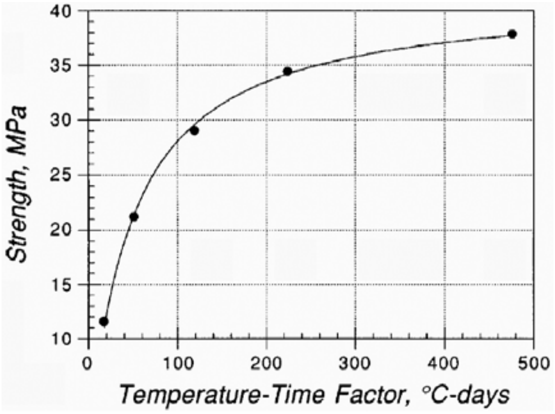

Figure 2-2: *Graph of Maturity Index VS* Concrete *Strength gain over time[2]*

2). Estimate the in-place strength,

Sensors are embedded in the concrete before concrete is placed in the field. The sensors provide measures of the maturity index whenever a strength estimated is desired. Using the previously derived strength maturity relationship for the concrete mix design, the compressive strength of concrete at the location of the sensor is identified.

3). Verify the Strength-Maturity relationship.

The maturity method is used to determine the concrete strength. However, the maturity method is based on temperature and time measurements only. There is no assurance that the in-place concrete has the correct mixture proportions as the design. As such, ASTM C 1074 requires verification of the potential strength of the in-situ concrete before performing critical operations, such as formwork removal or post-tensioning.[1][3]

Appropriate verification techniques as the supplement determination of the concrete maturity include:

- In-place tests that give indications of strength, such as Test Method C 803/C 803M (Test Method for Penetration Resistance of Hardened Concrete), Test Method C 873 (Test Method for Compressive Strength of Concrete Cylinders Cast in Place in Cylindrical Molds), Test Method C 900 (Test Method for Pullout Strength of Hardened Concrete), or Test Method C 1150 (Test Method for the Break-Off Number of Concrete).

- Early-age compressive strength tests in accordance with Test Method C 918 (Test Method for Measuring Early-Age Compressive Strength and Projecting Later-Age Strength) of standard-cured specimens molded from samples of the concrete as-delivered, or

- Compressive strength tests on specimens molded from samples of the concrete as-delivered and subjected to accelerated curing in accordance with Test Method C 684 (Test Method for Making, Accelerated Curing, and Testing of Concrete Compression Test Specimens).

3 Description of the Technology

3.1 Description of capabilities

For this pilot project, *intelli*Rock concrete maturity system supplied by Engius was used to implement the maturity method.

The system consists of three components (see Figure 3-1):

1) **A logger**. A sacrificial sensor that calculates the maturity index within the structure where it is placed. The system uses sensors that support the Nurse-Saul and/or the Arrhenius maturity methods. The logger measures 1.5 inch by 1.5 inch diameter.

2) **A reader**. The reader is used to communicate with and download maturity and temperature data from the loggers.

3) **Software**. The *intelli*Rock software facilitates the downloading of the estimated maturity index and temperature data from the reader into a computer.

Figure 3-1: *The* intelliRock *handheld reader and a logger*

The loggers are self-contained, battery operated, microprocessor based data loggers that are embedded directly into a concrete structure. The loggers measure, process, and store temperature data within the concrete itself. The loggers' battery life enables them to collect data up to 3 months, and the batteries have a shelf life of 5 years. The loggers used on the pilot project maturity record readings every 15 minutes, although *Engius* recently introduced a new data logger that records maturity readings on a one minute intervals. All values are stored in the reader by means of an 18-gauge wired connection. Up to 200 loggers may be saved onto the reader. The reader is then connected to a COM Port using a serial cable in order to transfer logger files from the reader to a PC. The logger's files are created in two formats, an Excel format file (.CSV) and a Secure format file (.SEC) (see Figure 3-2).

Logger data is downloaded to the reader. The data stored in the reader is then downloaded to a PC.

From the PC, data files can then be generated and exported to Excel or other type software. Secure files can also be generated.

Figure 3-2 *The Transferring process of the Logger data*

The *intelli*Rock software operates in the MS Windows platform.

3.2 Description of use

3.2.1 Calibration

After the maturity index-concrete strength relation has been established for a given mix design (see Figure 2-2), the *intelli*Rock system can be used to estimate the in-situ concrete strength. The system uses an embedded microprocessor and temperature sensors, therefore the system does not require temperature calibration and the temperature sensors function independently.

Once identified through ASTM C 1074, the datum temperature is adjusted through the reader's keypad (see Figure 3-3). Once entered, this datum temperature will be used in calculating the concrete maturity using the Nurse-Saul Function when starting all future loggers, unless it is changed to a different value.

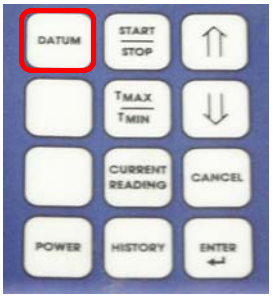

Figure 3-3: *The intelli*Rock *reader keypad*

3.2.2 Maturity reading

The general operation of the *intelli*Rock system is as following.

- ***Starting a Logger***

  The data logger is embedded into the concrete structure or test specimen leaving the data wires extended out of the concrete (see Figure 3-4). Next the data logger is activated through the reader to begin measuring and recording the concrete's thermal data.

Figure 3-4: *Placing an intelli*Rock *maturity logger into pavement*

- ***Display Current and Historical Readings***

  The reader is used to display the thermal history information recorded by the data logger (see Figure 3-5). The corresponding strength of the structure is determined from the maturity index gathered by the logger in conjunction with the previously determined strength-maturity relationship (see Figure 3-6).

Figure 3-5: *Connecting the intelliRock reader to an embedded intelli*Rock *maturity logger*

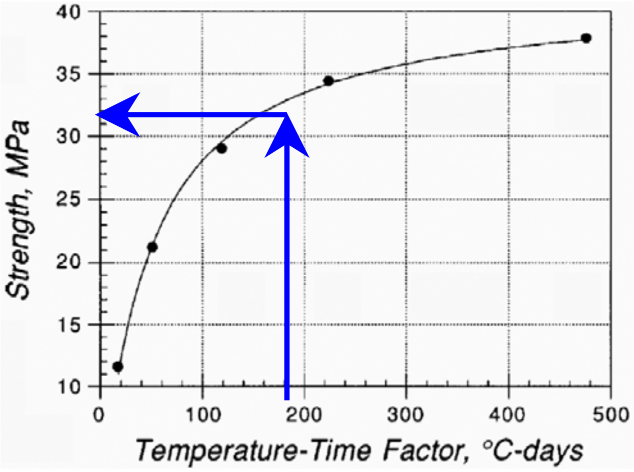

Figure 3-6 *Converting maturity to strength using the calibration curve*

- ***Saving Data onto the Reader for Transfer to Computer***

The thermal history data is saved to the reader by wired connection.

- ***System Uniqueness***

As mentioned, the maturity method has been in existence since the early 1950s. Unlike other enabling technologies that have been used for the maturity method, the *intelli*Rock system used in this pilot contains all of the components necessary to determine the maturity index on the data logger itself, including a microprocessor, thermistor and battery. Other maturity systems have required the collection of temperature data in the field and processing of the data elsewhere to calculate the maturity index. As such, the system used in this pilot allowed real-time estimates of concrete strength directly by field personnel. Some other maturity systems typically require a permanently connected external device to process maturity and temperature data. These devices have been susceptible to damage, theft and vandalism. Furthermore, if the external devices lose power or become disconnected to the thermocouple, data loss will occur. The *intelli*Rock system avoids these issues by embedding the entire maturity device in the concrete.

4 Description of the Pilot Implementation

The system used in this pilot has been used before on infrastructure projects, particularly in roadway and bridge projects. In order to better understand its application in the construction of an industrial facility, this FIATECH pilot test was conducted on the Amgen OPUS Project located in Juncos, Puerto Rico. Fluor Corp. was the EPC contractor for the facility. The Amgen OPUS Project involved the construction of a bio-pharmaceutical process facility with over 300,000 square feet of expansion to the already existing facility. The scope of the construction work included a large volume of concrete placement and the use of prefabricated concrete panels. The pilot test was conducted over approximately two months of the main concrete construction phases of the project. The purpose of the pilot program was to document experience in the use of current concrete maturity method using current technology.

4.1 Program/process as planned and executed

Two concrete mix designs were investigated as shown in Table 4-1. A total of six placements were instrumented to monitor the concrete maturity development as the outline depicts in Table 4-2

Table 4-1 *The Concrete Mix Design for the Concrete Maturity Pilot*

ID	Concrete Mix Design Description
1	4000 PSI Regular Mix 6.70 sacks of cement* .44 W/C ratio 4" slump at the end of the pump hose Daratard 152 = 2 oz.* WRDA 60 = 5 oz.*
2	Structural Lightweight Concrete 4000 PSI Mix 7.82 sacks of cement* .42 W/C ratio 6" slump at the end of the pump hose Daratard 152 = 15 oz.* WRDA 60 = 59 oz.* Darex = 2.2 oz. *
Required to reach 4000 psi strength at 28 days. (* = per cubic yard)	

Table 4-2 *The Concrete Maturity Monitoring Plan*

Location	Placement Date	Dimensions/volume	Concrete Mix Design
4000 PSI Regular Mix Epogen Building Grade Beam, Axis J Footing 2-7.	8/6/2003	14’6” W x 160’0” H x 5’0” D 460 Yards	1
LSC Epogen Building Third Floor Slab, Column Line 7 to 8, A to E Axis and Column Line 8 to 9 A to A.7.	9/30/2003	30’0” W x 140’0” H x 5 1/4” D 7’ ½” W x 15’0” H x 5 1/4” D 15”0’ W x 7’1/2” H x 5 1/4” D 7’ ½” W x 15’0” H x 5 1/4” D 89.50 CY	2
LSC Epogen Building Third Floor Slab, Column Line 1 to 2, A.5 to E Axis.	10/1/2003	30’0” W x 125’0” H x 5 1/4” D 62 CY	2
LSC Epogen Building Third Floor Slab, Column Line 3 to 4, A to E Axis.	10/3/2003	30’0” W x 140’0” H x 5 1/4” D 90.5 CY	2
LSC Epogen Building Third Floor Slab, Column Line 5 to 6, A to E Axis.	10/6/2003	30’0” W x 140’0” H x 5 1/4” D 90 CY	2
LSC Epogen Building Mezzanine Slab, Column Line 8 to 9, A to C Axis and Column Line 6 to 7 A to C Axis.	10/7/2003	2 30’0” W x 60’0” H x 5 1/4” D 60 C Y	2

4.2 Description of field activities

A datum temperature of $0\,^{\circ}C$, as prescribed by ASTM C 1074 - 98, was used in the correlation, strength estimation and verification maturity curves. Data loggers and pertinent system were used to measure and record the maturity index of the test cylinders and the in-situ concrete.

Figure 4-1 (page 15) shows the process of the pilot as described by the following.

4.2.1 Develop mix-specific strength-maturity relationship curves

The software provided with the *intelli*Rock system was used to develop the mix-specific strength-maturity correlation curves based on the compressive strength test results and maturity data.

For every concrete mix design, a set of twenty test cylinders were used to establish the maturity curve, two of the twenty test cylinders were cast with loggers embedded inside of them. Compression tests were performed on the other cylinders after 1, 2, 5, 7, 14 and 28 days of curing. Three cylinders were tested at each age. At the same time, the values of the two maturity readings were recorded. From these data, the maturity curve was plotted.

4.2.2 In-place concrete maturity measurement

After the strength-maturity relationship curve was identified for each mix design, the data loggers were used to measure and record the maturity index of the in-situ concrete. Depending on the amount of concrete being placed, one to four data loggers were used in each pour. The data loggers were attached to the reinforcing steel as shown in Figure 4-2. After the concrete was placed, the data logger was activated to begin recording the thermal history and calculate the maturity values of the placement. The maturity value was updated every 15 minutes by the data loggers. The *intelli*Rock software was used to estimate the in-place concrete strength with the maturity data, based on mix-specific strength-maturity relationship curves.

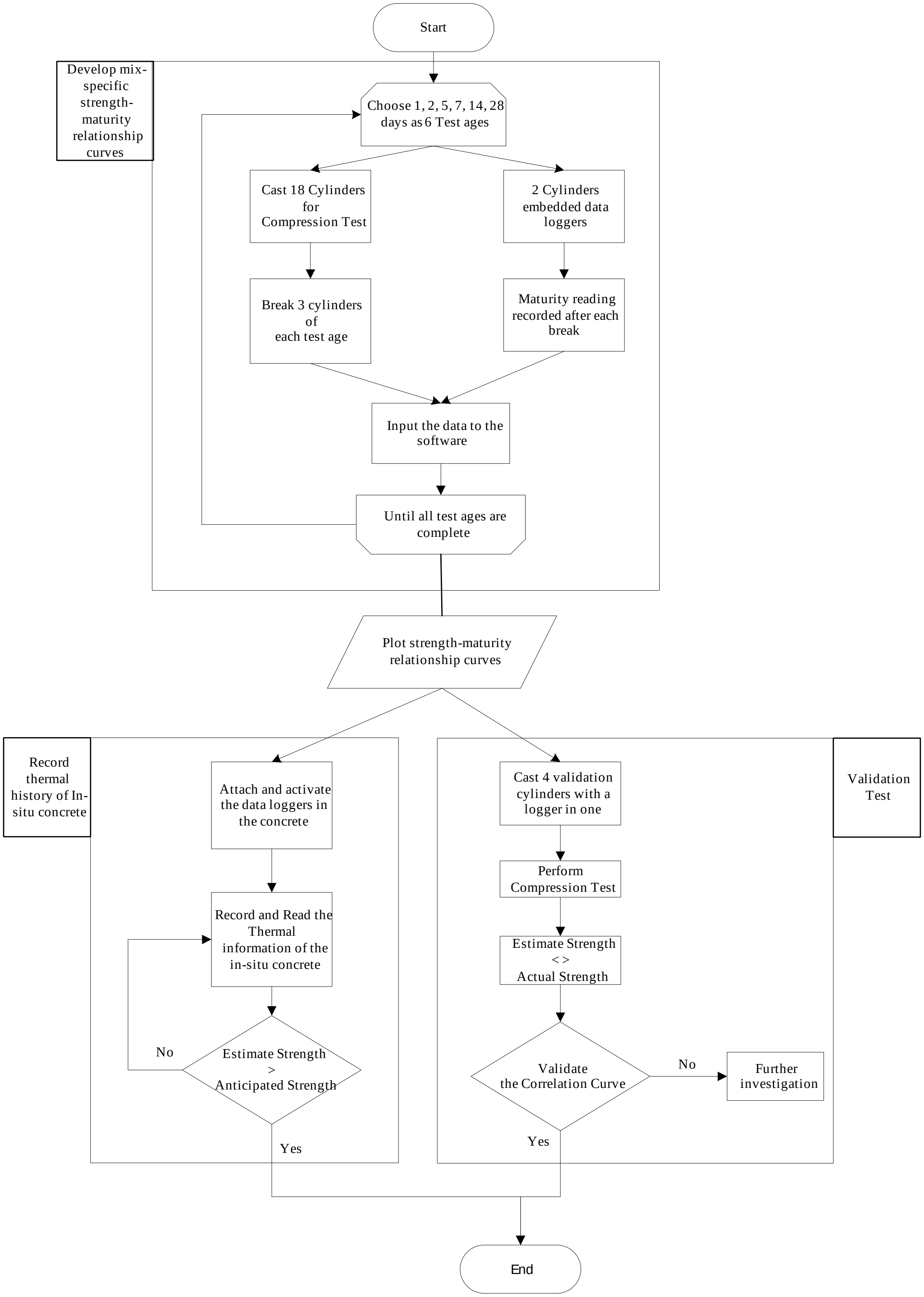

Figure 4-1 *the maturity method process used in the pilot*

Figure 4-2 *Data logger Installation Prior to Concrete Placement*

4.2.3 Validation cylinders

For the first design mix, nine test cylinders were cast with data loggers embedded, using the project concrete on the day the beam was placed, as shown in Figure 4-3. For the second mix, two test cylinders with data loggers for each separate placement were cast using the project concrete on the day the slab was placed. The common method is to cast four cylinders and break, and then compare the average of the three breaks to the maturity/strength of the fourth cylinder, which contains a logger.

Figure 4-3 *Validation Cylinder cast on site*

The test cylinders were exposed and cured at the same temperature conditions as the project concrete. Compressive strength tests were conducted when the maturity reading from the data loggers indicated that the estimated concrete strength met the design requirement. The maturity and the compressive strength of the cylinders were measured to generate two or more strength-maturity data points, which were then compared with the strength-maturity relationship curve. If the verification points were within 10% of the correlation curve, then the strength-maturity relationship curve was considered valid. If the verification points were outside the 10% margin, further investigation is needed to examine whether the entire strength-maturity curve has shifted or some change has occurred in the batching process.

4.3 Results

4.3.1 Technical performance

Table 4-3 shows the maturity and compressive strength data used for the correlation curve. The average values for the maturity indices and the compressive strength were calculated and plotted in Figure 4-4.

Table 4-3 *Maturity and compressive strength data for the correlation curve*

Time (hours)	Actual Compressive Strength, (psi)		Specimen Maturity (°C-Hrs)		Temperature (°C)		Average Age (days)
24		2,218		853		29	1
		2,077		838		27	
		2,225					
	Avg.=	2,173	Avg.=	846	Avg.=	28	
48		2,890		1,540		28	2
		2,995		1,508		27	
		2,834					
	Avg.=	2,906	Avg.=	1,524	Avg.=	28	
120		4,035		3,498		26	5
		4,014		3,451		26	
		4,158					
	Avg.=	4,069	Avg.=	3,475	Avg.=	26	
168		4,464		4,767		26	7
		4,359		4,721		26	
		4,310					
	Avg.=	4378	Avg.=	4744	Avg.=	26	

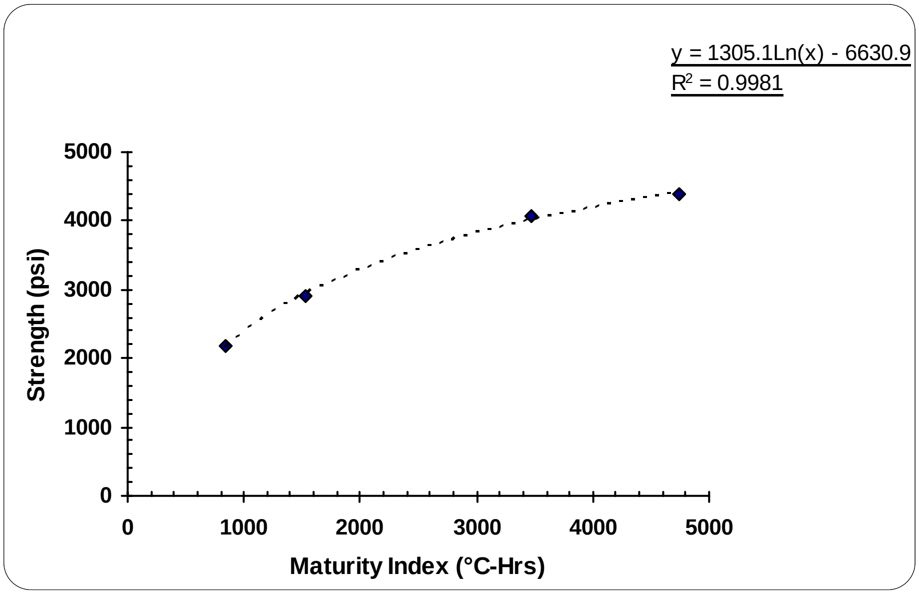

Figure 4-4 *Strength-Maturity Relationship Curve of Design Mix 1*

The correlation curve was generated according to the Nurse-Saul Material Function (Equation 2-1). The graph of the natural logarithms curve adequately fit the data as shown by the R^2 value.

Figure 4-5 illustrates the concrete hydration temperature development at four locations within the grade beam after concrete placement.

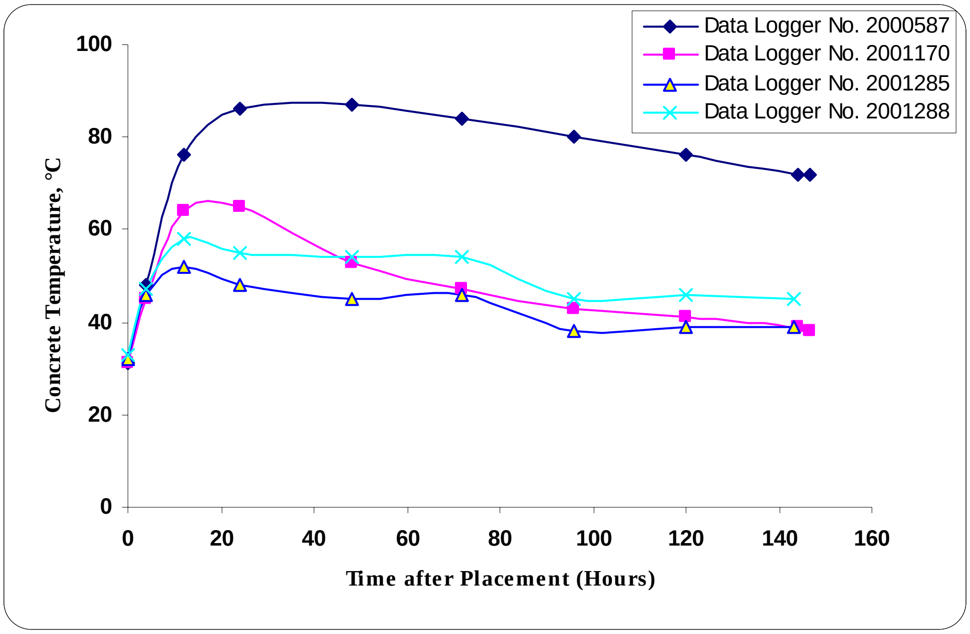

Figure 4-5 *Concrete Hydration Temperature Development for the Grade Beam*

Data logger No. 2001170 was placed 3 feet deep in the center of the placement next to the north wall; data logger No. 2000587 was placed 3 feet deep in the concrete of the placement, and data loggers No. 2001288 and 2001285 were placed 4 inches deep on the side of the placement. It is clear from Figure 4-5 and also shown in Figure 4-6 that strength gain within a concrete structure occurs non-uniformly, which is a factor that typically goes unmeasured using traditional techniques of estimating concrete strength. In order to take advantage of the technology's sensing capability, it is important to carefully consider the location of maturity sensors. In general, the following guidelines for sensor location are considered:

1). Regions within a particular structure where the strength requirement are most significant, (i.e. where dead and live loads are anticipated to be the greatest);

2). Regions within a structure, particularly along exterior regions, typically experiencing lower temperatures of hydration and hence lower early strength gain;

3). Regions within a particular structure requiring early strength development; and

4). Regions that are most representative of the concrete placed.

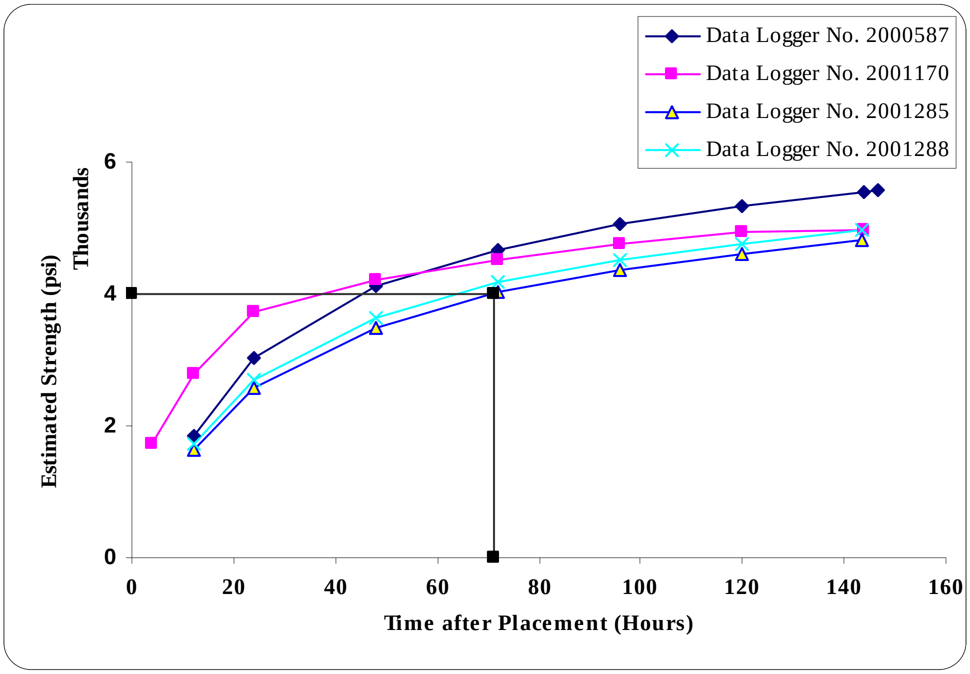

Figure 4-6 *Comparison between the strength development for each of the instrumented position in the grade beam*

Figure 4-6 also demonstrates the use of the maturity sensors to accelerate construction. The concrete for mix design 1 had a twenty eight-day design strength of 4000 psi, which was required before formwork removal and exposure of the structure to live loads. Since the sensors provided real-time estimates, field crews were able to precisely monitor when the concrete reached this requirement. As a result, crews were able to remove concrete forms 2 days earlier than normal allowing them to accelerate the construction schedule.

4.3.2 QA/QC performance

The purpose of the mix validation cylinders was to certify the quality of the concrete delivered to the jobsite, and to demonstrate that the strength-maturity relationship of the validation cylinders would match the strength-maturity relationship curve for the design mix 1 (Figure 4-4).

Figure 4-7 was plotted based on the data of validation cylinder tests. It shows the actual compressive strength of the test cylinders are well within limit and the strength-maturity relationship curve was acceptable for the mix design as established by the Nurse-Saul method. Since there was little variation between the validation tests and the strength-maturity curve, the project's engineer did allow the determination of formwork removal and live load exposure to be based solely on the data logger's maturity reading.

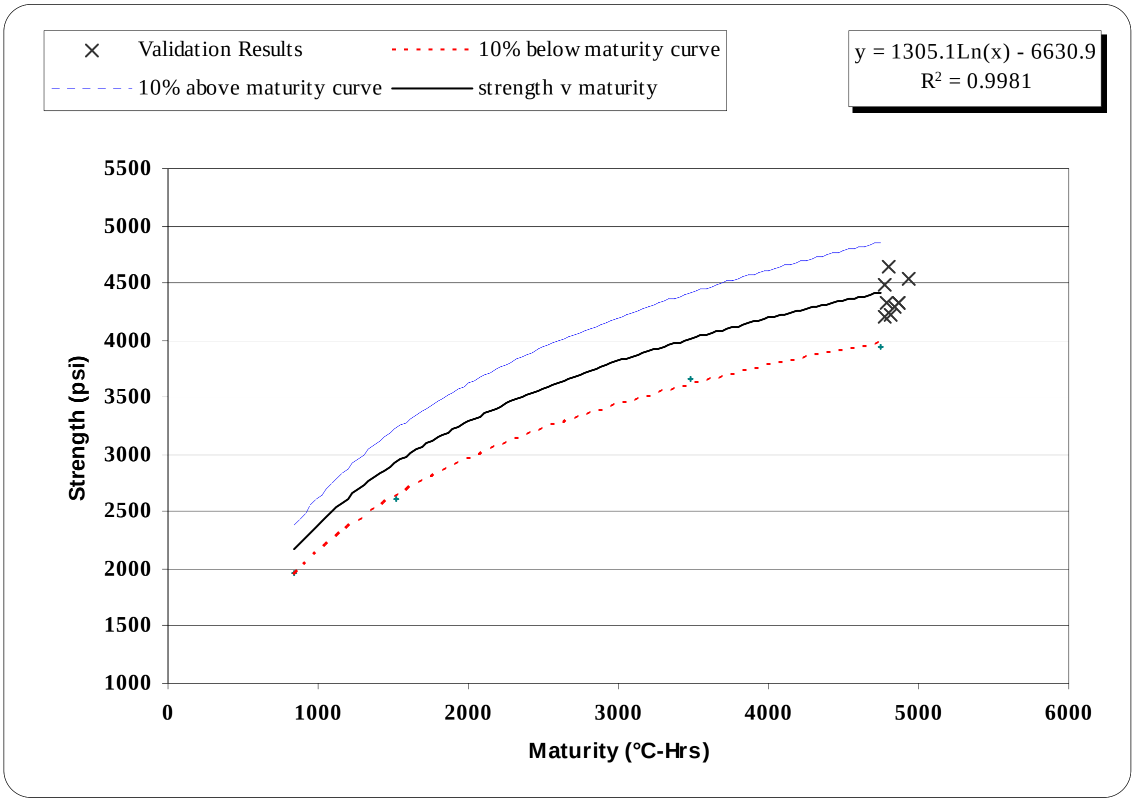

Figure 4-7 *Verification of Strength-Maturity Relationship Curve of Design Mix 1*

5 Analysis of Pilot Test Results

As shown, the concrete maturity method is a relatively simple approach for estimating the in-situ strength of concrete based on the measured thermal history in the structure and a previously established strength-maturity relationship. The application of the maturity method provides some important advantages when used in conjunction with, or instead of, traditional destructive testing techniques.

5.1 Narrative of the data logger's impact on QA/QC

Using the *intelli*Rock system, the contractor was able to assess the quality of the concrete through monitoring of the time-temperature profile at a more frequent interval than actual concrete sampling and QA/QC test specimens. It also showed strength variations that existed at different locations within the structure.

Generally the quality control of the concrete was improved because the strength estimates were based on data from the actual structure instead of separate specimens, especially for early strength estimates.

5.2 Narrative on the data logger's impact on schedule

The *intelli*Rock maturity loggers provided a documented history of the concrete within the structure and enabled the contractor and engineer to estimate the strength within a structure at any time and as many times as necessary until the desired strength was achieved. Since the *intelli*Rock's maturity sensors provided consistent strength estimates in agreement with established strength maturity relationships (Figure 4-8), the technology enabled earlier formwork removal and exposure of the structure to live loads. In general, the system correctly indicated that required strength was achieved one to two days earlier than scheduled.

The concrete maturity method also saves time in the QA/QC procedure. The preparation and testing of concrete cylinders requires time for the QA/QC technicians, as well as the time of field crews while concrete samples are collected. Due to a potential reduction in use of concrete cylinders, the use of the data loggers also reduces the need and logistic requirements for technicians to prepare concrete cylinders required for traditional QA/QC. It takes very little time to place the sacrificial maturity sensors used in these tests and to take maturity readings from them.

Most significantly, successor work activities that cannot commence until concrete strength is confirmed can often begin much earlier using this system. Because the systems allows frequent strength monitoring of curing concrete, design strength can often be confirmed days ahead of pre-planned cylinder breaks used to confirm strength by other traditional methods. Because concrete placement is often a critical path activity, the maturity method offers the possibility of significant project schedule savings.

5.3 Narrative on the data logger’s potential impact on cost

The maturity system had a positive impact on cost. The accelerated schedule also allows a reduction in labor costs. Where construction code permits, the system will allow a reduction in the number of concrete cylinders for compressive testing. Methods that rely on test cylinders use additional concrete and time in their preparation and testing. Furthermore, on most projects, an outside agency is required to prepare, test, record and report on the cylinder breaks, results in added costs over those of the maturity method. This activity results in added costs over those of the maturity method.

6 Lessons Learned Using Concrete Maturity Method

By allowing earlier formwork removal and load setting, the concrete maturity method does enable schedule and cost savings. In addition, the following specific lessons in use of the maturity method were acquired from experiences in the field of this pilot study.

- A single correlation curve can be used throughout the project for placement of the same mix design.

  Each mixture design requires a separate maturity-strength curve. If a large project is using the same mix design, the maturity-strength curve can be developed at the outset and used for succeeding placements. In addition to the traditional Quality Control method, the maturity method provides an additional control method to ensure adequate strength of a given mix design. However, careful Quality Control is still required in order to confirm that each batch is actually prepared using the appropriate design mix. Periodic validation of the correlation curve using test cylinders with data loggers embedded is recommended.

  In order to insure the accuracy of the maturity method, all concrete materials for establishment of the maturity-strength relation must be the same as those used in the concrete for the construction project. Also, the temperature to establish the maturity-strength curve should be close to the in-situ concrete.

- The strength development in a structure is not uniform

  As concrete gains strength, its temperature will vary due to the exothermic reaction of hydration. However, the strength development in a structure is not uniform due to differences in temperature and hydration in different parts of a given structure (e.g. temperatures are cooler near the surface of a massive pour compared to the interior portions of the placement). The embedded sensors enable the contractor and engineer to measure these differences between different areas of a single pour, and make more informed decisions in terms of formwork removal and exposing the structure to live loads.

The temperature to establish the maturity-strength curve should be close to the in-situ concrete. Furthermore, because the strength development in a structure is not uniform due to thermal gradients, the location of the maturity sensors should be considered. In most cases, maturity sensors should be placed in the critical areas of a concrete structure where strength development is most important.

Non-uniform strength gain in concrete structures has always existed. Unlike traditional concrete testing based on test cylinder data, the maturity method provides the ability of the contractors and engineers to monitor and assess the non-uniform strength gains of in-situ concrete.

- Broken wires

There were a couple of wires broken off from the data loggers, because carpenters were not aware their use. Once they were broken, a map of where the data loggers were located was needed, so that the carpenters could go back, expose the end of wires, and splice a new set of wires to enable continuation of the maturity readings. All personnel involved in any aspect of concrete construction should be educated on the use of the technology to ensure its protection in the field

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7 Conclusion

This pilot program provided experience for the contractor in the use of the maturity system technology that enabled real-time estimates of concrete strength using sacrificial sensors embedded in concrete placements. The pilot results depict the high degree of correlation obtainable between the maturity method calculation and the actual concrete strength. The actual compressive test results of the validation cylinders compared to their predicted compressive test based on the strength-maturity curve only deviated between -5.1% to $+4.6\%$ of the predicted strength, which was within the acceptable variation of $\pm 10\%$. This indicates that the concrete maturity method using sacrificial sensors is an efficient and reliable method for quality control in industrial concrete construction. The data from the sensors also provided measurement of the non-uniform strength gains of in-situ concrete, thereby providing more precise control to the contractor and engineer in determining when a newly placed concrete structure can be exposed to live loads and formwork can be removed.

Since this was a pilot test of a relatively new technology, the contractor continued to do all of the concrete testing that they normally would have done without the loggers. It was not possible during the pilot test to quantify the schedule and cost savings that resulted from the use of the maturity sensors. However, as the pilot study progressed, the engineer of record authorized the use of the maturity system to determine the timing of the following: 1) place live loads on elevated slabs, 2) remove forms from precast panels, and 3) proceed with non-destructive testing to clear non-conformance reports. It was clear from the pilot activities that the sensors could provide the contractor the opportunity to proceed with successor work activities earlier than normal, allowing them to accelerate the construction schedule. Also, the system has the potential of significantly reducing the number of concrete test cylinders, which would result in additional cost savings.

8 References

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