Embedded Wireless Temperature Monitoring Systems For Concrete Quality Control

By

Will Hansen, Ph.D.
Professor of Civil Engineering
University of Michigan
Ann Arbor, MI 48109
E-mail: whansen@umich.edu

Sunny Surlaker
Graduate Student in Civil Engineering
University of Michigan, Ann Arbor

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Executive Summary

The pilot study processes described in this report are field trials of newer technology (RFID-Radio Frequency Identification maturity tags) in the field of predicting concrete strength and performance in structures and pavements using the concrete maturity concept. One study was carried on by the personnel of the Professional Services Industries, Inc. during the construction of the University of Michigan CVC parking structure in Ann Arbor, Michigan. The second study was a project carried out by Dr. Will Hansen at the University of Michigan, Ann Arbor. This study was built to target application of RFID tags to issues (like construction curl) besides maturity. In a nutshell, this report examines the use of the concrete maturity concept, the use of the Radio Frequency ID Tag technology to predict concrete maturity, and the experiences gathered in field use of the technology.

The maturity method is a technique to account for the combined effects of time and temperature on the strength development of concrete. This method gives an estimate on development of the strength of concrete in real time based on the actual thermal history of a particular mix design. The studies on the maturity method have been carried on for more than 50 years (since the 1950s by Nurse, Saul and McIntosh) but practical methods to determine it efficiently have not been developed to that extent, due to which the technology has not yet found large scale use in construction.

The RFID tag (containing a data logger and a temperature sensor) is embedded in concrete at the time of placement, and the system provides wireless communication between the tag and a portable handheld device, such as a PDA. The portable handheld device retrieves this data wirelessly from the RFID tag and calculates the in-place concrete strength during hydration. This data can accelerate construction activities such as removal of form work, tensioning, and sawing for concrete as compared to the traditional methods of testing cubes. This technology also gives a good insight into construction of pavements by logging temperature gradients (due to weather and moisture warping) seen in early-age concrete. These gradients in pavements create a multitude of problems, such as built-in curl and temperature curl, which cause fatigue and ultimately failure of the concrete pavements. Results of the field study indicate the accuracy of the concrete maturity method in prediction of in situ strength and the potential savings in cost and time for any particular project.

Acknowledgements

The temperature data from two highway projects were obtained as part of an ongoing study at the University of Michigan for the Michigan Department of Transportation (MDOT). The authors would like to thank Tim Stallard and Andy Bennett, MDOT, for their help and advise. Thanks to Larry Mitti, Interstate Highway Construction (IHC) and his construction crew for providing help in sensor installation during paving on US-23 near Flint, Michigan. The opinions and findings by the authors do not necessarily reflect the views or policies of the Michigan Department of Transportation. This work does not constitute a standard, specification, or regulation by MDOT.

The data obtained from the UM parking structure project was acquired from Wake Inc. and PSI Inc. In this regard writers wish to acknowledge gratefully the support of Mr. Richard Yesh of Wake Inc. and Mr. Timothy Moore of PSI Inc.

Finally, the authors would like to acknowledge the co-operation and support of Yousef Nouri, UM Ph.D. student for help in editing this report.

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1. Introduction

The University of Michigan is evaluating new sensor-based technologies to applications besides maturity, such as monitoring temperature gradients in pavement slabs and analyzing their effects in long-term pavement performance, in separate projects, one being carried on for the Michigan Department of Transportation (MDOT) and the other for the Ann Arbor Cardiovascular Center parking structure. The scope of this project ranges from early-age monitoring of maturity and monitoring temperature gradients in pavements to monitoring effects up to 12 months after embedding of sensors.

1.1 Why Concrete Maturity?

The origin of the concrete maturity method can be traced to work on steam curing of concrete carried out in England in the late 1940s and early 1950s. A couple of incidents in the 1970s in the United States were cause for the maturity method to be studied here. On March 2, 1973, portions of a multi-story building, under construction in Fairfax County, Va., suffered a progressive collapse in which 14 workers were killed and 34 were injured. The cause of failure, as determined by the National Bureau of Standards (NBS), was premature removal of formwork, causing punching shear in the young concrete. Following this, on April 27, 1978, there was a major construction failure of a cooling tower being constructed on Willow Island, WV. The incident resulted in the death of 51 workers who were on the scaffolding anchored to the partially completed concrete shell. The diagnosis by NBS led to the same conclusions as before, and this stressed the need of research into estimating in-place concrete strength during construction. Thus, the NBS staff began an in-depth study on the maturity method. This method is a relatively simple approach to making reliable estimates of in-place strength development under variable temperature conditions.

1.2 History

Concrete Maturity as a concept is a reliable, proven, non-destructive strength estimation method. This method uses the time and temperature measurements to determine strength gain of in-place concrete. The origin of the concept was in England, and dealt with strength relating to accelerated curing methods. The product of time and temperature was proposed to be used to determine the maturity index. This led to the famous *Nurse-Saul* function and Saul's Maturity Rule: concrete of the same mix at same maturity [in °C-hours] has the same strength whatever combination of time and temperature goes to make up that maturity.

$M = \sum_{0}^{t}(T - T_0)\Delta t$, where M=Maturity Index, °C-hours

T=Average concrete temperature and T_0= Datum temperature

t= Elapsed time (hours or days) and Δt= time interval (hours or days)

In recent times the Arrhenius equation was proposed by Freiesleben Hansen and Pedersen to be more accurate in predicting maturity. The concept called for equivalent age of concrete at a reference temperature (generally taken to be 20°C) and overcame the main drawback of linearity in the Nurse-Saul maturity function. The equation is given below.

$$t_e = \sum_{0}^{t} e^{-\frac{E}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} \Delta t$$

Where, t_e = the equivalent age at the reference temperature,
E = apparent activation energy, J/mol, R = universal gas constant, 8.314 J/mol-K,
T = average absolute temperature of the concrete during interval Δt, Kelvin, and
T_r = absolute reference temperature, Kelvin.

The use of the equation above largely eliminated the discrepancies between strength-maturity relationships developed with different initial curing temperatures, that is, it eliminated the discrepancy at early maturity. This equation was used in the maturity studies at the University of Michigan.

As far as the history of using smart chips and sensors go, the concept found applications as early as the 1950s. The earliest studies used systems that needed temperatures to be recorded in the labs and the calculations to determine maturity, and eventually strength, to be processed elsewhere. This pointed the way to the use of semi-conductor technology in evaluating maturity. These in turn led to the use of *wired* micro-processor systems that embedded sacrificial data loggers into the concrete. These data loggers were connected to the data processing hardware by wires (also embedded into concrete). As construction procedures became tedious using wires, there was a need to combine two technologies: concrete maturity and wireless Radio Frequency ID sensors. These technologies and the latest in maturity sensor technology are shown in the **Figure 1** below.

Figure 1: Concrete Maturity Systems. (Wake Inc.)

2. About the technology used

The RFID technology used involves two components physical components that use the concept of maturity:

The Hardware: This includes the antenna, transponder, receiver and the Portable Data Collection Device (we will refer to the collection device as the tag or maturity meter in the report that follows).

The Software: The software used to calculate the maturity is "Pocket Concrete," manufactured by International Road Dynamics, Inc. (IRD)

2.1 Hardware

- The antenna emits radio signals to activate the tag and read and write data to it. The antenna is a conduit between a tag and the reader (transponder).
- The transceiver, or reader, is a device that extracts and decodes information from the tag. In the monitoring system used on-site, the transceiver was placed on the PCMCIA card used on the portable data collection device. The tags and the transceiver were developed by Identec Solutions.
- The tag or transponder used in the project is the i-Q32T, manufactured by Identec Solutions. The i-Q32T is a highly sophisticated data logger, which can withstand harsh environmental conditions and can capture and store temperatures. This can later be retrieved at an appropriate time. It can be buried in concrete up to 8 inches and still transmit data back to the transceiver.
- The portable data collection device can be one of the following units: any PC laptop, Hewlett-Packard's iPac Palm PC, or a portable manufactured by Unitech or LXE.

2.2 Software

The software used to actually calculate the maturity and the related strength of concrete is the "Pocket Concrete" developed by IRD Inc. This software runs on a PC platform, and calculates maturity based on the Nurse-Saul equations (time-temperature factor) or the Arrhenius equations (based on equivalent age of concrete). The software incorporates the readings taken by the i-Q32T into calculating in situ strength. Therefore, the in situ strength is determined by the actual in situ temperatures recorded in the concrete. **Appendix 1** shows the types of hardware and screenshots of the software used on the project**.**

3. Applications of Embedded Wireless Maturity Meters

To date, the embedded sensor technology is only being used for calculating maturity. However, concurrent studies are being undertaken to expand application to other uses such as logging temperature gradients in pavements. Also, effectiveness of use of multiple sensors along pavement depth is being studied. These applications are described below:

3.1 Single-Sensor-Based Applications

A single-sensor-based application is the use of only one sensor per depth of the member at the test location. This type of application makes sense in terms of economy and use in construction of buildings where slabs, etc. are not more than 8 in. deep. In such an application, it is the general rule of thumb to use about five sensors per pour of about 100-150 cubic yards. The pilot project carried on for the Ann Arbor CVC parking garage was an application using a single sensor per depth of slab or beam. The study is explained in detail in the following sections.

3.2 Multiple-Sensor-Based Applications/Studies

Multiple-sensor-based application is the use of two or more sensor per depth of member at one test location.

a) **Use in Finding Maturity**: The first study demonstrates the effect of tag locations on determining maturity of large slabs, such as those in pavements. Maturity, as we know, depends on the temperature; this is what the maturity meters described in the preceding section measure and use to calculate maturity. A study funded by the Michigan Department of Transportation (MDOT) was carried on at University of Michigan during the construction of the US-23 and I-94 freeways. This study is described in detail in the following sections.

b) **Application to log temperature gradients and construction curl:** Another application for which the sensors may be used is to log and determine temperature gradients in pavements. This application is important, as there may be an existing non-linear temperature gradient (difference of temperature between the bottom and the top of the slab) in the early age pavement at time of final set (as is generally the case during summer construction). This means that the solidifying concrete sets with a positive temperature (maybe up to 30ºF) difference between top and bottom of slab. At later stages when the top surface cools down it contracts substantially thereby causing curl as seen in **Figure 2** below. This phenomenon is called **construction-curl** and becomes important in sensitive projects such as pavement slabs. Shrinkage due to moisture loss from slab surface and climactic changes (onset of cold weather and daily temperature variation) in tandem with construction-curl further aggravates the curling condition, because at this stage there is a negative temperature difference between slab top and bottom (contrary to early-age solidified concrete). This causes the slab to permanently curl up in a shape as seen in **Figure 2** below. The effect of changing gradients on slabs concreted during hot weather (summer construction) is shown in the **Figure 2** below.

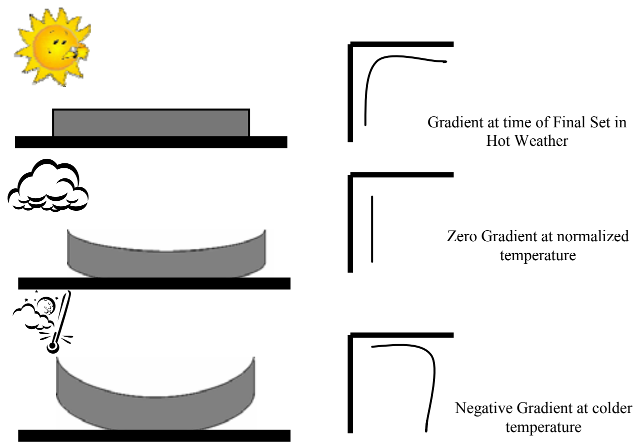


Figure 2: Effect of changing temperature gradients on amount of slab/construction curl

An in-depth description of this application is mentioned in later sections of this report.

4. Pilot Project I – CVC Parking Structure

The concrete maturity measurement system used on this structure has previously been used for applications in structures such as bridge decks, columns and massive concrete structures. To better study the applications of this technology in actual construction practices a pilot project was undertaken during the construction of a parking structure in Ann Arbor, Michigan (**Figure 7**). The structure, being constructed by Devon Industrial Group (DIG), is a parking garage for the Cardio-Vascular Center (CVC) in Ann Arbor, Michigan. The garage has three levels and a basement. The third level is a plaza and will have soil, grass and walkways but no parking. The concreting for the structure was done in twelve (12) major pours and smaller pours for ramps and other smaller elements. The maturity monitoring system for the project was provided by Wake Inc. The complete QC testing for this project was done by Professional Services Inc. (PSI).

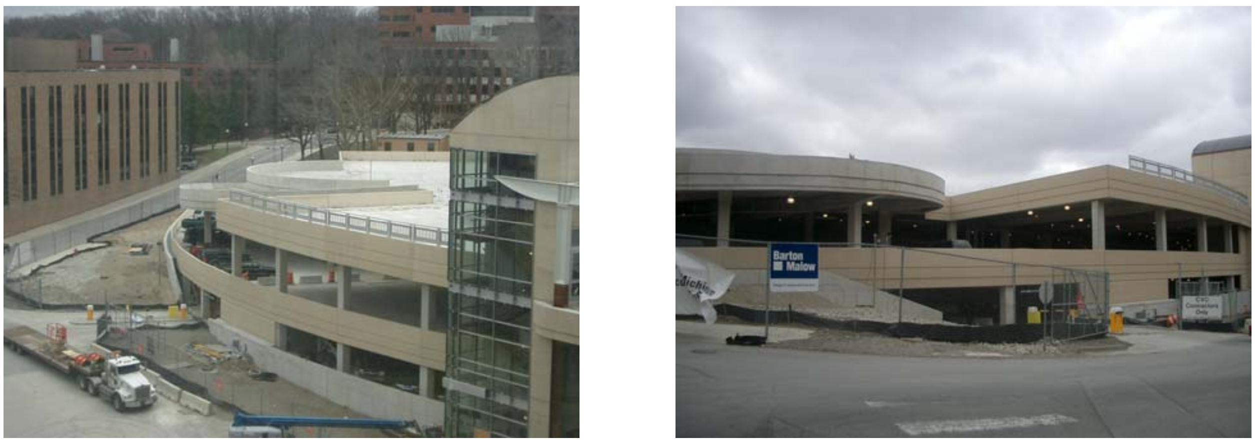


Figure 3: CVC and parking structure

4.1 Overall Goal

The overall goal of the pilot project was to post-tension the tendons at a concrete strength of 3000 psi as early as possible (in two or three days, but in no case after more than 96 hours). The maturity monitoring system using RFID tags was used to ascertain this tensioning time.

4.2 Project Objective

The main objective of the pilot project is to use the RFID technology along with the maturity concept under practical site conditions. The objectives also include describing experience gained from use of the technology on site and describing the impact of use of the concrete maturity method using sacrificial sensors on project QA/QC, cost, and schedule.

4.3 Scope

The scope of this project is limited to studying application of RFID technology and the maturity method to construction projects and its potential benefits over conventional methods of strength determination.

4.4 Related Project Background

The CVC garage is a frame structure in which the beams and slabs are post-tensioned. The tendons are tensioned to 5300 psi; this required the concrete strength to be a minimum of 3000 psi. The RFID tags were taped to the rebar steel. A few tags were placed at the edges of the slab where tensioning was to occur. On average four tags were used per pour (in the twelve [12] major pours). The data on pours seven, eight and nine (7, 8 and 9) are studied for this report. The tag data is collected and compared for three different days when the concrete was placed. The days lie in end of June, mid-July and mid-August.

4.5 Experimental Setup

The setup and construction was carried out in the following steps:

- The carpenters built a wooden "deck" complete with beam troughs. The rodbusters then placed the resteel and tendons. After the steel was inspected and approved, the tags were taped to the rebar steel at predetermined locations and then concrete was poured. The concrete used on site had a minimum mix to provide 5000 psi strength. (**Fig 4 and 5**)
- The tendons are woven steel strands that are greased and placed inside of a plastic sleeve. The tendons were usually set up to have a live end and a dead end. The dead end had a plastic anchor or terminator embedded in the concrete and the live end was fed through a plastic mold that created a pocket on the edge of the slab so that the tendons could be accessed for stressing. Most sections were built in this manner.
- The remaining sections had two live ends. In each live end a set of wedges was placed on the tendons in the pocket created in the slab edge. These wedges gripped the tendons and held them in place after they were stressed.
- The post-tensioning was done by measuring elongation of the tendons. The tendons were marked at three-inch intervals using a wooden board and paint. After tensioning, these intervals were measured again to ascertain the tensioning.
- If concrete maturity meters were not used, then the compressive strength of sample cylinders would have been used to determine if the concrete had achieved 3000 psi.
- On our project, we used tags and field cured cylinders. The field cured cylinders were left on the deck to experience the same curing conditions as the slab.
- Before we began stressing we usually made sure that both the field cured cylinders and the meters showed strengths above 3000 psi.

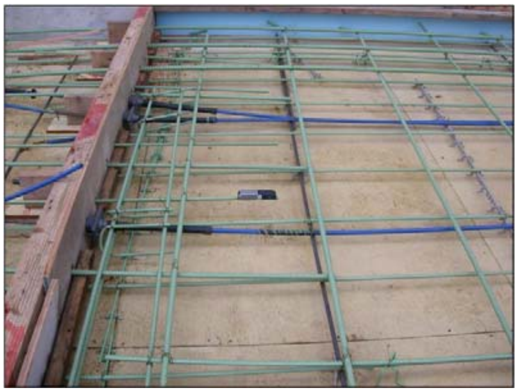
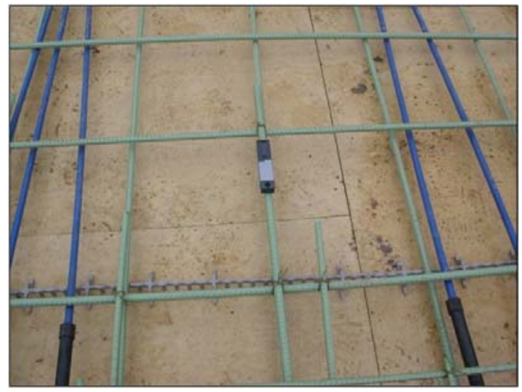
 

Figure 4: Use of Tags in Slab Pour in Mid-slab Portion and at edge of Slab (Courtesy PSI Inc.)

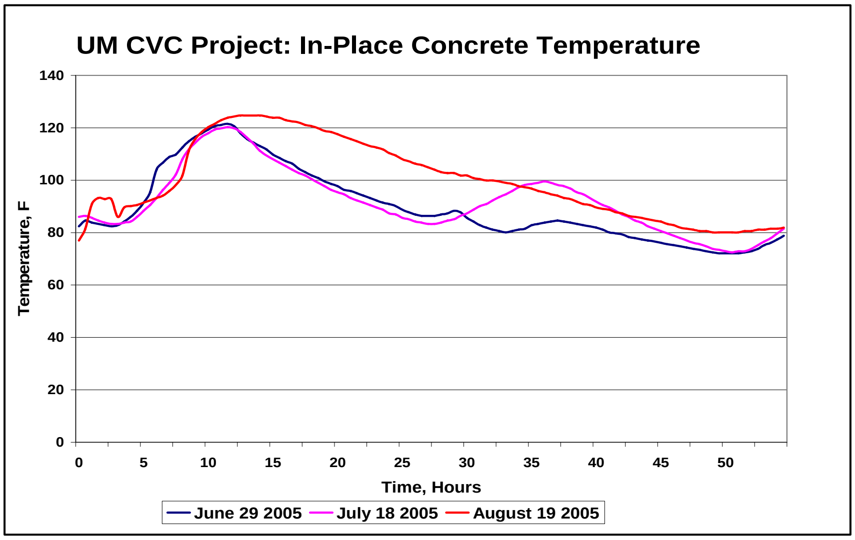
Figure 5: Use of Tags in Beam Pour Troughs amidst the Tensioning Strands (Courtesy PSI Inc.)

4.6 Performance Metrics and Methodology

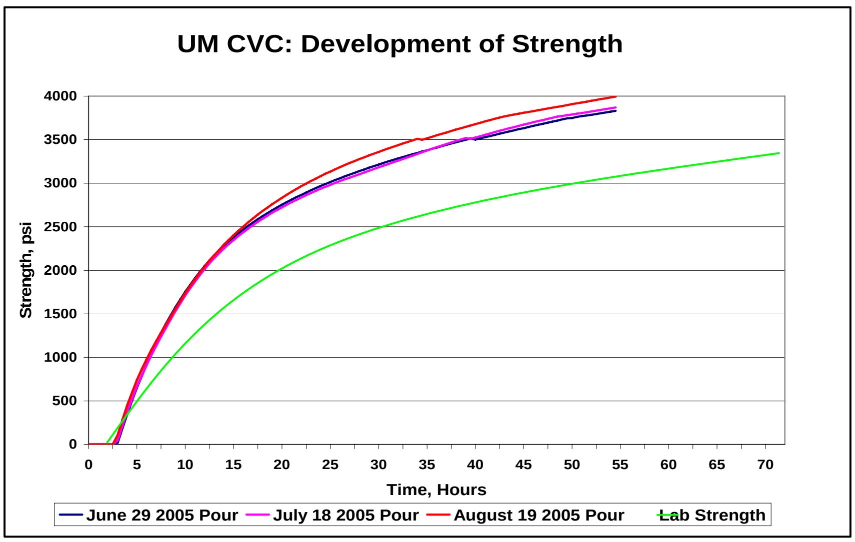
The main parameter to be measured for this pilot project was just to find when the concrete reached the designated 3000 psi strength to be post tensioned safely. The methodology used to ascertain this was maturity (we read this from the embedded tags) and testing of field cured cylinders. The pour plan and approximate locations of placement of tags are shown as **Appendix 2**. The temperature readings for the maturity were logged every half hour by the smart tags. This data was supplemented by testing standard 6” x 12” test cylinders. The software used on the collection system assembled the data for maturity and calculated the strength for concrete. The mix design for the particular 5000 psi pours and the quantities they were used in is shown as **Appendix 3**. A sample of the calculation sheet generated is attached as **Appendix 4**.

4.7 Findings and Interpretations

It was found from pour readings (recorded by the tags in concrete) on three separate pouring days that the 3000 psi strength for post-tensioning was achieved in the window of 22 to 25 hours from the time the tags were embedded in concrete. The field-cured cylinders, when tested in the lab, yielded about the same strength in about 67 hours (actually 3 days). This implies the contractor can start the post-tensioning after 25 hours instead of three days (if we follow the test cylinders). This will essentially save time and money on the project. A graph of concrete strength and temperature vs. time is as shown in **Figure 6** below (graph generated by the pours).



(6a)



(6b)

Figure 6: Data From UM-CVC: Figure 6a: Variation of Concrete temperature with time**.**

Figure 6b: Concrete Strength vs. Time as Logged by the Temperature Sensor. (Data provided by PSI Inc.)

Therefore the use of advanced RFID technology can greatly aid project progress by giving us the exact time the concrete strength reaches the required state. Therefore, even if there are variances in exposure conditions (temperature is very hot or very cold) the contractor can keep a close watch over in-situ concrete strength development and can schedule his activities (like post-tensioning or form removal) in accordance with when the concrete has reached desired strength.

This data can be interpreted in a multitude of ways. In 99% of the cases the test cylinder cures at a different rate than the actual pour. A small amount of concrete equals a lower hydration rate. This implies that temperature differences are major with a small amount of concrete such as a test cylinder versus a parking deck pour. The fact is, the cylinder will not gain strength at the same rate as the large pour. Time will be saved by post-tensioning at the proper in-situ strength and moving on to the next pour. In case the maturity method is used instead of testing cylinders, the readings should be validated by NDTs like Schmidt's Hammer.

The embedded tags, therefore, provide an additional control to monitor strength of the concrete and aid greatly in quality assurance. It is also an additional assurance that the concrete has reached the desired strength and will not fail and cause damage to life and property. This is the big advantage of using concrete maturity as well as having a temperature record of the concrete curing for quality assurance to achieve the durability that is required of the concrete pour.

5. Potential Benefits on Infrastructure Project

The fees charged to University of Michigan Plant Extension (client) was greater using the maturity technology, predominantly because it was not specified originally and test specimens (cylinders) were not being molded at a reduced rate. Reducing the number of test specimens to approximately 1/3 of those specified would have provided a cost savings on the order of $250 in cylinder testing costs alone.

It is believed that the use of the maturity technology can save the contractor approximately half a day per concrete placement of crew time by showing that the required concrete strength has been met, potentially allowing a reduction in curing activities (heating/covering) and earlier start of post-tensioning activities. This savings is estimated to be on the order of $2,000.

Maturity technology can also indicate that the concrete is not safe to start post-tensioning. Should the concrete not have the required compressive strength to resist the forces of post-tensioning, injury or death to those in the immediate area of the post-tensioned slab is likely in case a post-tensioning strand or accessory pulls loose from the concrete.

Without the use of concrete maturity technology, PSI would have had one or two field technicians on the job site during concrete placements. Standard tests such as sampling, slump, air content, density, temperature and strength specimens (cylinders) would have been performed. The test cylinders would then have been placed and cured with the structure. At the appropriate day and time, the test cylinders would have been returned to the laboratory for testing, where they would be logged in and tested by the laboratory technician. The compressive strength measured in the laboratory would then be relayed back to the project site and the contractors. During the transportation and testing period, the contractor would be waiting for results and a go/no-go decision. The waiting time will therefore be reduced using the maturity-strength method.

With the advances in concrete maturity using established ASTM standards, in-place concrete strength can be determined accurately in real time. It was estimated by one contractor that the project should pick up about one day a week because of greater efficiency using the embedded maturity monitoring system.

6. Pilot Project II – Application of Embedded Tags to Monitor Maturity, Temperature Gradients and Curl in Pavement Systems

The second project using the RFID tags aims at monitoring curling of flat slabs and pavements by recording the temperatures across the depth of the slab. Using these temperature profiles we can find lowest maturity across the depth of slab and use temperature data to calculate slab uplift. **Figure 7** below illustrates the slab curling phenomenon. The second field project utilized five RFID sensors for monitoring maturity and temperature gradients within the pavement cross section constructed during June (I-94) and late October (US-23) of 2005. Sensors were embedded in concrete at four different depths and one sensor was used to obtain ambient temperature data. The embedded sensors were used to ascertain the earliest time that construction traffic could be allowed onto the pavement after placement without causing damage to concrete. Also, for a contractor paving in both summer and fall seasons, rate of development of maturity (strength gain) becomes an important parameter to monitor. In projects of such a sensitive nature, it also becomes important to find at what depths the sensors need to be embedded because temperature and thus strength development is varying with depth and season (summer versus fall). Temperature readings are still being collected as of 10 months after construction for the US-23 project near Flint, Michigan. As of June 2006, over 10,000 temperature readings per tag have been logged and these results were downloaded to a computer within 20-30 seconds per sensor.

Further temperature sensors combined with wireless technology have been used by MDOT in several new bridge deck and pavement projects for the purpose of evaluating whether this technology can be used in developing new specifications for monitoring pavement performance. University of Michigan, Ann Arbor is currently using this technology (wireless temperature sensing) from Wake Inc. in a pavement project for developing acceptance criteria when built-in curl exists.

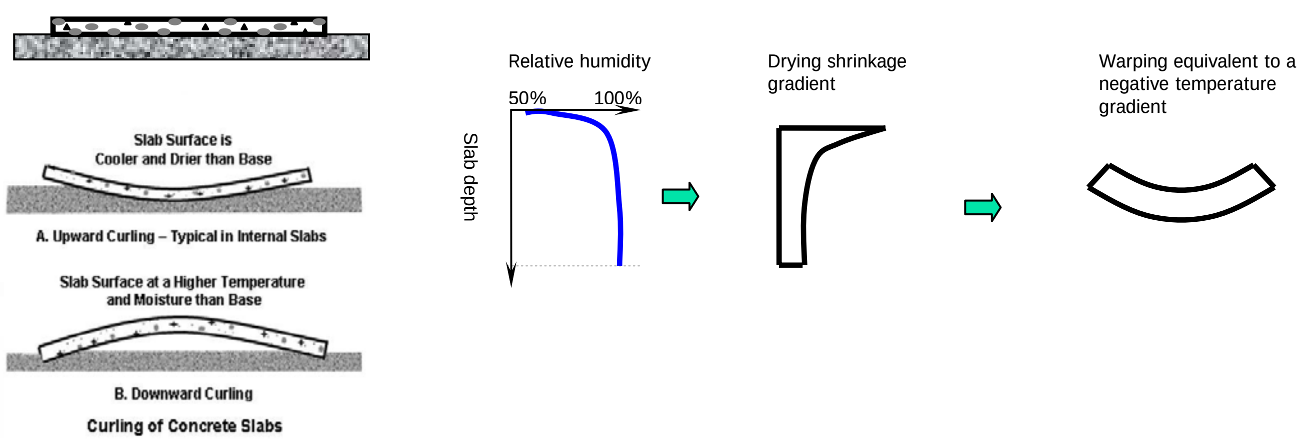


Figure 7: Slab curling phenomena due to temperature gradients and due to rapid drying shrinkage (NRMCA CIP 19 and U of Michigan)

6.1 Overall goal

The main goal of the project was to study the effect of ambient conditions (namely temperature and moisture) on paving and its effect on long term pavement performance.

6.2 Objectives

The main objectives of the project are, then, to monitor the effects of hot and cold weather construction (the cause of built-in or construction curl) on pavement performance. The focus of the project will then be to monitor maturity and strength development and predict the slab-base contact due to the built-in curl (caused by temperature differentials during hot and cold weather concreting). The project also briefly focuses on the importance of using multiple sensors at a test location, so as to obtain a temperature profile and not just a single temperature reading. The objective is then to show that the maturity system can be used for applications besides maturity, which is to monitor temperature gradients and eventually slab curl in jointed pavements.

6.3 Scope

The scope of the project is limited to use of the wireless embedded maturity monitoring system to monitor temperature gradients in the pavement at time of construction and during early ages. These gradients will eventually lead to much more accurate maturity readings and an effective QA/QC system to reduce the effects of construction curl and rapid drying shrinkage on pavement performance.

6.4 Project Background

The phenomena of construction curl, rapid drying shrinkage, and the daily temperature variations, working in tandem with axle loading, easily cause the pavement to reach its fatigue threshold and thereby fail rapidly. It thus becomes imperative that there be a way to monitor the formation of temperature gradients in early-age concrete and then apply known curing techniques to mitigate effects of gradients and drying shrinkage. That is where the maturity monitoring system can effectively step in. Sensors embedded at four different depths in a slab will provide the exact gradient the slab experiences at time of final set. Additionally, the system will provide maturity at different levels in the slab. We know concrete fails by the weakest strength and therefore at its lowest maturity. This can be easily read off the sensor showing the lowest temperature reading in the pavement slab.

This study was carried on over two freeways in the vicinity of Ann Arbor, MI. The study for summer construction was carried on along I-94 and the fall (cold weather) construction was carried on along US-23. The project was funded by MDOT.

Figure 8: Worksite for Projects (University of Michigan, Ann Arbor)

6.5 Experimental Setup

- Two JPCP projects, constructed on a hot and sunny day in early summer and on a cold and cloudy day in late fall, were investigated to determine the effect of paving conditions on the magnitude of built-in curl.
- Both projects were instrumented with the wireless temperature sensors, which were programmed to collect temperature data from the start of construction in 30 minute intervals.
- The concrete section used for sensor placement was hand-scooped immediately after placement. The sensors were placed at four different depths at the same location (mid-slab and approximately 0.6 m from the longitudinal edge with shoulder) starting from the top of the base, then approximately 2 in., 4 in., 6 in., and 8 in. above the slab bottom.
- One sensor was located off the shoulder for ambient temperature measurements. Creep effects were determined from laboratory testing for similar temperature histories as in the field for concrete specimens with cross section of 100 mm by 100mm and 830 mm in length.
- Final Set time was determined in the laboratory for three different curing temperatures to determine set time of field concrete. **Figures 9 to 11** show the tag setup procedure.

Figure 9: Experimental setup for the tags (University of Michigan, Ann Arbor)

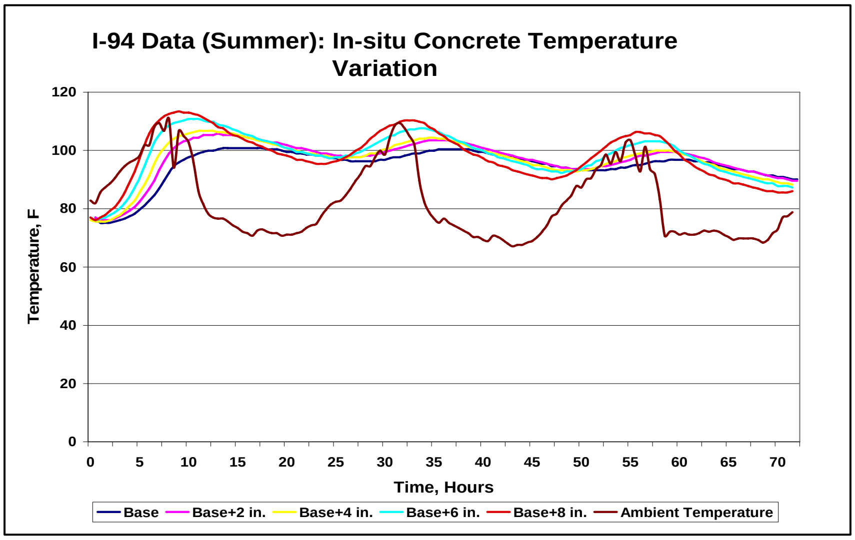
Figure 10: Scooping out of fresh concrete and placement of tags (University of Michigan, Ann Arbor)

Figure 11: Finishing of the road surface and tag placed by side of road for monitoring ambient temperature. (University of Michigan, Ann Arbor)

6.6 Findings and Interpretations

a) Maturity.

For this study, the wireless maturity meters were embedded during the reconstruction of the freeways. The smart tags were placed at depths of 2 in., 4 in., 6 in., and 8 in. from slab base for slabs 12 in. thick. The temperature development at various depths in the slab was logged, and the corresponding maturity of concrete was found for these temperatures. The temperature variation of the in-situ concrete and the temperature gradients at time of final set in concrete is shown in **figures 12 and 14** below. **Figure 13** shows the development of strength in the concrete in the lab and in the field.



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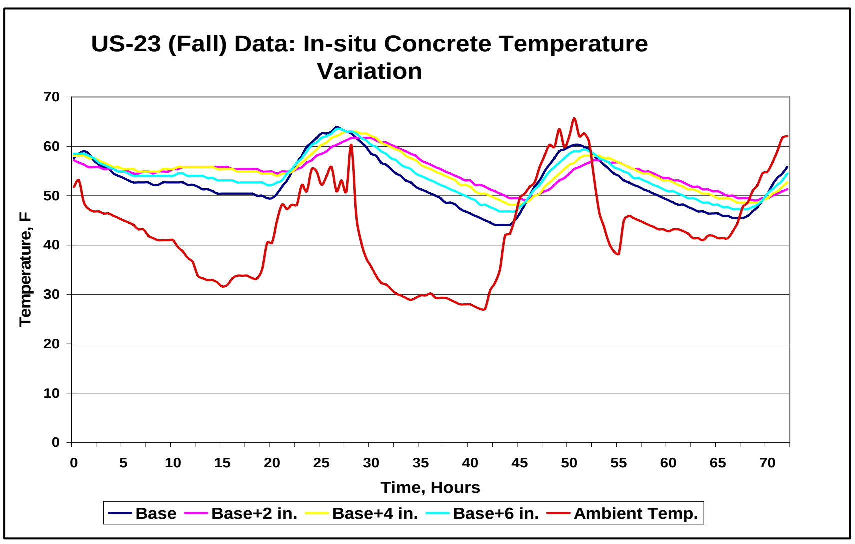
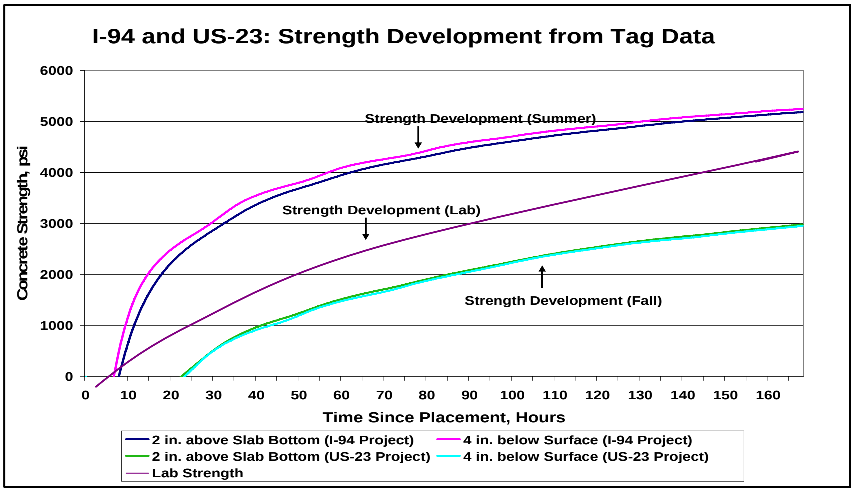


(12b)

Figure 12a: In-situ Concrete Temperature for I-94 for initial 72 Hours**. Figure 12b**: In-situ Concrete Temperature changes for US-23 for initial 72 Hours.



Data from I-94 and US-23: Figure 13: Comparison of Maturity development for the first 168 hours. (University of Michigan, Ann Arbor)

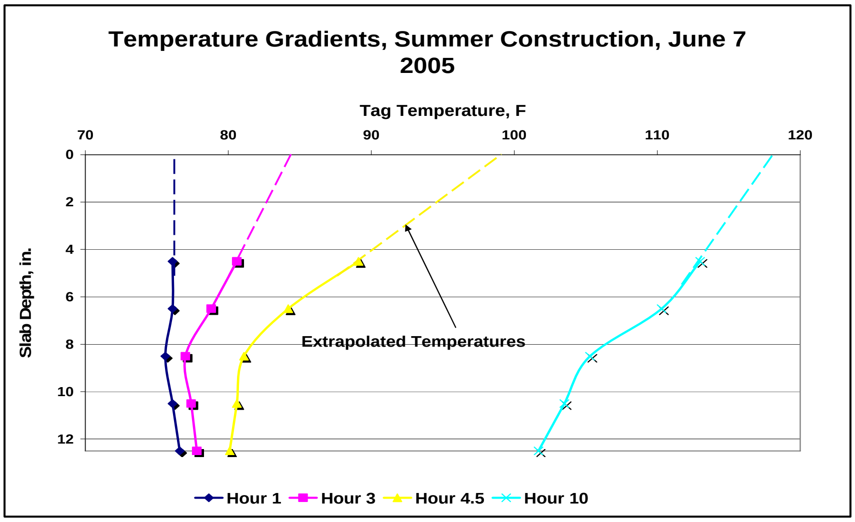


Figure 14a: Difference of temperature and the gradient in slab up to time of final set. Temperature data provided by Tim Stallard, MDOT (Hansen et al)

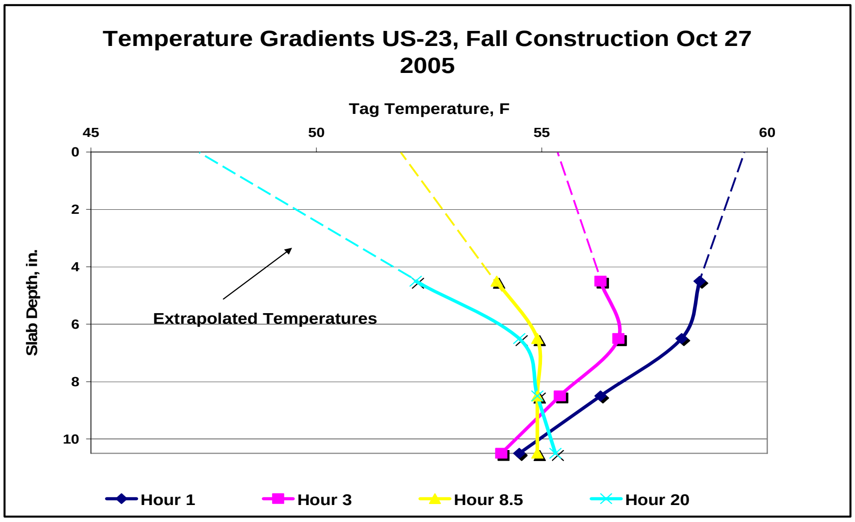


Figure 14b: Difference of temperature and the gradient in slab up to time of final set. Temperature data provided by Tim Stallard, MDOT (Hansen et al)

It is seen for the I-94 pavement that the daily high temperatures and the concrete temperature are almost the same (about 90°F-110°F). Similarly, the concrete temperature is substantially lower for the US-23 pavement (fall construction) than summer concrete temperatures (about 50°F-80°F). What this implies is that maturity development in fall (cold weather) is lower than summer (hot weather). **Figure 13** shows this. This further implies that the rate of strength development in cold weather concrete is substantially slower than hot weather concrete.

Therefore what we see from **Figures 13** is that to reach any target strength, say 3000 psi, the concrete cured in the laboratory requires 85 hours. The same concrete on the field (in the pavement) during the summer (hot weather) needs 30 to 35 hours. The same mix during fall construction (cold weather) requires more than 160 hours to reach the target 3000 psi strength. What this means is that the rates of strength gain for different temperature conditions are substantially different and that relying solely on lab testing of concrete may not be representative of the actual state of the concrete. This is where the use of the embedded wireless RFID maturity meters can be very helpful. These will indicate the correct maturity and strength of the in-situ concrete.

Also, we see that for the same concrete, time taken to reach a maturity across different depth of slabs (at base and near top of slab) varies by about 4 hours for summer and about an hour for fall construction. This clarifies the fact that use of a single sensor at mid depth in a slab more than 12 in. in depth may give an erroneous maturity and therefore may be a higher strength. Concrete as we know it fails at it lowest strength. Therefore it is imperative that we know at what depth the lowest temperature, maturity and strength will occur (in a nutshell these can be seen from graphs as in **Figure 14**). **Figure 14** also shows the difference in temperature at the top and bottom of the slabs. This type of data would be **impossible to obtain** if only one sensor was used per slab depth at a test location. It is therefore advisable that three or more tags be used per sensor location to get the most accurate maturity and strength. This will further lead to the conclusion that the maturity of the paving system will be a function of the lowest temperature seen in a slab, and not necessarily the temperature at mid-slab.

Using the maturity system, an effective QA/QC system can be developed wherein the pavement slab can be effectively monitored for gradients and strength across its depth. Methods to hasten the construction progress using real time data can be used effectively by the contractor to increase profits. Using multiple sensors also paves way for studies in modeling slab uplifts and taking measures to mitigate it. This is seen in the following section.

b) Construction Curl

For this study the data used was essentially the same as that obtained for the maturity study above. The temperature gradients such as those seen in **Figure 14** above were used to calculate slab uplift, using modeling software called ISLAB 2000. The software incorporated axle loading and loss of moisture conditions to find tensile stresses and fatigue limits in the concrete pavement. The findings and inferences that followed this exercise are discussed below.

Built-in curl is substantial for hot weather paving conditions, resulting in a temperature on the top that is 10-12 ^{0}C higher than the bottom surface, while a much smaller and opposite built-in curl (about -2^{0}C) was found for late fall paving conditions. Hot weather built-in curl is of the same magnitude as the daily temperature curl. This results in an unfavorable slab shape with permanent slab uplift at transverse joints and outer edges, and associated loss of slab support. Late fall construction, on the other hand, is favorable for permanent slab–base contact conditions as it reduces the slab uplift from daily temperature curl. The **figures 15 and 16** below (graphs) show the temperature difference (between top and bottom of slab) in pavement for summer and fall construction, the slab uplifts for different construction seasons and the tensile stresses in the pavement.

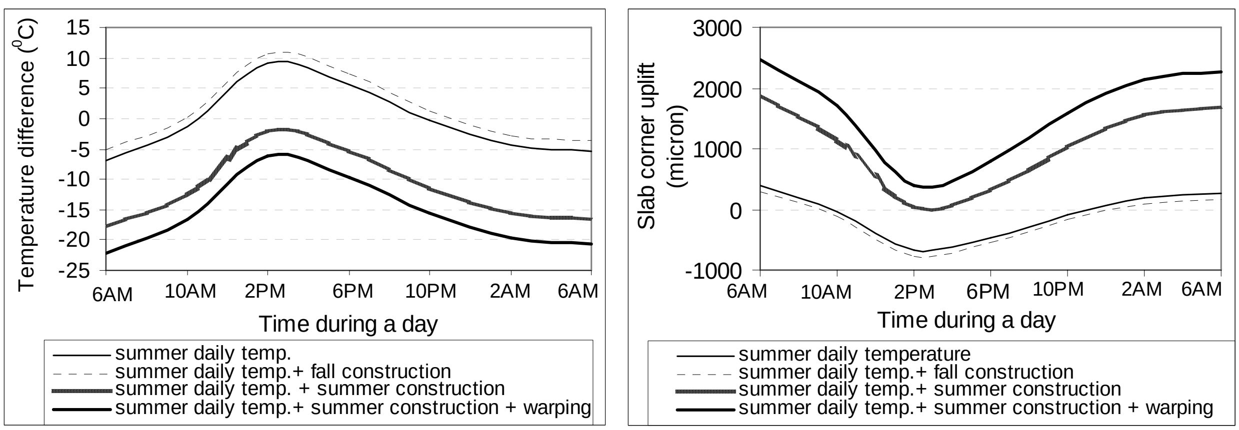


Figure 15: Temperature difference between top and bottom of slab during a typical summer day and slab corner uplifts during a typical summer day under the four climate loading cases (Hansen et al). Data from I-94 project (12.5 in. thick pavement).

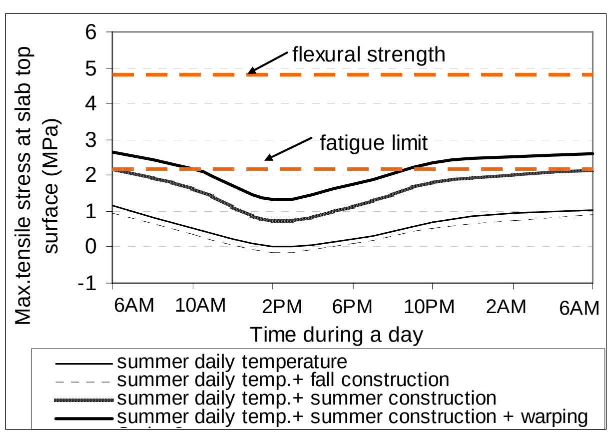


Figure 16: Tensile stresses at slab top surface under combined climate and truck loadings

Thus it was seen in **Figure 16** that the sum of daily temperature gradients, the built-in curl, and moisture warping can push the tensile strength at the top of the slab over the fatigue limit and cause premature cracking in the slab. **Figure 17** below shows an example of one such crack.

Figure 17: Photo showing Premature Cracking due to negative temperature gradients (University of Michigan, Ann Arbor)

Therefore what we see is that the data collected for maturity can be further expanded to model slab uplifts during pavement construction. With the availability of such modeling tools, the contractor can take effective steps in mitigating the formation of temperature gradients (and therefore construction curl)

6.7 Recommendations for Future Studies

Applications involving use of multiple sensors at a location and the advantages it accrues need to be further studied to arrive to a steadfast conclusion. Number of sensors and importance of sensor locations in large pours can be studied to optimize number of sensors used per cubic meter of concrete.

7. Potential Benefits and Opportunities on Similar Projects

The use of maturity meters in large pavement slabs will give an excellent indication of current strength of concrete. This will be a guideline to the contractor as to when to allow curing trucks or other heavy equipment on the early-age concrete pavement. This can decrease potential costs by cutting wait time to allow through traffic on the pavement. In addition, the use of multiple sensors will allow monitoring of gradients in early age concrete. This will enable the contractor to devise better curing strategies such as use of appropriate shrinkage-reducing admixtures or more intense curing methods. In any case, it does log a record of temperature gradient over time, which can be used both for QA/QC procedures and to ensure long term performance.

8. Summary and Conclusions

Experience from the Willow Island cooling tower incident shows that, in most cases, the rate of strength gain of the actual structure and the test cylinders were not the same. In the U.S., this resulted in studies being carried out on the maturity concept of concrete. The maturity concept, in practice for more than 50 years, is an established method of determining in-situ strength of concrete by monitoring internal temperature of concrete. Advances in microprocessor and wireless technologies over the last couple of decades have led to the development of Remote Frequency ID (RFID) smart tags. These tags can log, and wirelessly transmit, the temperature readings from within a concrete pour. These developments led to the joining of the maturity concept with the RFID technology to give us an efficient state-of-the-art system which can monitor temperature in concrete and calculate its in-place strength, all at the click of a button. The system consists of a combination of hardware, like handheld portables, loaded with IRD's Pocket Concrete software, and the RFID tags.

Two studies were carried out to monitor performance of this system in different field conditions. The first pilot project was the CVC parking structure in Ann Arbor, Michigan. This project used the system in construction of beams and slabs. The readings provided by the system indicated that the system reached its particular target strength of 3000 psi more than 24 hours earlier than that indicated by compression testing of field cured cylinders. The results generated by the maturity system conformed closely to the calculations carried out to monitor maturity by the ASTM C 1074. The difference in strengths was explained by the fact that the even the field-cured specimens gain strength at a different rate compared to the pour, due to largely different volumes. It was, however, concluded that the use of a maturity monitoring system on similar infrastructure projects in the future will greatly aid in accruing potential economic benefits, increasing the factor of safety on projects and providing a reliable quality control document.

The second project broadened the scope of application of the embedded wireless technology to applications besides maturity, namely monitoring and control of temperature gradients and eventual curling in concrete pavements. This study also shone the spotlight onto the fact that use of multiple sensors at a monitoring location may accrue more benefits from use of the technology than use of a single sensor alone. It will therefore be a better investment on part of the contractor to get more information out of the system, namely temperature gradients and maturity.

So, in general, it can be concluded that the use of maturity monitoring systems, depending on the applications, may have some of the following benefits:

- Data is available real time.
- Constantly monitoring the in-situ temperature.

- Temperature monitoring can continue for years.
- Data can be transferred, analyzed and archived.
- Documents proof of quality assurance.
- Eliminates concerns of weather problems.
- Eliminates concerns of construction problems.
- Real time data is available to identify a change.
- Optimizes time for form removal.
- Compressing the schedule can allow contractors to get paid sooner and reduce worker hours.
- Reduction of lane rental costs.
- Project timeline reduction to achieve bonus dollars.
- Post-tensioning tendons can be stressed sooner.

However, further studies to optimize use of maturity tags in field conditions should be undertaken. More research is also required to try and standardize parameters, such as relationships between strength development as logged by the system and compression testing of field cured cylinders.

9. References:

- Timothy Moore, Specifications and Project Data, CVC Parking Structure, PSI Inc. 2005.
- National Ready Mix Concrete Association (NRMCA) Publication (Concrete in Practice, CIP) Numbers:

  - CIP 10: Strength of In-Place Concrete
  - CIP 11: Curing In-Place Concrete
  - CIP 12: Hot Weather Concrete
  - CIP 27: Cold Weather Concrete
  - CIP 28: Effect of Moisture on Concrete.

- Springenschmid, R., Plannerer, M, Experimental Research on the Test Methods for Surface Cracking of Concrete, Institute for Building Materials, Technical University Munich, Germany, 2001.

- Hansen, W., Wei, Y., Smiley, D., Peng, Y. and Jensen, E.A., 'Effect of paving conditions on built-in curling and pavement performance', International Journal of Pavement Engineering, 2006, Accepted.

- Richard Yesh, Concrete 'Maturity Monitoring System', Presented at the Alpena College, Wake Inc. (manufacturers of the wireless maturity systems), 2005.

Appendices

Appendix 1: The Hardware and Software used as Maturity Monitoring System

Figure: The HP iPac used as the portable data collection device to measure concrete maturity (Wake Inc.)

Figure: The Unitech and LXE handheld portable computers that may be used with the i-Q32T Tags. (Wake Inc.)

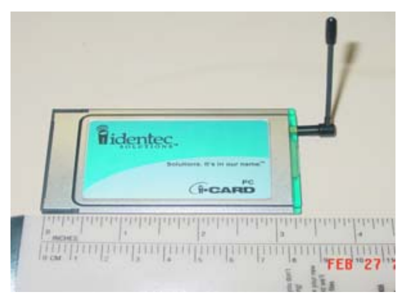


Figure: The i-Q32T tag/transponder and the PCMCIA card transceiver. (Wake Inc.)

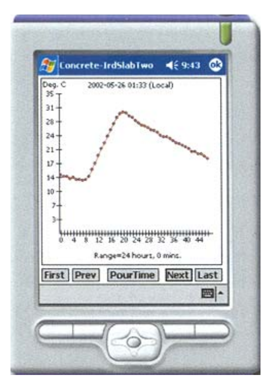
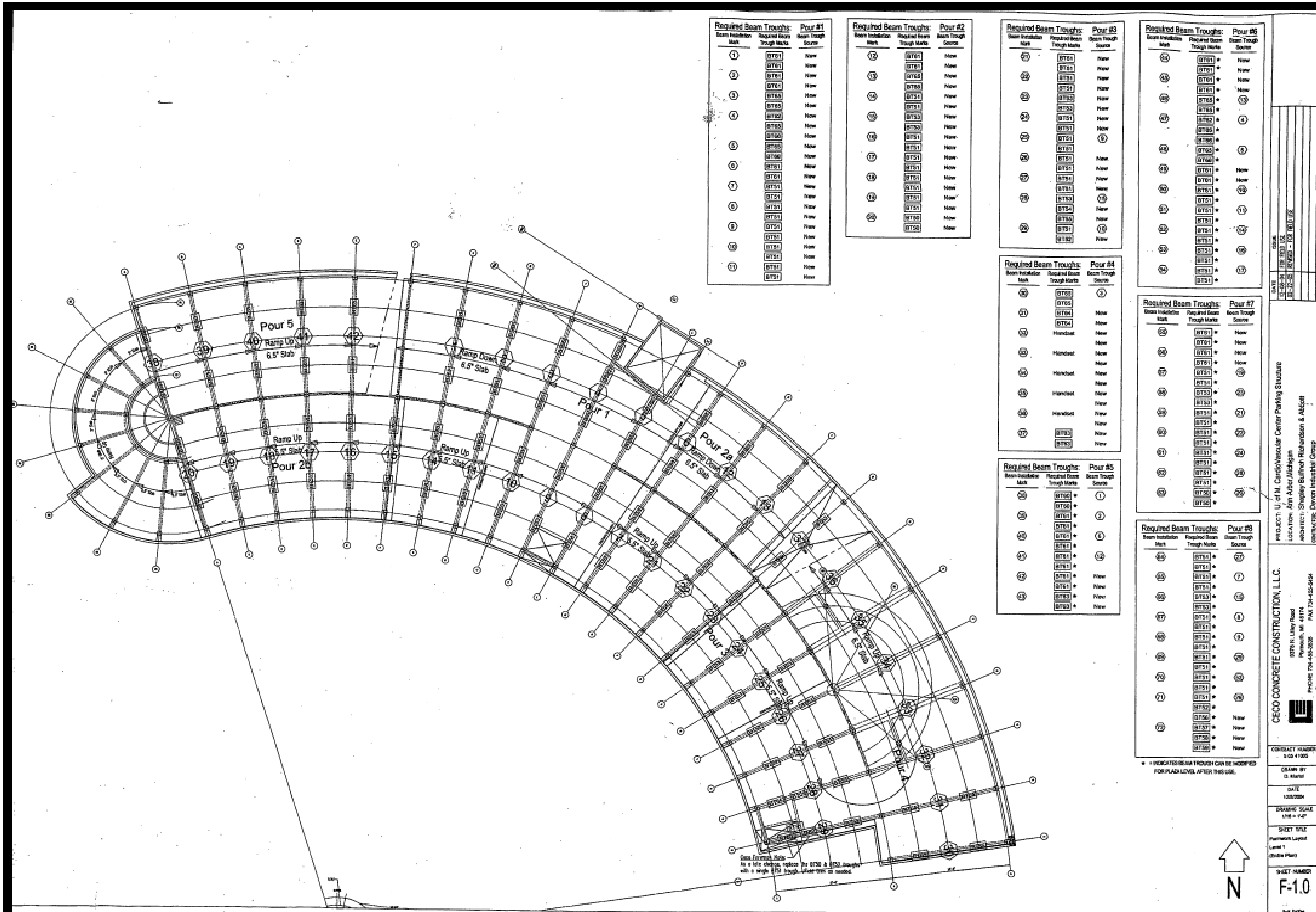
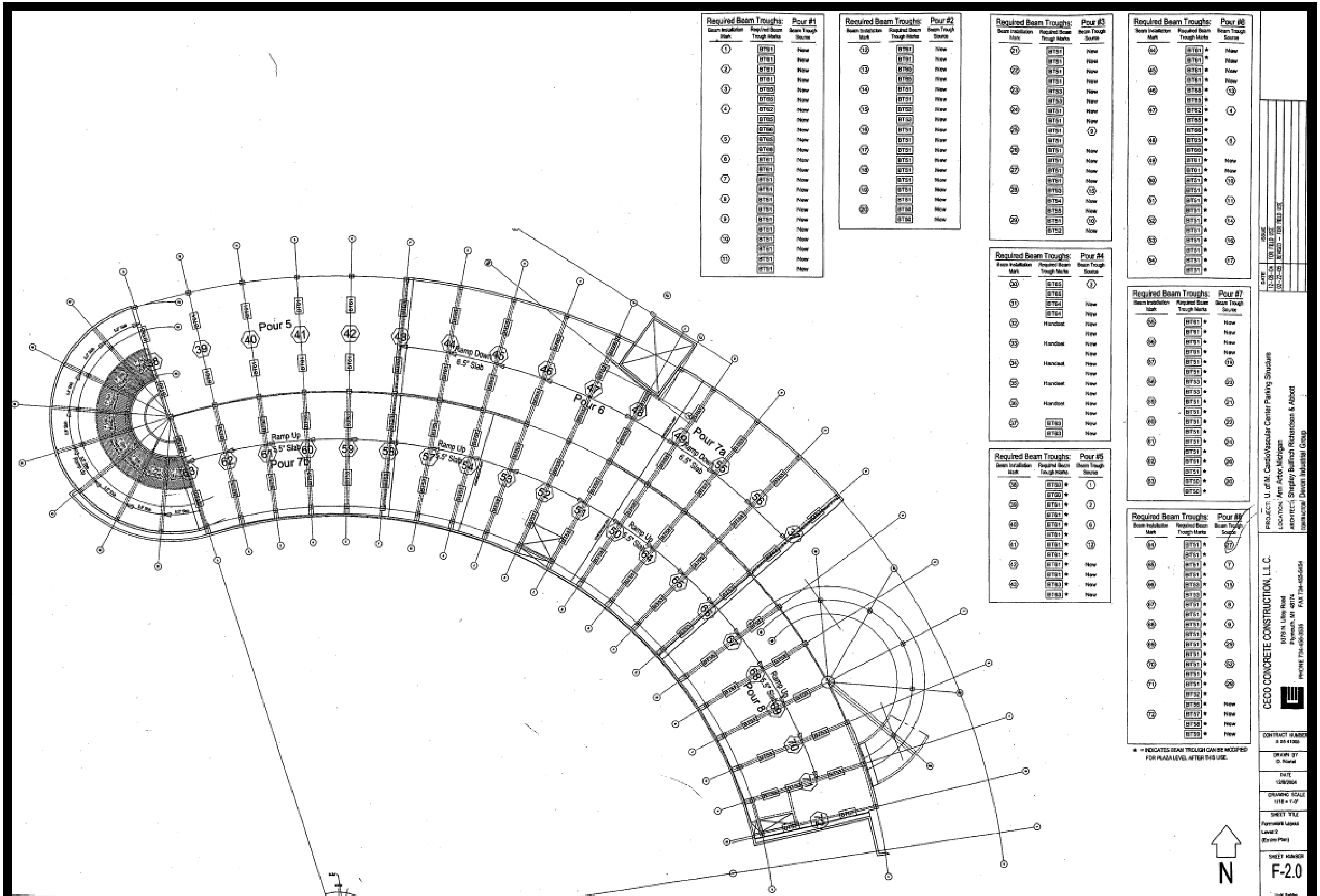


Figure: Screenshots of IRD's Pocket Concrete software. (Wake Inc.)

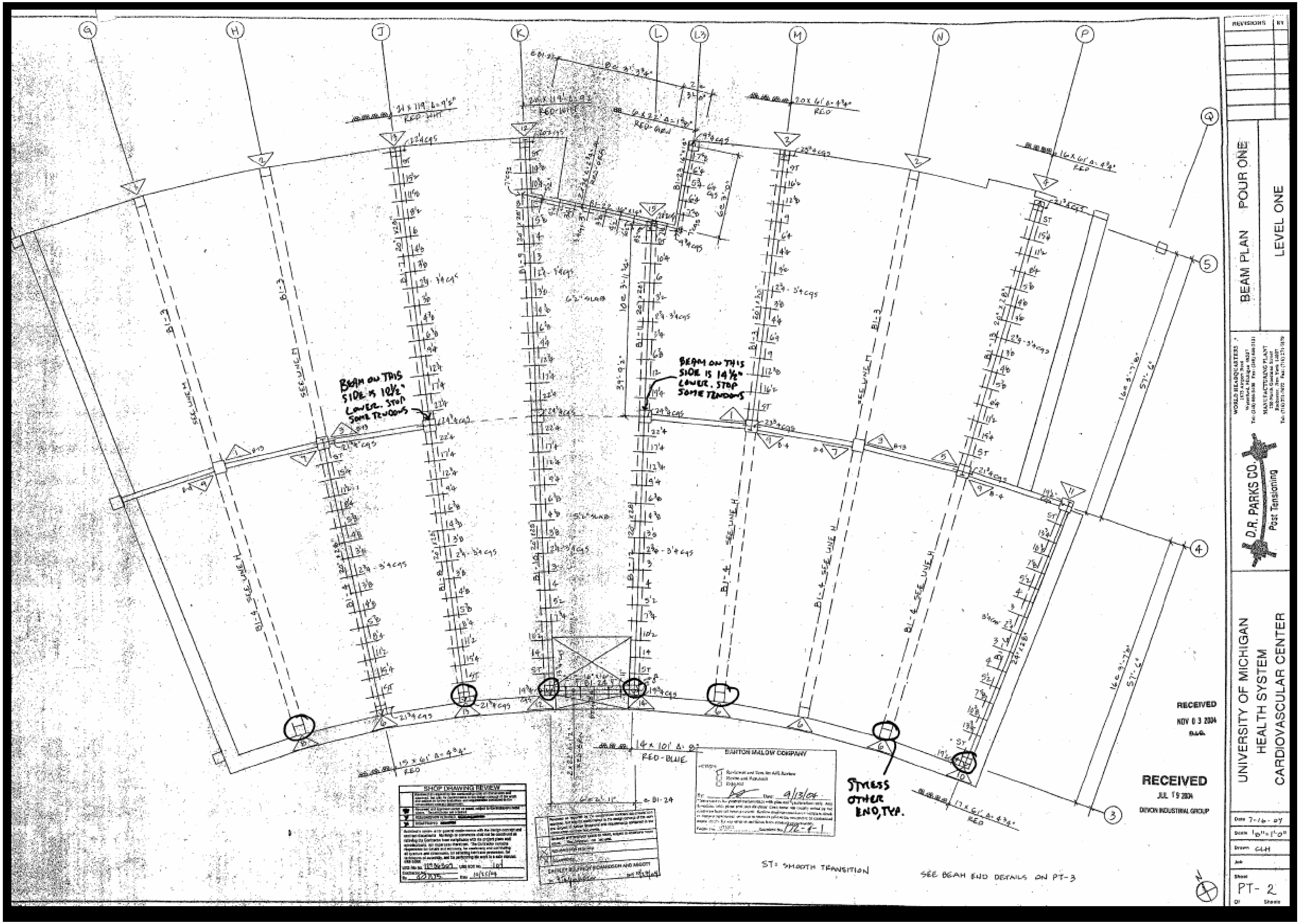
Appendix 2: Site Layouts for CVC Parking Structure – Pour Schematic



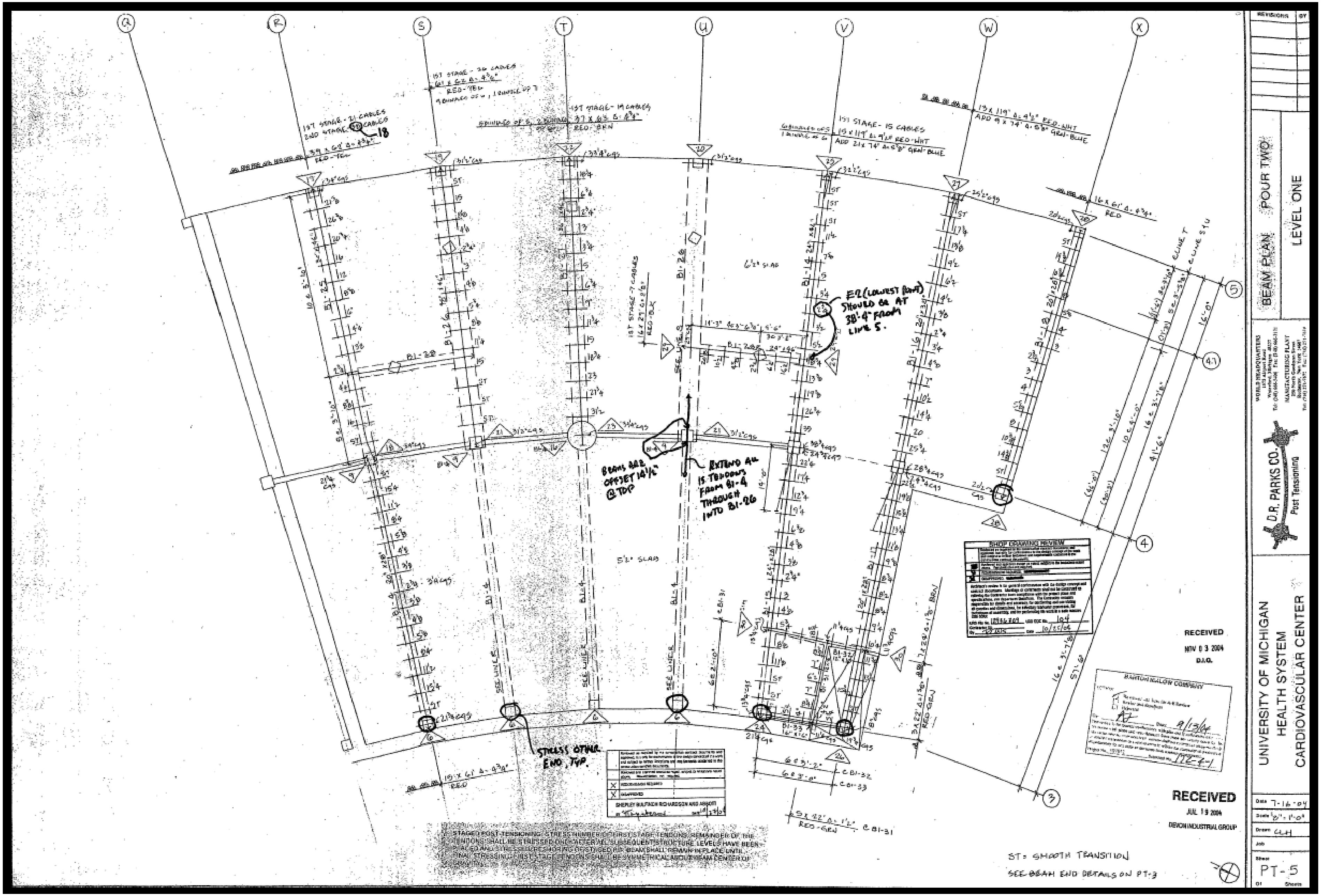
Appendix 2: Site Layouts for CVC Parking Structure – Pour Schematic



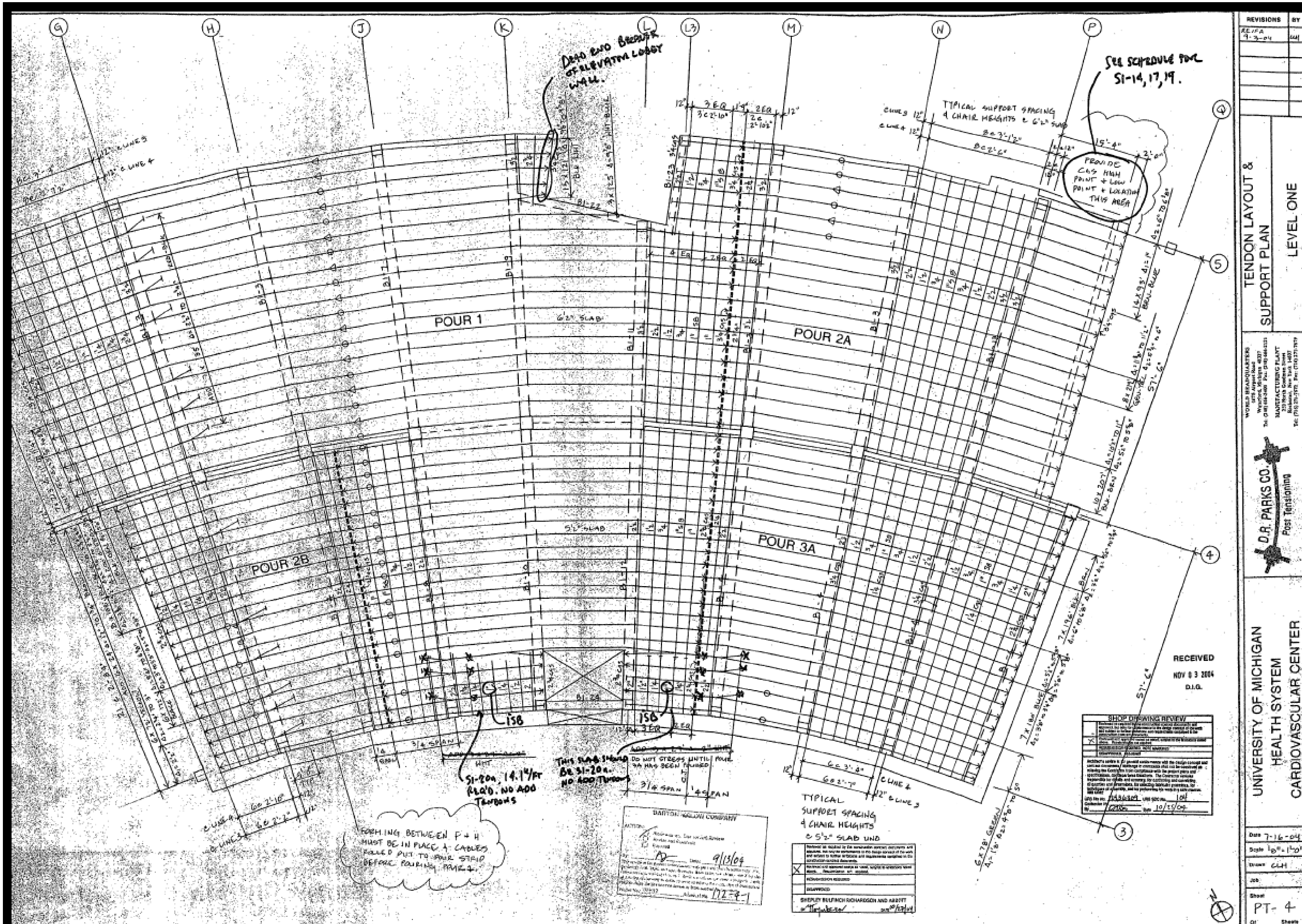
Appendix 2: Site Layouts for CVC Parking Structure – Pour 1



Appendix 2: Site Layouts for CVC Parking Structure- Pour 2



Appendix 2: Site Layouts for CVC Parking Structure – Layout of tendons



Appendix 3: Mix design and Concrete Usage Tables for CVC Parking garage (Timothy Moore, PSI Inc.)

The mix design prepared was for the Devon Industrial Group and was designed to be placed by pump for members Grade III Beams, Columns, and suspended Slab. The design was done for a 5000 psi concrete. The Mix Design is shown below

Material	Wt. LB/Cu. Yd. (Saturated and Surface Dry	Yield in Cu. Ft.
Cement, Type I, ASTM C 150	415	2.11
Ground Slag Grade 120, ASTM C 989	173	1.06
Fly Ash, Class C, ASTM C 618	103	0.63
Fine Aggregates, ASTM C 33	1081	6.66
Coarse Aggregates, ASTM C 33	1680	10.36
Water	276	4.43
Total Air	6.5 +/- 1.5	1.76
Total		27.00

Admixtures: High Range Water Reducer, ASTM C 494: 82.8 US oz.
Corrosion Inhibitor, Type C, ASTM C 494: 3.5 Gallons.
Air Entrainment ASTM C 260 : 6.9 US oz.

W/C Ratio: 0.40

Slump, in.: 3.0 max

Unit Wt pcf: 138.1

Specifications: 5000 psi ASTM C 33 (#57) (Limestone)

Mix Design Based on ACI 301.

Appendix 3: Mix design and Concrete Usage Tables for CVC Parking garage

Pour Data:

Pour Number	Pour Date	Concrete Volume (YD 3)	Concrete Strength (PSI)
1	4/8/2005	325	6067
2 a, b, & c	4/21/2005	369	6725
3	5/3/2005	190	5657
4	5/21/2005	484	6878
5	5/31/2005	210	6318
6	6/21/2005	440	6359
7 a, b, & c	6/29/2005	230	6736
8 a & b	7/18/2005	320	7040
9	8/19/2005	645	6420

Appendix 4: Data and Calculation Sheet Generated by IRD Software

(Ref: PSI Inc.)

IRD Concrete MaturityMeter: Concrete Report

Time/Date of Report 7/12/2005 13:56

Tag Id: 0.200.66.111
Tag Location: a.1-3.5

Concrete Summary:

Chronological Age:	2.14	Days
TTF:	2277.3	Deg.C-Hrs
TTF datum temp.	-10	Deg.C
Current Strength:	3822	psi
Pour Time:	6/29/2005 9:00	Local

Temperature Log Summary:

Logging Interval	30	Minutes
Start Time	6/29/2005 9:00	Local
End Time	7/1/2005 12:21	Local
Sample Count	104	
Average Temperature	93.66	Degree F.
Highest Temperature	122.45	Degree F.
Lowest Temperature	76.1	Degree F.

Temperature Log Data:

TagTemperature Degree F.	Time Local	TTF Deg.C-Hrs	Strength psi	Time
83.8	6/29/2005 9:10	6.6	0	0.5
86.9	6/29/2005 9:40	26.4	0	1
87.3	6/29/2005 10:10	46.7	0	1.5
88.3	6/29/2005 10:40	67.2	0	2
89.6	6/29/2005 11:10	88	0	2.5
91.4	6/29/2005 11:40	109.3	0	3
92.3	6/29/2005 12:10	130.9	94	3.5
94.6	6/29/2005 12:40	153	282	4
97.3	6/29/2005 13:10	175.7	464	4.5
100.4	6/29/2005 13:40	199.3	628	5
108.9	6/29/2005 14:10	224.5	785	5.5
112.5	6/29/2005 14:40	251.4	934	6
113.9	6/29/2005 15:10	278.9	1072	6.5
114.8	6/29/2005 15:40	306.8	1197	7
116.2	6/29/2005 16:10	335	1313	7.5
118.4	6/29/2005 16:40	363.7	1421	8
120.2	6/29/2005 17:10	392.9	1523	8.5
121.5	6/29/2005 17:40	422.6	1619	9
122.4	6/29/2005 18:10	452.6	1709	9.5
120.6	6/29/2005 18:40	482.5	1793	10
118.4	6/29/2005 19:10	511.8	1870	10.5
117	6/29/2005 19:40	540.6	1942	11
115.3	6/29/2005 20:10	569	2009	11.5
114.3	6/29/2005 20:40	597	2072	12
113.4	6/29/2005 21:10	624.7	2132	12.5

Appendix 4: Data and Calculation Sheet Generated by IRD Software

(Ref: PSI Inc.)

112.5	6/29/2005 21:40	652.2	2188	13
111.7	6/29/2005 22:10	679.5	2242	13.5
110.3	6/29/2005 22:40	706.4	2293	14
108.9	6/29/2005 23:10	733	2342	14.5
108	6/29/2005 23:40	759.2	2388	15
107.2	6/30/2005 0:10	785.2	2432	15.5
106.7	6/30/2005 0:40	811	2475	16
105.3	6/30/2005 1:10	836.6	2515	16.5
104.4	6/30/2005 1:40	861.9	2554	17
103.5	6/30/2005 2:10	886.9	2592	17.5
102.7	6/30/2005 2:40	911.6	2628	18
101.8	6/30/2005 3:10	936.1	2663	18.5
100.4	6/30/2005 3:40	960.3	2697	19
99.5	6/30/2005 4:10	984.2	2729	19.5
98.2	6/30/2005 4:40	1007.7	2760	20
97.3	6/30/2005 5:10	1031	2790	20.5
96.3	6/30/2005 5:40	1054	2819	21
95.4	6/30/2005 6:10	1076.7	2847	21.5
95	6/30/2005 6:40	1099.3	2874	22
94.1	6/30/2005 7:10	1121.7	2900	22.5
93.2	6/30/2005 7:40	1143.8	2926	23
92.8	6/30/2005 8:10	1165.7	2951	23.5
92.3	6/30/2005 8:40	1187.5	2975	24
92.3	6/30/2005 9:10	1209.3	2999	24.5
92.8	6/30/2005 9:40	1231.1	3023	25
93.2	6/30/2005 10:10	1253.1	3046	25.5
94.1	6/30/2005 10:40	1275.2	3069	26
95	6/30/2005 11:10	1297.6	3092	26.5
93.6	6/30/2005 11:40	1319.9	3114	27
90.5	6/30/2005 12:10	1341.6	3136	27.5
89.1	6/30/2005 12:40	1362.7	3156	28
88.3	6/30/2005 13:10	1383.4	3176	28.5
86.9	6/30/2005 13:40	1403.9	3195	29
86	6/30/2005 14:10	1424	3214	29.5
85.6	6/30/2005 14:40	1443.9	3232	30
85.6	6/30/2005 15:10	1463.8	3250	30.5
86.4	6/30/2005 15:40	1483.8	3268	31
86.9	6/30/2005 16:10	1504	3286	31.5
87.8	6/30/2005 16:40	1524.4	3303	32
89.1	6/30/2005 17:10	1545	3321	32.5
89.6	6/30/2005 17:40	1566	3339	33
90.1	6/30/2005 18:10	1587	3356	33.5
90.1	6/30/2005 18:40	1608.2	3373	34
90.1	6/30/2005 19:10	1629.3	3391	34.5
89.1	6/30/2005 19:40	1650.3	3407	35
88.7	6/30/2005 20:10	1671.1	3424	35.5
88.3	6/30/2005 20:40	1691.8	3440	36
87.3	6/30/2005 21:10	1712.3	3456	36.5
87.3	6/30/2005 21:40	1732.7	3471	37
86.4	6/30/2005 22:10	1752.9	3487	37.5
85.6	6/30/2005 22:40	1772.9	3502	38
84.6	6/30/2005 23:10	1792.7	3516	38.5

Appendix 4: Data and Calculation Sheet Generated by IRD Software

(Ref: PSI Inc.)

84.2	6/30/2005 23:40	1812.2	3504	39
83.8	7/1/2005 0:10	1831.7	3518	39.5
82.8	7/1/2005 0:40	1850.9	3532	40
82.4	7/1/2005 1:10	1870	3546	40.5
81.9	7/1/2005 1:40	1888.9	3560	41
81.5	7/1/2005 2:10	1907.7	3574	41.5
81.1	7/1/2005 2:40	1926.4	3588	42
80.6	7/1/2005 3:10	1945	3602	42.5
80.1	7/1/2005 3:40	1963.4	3616	43
79.3	7/1/2005 4:10	1981.7	3629	43.5
79.3	7/1/2005 4:40	1999.8	3642	44
78.8	7/1/2005 5:10	2017.9	3656	44.5
78.3	7/1/2005 5:40	2035.8	3669	45
77.9	7/1/2005 6:10	2053.6	3682	45.5
77	7/1/2005 6:40	2071.2	3695	46
76.6	7/1/2005 7:10	2088.7	3708	46.5
76.6	7/1/2005 7:40	2106	3721	47
76.6	7/1/2005 7:51	2112.3	3726	47.5
76.1	7/1/2005 8:21	2129.6	3738	48
77	7/1/2005 8:51	2147	3751	48.5
77.4	7/1/2005 9:21	2164.6	3763	49
78.8	7/1/2005 9:51	2182.4	3773	49.5
80.1	7/1/2005 10:21	2200.6	3782	50
81.5	7/1/2005 10:51	2219.1	3792	50.5
82.8	7/1/2005 11:21	2238.1	3802	51
84.6	7/1/2005 11:51	2257.4	3812	51.5
86	7/1/2005 12:21	2277.3	3822	52

Concrete Strength Compression Tests:

Concrete Type: Tag 204 2-11-05

User Entered Compression Test Results:

TTF Deg.C-Hrs	Strength psi
617	2475
2110	3285
4880	4850
9881	5495
19753	6905
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0

Appendix 4: Data and Calculation Sheet Generated by IRD Software

(Ref: PSI Inc.)

0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0

Plowman's Formula for curve fitted to user user entered data:

S = A + B log(M)

where S is strength in Mpa
where A is strength in Mpa at Day1
where B is slope of the strength gain
where M is maturity of the concrete in TTF (Nurse-Saul)

Value for A: 16
Value for B: 20.8

Concrete Strength Prediction Data:

Daily Strength Data (may have been manually edited):

TTF DegC-Days	EA days	Strength psi
720	1	2318
1440	2	3229
2160	3	3761
2880	4	4139
3600	5	4432
4320	6	4671
5040	7	4873
5760	8	5049
6480	9	5203
7200	10	5342
7920	11	5467
8640	12	5581
9360	13	5686
10080	14	5784
10800	15	5874
11520	16	5959
12240	17	6039
12960	18	6114
13680	19	6185
14400	20	6252
15120	21	6316
15840	22	6377
16560	23	6435
17280	24	6491
18000	25	6545
18720	26	6596
19440	27	6646
20160	28	6646

Appendix 4: Data and Calculation Sheet Generated by IRD Software

(Ref: PSI Inc.)

HourlyStrength Data (mayhave been manuallyedited):

TTF DegC-Days	EA days	Strength psi
30	0.04	0
60	0.08	0
90	0.13	0
120	0.17	0
150	0.21	259
180	0.25	498
210	0.29	700
240	0.33	876
270	0.38	1030
300	0.42	1169
330	0.46	1294
360	0.5	1408
390	0.54	1513
420	0.58	1611
450	0.63	1701
480	0.67	1786
510	0.71	1866
540	0.75	1941
570	0.79	2012
600	0.83	2079
630	0.88	2143
660	0.92	2204
690	0.96	2262
720	1	2318
750	1.04	2372
780	1.08	2423
810	1.13	2473
840	1.17	2521
870	1.21	2567
900	1.25	2611
930	1.29	2654
960	1.33	2696
990	1.38	2737
1020	1.42	2776
1050	1.46	2814
1080	1.5	2851
1110	1.54	2887
1140	1.58	2922
1170	1.63	2956
1200	1.67	2989
1230	1.71	3022
1260	1.75	3053
1290	1.79	3084
1320	1.83	3114
1350	1.88	3144
1380	1.92	3173
1410	1.96	3201

Appendix 4: Data and Calculation Sheet Generated by IRD Software

(Ref: PSI Inc.)

1440	2	3229
1470	2.04	3256
1500	2.08	3282
1530	2.13	3308
1560	2.17	3334
1590	2.21	3359
1620	2.25	3383
1650	2.29	3407
1680	2.33	3431
1710	2.38	3454
1740	2.42	3477
1770	2.46	3499
1800	2.5	3522