University of Alberta

Field Study of Concrete Maturity Method in Very Cold Weather

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the

requirements for the degree of *Master of Science*

in

Construction Engineering and Management

Department of *Civil and Environmental Engineering*

Edmonton, Alberta

Spring 2006

Your file Votre référence
ISBN: 0-494-13785-1
Our file Notre référence
ISBN: 0-494-13785-1

Dedication

To my parents Mohammad and Ozra and my brothers Omid and Afshin, for their incredible support, love and enthusiasm

Abstract

The objective of this study was to assess the reliability and potential benefit of using the concrete maturity method in very cold weather. This report reviews the concrete maturity method, describes the technology, explains field observations, and discusses potential benefits of using concrete maturity method and technology in very cold climates.

The concrete maturity method is based on the idea that concrete strength development is strongly correlated with the curing temperature history. Findings from a case study in application of maturity method indicated significant potential reduction in project schedule. The study results indicated that the concrete maturity methodology enables better quality control through the accurate estimation of in-place concrete strength. In addition, the real time information available through the concrete maturity method allowed the project manager to be proactive in managing heating and protection to ensure that the proper level of concrete strength was developed.

Acknowledgements

The work described in this report would not have been possible without the contributions of a number of organizations and individuals. The author would like to thank Dr. Hyoungkwan Kim, my supervisor, and Dr. Hamid Soleymani from the University of Alberta, Mr. Scott Hounsell and Mr. Michael King from Fluor Corporation and Mr. Charles R. Wood from FIATECH for their support and expertise throughout this project. The author would also like to thank Imperial Oil, to allow conducting the pilot study, during the foundation construction phase of their ULSD project at the Strathcona Refinery, in Edmonton, Alberta, Canada. I would like to thank BIRD Construction, the project's foundation sub-contractor, for their assistance and co-operation during the field study. I am also grateful to Mr. Mike Fox and Mr. Jim O'Daniel at Engius for providing the technology and technical expertise to this study.

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List of Symbols, Nomenclature, or Abbreviations

M (t): The temperature-time factor at age *t*, degree-days or degree hours

Δt: A time interval, days or hours

T_a: Average concrete temperature during the time interval, Δt, ^oC

T_0: Datum temperature, ^oC

t_e: Equivalent age at a specified temperature T_s, days or hours

E: Apparent activation energy, J/mol

R: Universal gas constant, 8.314 J/mol-K

T_s: Specified temperature, K

CSA: Canadian Standard Association

ASTM: American Society of Testing and Materials

ACI: American Concrete Institute

USB: Universal Serial Bus

CSV: Comma Separated Values

SEC: Secret Key Ring File

ULSD: Ultra-Low Sulphur Diesel

1.0 Introduction

1.1 Cold weather concreting and the concrete maturity method

American Concrete Institute (ACI 306R-88) defines cold weather concrete curing as "*A period when more than three successive days the mean daily temperature drops below 4°C*". Concreting in temperatures below 5°C requires precautionary procedures to prevent the concrete from freezing. Freezing temperatures in the concrete mix can reduce its strength to about 50% of the required strength (Kosmatka et al. 2002). Major impacts of freezing and thawing are deformation and cracking in concrete. According to the Canadian Standard Association (CSA) A23.1, it is critical to have temperatures above 5°C to prevent major damages to concrete, especially in the first 24 hours after pouring. Concrete that has been frozen once in the early stages will not be sufficiently watertight and will not gain the same strength as concrete that has not been frozen. In order to reduce these effects, enclosures, insulations, and heaters are widely used to prevent freezing damages and to ensure the quality of concrete in cold weather. (Kosmatka et al. 2002)

In cold weather, it is critical to control the temperature of the concrete to obtain its required strength. To measure the developed strength and ensure the quality of the concrete, cylinder or cube specimens are normally used for testing. Traditionally, the specimen's testing data is used to determine the removal time of forms, enclosures, and heaters. A major problem with using the specimens casting method for cold weather concreting is that the specimens are cured in environments significantly different from the actual in-situ environment. Different curing conditions for the testing specimens make it difficult to accurately measure the actual strength of the in-situ concrete. This indicates a strong need to use new techniques to better understand the strength development of in-situ concrete.

The concrete maturity technique is a relatively reliable methodology for evaluating the strength gain of concrete. It was first proposed in England in late 1940's and early 1950's (McIntosh 1949, Nurse 1949, Saul 1951). This method relies on the idea that concrete strength development is strongly correlated with the concrete temperature history. New technologies provide sensors which can be placed in concrete and record the temperature of the concrete for the duration of curing. These sensors (loggers) measure the temperature of the concrete and employ the maturity concept to evaluate the concrete strength.

1.2 Potential benefits of the concrete maturity method for cold weather construction

The use of the maturity method for cold weather concreting provides valuable information as to when the formwork and the heating and hoarding systems can be removed. The possibility for early removal of formwork, heating, and hoarding shows a significant potential for time and cost savings from an overall project perspective. Furthermore, this technique can improve the concrete quality control process, since precautionary actions can be taken when insufficient strength is estimated.

1.3 Report objectives

The objectives of this report are to:

- Provide designers and contractors with a background and current technology of the concrete maturity method.
- Document and illustrate the detailed procedure for implementing the concrete maturity method in a cold weather environment.
- Discuss the capabilities and limitations of the concrete maturity method for a cold weather industrial construction project.
- Determine the reliability of concrete maturity technology to predict, on a continuous (on-demand) basis, the strength of concrete in cold weather.
- Make a general assessment of the potential economic benefits of using the concrete maturity method in cold weather.

This report includes a description of the concrete maturity method in construction (section 2), a description of the study implementation in an industrial project (section 3), results and analysis from the pilot implementation (section 4), datum temperature sensitivity analysis (section 5) and conclusions (section 6).

2.0 Description of the concrete maturity method

2.1 Concrete maturity methodology

The concrete maturity technique is an alternative strength evaluation methodology which uses the temperature of the concrete to estimate strength development. The rationale behind the maturity technique is that there is a correlation between the strength of the concrete and its temperature in the early stages after pouring (Rasmussen et al. 2004). Because the temperature of concrete is recorded in short time intervals, the maturity technique provides a detailed early age concrete temperature history, which can be used to protect the concrete against damaging temperature fluctuations (Tepke et al. 2004). This feature of the technique also allows for continuous monitoring of concrete strength development during the curing.

In order to apply the concrete maturity technique, the strength-maturity relationship should be identified, the thermal profile of the concrete component should be determined, and finally, the strength-maturity correlation needs to be validated. The following sections provide more details regarding this process.

2.1.1 The strength – maturity relationship

According to ASTM C1074 (Standard Practice for Estimating Concrete Strength by the Maturity Method), the relationship between the concrete temperature and maturity index, which is also called the temperature-time factor, can be calculated using the following relationship:

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

Where:

M (t) = the temperature-time factor at age *t*, degree-days or degree-hours

Δt = a time interval, days or hours

T_a = average concrete temperature during the time interval, Δt, °C

T_0 = datum temperature, °C

The datum temperature (T_0) in Equation (2-1) is defined as the lowest temperature above which concrete can develop its strength. The value for the datum temperature for Equation (2-1) is calculated by using the methodology provided in ASTM C1074. As illustrated in Figure 2.1, inaccurate values for datum temperature (T_0) result in wrong estimation of concrete strength.

For equation (2-1) Saul defined the principal of concrete maturity as "*Concrete of the same mix at the same maturity has approximately the same strength whatever combination of temperature and age goes to make up the maturity.*" (Saul 1951)

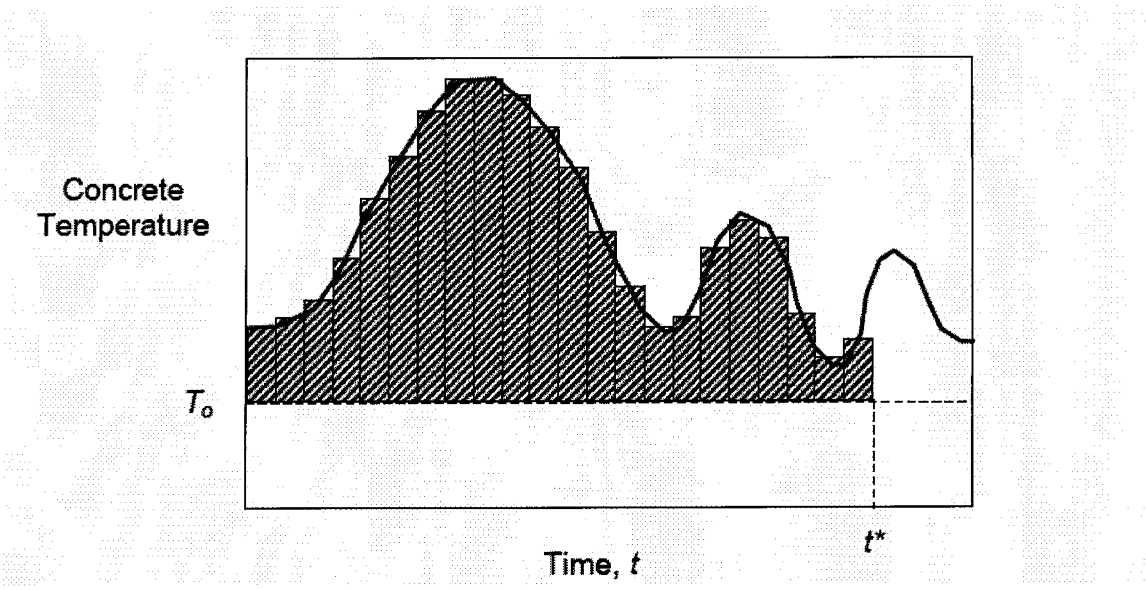

Figure 2.1 Schematic of temperature time-factor and temperature history based on equation (2-1) (Carino 1991)

Equation (2-1) assumes that at the early ages of curing, concrete strength has a linear relationship with temperature. In addition, Carino (2001) represented that a particular concrete mixture, does not acquire same strength-maturity relationship in different curing temperatures. This behavior named "Cross over" states that "For equal values of the maturity index, specimens with higher early-age temperatures resulted in higher initial strengths and lower long-term strength". So, concrete with low early-age temperature gains lower strength in early ages and higher strength in later ages and high early age concrete temperature results in higher strength in early age and lower strength in later ages.

In 2005, Abdel-Jawad improved Saul equation to reflect the effect of early-age concrete curing temperature on later-age strength (beyond seven days). He represented a methodology to incorporate the effect of water-cement (w/c) ratio and curing temperature on the concrete strength in later ages. Even though these modifications improved the result of concrete strength calculation, the calculated strength value is not independent from datum temperature. As a result equation (2-1) is unable to incorporate temperature effects as the concrete strength develops.

Therefore, Arrhenius function, Equation (2-2), has been proposed to calculate the equivalent age at a particular temperature, based on the rate of the chemical reaction in the concrete (Carino et al. 2001)

$$t_e = \sum e^{-\frac{E}{R}\left(\frac{1}{T_a} - \frac{1}{T_s}\right)} \Delta t \qquad (2\text{-}2)$$

Where:

t_e = equivalent age at a specified temperature T_s, days or hours

E = apparent activation energy, J/mol

R = universal gas constant, 8.314 J/mol-K

T_a = average temperature of concrete during the time interval Δt, K

T_s = specified temperature, K

Δt = a time interval, days or hours

In Equation (2-2), it is assumed that the specified temperature (T_s) is 23 °C, and the value for apparent activation energy (E) provided in ASTM C1074 is equal to 41500 J/mol.

In this methodology, Arrhenius equation properly calculates the temperature effect of the concrete strength for the first 14 days, but overestimates the concrete strength for ages after 14 days or approximately 40% of the 28 day strength. (Kim et al. 2001)

Several different types of temperature sensing devices are currently available in the form of microprocessor-embedded data loggers. These loggers are placed in concrete and left there to record the internal temperature of the concrete during the curing. In order to develop the strength–maturity relationship for a particular concrete mixture, 20 cylinder specimens from the concrete mixture are normally cast: 18 specimens without data loggers and the remaining two specimens with data loggers embedded inside them (Figure 2.2). For the first day of curing, the 20 specimens can be located in the construction site to make sure that their curing pattern matches that of the in-place concrete. However, the specimens are normally cured in standard moist curing laboratory conditions. Typically, at the curing ages of 1, 2, 5, 7, 14, and 28 days, three specimens are tested to obtain their average compressive strength. At the time of each compressive testing, information taken from the two specimens with data loggers is used to calculate the average temperature-time factor (maturity index) for that mix design. In this way, for each curing age, the compressive strength can find its corresponding temperature-time factor. Subsequently, the strength–maturity curve can be established through regression analysis. An example of strength–maturity curve is shown in Figure 2.3.

2.1.2 In-place strength measurement

To estimate the strength of concrete during curing, maturity sensors (data loggers) are placed in concrete members that the strength development needs to be estimated during construction. Data loggers are typically tied to reinforcing bars before the concrete is poured. These data loggers then record the thermal profile of the placed concrete. This thermal profile can be converted to the strength estimation using the strength-maturity relationship, Equation (2-1) or (2-2).

Figure 2.2 Cylinder specimens with embedded loggers

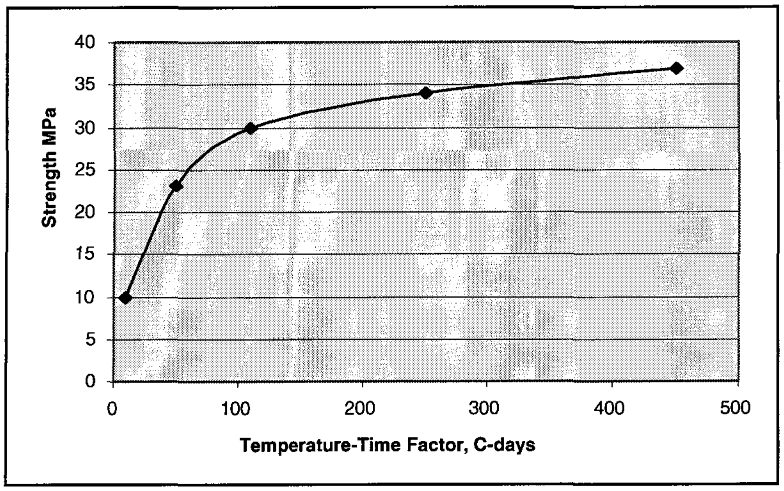

Figure 2.3 Example of strength – maturity curve

2.1.3 The strength-maturity relationship validation

The concrete maturity technique relies solely on the thermal profile of the concrete. However, there is no guarantee that the in-place concrete has the intended design specifications with the same thermal profile as the strength–maturity curve identified. Thus, there has to be a thorough validation process to ensure accurate estimation of the concrete strength. ASTM C1074 provides a comprehensive procedure to verify the accuracy of maturity technique in different situations. According to ASTM C1074, major factors for an accurate concrete strength estimate based on the maturity technique are:

1. Suitability of the selected maturity relationship for the concrete mixture.
2. Ability to verify the thermal profile, especially for the early-ages of the concrete mixture.
3. Verification of the mixture in accordance with design specifications.

2.2 Description of the concrete maturity system

In this pilot study, the *intelli*Rock system (produced by Engius) was used to deploy the concrete maturity methodology on different concrete structural members. This system includes the necessary hardware and software to use the maturity technique according to ASTM C1074. Three main components of the *intelli*Rock system are loggers, readers, and software.

Loggers:

Loggers are sensors which include memory, a battery, a temperature sensor, a micro computer, and a clock, all covered in a robust casing (Figure 2.4). These in-place sensors should be activated at the time of concrete placement through the use of a handheld reader. Two main categories of data loggers (MAT-02 and MAR-02) were used for this study. Both categories of loggers are useful to process real-time temperature data. The detailed specifications of these two loggers are shown in Table 2.1.

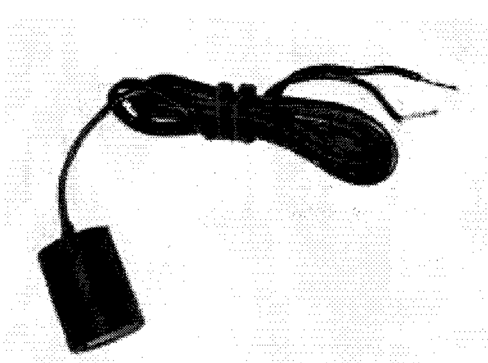

Figure 2.4 Data Logger

Readers:

Readers are used to download the recorded data from loggers and transfer it to computer application software. Since loggers include memory and a battery, it is not necessary to have loggers and readers connected all the time. With handheld readers, users can download the data at virtually any time and transfer the information to application software.

Figure 2.5 Reader

Software:

The *intelli*Rock system includes software to download the data from the reader to a personal computer through a USB port. Data will be stored in text (CSV) or secure format (SEC), which can be analyzed using Microsoft Excel for the development of the strength-maturity index graph for a specific design mix.

Table 2.1 Specifications of intelliRock data loggers

intelliRockll Logger Specifications		
Criteria	**MAT-02 Concrete Maturity Logger Specifications**	**MAR-02, Concrete Maturity Logger Specifications**
Temperature Accuracy	+/- 1°C(-20 to 80°C) +/- 2°C(80 to 99°C)	+/- 1°C(-20 to 80°C) +/- 2°C(80 to 99°C)
Temperature Resolution	+/- 1°C(-20 to 80°C) +/- 2°C(80 to 99°C)	+/- 1°C(-20 to 80°C) +/- 2°C(80 to 99°C)
Maturity Integration Period	1 minute	1 minute
Maturity Technique	ASTM C 1074 (Nurse-Saul Method)	Improved Arrhenius™
Logging Interval	Standard: 1 Hour Other Configuration Available	Standard: 1 Hour Other Configuration Available
Logging Duration	Standard: 28 Days Other Configuration Available	Standard: 28 Days Other Configuration Available
Additional Data Stored	Min/Max temperature User entered job and location names, notes, and events.	Min/Max temperature User entered job and location names, notes, and events.
Logger Dimensions	1-1/2 in. x 1-1/8 in. diameter	1-1/2 in. x 1-1/8 in. diameter
Standard Cable Lengths (Ft)	4, 8, 15, 30, 50, 100	4, 8, 15, 30, 50, 100
Wire	18 gauge	18 gauge
Recommended Max Storage/Operating Temperature	85°C (185°F)	85°C (185°F)
Max Logging Temperature Range	-20°C to 99°C (-4°F to 210°F)*	-20°C to 99°C (-4°F to 210°F)*
Absolute Max Storage/Operating Temperature	125°C (257°F)*	125°C (257°F)*
Logging Battery Life	1 year (estimated)	1 year (estimated)
Battery Shelf Life	5 years	5 years

* Performance not guaranteed above 80°C

2.3 Previous implementations and case studies

2.3.1 Amgen Opus Program Project - Puerto Rico

The concrete work of this 300,000 square foot project included concrete placement and prefabricated concrete panels for the new facility. The maturity technique had been implemented with sacrificial loggers during the two month duration of the main concrete work.

After developing a maturity method process, loggers were placed in selected concrete components to develop a thermal data profile for each concrete. This information was analyzed to obtain the concrete maturity graph for concrete placements and compare the concrete maturity technique with the traditional cylinder specimens' methodology.

The results of this pilot study confirmed that using the maturity technique helped the contractor to have a continuous quality assessment for concrete and be able to determine the right time to remove the formwork, allow live loads, and save a few working days for each concrete component (Goodrum et al. 2004).

2.3.2 Marriott Courtyard Project – Oklahoma

This 225-room hotel is located in downtown Oklahoma City. Estimated at $20 million, this project needed 7400 cubic yards of concrete mix with 5000 psi performance strength in 28 days. In order to estimate the in-place concrete temperatures, the concrete maturity methodology was implemented. The main result of applying the maturity technique in this project was faster concrete construction compared to the traditional cylinder specimens test. Another benefit was the possibility of stressing post-tension cables for elevated decks at 60% of design strength. Therefore, post tensioning was done at the right time with minimum risk for crack development or compressive strength failure.

In this project, most of the concrete pouring for the decks was conducted during winter. Using maturity sensors, it was possible for the project crew to check the temperature of the concrete on a regular basis and take precautionary actions to avoid freezing in the concrete or wasting energy by overheating the deck area. In addition, the maturity technique showed its capabilities for quality assurance of the concrete and the overall project workflow was reduced at least one day per concrete pour (Engius 2004a).

2.3.3 Memorial Stadium - The University of Oklahoma

In 2002, a project was started to add 8000 seats to the University of Oklahoma's Memorial Stadium at an estimated cost of $52 million. The duration of the project was 18 months. For this project, a total of 168 columns and 18,000 cubic yards of concrete were needed to construct the new decks.

One of the major challenges in this project was the schedule. The contractor could be penalized up to $2.5 million per game, if the stadium was not ready on time. Since most of the concrete work was on the critical path, any time savings or delays could effect the project finish date. Using the concrete maturity technique, the contractor was able to measure the in-place strength of the concrete according to ASTM C1074 concrete maturity methodology. In this project, the contractor wanted to use the maturity technique information to start stripping the forms at 75% of design strength, but before the seven day period indicated in the design specifications. Comparing the information from data loggers with strength-maturity graphs showed that, in most cases, the 75% design strength specification was achieved in fewer days than expected. As a result of using the concrete maturity technique, the contractor was able to save a significant amount of cost in man-hours (Engius 2004b).

3.0 Description of the study implementation

3.1 Description of the study

The purpose of the study was to ascertain the impact of the concrete maturity system in a cold weather environment. A study was conducted on the Ultra-Low Sulphur Diesel (ULSD) Project at Imperial Oil's Strathcona Refinery, located near Edmonton, Alberta, Canada. The ULSD project scope, is the addition of a new process facility to reduce the sulphur content of the refinery's on-road diesel to 15 parts per million (ppm). The scope of the project included 1892 m^3 of concrete that was poured from December 2004 to April 2005. The pilot study was conducted from January to April 2005. The normal temperatures for this period, based on information from Environment Canada's Webpage (www.weatheroffice.ec.gc.ca), is a daily average low of –11.7°C, -8.4°C & -2.6°C for the months of January, February and March, respectively which qualifies for the definition of cold weather concrete curing.

3.2 Concrete Mix Design

Two concrete mix designs were used during the course of construction (refer to Table 3.1 for concrete mix composition). Mix Design I was used in buried structures and paving slabs, while Mix Design II was used in aboveground structures.

Table 3.1 *Concrete Mix Designs*

Component (kg/m³)	**Mix Design I**	**Mix Design II**
Type 10 Portland Cement	0	276
Type 50 Portland Cement	263	0
Fly ash	115	86
Concrete sand	629	674
Blend sand	79	72
Washed rock (20 -14mm)	400	400
Washed rock (14-5mm)	616	597
Water	137	140
Admixtures (ml/m³)		
Air Entrainment	805.14	724.00
Superplasticizer	699.30	905.00
Water Reducer	646.38	959.30

Both mixes targeted 30 MPa concrete strength after 28 days with a slump of 80 ± 20 mm.

3.3 Logger locations used for this project

A total of eight foundations were monitored during the study, using a total of 29 data loggers. Figure 3.1 is a 3D image showing an overall view of the project area and monitored foundation locations. Table 3.2 provides information as the location description, number of loggers used, size of each pour and the mix design used.

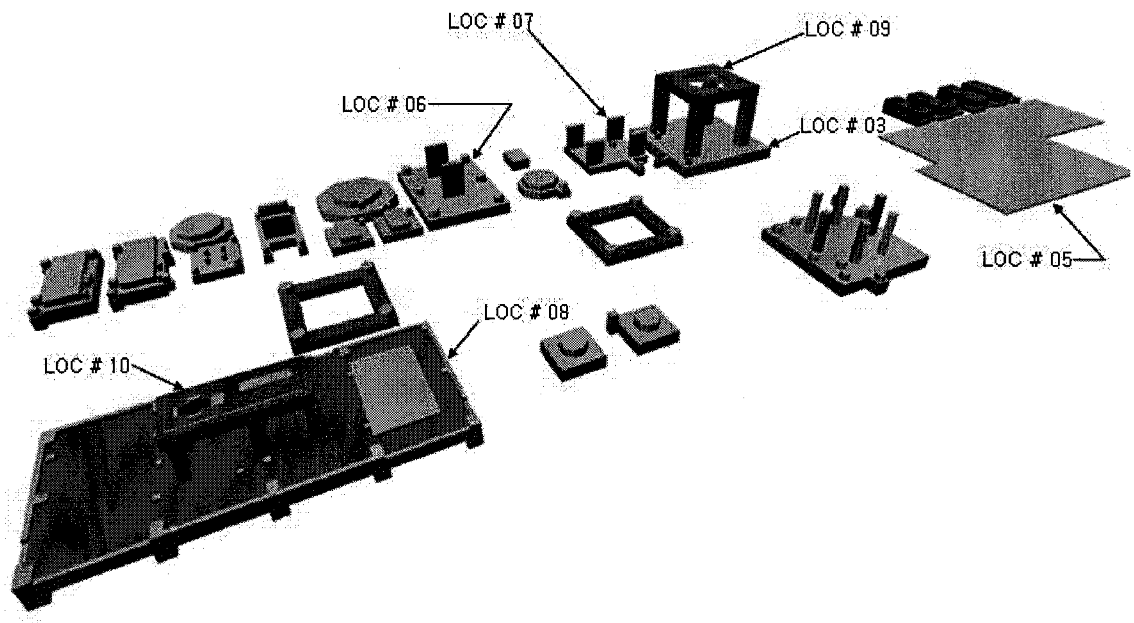

Figure 3.1 Overall test foundation view

Table 3.2 *Logger Location Plan*

Location #	Location Description	Number of Loggers	Volume of Concrete (m^3)	Mix Design
I	Vessel Table-Top	3	23	I
II	Mix Design I	2	N/A	I
III	Vessel Base	2 (+1 for Validation)	130	I
IV	Mix Design II	2	N/A	II
V	Area Paving Slab	4 (+1 for Validation)	73	I
VI	Steel Structure Base	2 (+1 for Validation)	74	I
VII	Exchanger Piers	2 (+1 for Validation)	1.5	I
VIII	Building Grade Beams	4 (+1 for Validation)	32	I
IX	Vessel Table-Top	2 (+1 for Validation)	30	II
X	Equipment Table-Top	3 (+1 for Validation)	19.5	II

Figure 3.2 illustrates the relative logger location and heater placement for location V, a concrete paving slab poured during the course of the pilot study. Detailed 3D images for each test foundation location can be found in Appendix A. The images are similar to the one shown below, and provide details as to the placement of the loggers in the foundations and heater location for each test foundation.

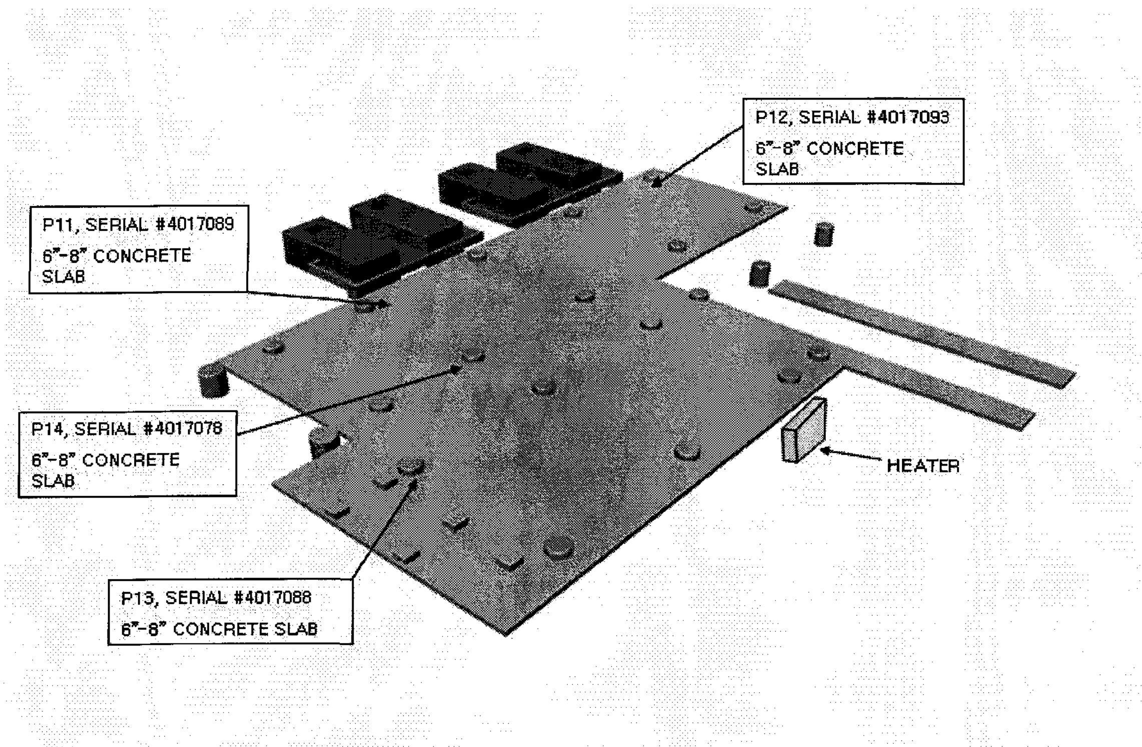

Figure 3.2 Location V, logger and heater placement

3.4 Field activities conducted

The concrete maturity method was used in parallel with the project specified standard QA/QC requirements. For each 50 m^3 of concrete poured, a set of four 10 cm diameter by 20 cm tall compression test cylinders were cast. One of these cylinders was broken at 7 days and with another two cylinders broken at 28 days. If the 28-day cylinders were equal to or greater than the required 28-day strength of 30 Mpa, the third cylinder was also cracked. If the strength is below the specified 28-day strength, the cylinder was broken 56 days after the pour to verify the strength.

The strength-maturity curve was established for each mix design by casting twenty test cylinders. Two of the twenty cylinders were cast with a data logger embedded in the center of the cylinder. The cylinders were field cured for 24 hours and then sent to the project's concrete testing lab to cure under lab condition per CSA A23.2-M94. Cylinders were broken at 1, 2, 5, 7, 14 and 28 days after casting and the concrete maturity, in °C-hrs, was recorded from the embedded data loggers on the corresponding day. Data from the broken cylinders and embedded loggers was recorded and entered into the software provided by Enguis to establish the strength-maturity curve for each mix design. In this study, based on the ASTM C1074 recommendation the value of the datum temperature was assumed equal to zero ($T_0 = 0°C$).

Once the curves had been established, the corresponding strength of the data loggers placed in the field location could be determined. Field locations were chosen, and loggers placed closest to and furthest from the heat source in the hoarding. The number of loggers chosen was based on the size of the concrete pour, number of heaters used and the size of the required hoarding.

3.5 Validation cylinders

For each in-situ location, a set of validation cylinders was cast. This set included three cylinders for compressive strength testing with one additional cylinder cast with an embedded logger. Cylinders were field cured for 24 hours and brought to the lab for final curing. During curing the embedded logger was monitored in the lab. Once the logger showed the validation cylinders had reached 30 MPa, based on the pre-established strength vs. maturity curves, the cylinders were tested in the lab to determine the strength readings. If these reading were 30 ± 3 MPa (i.e. 10%) the strength-maturity curve for the mix design was considered valid.

3.6 Construction process flowchart

Figure 3.3 is an illustration of how the concrete maturity method was integrated and run in parallel with the standard construction procedure for the project. In a typical conventional quality control process, concrete strength is determined by comparing the compressive strength of 28-day laboratory curing concrete specimens with required strength from project design specification. For the specific pilot project in this study, four concrete specimens were required for quality control for each set of concrete placement. Compressive testing of specimens is determined from one 7-day and three 28-day standard curing specimens. The average compressive strength of 28-day specimens is used to confirm the compliance of the concrete strength with project specification. To remove the forms, project specifications suggest specific ages for different concrete sections and mixtures. These ages are mainly based on this assumption that the strength of field concrete sections will reach to a minimum acceptable levels for safety and loading condition of structure. For example, for this pilot project, the concrete forms for load-bearing components should remain in place until the concrete has attained 2/3 of its specified 28-day strength.

Using concrete maturity method, compressive strengths obtained from cured specimens were used to establish a strength-maturity relationship for each concrete mix design used in the project. Data logger from field condition of concrete and the strength-maturity relationship were used to estimate the field strength of concrete. To validate the strength-maturity curve, three extra concrete specimens were cast for each concrete pouring. A logger was placed in one of the three specimens to provide the concrete maturity index. The other two specimens were tested to produce the compressive strength. This strength data, in conjunction with the concrete maturity index, were used to verify the original strength-maturity curve for the particular mix design.

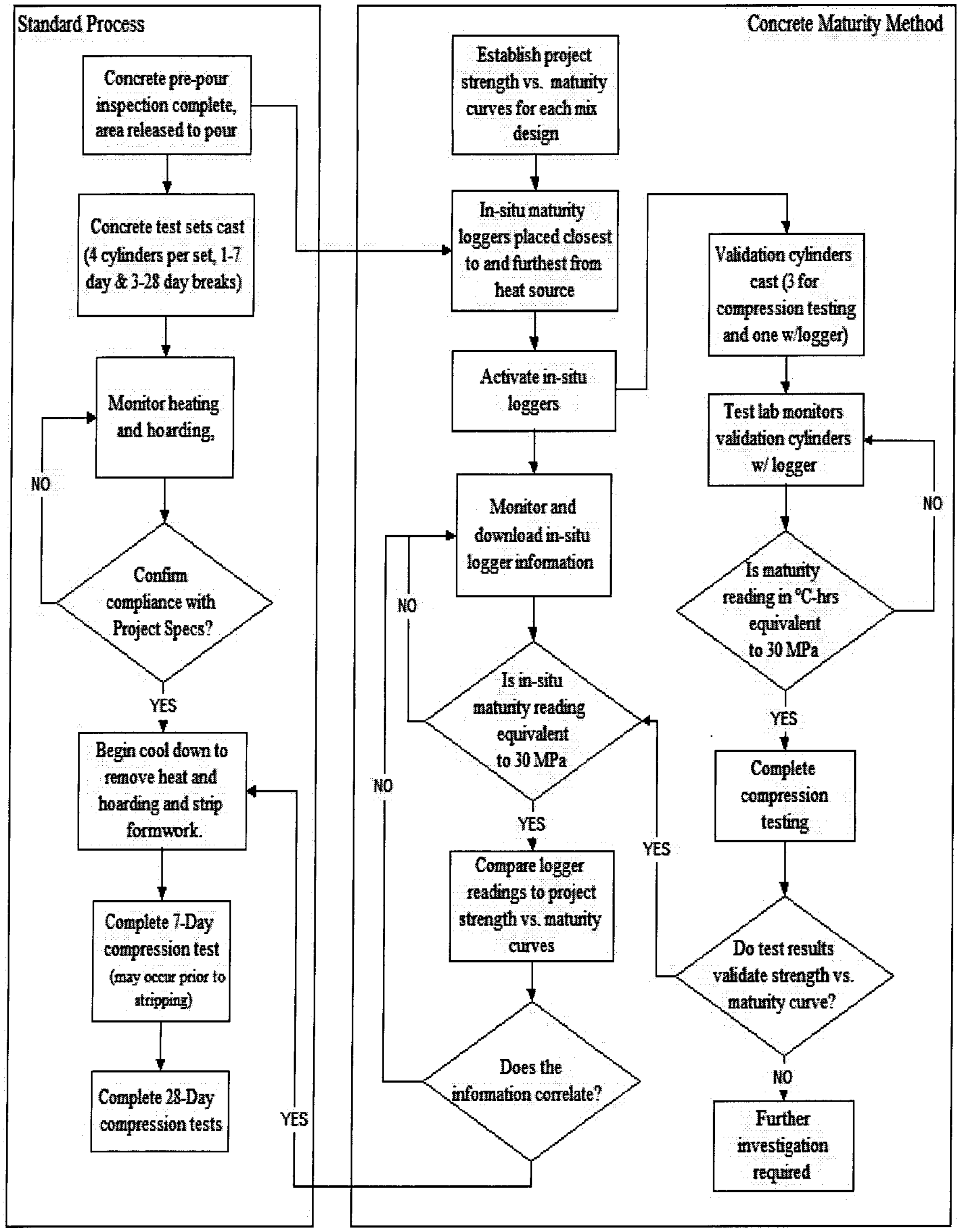

Figure 3.3 Process Flowchart

4.0 Results and Analysis

4.1 Results for design mixes

Table 4.1 shows the compressive strength and temperature-time factor (maturity) data for concrete mix design I, while Figure 4.1 shows the relationship between strength and maturity for the same mix design. The strength-maturity curve was plotted using the Saul maturity function (Equation (2-1)), as explained in Chapter 2. In addition, Figure 4.1 shows the maturity index requirements for form removal (20 MPa) and design strength (30 MPa), based on the design specifications for concrete mix design I.

Table 4.1 *Maturity and Compressive Strength data for the correlation curve of Design Mix I*

Time (Hours)	Specimen Strength (MPa)	Average Strength (MPa)	Specimen Maturity (°C-Hrs)	Average Maturity (°C-Hrs)	Average Temperature (°C)
24.0	5.3	5.5	373	378.0	19.0
	5.7		383		
	5.7				
48.0	16.3	16.1	884	889.0	23.0
	15.9		894		
	16.0				
120.0	27.0	25.7	2,641	2640.5	24.0
	24.5		2,640		
	25.6				
168.0	28.5	28.6	3,806	3798.0	24.0
	28.1		3,790		
	29.2				
336.0	36.4	36.5	7,840	7809.5	24.0
	36.0		7,779		
	37.2				
672.0	39.7	40.4	15,978	15879.0	25.0
	40.1		15,780		
	41.3				

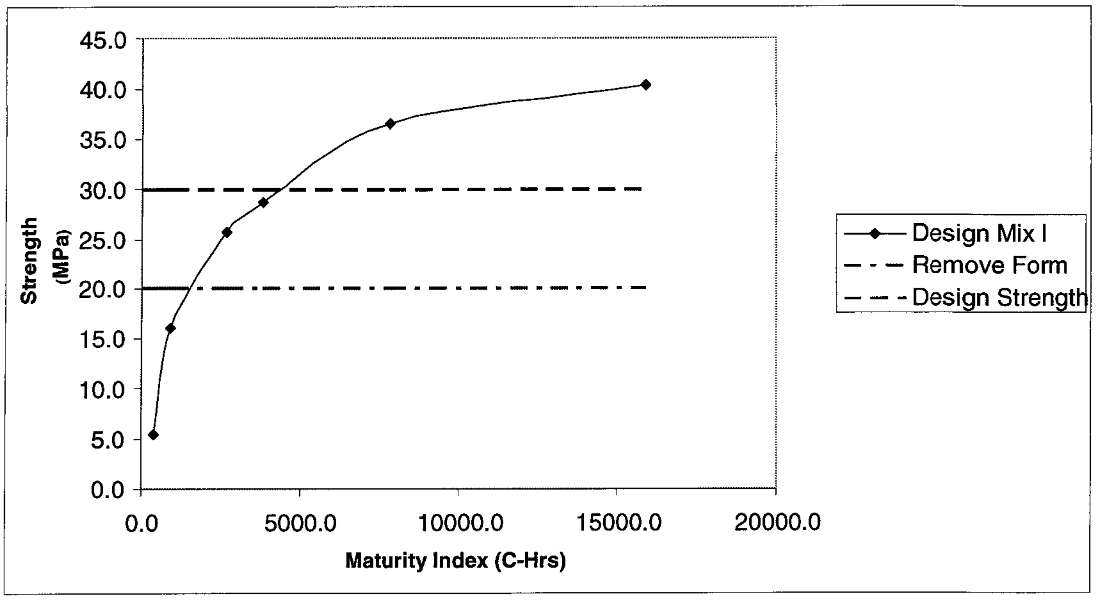

Figure 4.1 Strength-Maturity Relationship Curve of Design Mix I

Table 4.2 shows the compressive strength and temperature time factor (maturity) data for concrete Mix II, while Figure 4.2 shows the strength and maturity relationship curve for concrete Mix II, which was developed in the same manner as Figure 4.1. The two strength and maturity relationship curves (Figure 4.1 and 4.2) were used as the basis to estimate the strength development of the in-place concrete in this pilot study.

Table 4.2 *Maturity and Compressive Strength data for the correlation curve of Design Mix II*

Time (Hours)	Specimen Strength (MPa)	Average Strength (MPa)	Specimen Maturity (°C-Hrs)	Average Maturity (°C-Hrs)	Average Temperature (°C)
24.0	9.8	9.8	495	496.5	19.0
	9.8		498		
	9.7				
48.0	16.4	16.3	1,049	1049.0	23.0
	16.2		1,049		
	16.2				
120.0	24.8	24.5	2,704	2553.5	23.0
	24.0		2,403		
	24.8				
168.0	28.0	27.8	3,899	3898.5	23.0
	27.2		3,898		
	28.1				
336.0	33.9	33.2	7,949	7949.5	25.0
	32.8		7,950		
	33.0				
672.0	41.1	40.2	15,980	15980.0	23.0
	38.9		15,980		
	40.5				

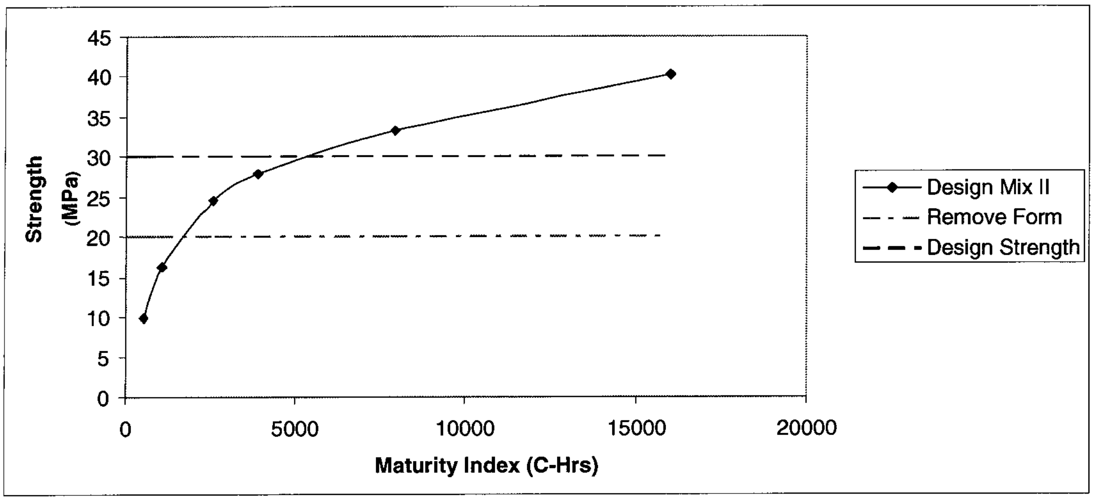

Figure 4.2 Strength-Maturity Relationship Curve of Design Mix II

4.2 Results for Concrete Components

Removal of form work before concrete gains sufficient strength can cause damage and eventually collapse in the concrete component. Maturity method is a non-destructive in-situ technique to estimate the strength of a concrete component based on time and temperature history of the concrete. (Carino et al. 2001)

In this project, concrete maturity method was implemented on eight concrete components including table tops, bases, slabs, piers and beams. In this section, based on the maturity data of in-place loggers, concrete temperature development curve and strength development curve for each concrete component was developed. These results were used to determine time savings of each concrete component.

4.2.1 Location I, Vessel Table Top

In this location, concrete placement activities were scheduled for 28 days starting with concrete pouring on January 29th and ending with shoring removals on February 25th. Concrete with the specifications of Design Mix I was poured on January 29th, as scheduled. The temperature in the hoarding reached a maximum of 24°C and a minimum of 8°C during the first five days of curing. No validation cylinders were cast for this location, since the same concrete mix was used to determine the strength-maturity relationship curve for Mix I. Figure 4.3 shows the concrete temperature history from the three loggers placed in the Vessel Table Top for 672 hours (28 days).

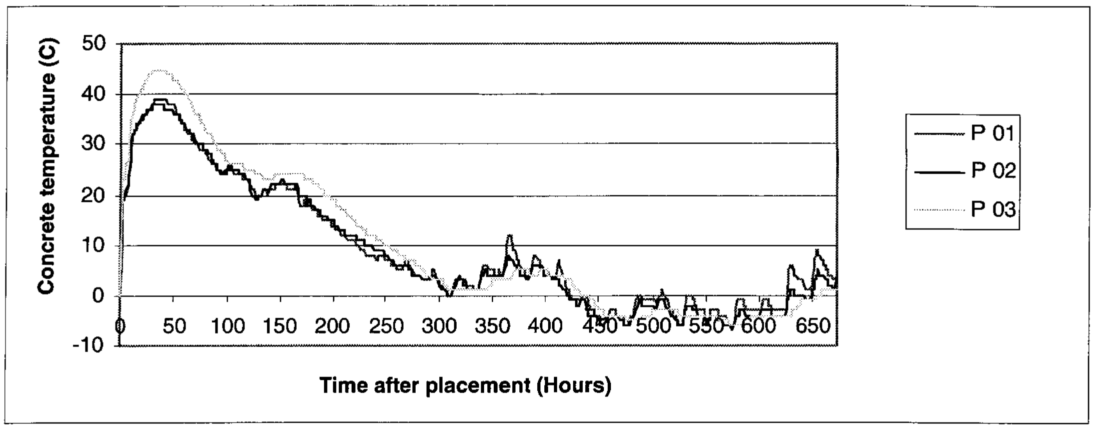

Figure 4.3 Concrete Temperature Developments for Vessel Table Top I

According to the project specifications, for this load-bearing component, forms supporting concrete weight cannot be removed until the concrete reaches 2/3 of its specified 28 day strength. According to the original subcontractor's schedule, 28 days was considered enough for concrete Design Mix I to gain the required strength. However, the strength development curve (Figure 4.4) for this location shows that the required 20 MPa strength for form removal was achieved after 48 hours of curing. Therefore, the shoring and forms could have been removed twenty six days prior to the scheduled date. It is also worth noting that the design strength requirement of 30 MPa was achieved in seven days instead of 28 days. As a result, the concrete test procedure in the project specifications, in combination with the concrete maturity method, enabled the general contractor to convince the sub-contractor to reduce the original scheduled duration of location IX and X from 28 days to 14 days.

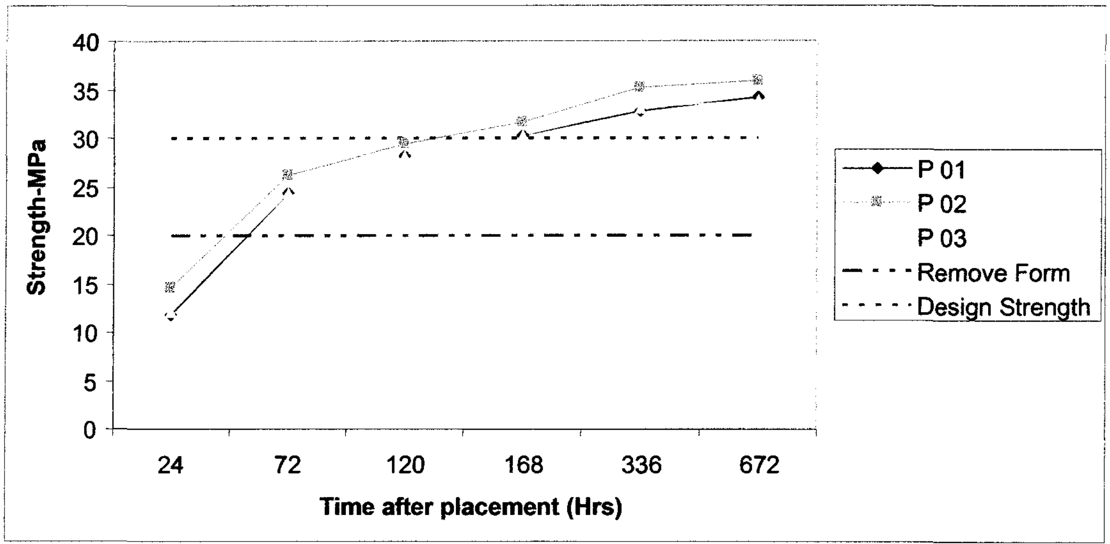

Figure 4.4 Strength Development Curve of Vessel Table Top I

Table 4.3 demonstrates strength calculation methodology for location I for the first 24 hours after pouring concrete. By correlating average maturity value ($M = \Sigma\ (T_a\text{-}T_0)\Delta t$) for this location with strength-maturity relationship of design mix I (figure 4.1), average strength of concrete component I is calculated.

Table 4.3 *Strength Calculation for the first 24 hours of Location I (Δt = 1 hour)*

Time (Hrs)	Logger-P 01 (°C)	Logger-P 02 (°C)	Logger-P 03 (°C)	Average Temperature-T_a (°C)	Datum Temperature-T_o (°C)	Average Maturity $(T_a-T_o)\Delta t$ (°C-Hrs)	Average Maturity $\Sigma(T_a-T_o)\Delta t$ (°C-Hrs)	Average Strength (MPa)
0	0	0	0	0.0	0	0.0	0.0	0
1	6	20	18	14.7	0	14.7	14.7	0.2
2	21	23	19	21.0	0	21.0	35.7	0.5
3	20	23	19	20.7	0	20.7	56.3	0.8
4	20	24	20	21.3	0	21.3	77.7	1.1
5	20	26	21	22.3	0	22.3	100.0	1.5
6	22	27	22	23.7	0	23.7	123.7	1.8
7	24	31	24	26.3	0	26.3	150.0	2.2
8	26	33	27	28.7	0	28.7	178.7	2.6
9	29	35	30	31.3	0	31.3	210.0	3.1
10	31	36	32	33.0	0	33.0	243.0	3.6
11	32	36	32	33.3	0	33.3	276.3	4.1
12	32	37	32	33.7	0	33.7	310.0	4.5
13	33	38	33	34.7	0	34.7	344.7	5.1
14	33	39	33	35.0	0	35.0	379.7	5.6
15	33	39	34	35.3	0	35.3	415.0	6.3
16	34	40	34	36.0	0	36.0	451.0	7.0
17	34	40	35	36.3	0	36.3	487.3	7.8
18	35	41	35	37.0	0	37.0	524.3	8.5
19	35	41	36	37.3	0	37.3	561.7	9.3
20	35	42	36	37.7	0	37.7	599.3	10.1
21	36	42	36	38.0	0	38.0	637.3	10.9
22	36	43	36	38.3	0	38.3	675.7	11.7
23	36	43	36	38.3	0	38.3	714.0	12.5
24	36	43	37	38.7	0	38.7	752.7	13.0

4.2.2 Location III, Vessel Base

The original schedule for concrete activities in this location was concrete placement on February 7th, followed by form removal on February 14th, and backfill around the base on March 7th. Concrete Mix I was poured on February 8th. The surface temperature of the concrete was recorded at a minimum of 18°C and the temperature in the hoarding was kept above 8°C during the first three days of curing. Validation cylinders were cast for this location and the result was within the 10% acceptable range for the strength-maturity relationship curve of design mix I. Figure 4.5 shows the concrete temperature history from the two loggers placed in the Vessel Base for 672 hours (28 days).

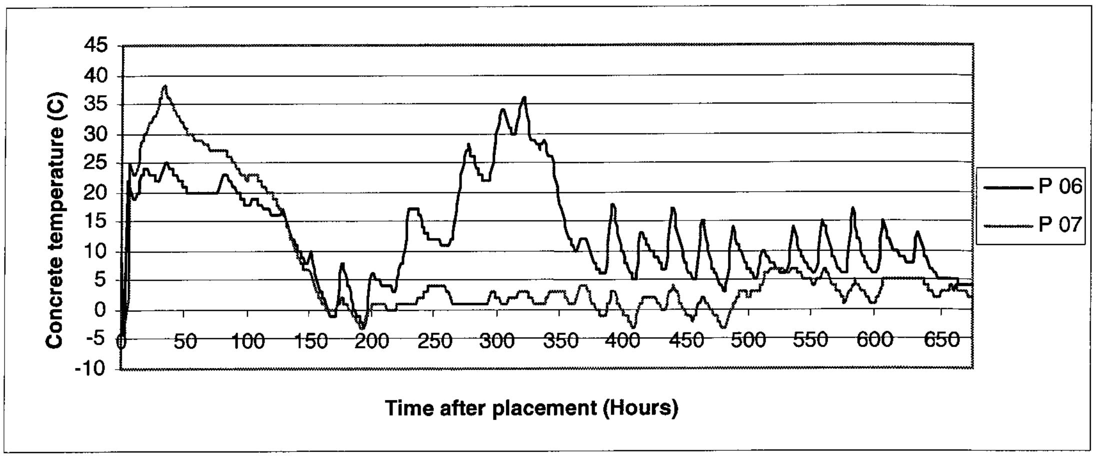

Figure 4.5 Concrete Temperature Developments for the Vessel Base

By correlating the maturity readings of the loggers in location III with the strength-maturity relationship curve for Mix I, the strength development curve of the Vessel Base was obtained (Figure 4.6). Using this graph, the right time for form removal and design strength achievement for location III can be determined. Analyzing the strength development curve (Figure 4.6) of this concrete base shows that the forms could have been removed in less than two days. For this non load-bearing component concrete maturity method reassured that the concrete component has reached its required strength for form removal after two days.

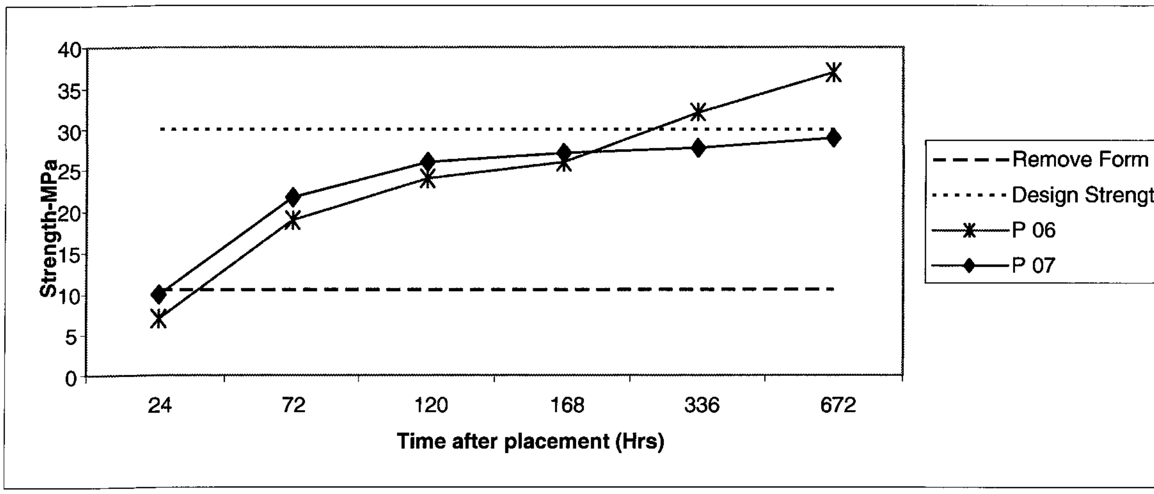

Figure 4.6 Strength Development Curve of Vessel Base

4.2.3 Location V, Substation Paving Slab

For the substation paving slab concrete, activities commenced with concrete placement on February 25th, according to the specifications for Mix I. Because of the large surface area of this slab, it was difficult to maintain the surface temperature of the concrete at around 15 to 20°C. In this location, the concrete surface temperature was between 4.6 and 11°C, and the minimum hoarding temperature was recorded at 2.2°C during the first four days of curing. For this location, validation cylinders were cast and the result was within the 10% acceptable range of the strength-maturity relationship curve of Mix I. Figure 4.7 illustrates the concrete temperature history from the four loggers placed in the Substation Paving Slab for 672 hours (28 days).

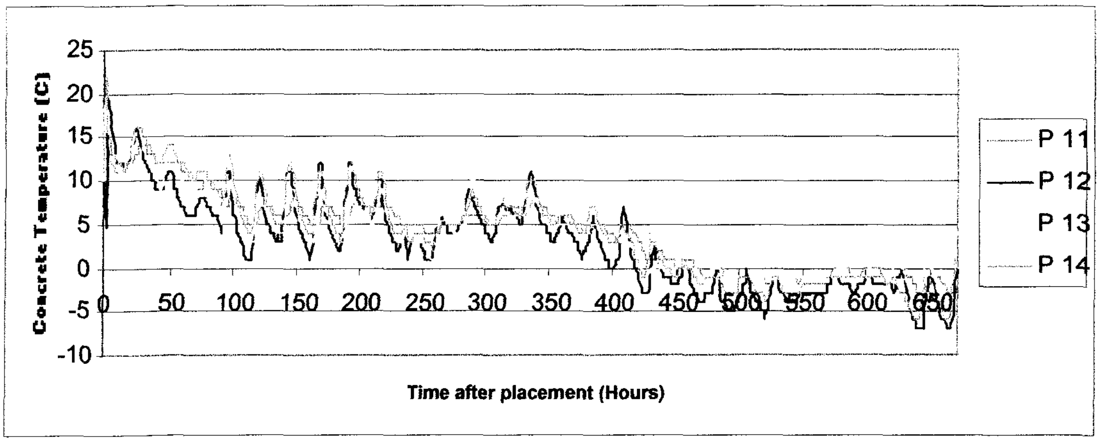

Figure 4.7 Concrete Temperature Developments for the Substation Paving Slab

The strength development curve (Figure 4.8) of this location demonstrates that the concrete gained 10.5 MPa in 48 hours, so the forms could have been removed after the two days required in the schedule. Although the concrete maturity methodology did not save any time according to the schedule, it reassured the contractor that forms could be removed at the scheduled time.

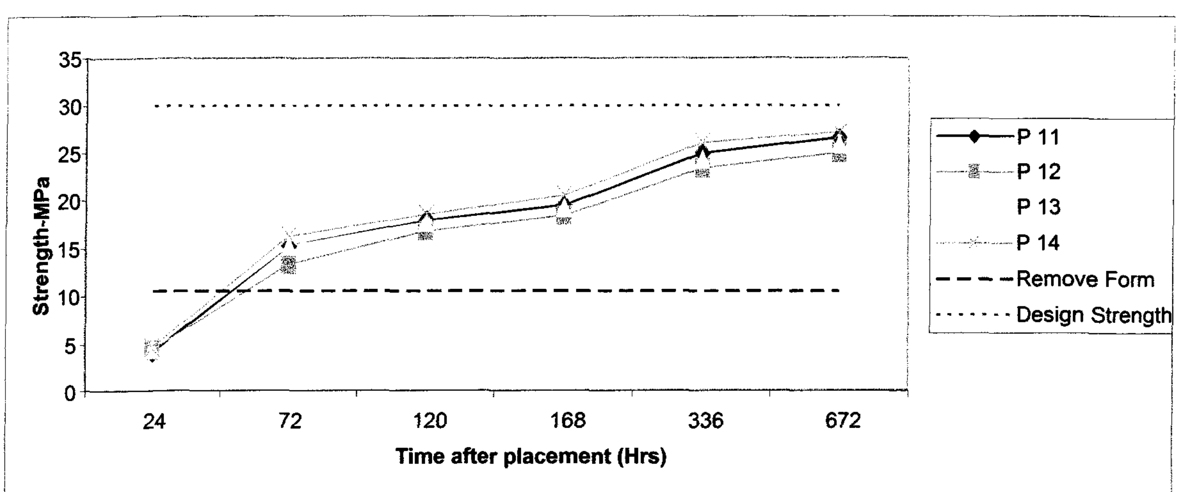

Figure 4.8 Strength Development Curve of Substation Paving Slab

4.2.4 Location VI, Steel Structure Base

For this location, concrete pouring was scheduled for March 1st, followed by removal of the forms on March 5th, and backfill around the base on March 6th. The next activity after the Steel Structure Base was column form work scheduled on March 6th. Concrete with the specifications of Mix I was poured on March, 1st. In this location, the concrete surface temperature was recorded above 20°C and the minimum and maximum hoarding temperatures were recorded at 11 and 22°C, respectively, during the first seven days of curing. Validation cylinders were cast for this location and the result was within the 10% acceptable range of the strength-maturity relationship curve of design mix I. Figure 4.9 shows the concrete temperature history from the two loggers placed in the Steel Structure Base for 672 hours (28 days).

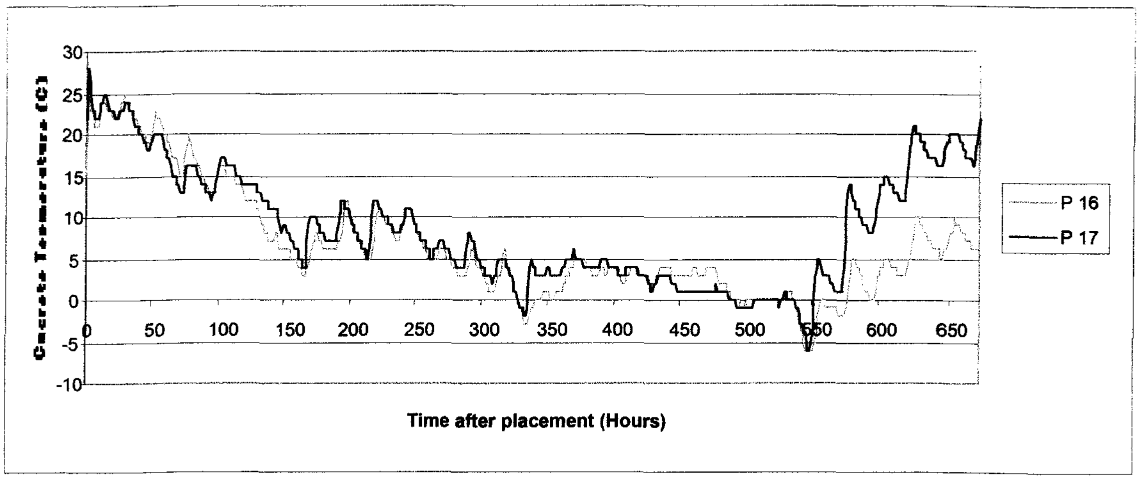

Figure 4.9 Concrete Temperature Developments for the Steel Structure Base

According to the strength development curve from this location (Figure 4.10), the concrete reached 10.5 MPa strength in less than 2 days (32 hours). So, the form removal activity and consequently backfill could have been started two days earlier than originally scheduled. As a result, the form work for the columns could have been started on March 3rd. Even though the concrete maturity methodology did not save any time according to the schedule, it reassured the contractor that forms could be removed at the scheduled time.

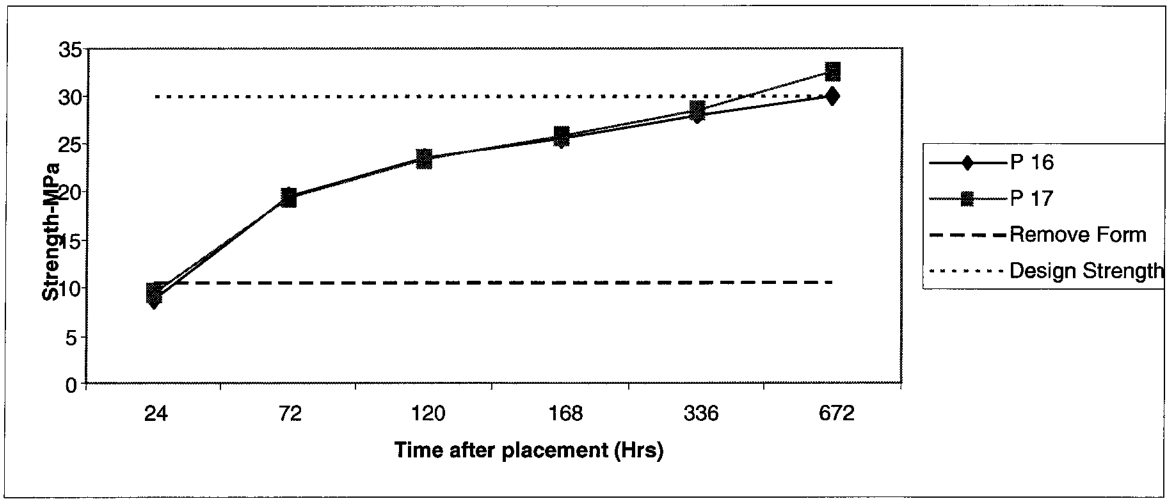

Figure 4.10 Strength Development Curve of Steel Structure Base

4.2.5 Location VII, Exchanger Structure Piers

For the exchanger structure piers, concrete was poured on March 1st according to the specifications for Mix I. In this location, the concrete surface temperature was recorded at above 10°C for the first seven days of the curing period. Validation cylinders were cast for this location and the result was within the 10% acceptable range of the strength-maturity relationship curve of design mix I. Figure 4.11 shows the concrete temperature history from one of the loggers placed in the Exchanger Structure Piers for 672 hours (28 days). The wiring of the second logger (P 20) was cut during the curing period and so the data is not included in Figure 4.11.

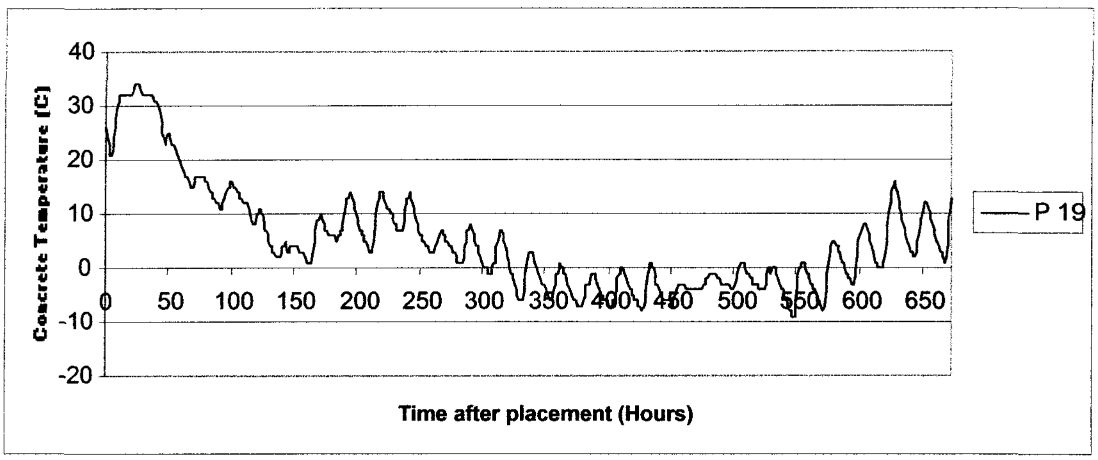

Figure 4.11 Concrete Temperature Developments for the Exchanger Structure Piers

As shown in Figure 4.12, the strength development curve of the exchanger structure piers indicates that the concrete reached the 10.5 MPa required strength for form removal 24 hours after pouring. The strength development curve supports the form stripping specification for the exchanger structure piers, since the specification permits the removal of forms as early as 48 hours after pouring. As a result, one day of time saving could have been made in this location. In addition, the concrete maturity data provided the project with valuable concrete quality information so that a sufficient level of concrete strength could be developed.

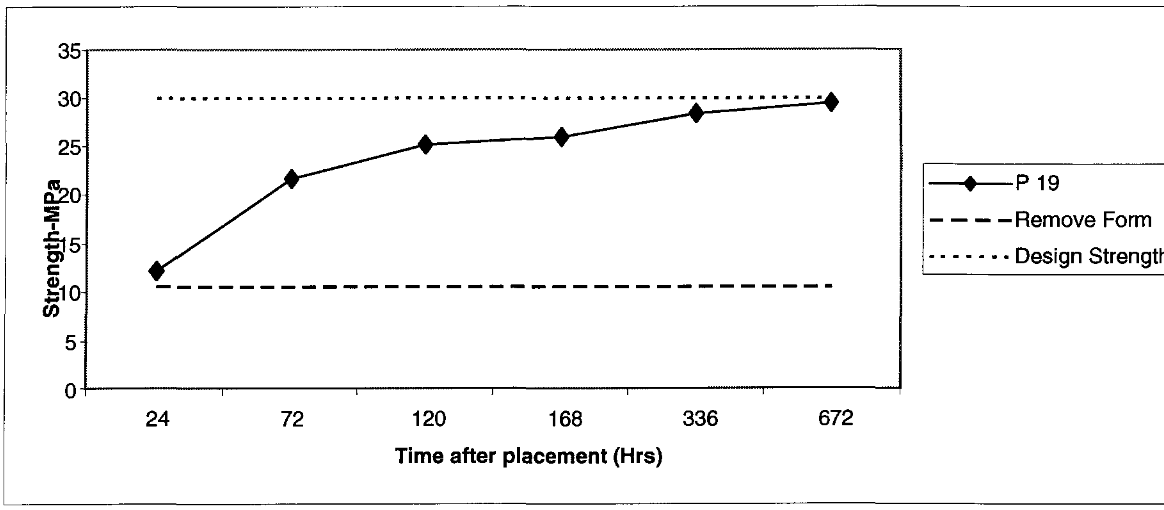

Figure 4.12 Strength Development Curve of Exchanger Structure Pier

4.2.6 Location VIII, Building Grade Beam

According to the original project schedule, concrete activities for this location were on the critical path of project. Concrete pouring at this location started on March 17th, in accordance with the specifications for Mix I. The hoarding temperature was recorded at between 4 and 17°C for the first four days after pouring. Validation cylinders were cast and the result was within the 10% acceptable range of the strength-maturity relationship curve of design mix I. Figure 4.13 shows the concrete temperature history from the four loggers placed in the Building Grade Beam for 672 hours (28 days).

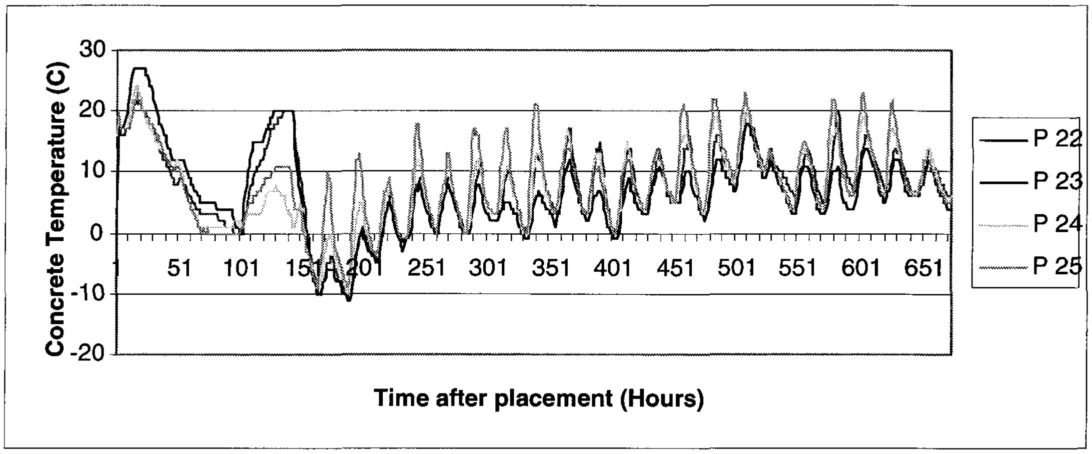

Figure 4.13 Concrete Temperature Development for the Building Grade Beam

Comparing the maturity readings in location VIII with the strength-maturity relationship curve of Mix I generates the strength development curve of the Building Grade Beam (Figure 4.14). Using this graph, the time of form removal and the design strength achievement for location VIII can be determined. The strength development curve (Figure 4.14) for the four loggers imbedded in the concrete shows that the concrete reached the strength of 10.5 MPa in two days. Since the forms were removed after 48 hours based on the project schedule and specifications, no time could have been saved at this location.

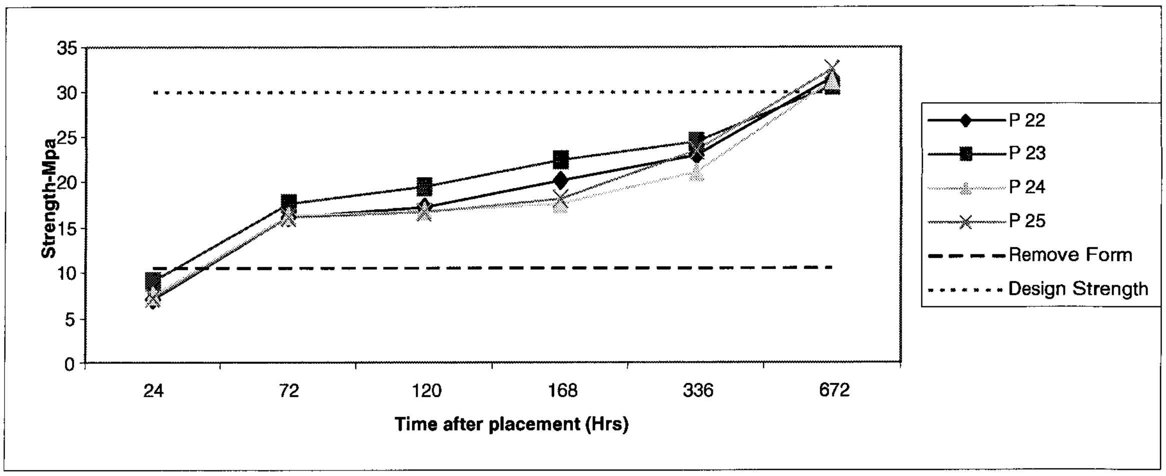

Figure 4.14 Strength Development Curve of Building Grade Beam

4.2.7 Location IX, Vessel Table Top (II)

For this location, concrete activities started with the pouring of concrete on March 21st, in accordance with the specifications for Mix II. The concrete surface temperature was recorded at between 18 and 28°C for the first four days of curing. Validation cylinders were cast for this location and the result was within the 10% acceptable range of the strength-maturity relationship curve of Design Mix II. Figure 4.15 shows the concrete temperature history from the two loggers placed in the Vessel Table Top (II) for 264 hours (11 days).

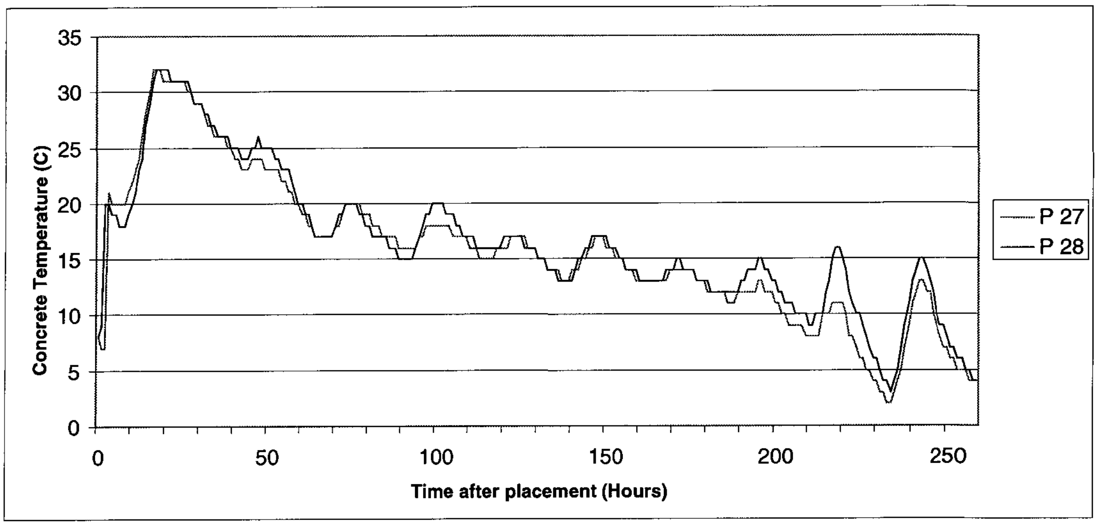

Figure 4.15 Concrete Temperature Developments for the Vessel Table Top II

Maturity readings from the strength development graph (Figure 4.16) indicate that the concrete achieved the required 20 MPa form removal strength in less than three days. Since the original scheduled date for the removal of the forms was April 18th, a total of 25 days could have been saved at this location. However, since the new project specification allowed for only 14 days of time reduction in the duration of concrete activities, the actual time savings for this location was 14 days.

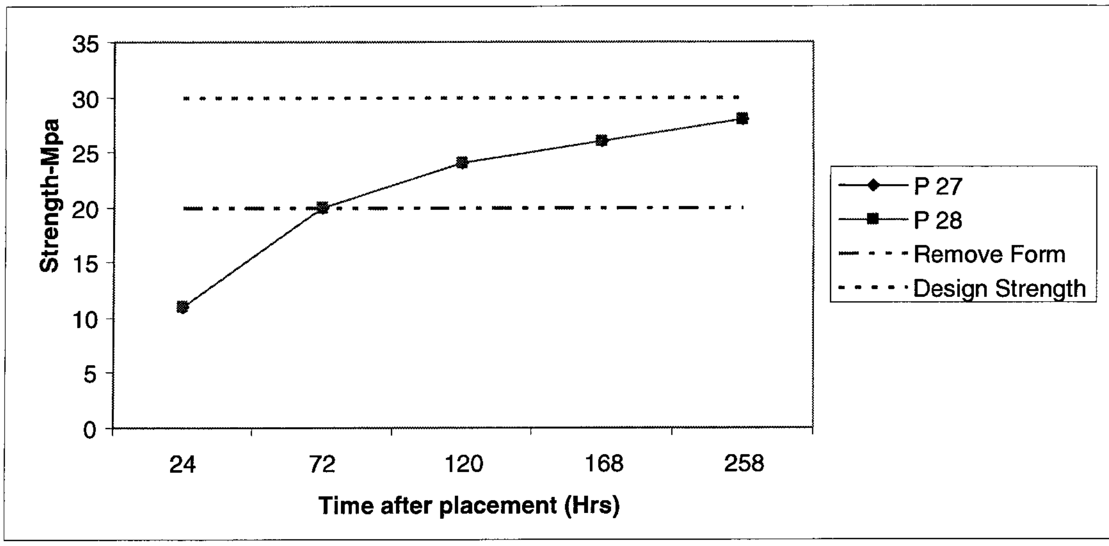

Figure 4.16 Strength Development Curve of Vessel Table Top II

4.2.8 Location X, Equipment Table Top

For this concrete table top, concrete pouring commenced on March 29th according to the specifications of Design Mix II. The concrete surface temperature was recorded at between 25 and 30°C for the four days after pouring. The hoarding temperature remained between 10 and 30°C and the heater was turned off three days after pouring. For this location validation cylinders were cast and the result was within the 10% acceptable range of the strength-maturity relationship curve of design mix II. Figure 4.17 shows the concrete temperature history from the three loggers placed in the Equipment Table Top for 672 hours (28 days).

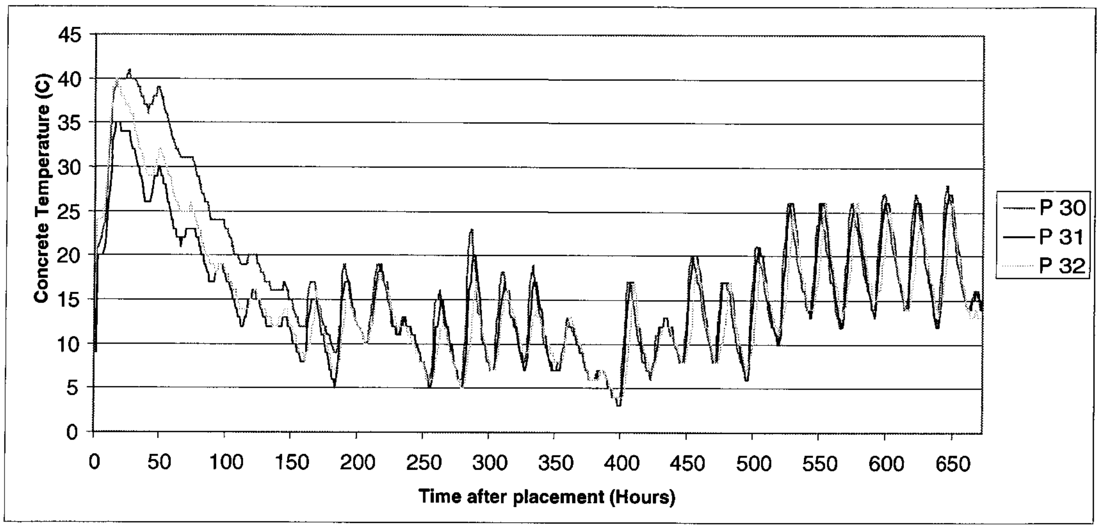

Figure 4.17 Concrete Temperature Development for the Equipment Table Top

According to the original project schedule, the form work was supposed to be removed on April 26th, 28 days after pouring. The concrete maturity strength development curve (Figure 4.18) of this location shows that the 20 MPa strength required to remove the forms was gained in less than three days. As a result, the forms could have been removed on April 2nd. Since the concrete activities for this location were critical to the progress of the project schedule, the overall project duration in the original schedule could have been reduced by 25 days. Since the original schedule duration for this load-bearing component was reduced from 28 days to 14 days, the actual form removal date was April 12th, resulting in a 14 days actual time saving.

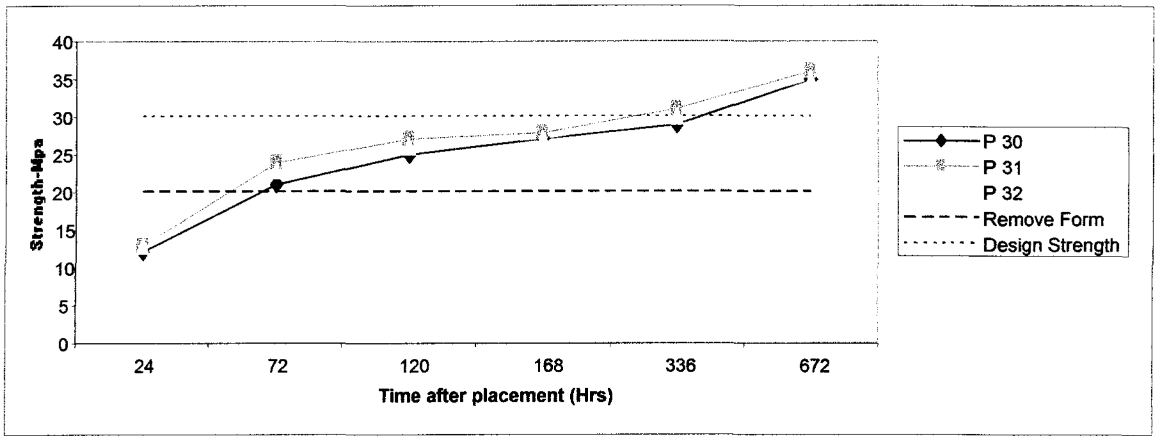

Figure 4.18 Strength Development Curve of the Equipment Table Top

4.3 Impact of the concrete maturity method on construction time

The concrete maturity method was implemented during the FIATECH pilot study in parallel with the project specified standard concrete QA/QC procedure. Although the concrete maturity method was not the governing quality control procedure, it provided timely and accurate field concrete maturity information, which could potentially lead to significant time savings.

4.3.1 Project Level Time Saving

The concrete activities of the Ultra-Low Sulphur Diesel Project at Imperial Oil's Strathcona Refinery were conducted from December 2004 through to April 2005. During this period, the maturity technique was implemented for eight concrete components (locations) to demonstrate the time savings that can result from this method on a project level. The effective duration for the activities related to this pilot project was from January 29 for the pouring of concrete for location I until April 26 for the removal of the form work for location X. Therefore, the total duration of the pilot project was 88 days.

In this section, the potential time savings for each of the eight concrete components (locations) of this pilot project were calculated by comparing the actual schedule, based on the project's design specifications, with a hypothetical schedule that could have been achieved with the implementation of the maturity technique. Four of the eight locations indicate a certain level of potential time savings through the early removal of the forms and the early attainment of design strength. The summation of the time savings for the eight concrete components is equal to a total of 77 days. However, since most of the activities are not on the critical path of the project, the 77 days is not the time savings on the project level. Critical path is the series of activities which their completion dates can not be delayed and determines the earliest completion date of project schedule (Ahuja et al. 1994). If the duration of an activity on the critical path reduced by one day, the entire project duration would be reduced by one day. Since the concrete activities of location X was critical to the progress of the original schedule, a total of 25 days could have been saved on the project level by employing the data from the maturity method. The 25 days is a noticeable time savings, which constitutes a 28% reduction in this portion of the project's original schedule duration (88 days). In locations IX and X, the concrete maturity method, in conjunction with project specified quality control procedures, allowed the removal of forms and shoring 14 days after concrete was poured, instead of 28 days that was originally allocated. Since the concrete activities of location X was on the critical path, a 14 days of actual time savings was recorded, which constitutes a 16% time reduction.

Table 4.4 *Schedule savings*

Location	Concrete Pouring	Original Form Removal	Form Stripping Spec.	Actual Concrete Maturity Form Removal	Actual Schedule Savings (Days)	Possible Concrete Maturity Form Removal	Possible Schedule Savings (Days)
I	Jan-29	Feb-25	Load-bearing	Feb-25	0	Jan-31	26
III	Feb-07	Feb-09	Non Load-bearing	Feb-09	0	Feb-09	0
V	Feb-28	Mar-02	Non Load-bearing	Mar-02	0	Mar-02	0
VI	Mar-01	Mar-03	Non Load-bearing	Mar-03	0	Mar-03	0
VII	Mar-01	Mar-03	Non Load-bearing	Mar-02	1	Mar-02	1
VIII	Mar-17	Mar-19	Non Load-bearing	Mar-19	0	Mar-19	0
IX	Mar-21	Apr-18	Load-bearing	Apr-04	14	Mar-24	25
X	Mar-29	Apr-26	Load-bearing	Apr-12	14	Apr-01	25
Total					29		77
Total (Critical Path)					14		25
Duration					88		88

4.4 Impact of the concrete maturity method on QA/QC

In construction projects, concrete quality control is a procedure to assure that concrete satisfies specific properties required in design, construction and performance of the concrete. Concrete quality control procedures mainly evaluate concrete mixture properties, cement requirements and strength requirements (Kosmatka et al. 2002).

In this study, for each concrete component tested, a set of validation cylinders was cast to verify the quality of the concrete and show that the strength-maturity curve of the concrete design mix would be equivalent to that obtained from the validation cylinder tests. Figures 4.19 and 4.20 demonstrate that the compressive strength value from the validation cylinder tests for all the concrete components are within the 10% acceptable range of the strength-maturity relationship of their corresponding design mix. These validation results indicate that the strength and maturity curves for the two mix designs can be used with confidence to determine the time for early removal of form work, or for allowing live loads onto the concrete component.

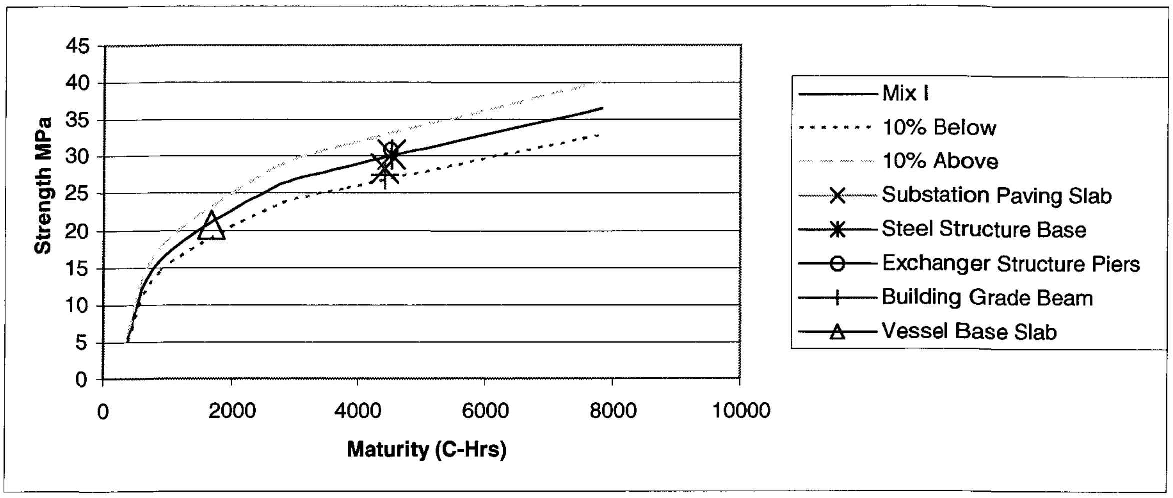

Figure 4.19 Verification of Strength-Maturity Relationship Curve of Design Mix I

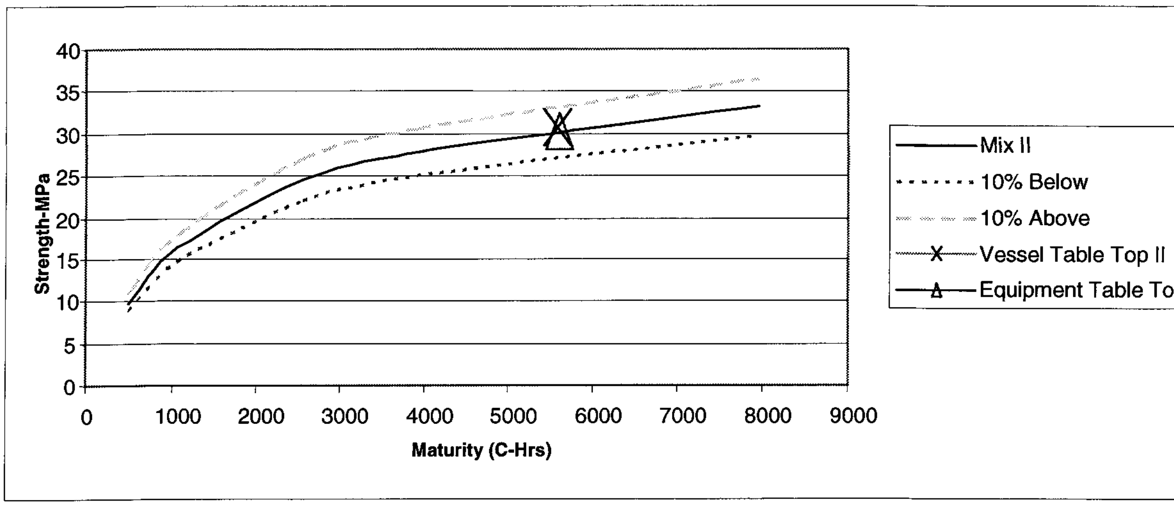

Figure 4.20 Verification of Strength-Maturity Relationship Curve of Design Mix II

In this project, the quality requirements are divided into the following two categories:

1. Project specifications for form stripping.
    a. "Non-load bearing forms, such as columns, walls, sides of beams and other vertical forms not supporting concrete weight, shall remain in place for at least 48 hours after pouring concrete. Forms for tanks rings, pump foundations and similar low structures shall remain in place at least 24 hours after pouring. After this time they may be removed as soon as the concrete has hardened sufficiently to resist damage during removal."
    b. "Load bearing forms, such as soffits, slabs and other forms supporting concrete weight shall remain in place until the concrete has attained 2/3 of its specified 28-day strength. Under average temperature conditions, 5°C to 27°C (41°F to 81°F), the time required to obtain this strength is 10 days for concrete made with sulphate-resistant Type 50

cement, and 7 days for concrete made with Type 10 cement. Equipment may be erected after concrete has attained 2/3 of its specified 28-day strength, after reshoring the concrete and with the prior approval of the Structural Engineer."

2. Project specifications for concrete testing
   a. "Structures and Foundations:
      - One test set shall be taken for each day's pour and at least one test for each 50 cubic yards (38 m^3) placed.
      - In addition, at least one shall be made for each foundation exceeding 10 cubic yards (7.5m^3)."
   b. "Paving and Slabs at Grade:
      - At least one test per 45 cubic yards (38 m^3), or portion thereof, poured at any one time placed.
      - At least one set for each different class of concrete placed on any one day."

In this project, the subcontractor's quality control specification for load-bearing concrete components indicated that forms and shorings could be removed 28 days after concrete was poured. For locations I, IX and X of this study, form and shoring removal was, therefore, scheduled to take place 28 days after pouring the concrete. However, the results of the concrete maturity method for location I showed that forms could have been removed only two days after concrete was poured. The combination of these findings and project design specifications was the primary reason for the general contractor to convince the subcontractor to reduce the 28 days curing requirement for form and shoring removal of load-bearing concrete components to 14 days. As a result, for other load-bearing components including locations IX and X, form and shoring were removed after 14 days instead of 28 days.

In form stripping requirements, it was assumed that the concrete would gain the required strength within 24 or 48 hours for the non load-bearing components and within seven or 10 days for the load-bearing components. This is in accordance with the CSA A23.1 standard which indicates that in order to remove the forms of non load-bearing concrete components; concrete surfaces need to be cured for the time necessary to gain 35% of the specified 28-day strength or 10.5 MPa in this project. The study results show that the concrete maturity methodology enables better quality control through the accurate estimation of in-place concrete strength.

4.5 Impact of the concrete maturity method on cost savings

In cold weather concreting, heating and hoarding is necessary until the concrete reaches the strength required for form removal, according to the project specifications. For each day of earlier removal of the forms, one day's worth of heating costs can be saved. Table 4.3 shows that the total heating energy required is estimated to be 546.84 M-BTU for all concrete components in this study. This calculation is based on an hourly heating requirement for each location multiplied by the one week (168 hours) of heating duration necessary according to the project specifications. Table 4.3 also shows the total energy needed for these components based on the data obtained from the concrete maturity methodology is 179.08 M-BTU. By comparing these two quality control procedures, it is estimated that a total of 367.76 M-BTU heating energy could have been saved.

The heating and hoarding cost is, in fact, a fragment of the total cost savings that could be realized using the concrete maturity method. The forms that become available from early removal can be used for other concrete activities in the project, or returned to the supplier, which results in savings in the shoring and forms rental cost per day. If the overall project duration is reduced, the supervisory and overhead costs of the project are also reduced. As mentioned previously, a 28% reduction could have been achieved if the concrete maturity method had been fully adopted. Therefore, the indirect cost savings equivalent to the 28% time reduction could have reasonably been expected.

Table 4.5 *Comparison of heating duration between the standard and maturity methods*

Location #	Location Description	K-BTU's / Hour	Duration Standard-Hrs	Total M-BTU (Standard)	Maturity Duration-Hrs	Total M-BTU (Maturity)
I	Vessel Table-Top	375	168	63	47	17.63
III	Vessel Base	930	168	156.24	48	44.64
V	Area Paving Slab	90	168	15.12	48	4.32
VI	Steel Structure Base	90	168	15.12	32	2.88
VII	Exchanger Piers	90	168	15.12	24	2.16
VIII	Building Grade Beams	375	168	63	48	18
IX	Vessel Table-Top	930	168	156.24	72	66.96
X	Equipment Table-Top	375	168	63	60	22.5
	Total			546.84		179.08

5.0 Datum temperature sensitivity analysis

In this section, a sensitivity analysis for strength maturity curve of each concrete component with different datum temperatures is implemented. In addition, Arrhenius equation was used to calculate the strength maturity curve for every concrete components of this study. Then the results were investigated to see the effects of datum temperature and Arrhenius calculation on strength-maturity curve and shoring and form removal schedule of each concrete component.

For Saul equation for maturity measurements, three different datum temperatures are mostly recommended. These values are -10°C (Carino et al. 2001) for the concrete that is slower in strength gaining, 0°C for most of the concrete applications and 6.5°C for fast early strength gaining concrete (Luke et al. 2002). Datum temperature equal to -10°C has been recommended in literature as minimum possible value for datum temperature, since below this temperature concrete hydration will stop. Datum temperature equal to 0°C is the most recommended and used value in literature and is recommended by ASTM C 1074 and can be used in most applications. Datum temperature values between 0°C and 6.5°C are mostly calculated in different field or lab conditions. In this study a sensitivity analysis with datum temperature values equal to -10°C, 0°C and 5°C is implemented and strength calculation results are compared with those obtained from Arrhenius equitation.

Location I

Figure 5.1 represents the strength-maturity curve of location I, based on Saul equation with different datum temperatures and Arrhenius equation. It shows that in early ages of concrete strength development, calculated strength for T_0 = -10°C is less than the strength values based on T_0 = 0°C and T_0 = 5°C. The results are reversed in later ages. As a result calculated strength for T_0 = -10°C is more than strength values based on T_0 = 0°C and T_0 = 5°C. So, higher datum temperature in Saul equation results in higher early age strength and lower later age strength for this concrete component. As previously mentioned, for concrete with different early-age temperatures Saul equation results in "Cross over" behavior. Datum temperature sensitivity analysis of this location shows that "Cross over" behavior is not only the result of different early-age concrete temperature but also the result of different datum temperatures in calculation of strength-maturity calculation for a concrete component with a single curing temperature profile. Figure 28 represents that different datum temperatures result in "Cross over".

Furthermore the results of Arrhenius equation show higher strength values in early ages compared to the Saul equation values, and in later ages they get to almost the same value as Saul calculation for T_0 = -10°C.

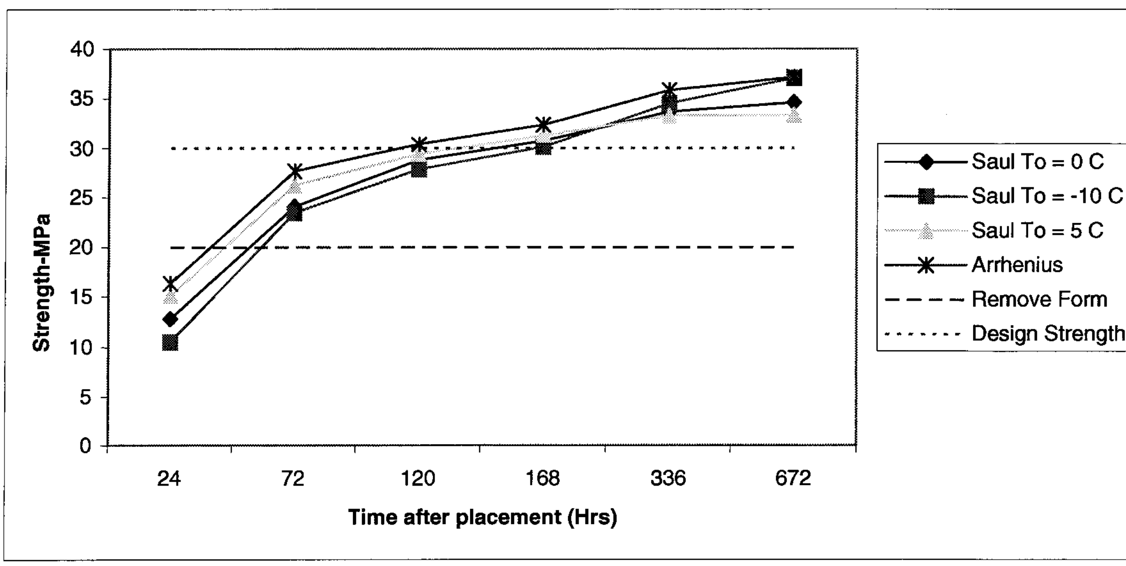

Figure 5.1 Datum temperature sensitivity analysis of vessel table top I

According to the project specification, for this load-bearing component shoring and forms can not be removed until concrete reaches strength equal to 20 MPa. The result of strength calculation based on Saul equation with different datum temperatures and Arrhenius equation show that for this location regardless of datum temperature values or calculating functions, shoring and forms could have been removed after 48 hours (for T_0 = -10°C in 52 hours) , and design strength was achieved in seven days or less instead of 28 days. So in this location different datum temperature values and different calculation methodologies will not have a significant effect on schedule reductions calculated in section 4 and shoring and forms could have been removed two days after pouring concrete.

Location III

Figure 5.2 shows strength calculation based on Saul equation with different datum temperatures and Arrhenius equation for location III. In this location calculated strength values are more consistent. As well, strength –maturity relationship curves with different datum temperatures demonstrate the "Cross over" behavior. In addition Arrhenius equation results are close to those from Saul equation.

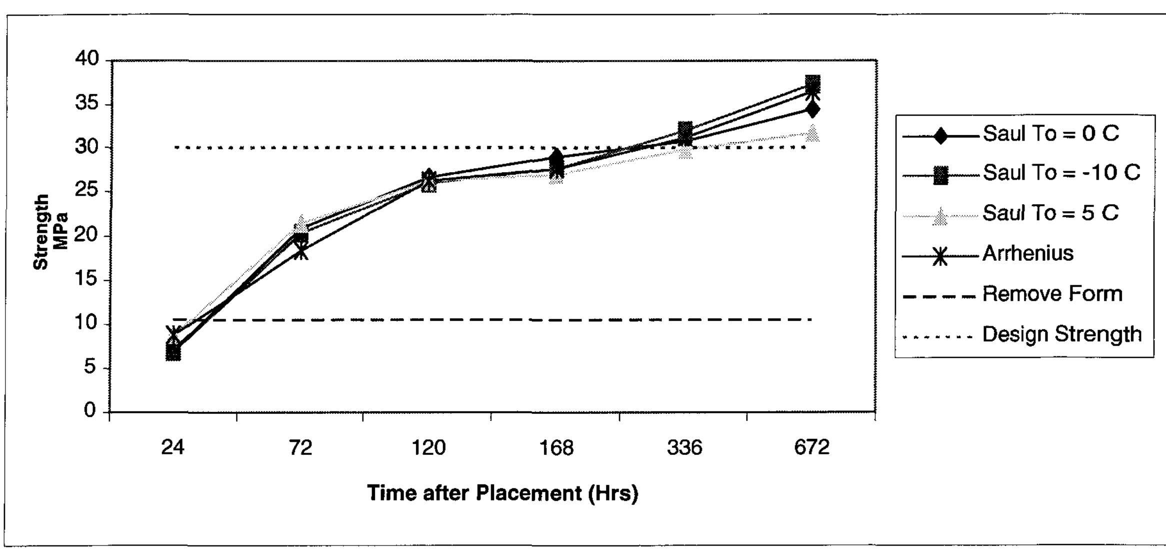

Figure 5.2 Datum temperature sensitivity analysis of vessel base

Based on the project specifications, for this non load-bearing component forms can be removed if concrete reaches strength of 10.5 MPa in 48 hours. Figure 29 shows that based on different methods of strength calculation, this concrete component gained enough strength for shoring and form removal in less than 48 hours. This is in accordance with the result from section 4.

Location V

For this concrete component, strength-development curve based on Saul and Arrhenius equations is represented in Figure 5.3. The results show that this location concrete component achieves form removal required strength in 48 hour except for Saul calculation with T_0 = 5°C. In this location, "Cross over" happened in the first few hours after hydration started. In addition, Saul calculation with T_0 = 5°C shows that concrete component does not reach required design strength after 28 days.

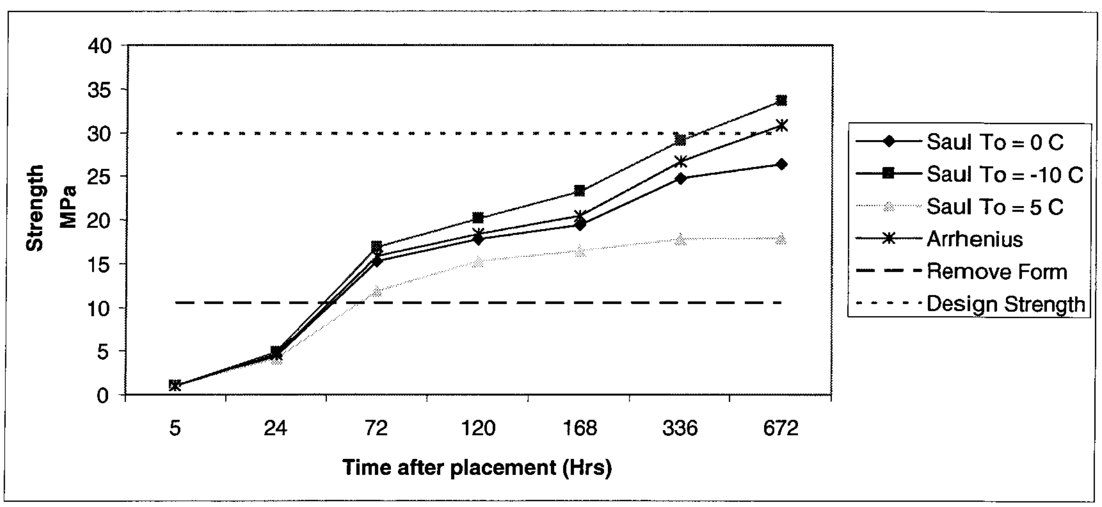

Figure 5.3 Datum temperature sensitivity analysis of substation paving slab

Locations VI, VII and VIII

Figures 5.4, 5.5 and 5.6 show strength-maturity curve for concrete components VI, VII and VIII respectively. In addition to the strength-maturity curve based on Arrhenius equation, these graphs show the effect of datum temperature on lower early-age and higher later-age strength calculation and demonstrate the "Cross over" behavior for each concrete component.

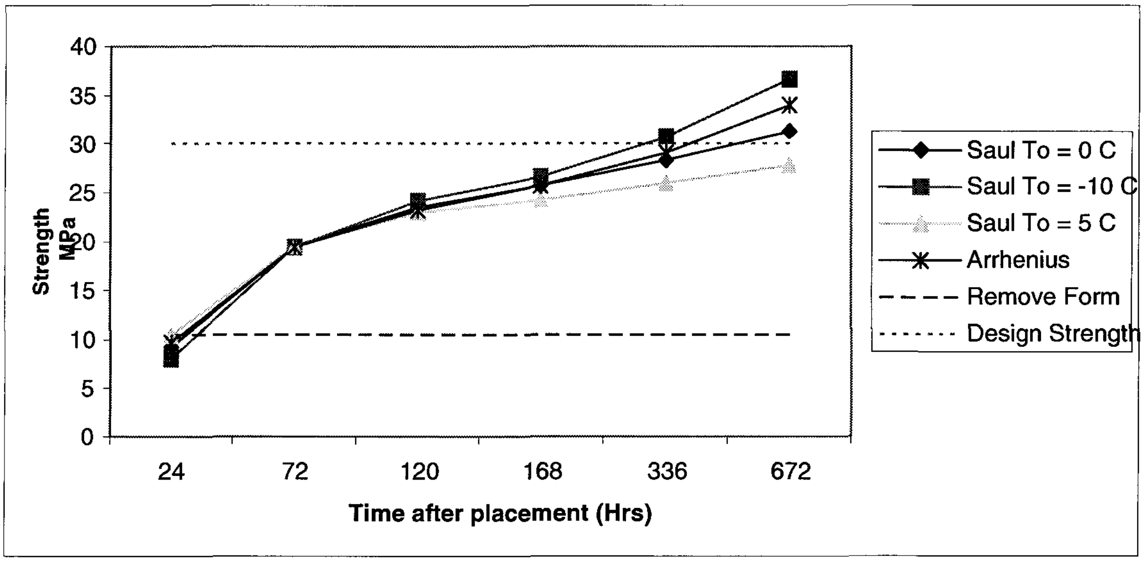

Figure 5.4 Datum temperature sensitivity analysis of steel structure base

For these non load-bearing concrete components, concrete reaches its required 10.5 MPa strength in less than 48 hours. In addition, in location VII concrete reaches its required strength in almost 24 hours regardless of calculation methodology or datum temperature value. These results indicate that previously calculated schedule savings remain the same.

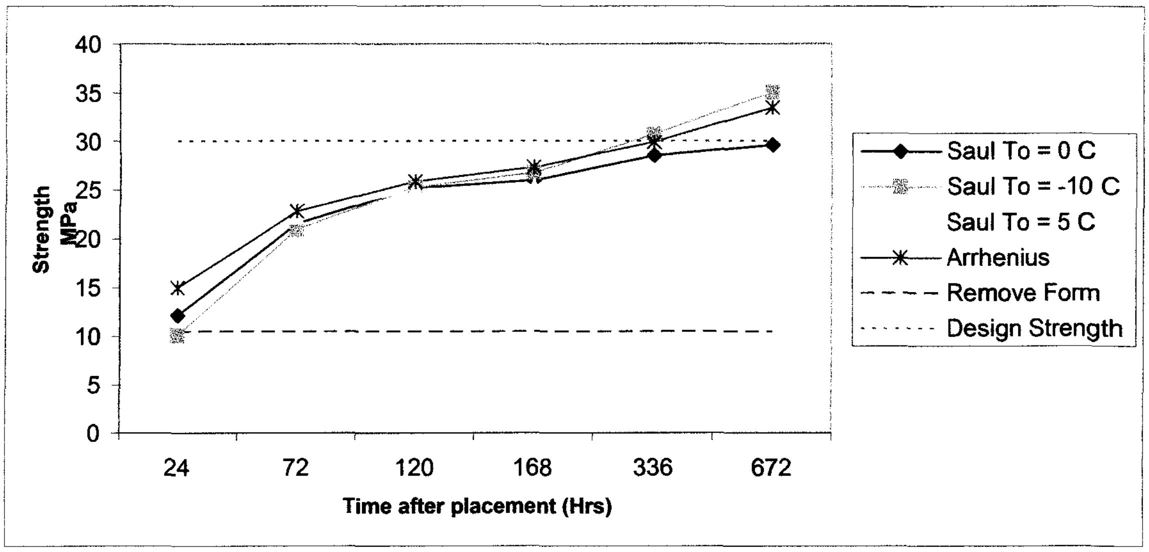

Figure 5.5 Datum temperature sensitivity analysis of exchanger structure pier

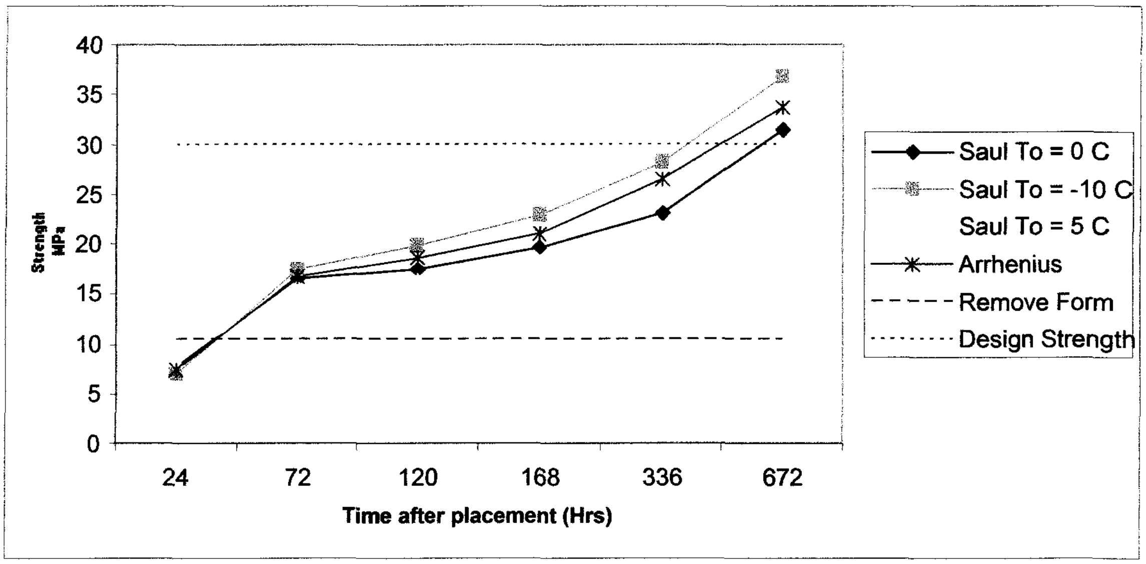

Figure 5.6 Datum temperature sensitivity analysis of building grade beam

Another observation is that for these concrete components, Saul calculation with datum temperature equal to 5°C, results in less than required design strength after 28 days (30 MPa).

Locations IX and X

In locations IX and X, calculation of concrete strength for Saul equation with different datum temperatures and the strength-maturity relationship based on Arrhenius equation are shown in Figures 5.7 and 5.8. The strength maturity results for these locations emphasis that both components achieved their required 20 MPa strength in three days or less. This is in compliant with both project specifications and schedule savings shown in the previous section. As well, these locations show the "Cross over" behavior based on different datum temperature calculations.

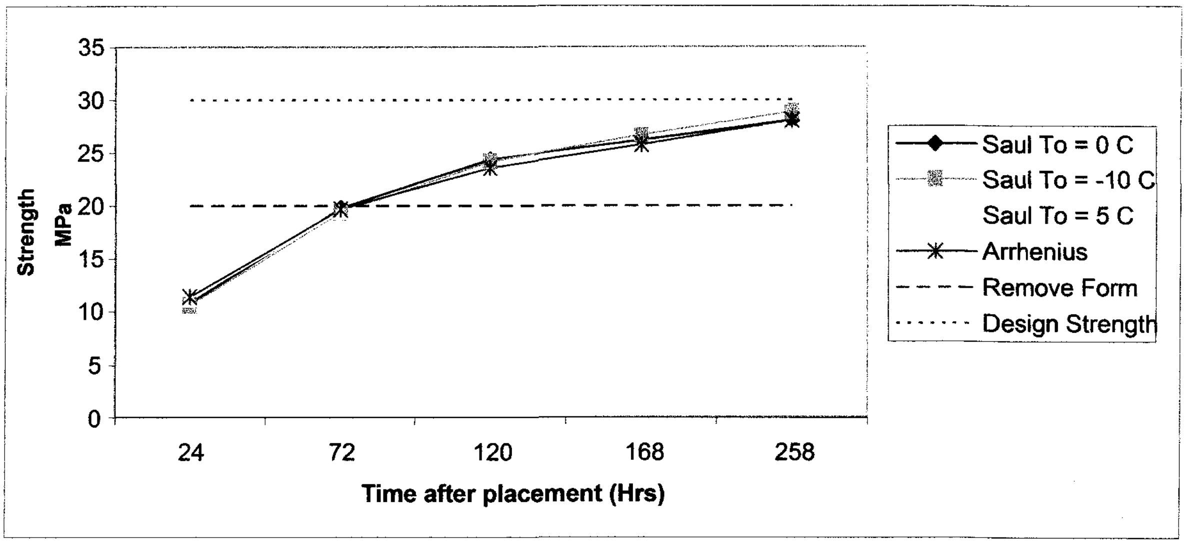

Figure 5.7 Datum temperature sensitivity analysis of vessel table top II

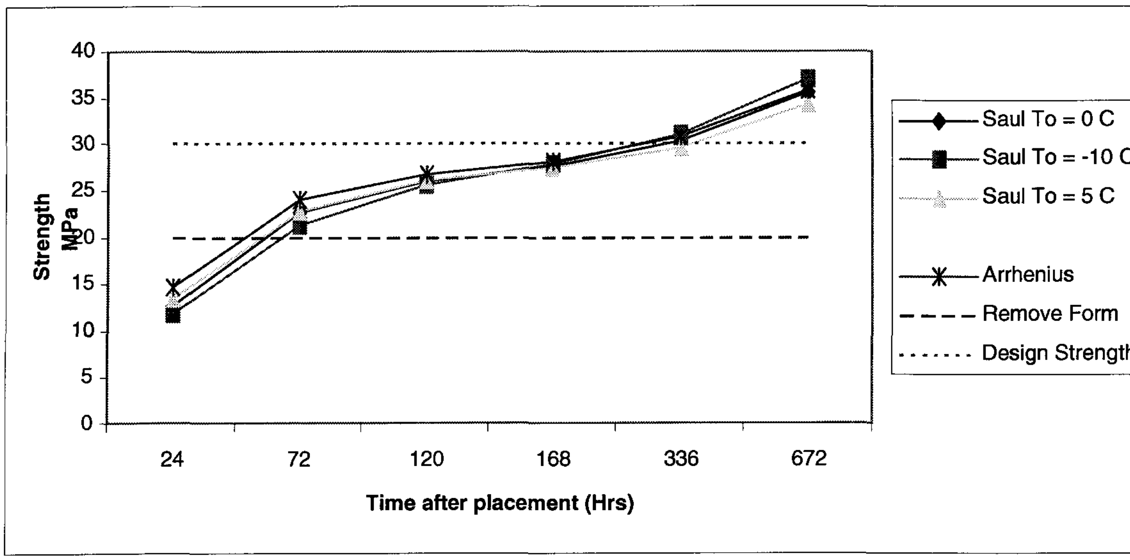

Figure 5.8 Datum temperature sensitivity analysis of the equipment table top

5.1 Sensitivity analysis results

Results of sensitivity analysis show that strength-maturity calculation based on Saul equation with different datum temperatures (-10, 0 and 5°C) will result in the "Cross over" behavior for the concrete components of this study. Besides, this sensitivity analysis shows that for calculation with datum temperature equal to 5°C, four locations (V, VI, VII and VIII) could not reach their required design strength (30 MPa) in 28 days. The reason is the definition of datum temperature. Datum temperature is defined as a temperature below which concrete hydration will stop. Looking at concrete temperature verses time graph of all eight components, one can distinguish that all components experienced temperatures below 5°C for a relatively long period of time after heating and hoarding was removed. This period of time is quite longer for locations V, VI, VII and VIII. So the concrete strength underestimation effect in later-ages is more than those in other locations. On the other hand calculations based on T_0 = -10°C show that in early ages the strength calculations are less than the values calculated with other datum temperatures or Arrhenius equation. So strength-maturity calculation with T_0 = -10°C is relatively conservative to measure the concrete strength in early-age curing. Therefore, shorings and forms could have been removed slightly later than timings acquired from strength-maturity curves with higher datum temperatures.

As a result, it is recommended that for concrete curing in cold weather, datum temperature value should be calculated based on ASTM C1074 procedure. If an assumption is required, datum temperature value is better to be -10°C or the minimum of average temperature of each concrete component (e.g. -6°C for location I and -5°C for location V). If the minimum temperature value is less than -10°C then curing procedure should be investigated.

In addition strength-maturity calculation based on Arrhenius equation is in accordance with the results from Saul equation. The significance of this finding is assurance for the values calculated based on these methods as they are compared with each other.

6.0 Conclusions

Based on observations during this study, it is believed that the concrete maturity method and current technology, such as that used in this study, can be a reliable accurate prediction of in-situ concrete strength on a continuous (real-time) basis during curing. Although the concrete maturity method was not the governing quality control procedure on the project observed in this study, it provided timely and accurate field concrete maturity information, which could potentially lead to significant time savings if the method were used as the governing quality control procedure.

Forms and Shoring- In this project, the subcontractor's quality control specification for load-bearing concrete components indicated that forms and shoring could be removed 28 days after concrete was poured. In form stripping requirements, it was assumed that the concrete would gain the required strength within 24 or 48 hours for the non-bearing components and within seven or 10 days for the load-bearing components. Findings from this study enabled the project general contractor to convince the concrete subcontractor to reduce the 28 days curing requirement for form and shoring removal of load-bearing concrete components to 14 days. As a result, actual form and shoring were removed after 14 days instead of 28 days on other load-bearing components.

Quality Control - The study results show that the concrete maturity methodology enables better quality control through the accurate estimation of in-place concrete strength. The real time information available through the concrete maturity method allowed the project to be proactive and ensure that the proper level of concrete strength was developed, yet still remove forms well ahead of the standard schedule.

Cost Savings - For each day of earlier removal of the forms, one day's worth of heating costs can be saved. The total heating energy required for all concrete components in this study was estimated to be 546.84 M-BTU under standard QC procedures. This calculation is based on an hourly heating requirement for each location multiplied by the one week (168 hours) of heating duration necessary according to the project specifications. Total energy needed for these same components based on the data obtained from the concrete maturity methodology would be 179.08 M-BTU if the maturity method were used as the primary Q/C procedure, resulting in an estimated savings of 367.76 M-BTU heating energy.

Heating and hoarding cost is a relatively small part of the total cost savings that could be realized using the concrete maturity method. The forms that become available from early removal can be used for other concrete activities in the project, or returned to the supplier, which results in savings in the shoring and forms rental cost per day. If the overall project duration is reduced, the supervisory and overhead costs of the project are also reduced. As mentioned previously, a 28% time savings could have been achieved if the concrete maturity method had been fully adopted. Therefore, the indirect cost savings equivalent to the 28% time reduction could have reasonably been expected.

Sensitivity analysis - For Saul equation a sensitivity analysis for datum temperature was implemented and the strength-maturity curves were compared with those from Arrhenius equation. This comparison showed that in this study, different calculation methodologies result in the same shoring and form removal schedule savings and overall schedule reductions.

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Appendix A

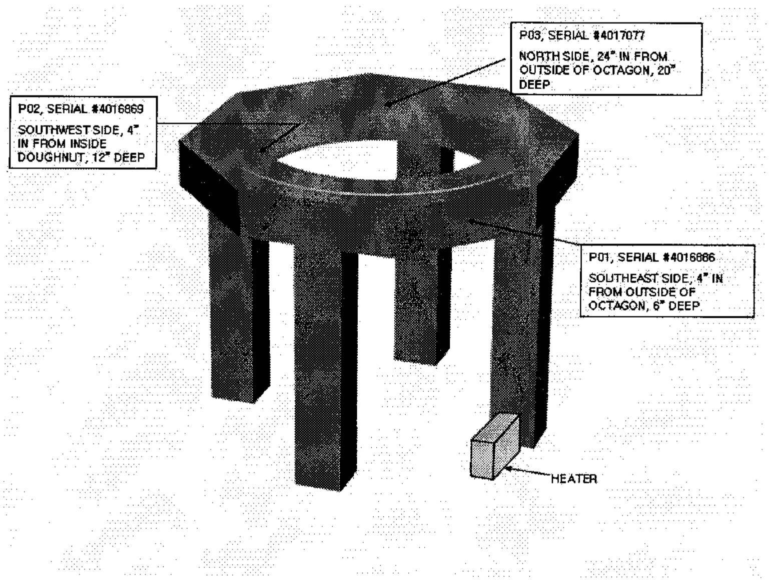

Figure A.1 Location I, Vessel Table Top

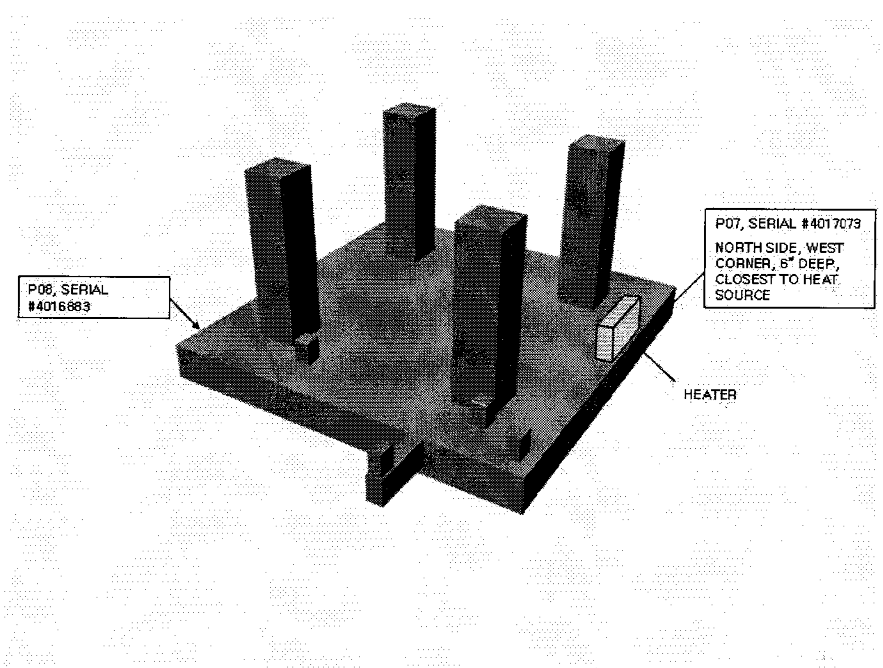

Figure A.2 Location III, Vessel Base

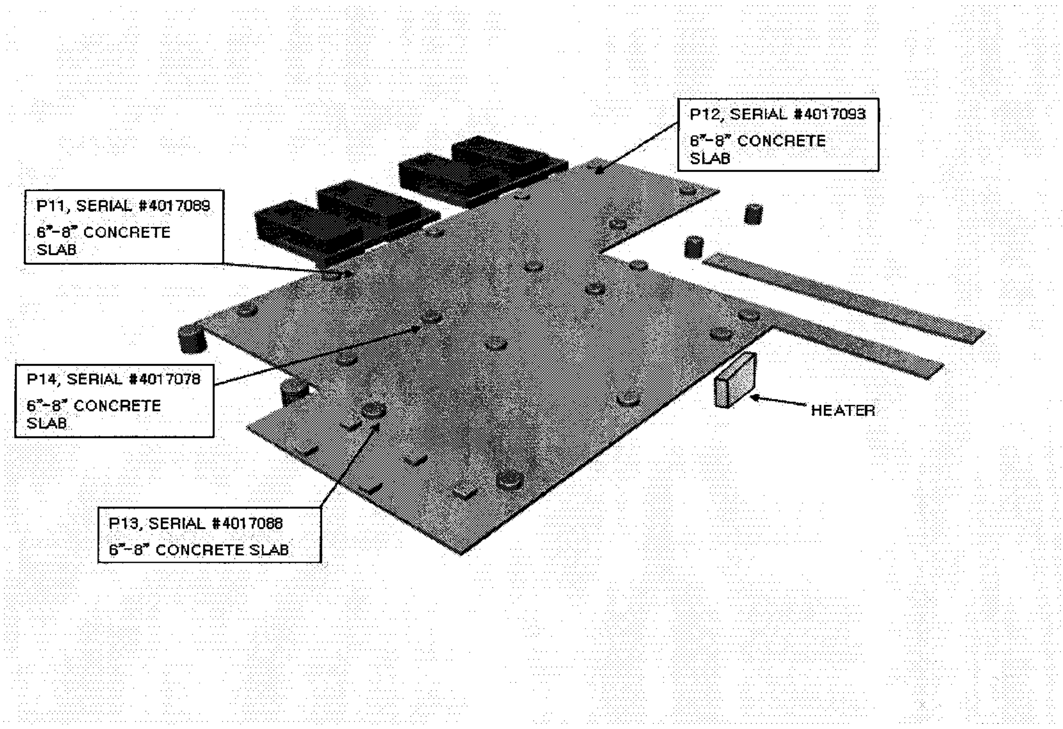

Figure A.3 Location V, Substation Paving Slab

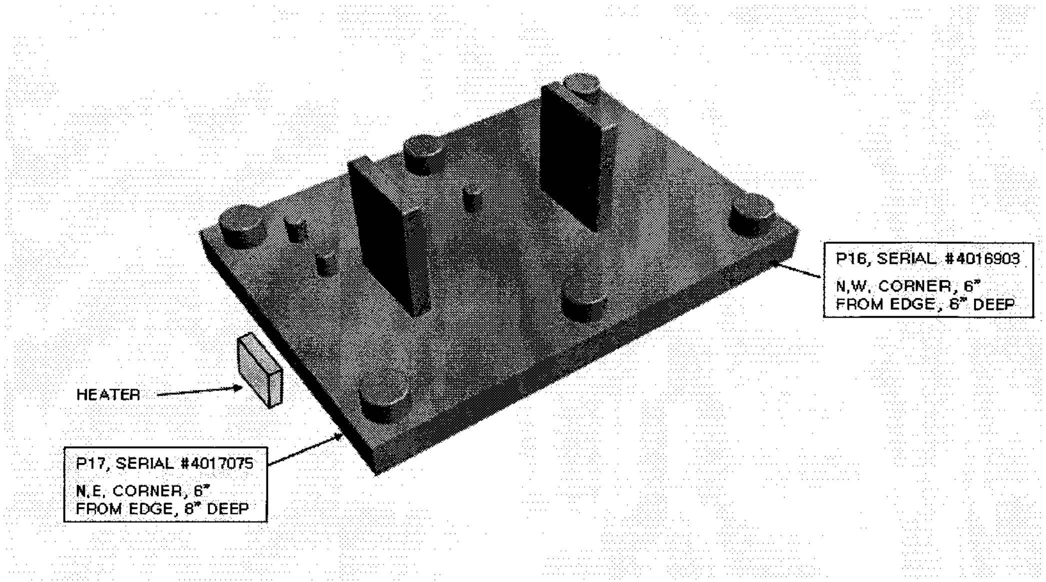

Figure A.4 Location VI, Steel Structure Base

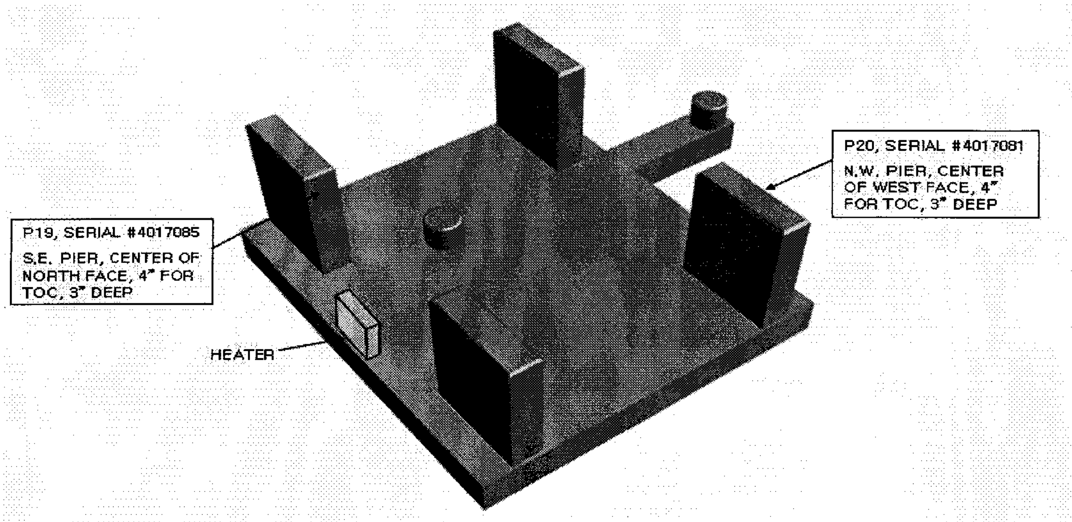

Figure A.5 Location VII, Exchanger Structure Piers

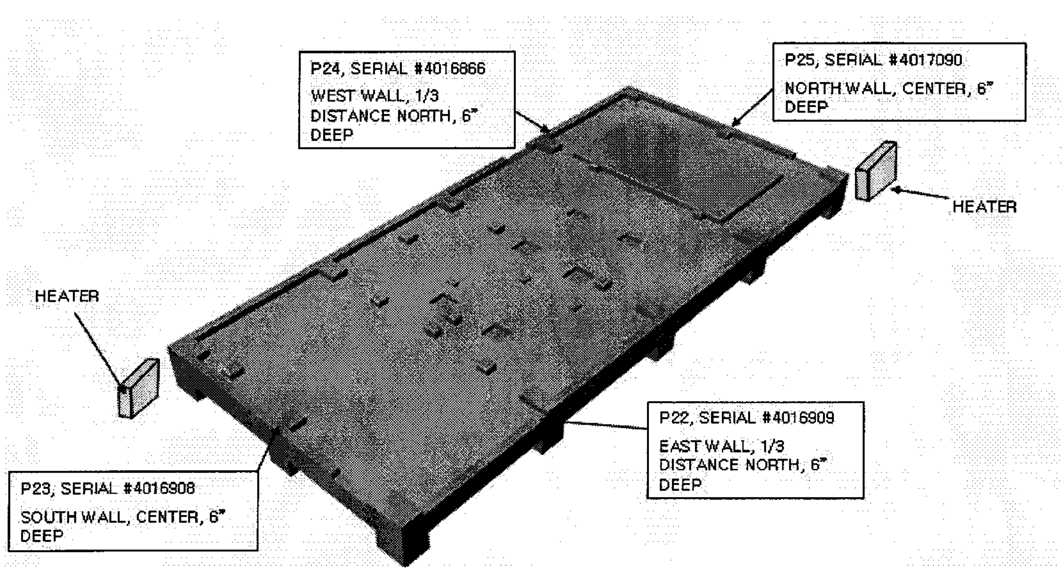

Figure A.6 Location VIII, Building Grade Beam

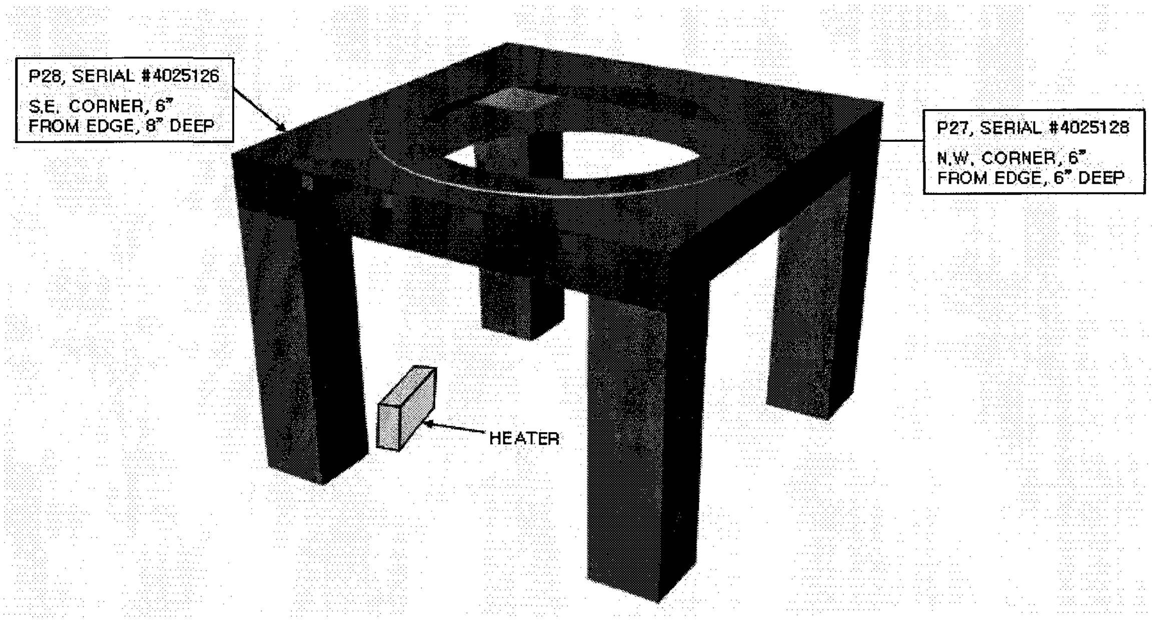

Figure A.7 Location IX, Vessel Table Top II

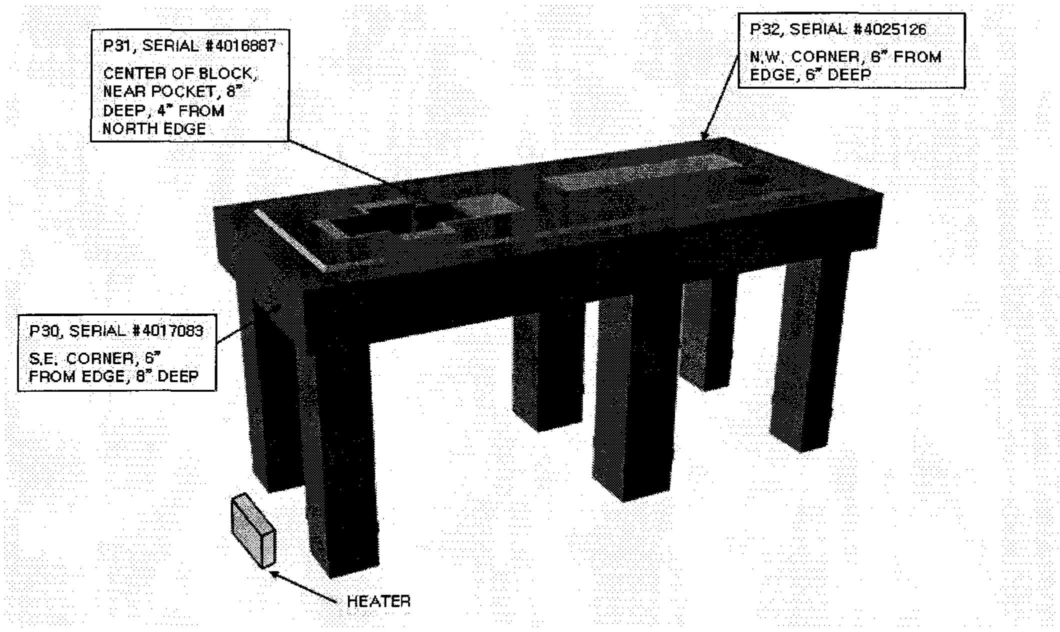

Figure A.8 Location X, Equipment Table Top