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Efficiency of Concrete Sensors and Maturity Method for Compressive Strength Prediction and Mass Concrete Placement

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Abstract

The monitoring of temperature after concrete placement using wireless sensors technology is one of the most promising methods that can provide results for concrete temperature, strength and maturity. These wireless concrete sensors measure the concrete properties as it dries and hardens and share the real-time data to a mobile phone app, which keeps records and provide infographic information. The data obtained from these smart sensors can be related to the project specifications and concrete mix design data that assist for early realizations of the structure integrity. As compared to conventional method, the new wireless sensor technology reduces delays in receiving test results and possibly will eliminate the need of collecting concrete cylinder for tests, saving transport and lab testing time and costs.

This paper presents actual utilization of the concrete sensors in mass concrete structures for monitoring the temperature to comply with the ACI 301-10 requirements. Also, it compares the concrete compressive strength result by using the maturity index for sensors with the conventional concrete crushing to verify their behavior, accuracy, and applicability for quality monitoring of concrete applications.

Keywords: Concrete Temperature; Wireless Concrete Sensors; Mass Concrete; Maturity Index

1. Introduction

The conventional concrete, which has been used as a main material in the construction industry for many years, is produced by mixing water, Portland cement, fine aggregate (sand) and coarse aggregate (particles of gravel or crushed stone). The mixing of these concrete constituents creates a hydration reaction that develops the strength progressively and the concrete mechanical properties are also evolved with time accordingly. Therefore, the heat of hydration demonstrates the change of fresh and hardened states. In project construction, the main acceptance criteria used for concrete is the compressive strength that is determined by crushing of cylinder samples at age of 28 days in reference to ASTM C39. However, the criticality of other concrete quality control tests and requirements may take the same importance depending on the structure types, mix design proportion, environmental conditions and the required properties.

Mass concrete defines by American Concrete Institute (ACI) as “any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from the hydration of cement and attendant volume change to minimize cracking” [1]. The thermal cracks are anticipated in case of heat of hydration developed at the center of mass structure maintaining slow rate of temperature dissipation, while the surface temperature is low due to the ambient weather. This result of the high temperature differential poses the ultimate risk to the designed life cycle of the structure. To avoid the cracks, ACI limits the allowable Maximum temperature difference between center and surface of placement not to exceed 19°C and requires development of a thermal control plan prior to the mass concrete placement. The plan should address the concrete mix design, the concrete placement conditions, and measures after concrete placement.

In the recent years, development and use of concrete temperature sensors for special applications have been reported. These sensors are easy to install and utilize while they improve concrete quality monitoring as; measure temperature in its fresh concrete state and the ambient, predict the in-place concrete strength by means of Maturity Method, graph and transmit the record readings in real time to mobile devices. The mentioned capabilities are offered with less human interference and can be used for considerable benefits in construction projects for instance, enhance curing conditions, optimize the timing of formwork removal and structure serviceability.

This paper presents a case study for utilization of concrete maturity sensors for construction of mass concrete foundations for compressors at one of Saudi Aramco gas plant projects in Saudi Arabia. The strength-maturity relationship was created in an accredit laboratory prior to the utilization of the concrete mixture. Then, the thermal control plan implementation and result are demonstrated. The concrete compressive strength predicated using the maturity methods and concrete sensors was compared and validated with data from the compressive cylinder test.

2. Case Study

The objective of this study mainly is to determine the effectiveness and accuracy of the temperature sensor when applied for the following;

- Monitoring the maximum temperature and temperature difference to address the resulting thermal stresses of mass concrete.
- Estimating concrete strength by Maturity Method and compare it with the conventional concrete strength testing method.

Where Maturity Method is a technique for estimating concrete strength based on the assumption that samples of a given concrete mixture attain equal strengths if they attain equal values of the maturity index. Wherein Maturity Index is expressed either in terms of the temperature-time factor or in terms of the equivalent age at a specified temperature [2].

It is noteworthy during Construction stage to plan and monitor the concrete's behavior, as the concrete strength develops after placement. These pose an important aspect to the quality assurance and construction project managements, when dealing with concrete strengths and critical construction timetables and that is the scenario for the construction of the mass foundations in this case study.

2.1 Deployment of Concrete Temperature Sensors to Mass Concrete Foundation at Gas Plant Project

Concrete placement was conducted for a mass foundation on Compressor Facilities in the gas plant project. The concrete sensors were utilized to monitors the developmental temperature rise and temperature difference between the center and the exterior surface after concrete placement. This was the first utilization of the temperature sensors for the project to comply with the mass concrete requirements as mandated by the client engineering standard and international standards, ACI 301 [3]. The subject compressor foundation falls under the requirements of a mass concrete due to its dimension, which measures as 17,350mm (Length) x 5,950mm (Width) x 3,740mm (Height) [4]. A Thermal Control Plan is required to be prepared and submitted following the requirements of ACI 301. The concrete temperature sensors were required to monitor and control the temperature from the time the concrete is placed until the center has cooled down from its maximum [1]. Because of these requirements, the project requested a third-party laboratory to provide temperature sensors and subsequent monitoring. As reported in the first compressor mass foundation No.1, the sensors recorded unexpected result and are bordering with the maximum limits, these necessitates to implement immediate mitigation measures as described in the thermal control plan as shown in figure 1.

Figure 1: Insulation, Water Curing and Shading as Mitigation Measure for Compressor Mass Foundation No. 1

2.2 Applications of Temperature Sensor

The used concrete sensor is a mobile-based wireless sensor called SmartRockTM as shown in figure 2 that was supplied and enabled a real-time reading along with continuous recording of the concrete structure temperature. A Quality Control and Quality Assurance tool that uses non-destructive test method and are easy to install and utilize while providing more improved concrete quality monitoring.

Figure 2: Wireless Sensor – Smart Rock™

2.3 Temperature Monitoring for Mass Concrete Structure

The primary objective of the thermal control plan is to address the increasing temperature and temperature difference, by not exceeding the maximum limits as directed by ACI 301 and SAES-Q-001 criteria for Mass Concrete;

- Maximum temperature of concrete after placement shall not exceed 158°F (70°C), and
- Maximum temperature difference between center and surface of placement shall not exceed 35oF (19°C).

Part of the Thermal Control Plan is the deployment of the mobile-based wireless sensors from an accredited third-party laboratory. The description and procedure shall at least clearly state, but not limited to the following [5];

a. Description of equipment and procedure that will be used to monitor and log temperatures and temperature differences.

b. Reference and criteria to be applied in monitoring concrete temperature.

c. Drawing for the location of temperature sensors.

d. Description of format and frequency of providing temperature data.

e. Appropriate and immediate mitigation measures to maintain control the temperature criteria.

The mass concrete requirement for monitoring and controlling the maximum and difference in temperature was implemented. As a minimum, temperature sensors were placed at the center of the mass placement and at a depth 2-inch from center of the nearest exterior surface. Additional sensors were placed in nearby shaded area to measure the ambient temperature and back-up sensors at each location within the concrete in case these sensors fail [5]. These sensors were identified and programmed in a mobile device, while the application can be downloaded and installed instantly. Other stakeholders or interested parties in monitoring the mass concrete can have their access to the same application to view and monitor, through the third-party laboratory.

2.4 Control of Concrete Temperature on the Compressor Mass Foundation No. 1

The foundation No. 1 Dimension are 17,350mm in (Length) x 5,950mm (Width) x 3,740mm (Height). The concrete temperature monitoring started for the foundation on October 29 up to November 04, and was recorded by the third-party laboratory [6]. Six (6) wireless sensors were installed at three locations of the foundation, as shown in figure 3, that is two sensors per location designated as top and center. In addition, one for the ambient temperature that was placed in a shaded area. These sensors were linked by the third party to the mobile application, monitored and was subsequent reported to the project stakeholders.

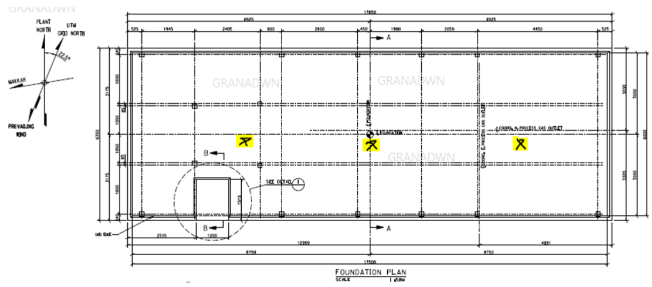

Figure 3: Locations of Sensor for the Compressor Foundation No. 1 [2]

The temperature was recorded up to 308 readings in each point at 30 minutes interval for all locations and presented in the third-party report [6]. In the monitoring record, as shown in figure 4, the temperature started to have significant temperature difference at Point#2 (21.02°C) and Point#3 (25.47°C) on the third day from concrete pouring date, where additional insulations were applied to reduce the temperature. It continued for three to twenty-four hours, respectively. Although the recorded maximum temperature did not reach the specified maximum limit (70°C), the result is bordering (68.48°C). The investigation showed that these temperature differences occurred due to the delay in applying the planned mitigation measures, mainly the insulation of the mass foundation before it reaches the specified limit.

Compressor Mass Foundation No. 1	Point-1 (Top)	Point-1 (Center)	Point-2 (Top)	Point-2 (Center)	Point-3 (Top)	Point-3 (Center)
Highest Temperature Reading °C	55.67	68.16	56.59	68.48	53.89	67.84
Date & Time Reading Attained	11/1/2020 6:46	11/1/2020 19:44	11/1/2020 7:09	11/2/2020 5:09	11/4/2020 5:15	11/2/2020 8:15
Maximum Temperature Differential °C	18.6		21.02		25.47	
Date & Time Reading Attained	10/30/2020 5:46		11/1/2020 17:09		11/1/2020 16:46	

Figure 4: Temperature Report on Compressor Foundation No. 1 [6]

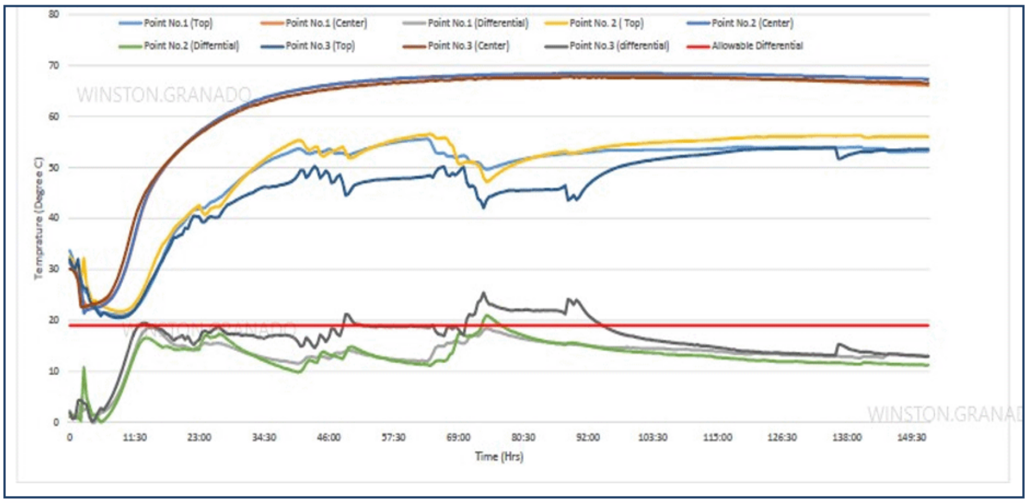

Figure 5: Temperature Report on Compressor Foundation No. 1 [6]

The succeeding concrete placements for similar Compressor Foundations (2 and 3) were notably in compliance with the temperature requirements for mass concrete. These results, as shown in figure 6 and 7 are due to the lessons learned from the similar foundation#1, were the thermal controls (e.g. 4inch Insulation, Tarpaulin, and continuous water curing) was immediately in-place and the ambient temperature that day was supportive.

3. Estimating Concrete Strength by Maturity Method

3.1 Estimating Concrete In-Place Strength for Facilities Foundation

Strength - Maturity relationship, which is an empirical relationship between concrete strength and maturity index is obtained by testing specimens whose temperature history up to the time of the compressive test has been recorded.

The Strength-Maturity Relationship was conducted for the project calibration utilizing the standard practice for estimating Concrete Strength by the Maturity Method - ASTM C1074-19, through a Third-Party Laboratory. Eighteen (18) Concrete Cylinders were prepared by the Third-Party laboratory as representative samples with Two (2) being placed with temperature sensors following the standard method. The successful practice of the standard method resulted in the development of the report of the strength-maturity relationship [6].

3.2 Strength – Maturity Relationship

The Strength – Maturity relationship was developed utilizing the mix design in figure 8, with eighteen (18) concrete specimens and a pair of sensors that records the temperature at specified time with concrete compressive strength testing, as presented in figure no. 9. The recorded data of Strength – Maturity relationship was then plotted to a curve as revealed in figure no. 10 presenting the (±10%) limits, which is an indicator that if the difference consistently exceeds the limits a new strength-maturity relationship is to

Compressor Mass Foundation No. 2	Point-1 (Top)	Point-1 (Center)	Point-2 (Top)	Point-2 (Center)	Point-3 (Top)	Point-3 (Center)
Highest Temperature Reading °C	64.46	69.2	65.11	68.9	64.56	68.98
Date & Time Reading Attained	11/15/2020 9.45	11/16/2020 14:00	11/15/2020 2:00	11/16/2020 9:30	11/14/2020 3:15	11/16/2020 15:15
Maximum Temperature Differential °C	14.84		14.12		12.67	
Date & Time Reading Attained	11/13/2020 6:45		11/12/2020 22:30		11/15/2020 9:15	

Figure 6: Temperature Report on Compressor Foundation No. 2 [6]

Compressor Mass Foundation No. 3	Point-1 (Top)	Point-1 (Center)	Point-2 (Top)	Point-2 (Center)	Point-3 (Top)	Point-3 (Center)
Highest Temperature Reading °C	68.15	58.63	67.75	59.7	67.84	59.4
Date & Time Reading Attained	11/26/2020 5:30	11/24/2020 10:15	11/25/2020 22:00	11/24/2020 10:30	11/26/2020 11:45	11/25/2020 10:15
Maximum Temperature Differential °C	17.95		16.32		14.95	
Date & Time Reading Attained	11/27/2020 14:15		11/27/2020 13:45		11/22/2020 23:45	

Figure 7: Temperature Report on Compressor Foundation No. 3 [6]

Concrete Properties per Cubic Meter

Source Name : Ready Mixed Concrete, BP No. 1 LUP,

Mix ID No. : TAN (1)-32V-03

Compressive Strength : 32 Mpa (4640 Psi)

No.	Materials	Quantity	Remarks
1	Cement (Kg.)	370	Type V
2	3/4" Aggregate(Kg.)	680	Crushed
3	3/8" Aggregate(Kg.)	430	Crushed
4	Sand (Kg.)	750	Natural
5	Water (Kg.)	84	
6	Ice Flakes (Kg.	60	
7	Admixture 1 (L)	2.11	Type F, Superplasticizer
8	Admixture 2 (L)	2.78	Type A, Retarder
9	Water Cement Ratio	0.39	

Figure 8: Mix Design Properties [7]

be developed [2]. The resulting curve is used to estimate the concrete compressive strength to allow the safe removal of formwork or reshoring's and a subsequent passage of new activities.

Date	Time (hr:min)	Time Interval	Specimen 1		Specimen 2		Specimen 1&2Average		Strength (PSI)			Average (MPA)
			Average Conc Temp (°C)	TTF (°C.hr)	Average Conc Temp (°C)	TTF (°C.hr)	Average Conc Temp (°C)	TTF (°C.hr)	1	2	Average (PSI)	
11/12/2020	5:40 PM	0	31.1	-	32.95	-	32.03	-	-	-	-	-
11/13/2020	5:40 PM	24	27.33	655.92	26.78	642.72	27.06	649.32	3289	2911	3100	21.4
11/15/2020	5:40 PM	72	23.61	1699.92	23.63	1701.36	23.62	1700.64	5197	6040	5978.5	41.2
11/19/2020	5:40 PM	168	22.55	3788.4	22.6	3797.8	22.58	3792.6	6479	6361	6420	44.3
11/26/2020	5:40 PM	336	22.18	7452.48	22.34	7506.24	22.56	7479.36	6262	6151	6206.5	42.8
12/10/2020	5:40 PM	672	22.43	15072.96	22.51	15126.72	22.47	15099.84	8173	8931	8552	59

Figure 9: Data for the Strength and Maturity (Temperature-Time Factor)

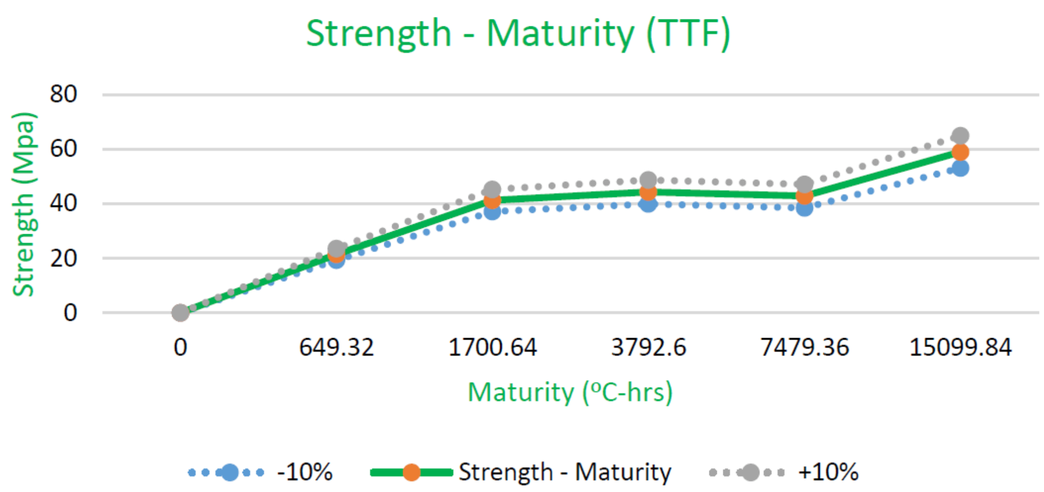

Figure 10: Strength – Maturity Relationship Curve with Limits

3.3 Estimate In-Place Strength

The estimates of the in-place compressive strengths of concrete have used the Maturity Method, that assumes that samples of the given concrete mixture attain equal strength, if they attain equal values of the maturity index [2]. In this case the maturity index (°C – hrs) was figured in using one of the maturity functions the "Temperature-time Factor (TTF)" from the measured temperature history of the concrete. The Maturity Index shall be then encoded to the maturity instruments, while the temperature sensors shall be imbedded to the structure before concrete placements.

3.4 Effectiveness and Accuracy of Maturity Method in Determining Compressive Strength Test Results

The measured strength for the early-aged of field-molded cylinders are compared with the strengths estimated from the established strength-maturity relationship and maturity index of the test cylinders. These cylinders were subjected to standard curing in compliance to ASTM C31 Standard Practice. However, if the variance consistently exceeds 10 %, a new strength-maturity relationship is to be developed [2]. In this report, the ongoing concrete placement to foundation no. 4 equipment foundation was used to validate the effectiveness of the Maturity Method. Due to the volume of concrete placed to foundation no. 4, a minimum of four (4) sets of cylinders were sampled by the third-party laboratory, as shown in figure no. 11. The cylinders were tested in accordance ASTM C39 and were then compared with average strength from the Maturity of the ongoing project. As shown in the figure no. 11 comparison, the variation of these two methods is 1.6% which is within an acceptable variance of 10%.

4. Comparison of Conventional Test (ASTM C39) and Estimates Using Maturity Method (ASTM C1074)

Additional comparison test was conducted for the on-going concrete placement of the project to concrete pedestals (1.0m x 1.2m x 2.0m) to validate the effectiveness of the Maturity Method, utilizing similar maturity index, practice and test methods. As shown in the figure 12, the variations are much acceptable (2.9%) in early stage of 7days but increased in the later stage.

Set No.	7 Days compressiveStrength of Concrete Cylinder (Mpa)	Average Strength from Maturityof ongoing project (Mpa)
1	43.5	52.85
	42.5	
2	59.7	
	58.6	
3	53.3	
	52.1	
4	53.1	
	53.3	
Average	52.01	
Difference	0.84 Mpa	
Variation	**1.6 %**	

Figure 11: Data Comparison for the Strengths of Molded cylinders and Maturity Index

5. Discussion

The application of the temperature sensors to mass concrete structures have positively supported the construction team in attaining compliances to standard requirements and promotes quality assurance in avoiding the adverse effects of heat of hydrations. The sensors have successfully demonstrated its capability to provide the following information's in conjunction with the standard requirements [5];

Module	Test Aged (Days)	Test Method	Result (Mpa)	Difference (Mpa)	Variation(%)
4	7	ASTM C39	48.2	1.4	2.9
	7	ASTM C1074	49.6		
	28	ASTM C39	55.0	6.4	11.6
	28	ASTM C1074	61.4		
6	7	ASTM C39	49.0	0.1	2.9
	7	ASTM C1074	48.9		
	28	ASTM C39	56.3	4.9	8.7
	28	ASTM C1074	61.2		

Figure 12: Data Comparison for the Strengths of Molded cylinders and Maturity Index

1. The capability to measure and record the developmental temperature rise and temperature difference between the center and the exterior surface after concrete placement.

2. Timely reporting of temperature readings, wherein the readings has been programmed to 15 minutes close intervals for seven days while the standard requirement is every hour.

3. The sensor is capable to measure readings from -30oC (-22oF) to 80oC (176oF), while the requirement is 0.00oC (32oF) to 100oC (212oF) [8].

4. The accuracy of temperature readings to 0.1oC [8].

5. The sensor can monitor temperatures up to seven (7) days or more, hence it is required only to monitor concrete until the requirements are met, which is utmost on the fifth day.

6. Only Two (2) sensors has been monitored inoperational out of hundreds of sensors installed in the project. [6]

Furthermore, the reports generated by the wireless sensors shows a graft representation for the best-fit curve to the readings that gives continuous real-time concrete temperature statistical data, that is supplemented by being handy with flexibility thru mobile devices, for Contractor to perform appropriate and immediate actions. The used of wireless sensor found to be effective to better anticipate and plan for mitigation measures on critical developmental stages before exceeding the requirements, which was reflected in the third-party reports [6]. It can be noticed from figure no. 5, that the temperatures are increasing rapidly from first to second day, and it reaches the peak in the third day. It is then started to decrease on the fifth day while the monitoring extends up to sixth day. The resulting concrete data's during the trials between the conventional compressive strength test (150 by 300mm cylinders) and maturity method when compared shows significant accuracy (1.6%) when validated to the acceptable variance of 10% [2]. It is also imperative to mentioned that the resulting variations in this study is almost negligible, when compared with the variation result that was conducted thru multi-laboratory precision (14%) using only conventional method per ASTM C39.

The establishment of the strength-maturity relationship of the concrete mixture that can be used to estimate the concrete compressive strength, open doors of significant contributions to construction team, that shows promising result when use with established test records and utmost accuracy to the details of the test parameters. The estimate of the in-place concrete strengths of intended structures using maturity method was found significantly effective to the following considerations;

1. Timely notification of concrete data at site, as an advance and in-place condition,

2. Safe removal of shoring's and formworks,

3. Opening passage for a subsequent or new construction activities, and

4. Can monitor critical and specific location of concrete member

6. Conclusions

The temperature wireless sensors have shown significant evidences of accuracy and effectiveness for monitoring the temperature development stages of a mass concrete structure. It is not just conforming to standard requirements and specifications set by ACI 301 and ASTM C1074, but exceeds the expected precision from conventional methods, when use as quality control tool part of a thermal control plan in addressing the effects of heat of hydrations. While it is also highly accessible in gathering concrete data to better construction planning.

Furthermore, the maturity method was also useful to estimate the in-place concrete strengths of these structures. However, the limitations of Maturity Method were noted including the in-place Compressive Strength Test that is specific only to Mix designs. Also, the variation slightly differs (1.6% - 2.9%) when maturity index is used to unequal size of structures. It is accurate mostly at the early age (7 days) of concrete and the estimate can be influenced, as time pass, by external factors e.g. weather, structure dimension, and curing method. Furthermore, when maturity method is used to estimate the in-place strength of concrete for the critical concrete operations, it is recommended to place the sensors in the critical locations such as the exposure conditions and structural designs.

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