

# A CASE STUDY ON MEASUREMENT OF TEMPERATURE RISE IN CONCRETE AND ASSESSMENT OF PROBABILITY OF CRACKING DUE TO HEAT OF HYDRATION

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## Abstract

Experimental study was carried out to investigate the temperature rise characteristics of the concrete used in a prototype component of foundation for Interchange station of Nagpur Metro Rail Project, Nagpur, Maharashtra State. The actual temperature rise was measured by embedding Thermo Couples – Resistance temperature detector (RTD) in the prototype structure during concreting. The measurements were taken at 5 locations in the component – a pile cap by inserting 3 thermo couples (TC's) at each location totaling to 15 in all. The monitoring of temperature recorded by thermocouples was done by digital recorder manually on hourly basis up to 13 days and then once in 3 hrs. up to next 21 days and beyond but restricted to 14 days in this reporting. The temperature at the time of insertion i.e. initial/starting temperature was noted and maximum temperature reached, the time to reach peak temperatures was recorded. The plot of time-temperature demonstrated the actual temperature rise, its trend both increasing and decreasing. The derived temperature rise equations with strong correlation coefficient “r” values could be used to predict the early age temperature rise in structures with similar geometry, concrete, weather conditions, curing and form removal.

Another purpose of this study is to know the probability of cracking based on the existing cracking assessment based on Korean methods as Indian specifications are non-existent and also to find the crack index for internally restraint cases based on temperature difference, both the elastic; hypoelastic models. The study indicated that the existing provisions based on crack index appear to be very conservative which tend to overestimate the probability of crack occurrence compared with construction observations on prototype structures.

**Keywords:** - Heat of hydration, maximum temperature, temperature gradient, crack index, internal restraint.

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## 1. INTRODUCTION

ACI 116 2005{1} Manual of Concrete Practice defines Mass Concrete as “any volume of concrete with dimensions large enough to require that measures be taken to cope with the generation of heat from the hydration of cement and attendant volume change to minimize cracking. ACI Committee 207.1R 2005{2} and RILEM Tech. Committee {16} give useful guidance in respect of thermal control plan and cracking in mass concrete. ACI Committee 224.R 2001{4} contains recommendations regarding crack control in mass concrete. The most important characteristics of mass concrete is thermal behavior. When cement is hydrated, the compounds react with water to acquire stable low-energy states, and the process is accompanied by the release of energy in the form of heat, Mehta 1999{13} this is an exothermic reaction and a large amount of heat is generated during the hydration process in

mass concrete elements. Since concrete has low conductivity, a great portion of generated heat is trapped inside the mass concrete and is dissipated slowly. This situation leads to a temperature increase inside and a temperature difference between the center and outer part of mass concrete element. The literature shows that the factors most relevant to cracking in massive structures are thermal stresses induced by thermal gradients - ACI 207 2007{3}. The heat generated causes a rise in temperature of concrete. If this rise occurred uniformly throughout a given concrete element without any external restraint, the element would expand until the maximum temperature has been reached. The concrete will then cool down with uniform contraction as it loses heat to the ambient atmosphere, this uniform expansion and contraction will result in no thermal stresses within the concrete element. According to Neville 1996{14}, restraint exists in all but the smallest of concrete members. The thermal restraints result in external

and internal cracking of concrete. Fig.1 below shows as example of temperature change (while cooling) which causes external thermal cracking of large concrete mass. The critical 20°C (35°F) temperature difference occurs during cooling - FitzGibbon 1976{9}

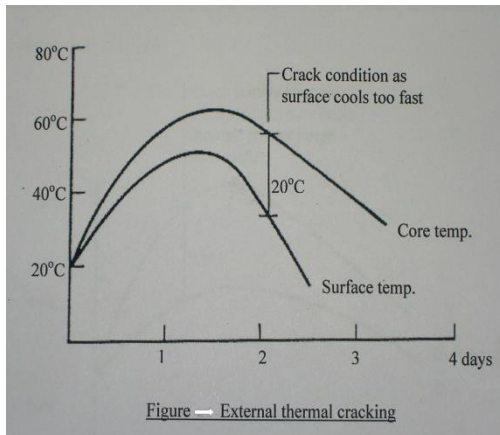


Figure 1: External thermal cracking

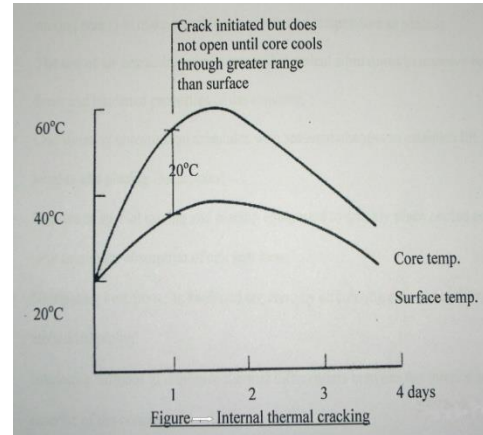


Figure 2: Internal thermal cracking

In massive concrete structures, internal restraint occurs from the inability of the heat to dissipate quickly from the core of the member due to the low thermal diffusivity of the concrete. A temperature differential is set up between the core of the concrete and the surface. The unequal thermal expansion in the various parts of the concrete member results in stresses, compressive in one part and tensile in the other. According to FitzGibbon 1976{9}, the cracking strain of concrete is reached when an internal thermal differential of 20°C (36°F) is exceeded. Fig. 2 above shows a pattern of temperature change (which occurs during heating), which causes internal cracking of a large concrete mass. Cracking due to thermal behavior may cause loss of structural integrity and monolithic action or may pave way for extreme seepage and shorten the service life of the concrete structure.

To avoid concrete surface cracking caused by heat generated in the concrete, European standard ENV206:1992{8} suggests that the limit on the maximum temperature difference between the centre and the surface is 20°C (36°F).

Common thought is that mass concrete principles only apply to large dams, but they apply to any large pour such as massive foundation, bridge piers, thick slabs, thick columns, retaining walls etc. Panarese 2003{15} postulated that when dimensions of concrete structures are more than 1 m, temperature rise shall be considered. As per ACI 301 2005{5} "Specifications for Structural Concrete" in general, heat generation should be considered when minimum cross-sectional dimensions approach or exceeds 760 mm or when cement contents above 356 Kg/m<sup>3</sup> are used.

## 2. RESEARCH SIGNIFICANCE

A large amount of research has been carried out aimed at controlling and minimizing early age cracks in concrete. The heat of hydration of concrete has been one of the most important issues investigated. There are many criteria for assessment of the hydration heat induced cracks. Some provisions adopt temperature-based assessment as well as stress-based assessment. Temperature based assessment has been frequently employed in practice to approximately decide the probability of occurrence of cracks based on the temperature difference, as temperatures can be readily assessed by field measurements as well as analysis and the reliability of temperature measurement is significantly higher than that of stress measurements. Consequently, The purpose of this study is to know the probability of cracking based on the existing cracking assessment based on Korean methods and also on the crack index for internally restraint cases both the elastic; hypoelastic models and practical consideration developed by Se-Jim Jeon and reported in ACI materials journal 2008{12}.

The temperatures recorded are the temperatures wherein the effects of exothermic reaction of hydration of cement and all the atmospheric effects such as radiation; convection, conduction so also the thermal properties of concrete have contributed in one way or the other and resultant is the temperatures actually measured. Hence, this study can be used, in future, to compare and validate the results of thermal analysis and modeling that can predict the temperature distribution and the thermal stresses resulting from thermal gradients within the structure.

### 3. REVIEW OF PROVISIONS REGARDING CRACKING ASSESSMENT

In the US the ACI guides namely ACI 207.2R-2007{3} and ACI 305 R {6} do not provide any specific criteria for cracking induced by the heat of hydration.

In Europe, as per CEB-FIB 1993 {7} crack risk criteria and various temperature difference criteria have been employed together in some large projects like Ores and tunnel.

Standard specification in Korea, as per Korea Concrete Institute 2003{12} and in Japan, as per Japan Concrete Institute 1986{10} adopt the crack index based on the splitting tensile strength of concrete and the tensile strength all of which are time dependent and can be obtained by thermal stress analysis. The Korean Standard Specification for Concrete 2003{12} however present simplified form of crack index as a function of temperature and for internally restrained case given by the equation,

$$I_{cr} = \frac{15}{\Delta T_i} \quad \text{-- equation (1)}$$

Where  $\Delta T_i$  = maximum temperature difference across the section in °C

Based on crack index, the crack probability relationship is as shown in Figure 1; which can be used to assess the cracking index and cracking criteria.

The following criteria is specified:

Criteria	$I_{cr}$ Value
to prevent cracks	$I_{cr} > 1.5$
to limit cracks	$1.2 > I_{cr} < 1.5$
to limit harmful cracks	$0.7 > I_{cr} < 1.2$

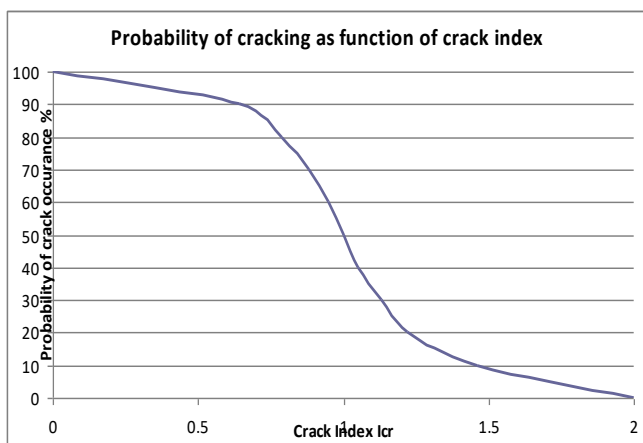


Fig 3: Crack probability relationship and cracking criteria.

The temperature difference across the section is the primary information required for the evaluation of the tendency of crack to form induced by the internal restraint.

As derived and reported by Jeon, 2008{11} the crack index for internally restraint cases for elastic model is given by the equation,

$$I_{cr(e)} = 15.4 / \Delta T_i \quad \text{-- equation (2)}$$

and this equation is valid near the peak temperatures when the maximum temperature difference occurs within 3 days after placing. Since elastic crack index depends only on the maximum temperature difference only and does not take into account the pattern of development of heat hydration, the member size, curing conditions, the form removal, the hardening properties of concrete etc. a more realistic hypoelastic model is also developed by Jeon, 2008{11} and is given by the equation,

$$I_{cr(h)} = 25 / \Delta T_i \quad \text{-- equation (3)}$$

### 4. THE EXPERIMENTAL PROGRAM AND SCHEME OF STUDY

The experimental program in the study was to measure and monitor the temperature rise in concrete prototype component - a pile cap of foundation for Interchange station of Nagpur Metro Rail Project, Nagpur, Maharashtra State. The temperature measurements were done by inserting an array of thermo couples at different locations and levels. The thermo couples used were PT100. The positions of thermo couples were as shown in figure 4 and figure 5.

The Location Plan, Plan and cross section of Pile cap showing the locations of thermo couples are as per Figs. 4, 5 and 6 respectively.

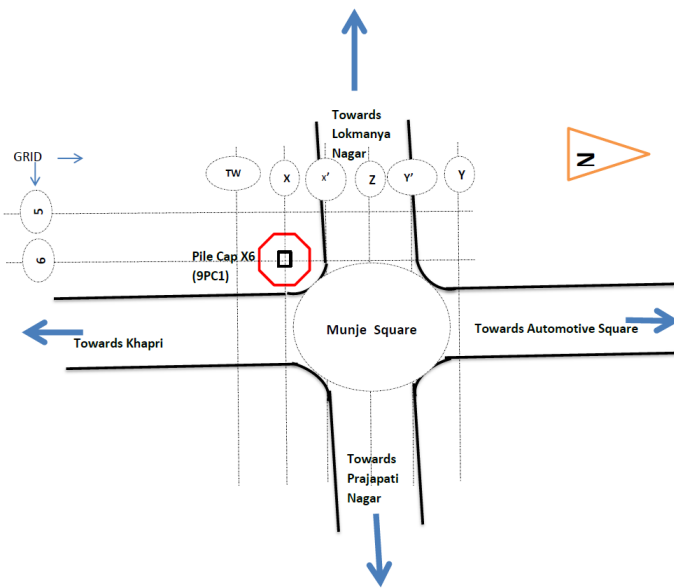


FIG -1. LAYOUT PLAN OF SITABULDI INTERCHANGE STATION

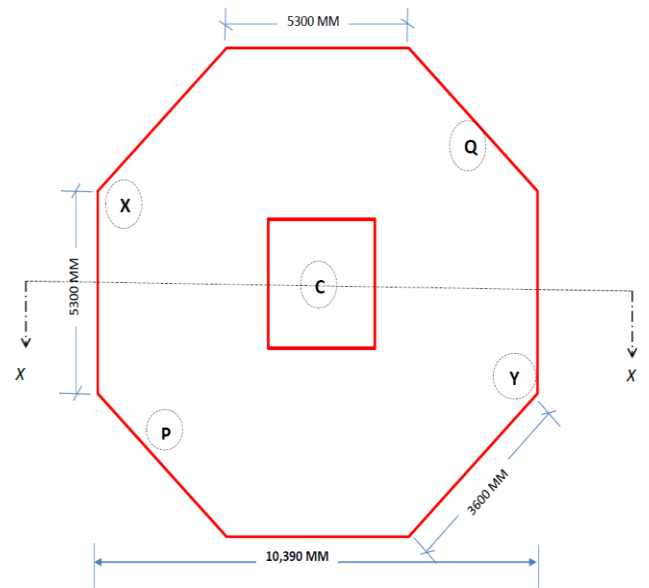


FIG-2. PLAN- PILE CAP X6 (9PC1)

Fig 4: Location Plan Fig 5: Plan of Pile cap

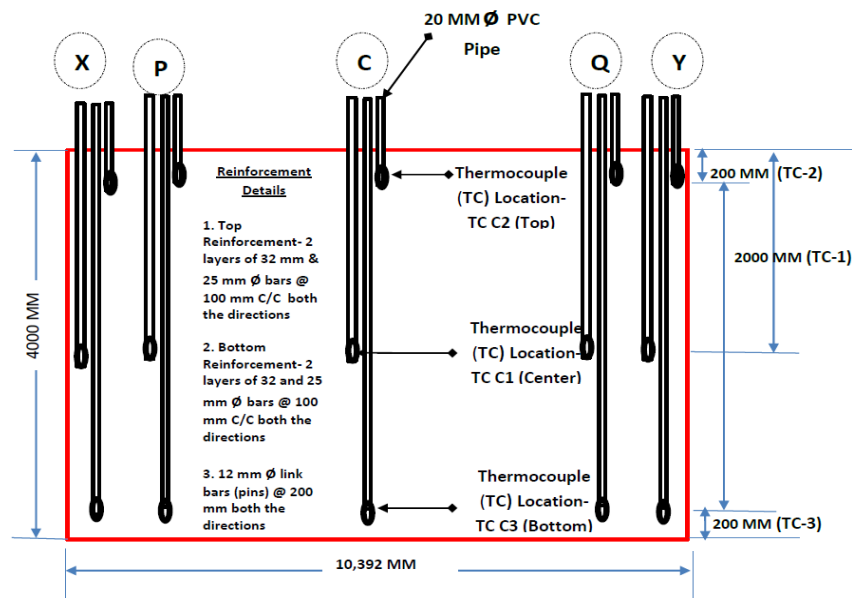


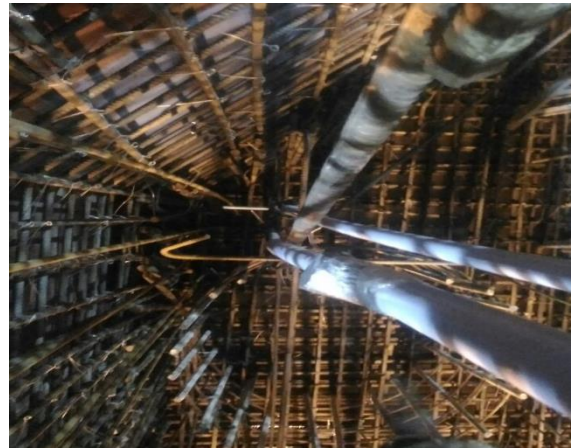
FIG-3. SECTION XX - PILE CAP X6 (9PC1) SHOWING LAYER WISE FIXING ARRANGEMENT OF THERMOCOUPLES AT BOTTOM, CENTER AND TOP

Fig 6: C/s of Pile Cap

The photograph (1), (2) and (3) shows the actual photo of locations of Thermo couples (TC) in pile cap and photograph (4) show the Pile Cap after Concreting wherein PVC Pipes as Casing for embedded TC's are clearly seen.



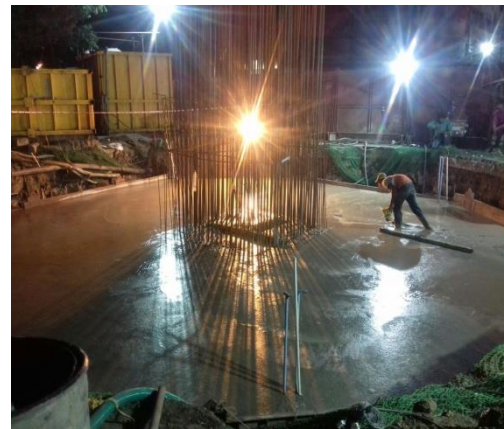
**Photograph (1):** Top layer



**Photograph (2):** Middle layer



**Photograph (3):** Bottom layer



**Photograph (4):** Pile Cap after completion of Concreting.

The scheme of study was to insert the thermo couples at five locations in pier cap namely location X, Y, P, Q, on sides and location C at centre (Figure 5). At all the locations the structure was having same geometry and cross-section. At a particular location, in cross section total three thermo couples were embedded in a layer. The thermo couples in the centre layer are Post fixed as 1, that at the top layer are Post fixed as 2 and that in the bottom layer are Post fixed as 3 (Figure 6). The thermo couples at the top and bottom were inserted 0.20m inside to accommodate the reinforcements. The thermo couples at the location on sides namely X,Y,P,Q were inserted 0.50 m from face of concrete inside the concrete structure, so that the effect of surface cooling is minimized. One TC protected from direct sunlight to measure the ambient temperature and was kept outside the structure.

The scheme of study adopted is as per Table:1 below

**Table 1:** Table showing the scheme of study

Sr.No.	Location	Number of T.C's	Notation**
1	C	3	C', C2, C3
2	X	3	X2, X3
3	Y	3	Y1, Y3
4	P	3	P3
5	Q	3	Q2, Q3

\*\* The Thermo Couples at Location X1; Y2; P1; P2 and Q1 had malfunctioned and so are not considered in this study. The Thermocouple at location C1 malfunctioned during embedment and was replaced with another TC with notation as C'.

Hence, 10 thermo couple readings were available for this study as 5 thermo couples had malfunctioned.

The formwork used was of steel shuttering and it was removed after 3 days.

The test results for cements are as per Table 2.

**Table 2:** Table showing the test results for cements

Type	OPC -53 Grade
W-M-Y	16-04-2018
% of Fly-Ash	Nil
Fineness(m <sup>2</sup> /kg)	293
Normal consistency (%)	29.0%
Soundness (Autoclave)	0.05

Setting time (min.)	150
Initial	230
Final	
Strength (N/mm <sup>2</sup> )	41.0
3days	50.4
7days	63.2
28days	

The mix proportion for the concrete Grade M-40 (20MSA) adopted was as per Table 3.

**Table 3:** Table showing the mix proportion for the concrete Grade M-40(20MSA)

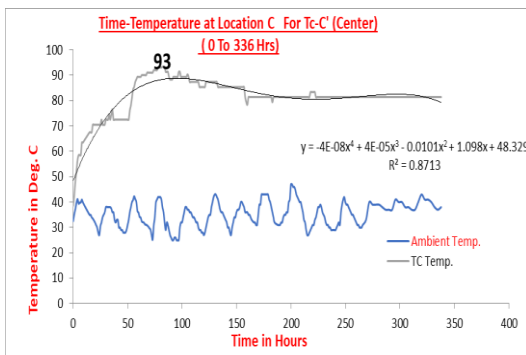
Cement (Kg.)		Water (Kg.)	Sand (Kg.)		Coarse aggregate (Kg)		Plasticiser (kg)
Cement OPC	GGBFS		River sand	Crushed sand	20mm	10mm	
53 grade	ISPL	143 KG	River sand	Crushed sand	626 KG	512KG	3.28KG
246 KG	164 KG		600 KG	257 KG			

The F.M. of R/sand was 2.9 and Crushed Sand was 3.15 which was very coarse sand and categorized as Zone-II and Zone-I as per IS 383.

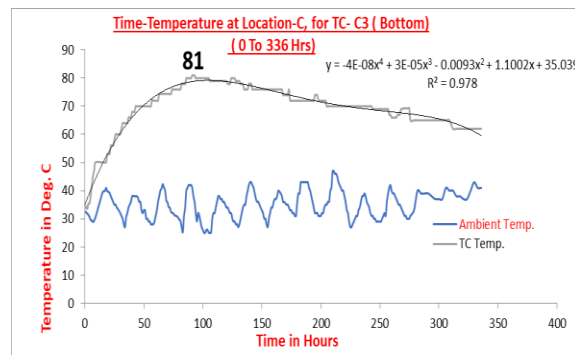
The monitoring of temperature recorded by thermocouples was done by digital recorder manually on hourly basis up to

13 days and then once in 3 hrs. up to 21 days but reporting is restricted to 14 days in this study.

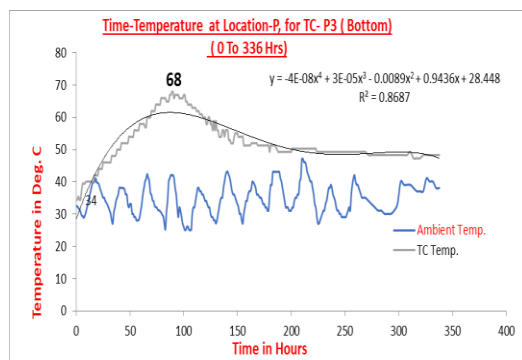
The sample graphs as shown in Fig.7 to Fig.12 below represents the plots of time vs. temperatures actually recorded for thermo couples for 14 days (336 Hrs.).



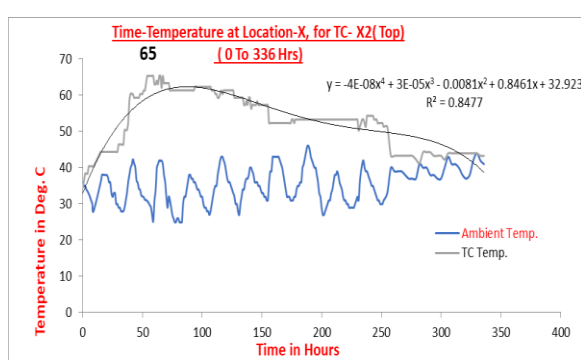
**Fig 7:** Time – Temperature record for TC- C'



**Fig 8:** Time – Temperature record for TC- C3



**Fig 9:** Time – Temperature record for TC-P3



**Fig 10:** Time – Temperature record for TC- X2

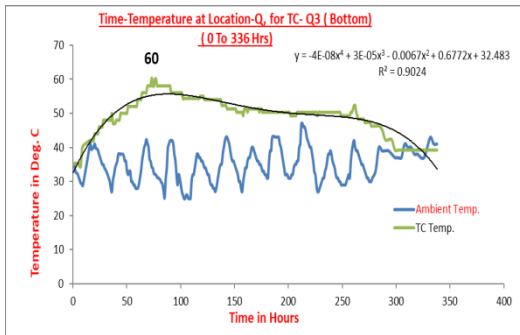


Fig 11: Time – Temperature record for TC-Q3

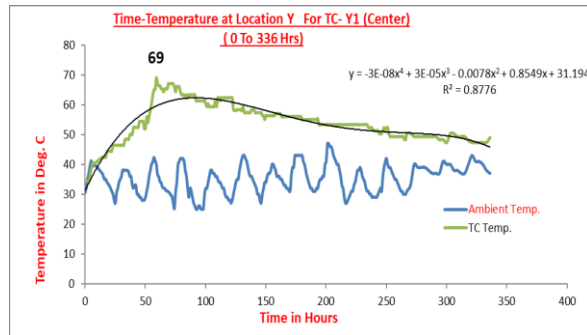


Fig 12: Time – Temperature record for TC- Y1

The derived equations for the time–temperature record as shown in graphs above, are tabulated in Table 4.

Table 4: Table showing the derived equations for Different Locations of Thermo couples for 14 Days i.e. (336 hrs.) in Concrete

Abstract of Derived Equations for Thermo Couples C;C2,C3,X2,X3,Y1,Y3,P3,Q2 & Q3 at Locations C,X,Y,P and Q for 14 days (336 Hrs.)				
Sr No	TC	Derived Polynomial Equation	R2	R
1	C'	$y = -4E-08x^4 + 4E-05x^3 - 0.0101x^2 + 1.098x + 48.329$	0.871	0.933
2	C2	$y = 9E-10x^4 + 9E-06x^3 - 0.0055x^2 + 0.9923x + 22.634$	0.804	0.897
3	C3	$y = -4E-08x^4 + 3E-05x^3 - 0.0093x^2 + 1.1002x + 35.039$	0.973	0.986
4	X2	$y = -4E-08x^4 + 3E-05x^3 - 0.0081x^2 + 0.8461x + 32.923$	0.847	0.920
5	X3	$y = -7E-08x^4 + 6E-05x^3 - 0.0149x^2 + 1.4373x + 28.579$	0.880	0.938
6	Y1	$y = -3E-08x^4 + 3E-05x^3 - 0.0078x^2 + 0.8549x + 31.194$	0.877	0.936
7	Y3	$y = -4E-08x^4 + 3E-05x^3 - 0.0078x^2 + 0.696x + 38.568$	0.787	0.887
8	P3	$y = -4E-08x^4 + 3E-05x^3 - 0.0089x^2 + 0.9436x + 28.448$	0.868	0.932
9	Q2	$y = -4E-08x^4 + 3E-05x^3 - 0.0078x^2 + 0.696x + 38.568$	0.952	0.976
10	Q3	$y = -4E-08x^4 + 3E-05x^3 - 0.0067x^2 + 0.6772x + 32.483$	0.902	0.950

The Table 5 shows the maximum (peak) temperatures recorded by thermo couples, the period to reach the maximum (peak) temperature, the ambient temperatures at that time.

Table 5: Table showing the details of temperature recorded by Thermocouples in concrete layer

Location	C			X		Y		P	Q	
Thermo Couple	C'	C2	C3	X2	X3	Y1	Y3	P3	Q2	Q3
Placement Temperatures °C	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5

Max.Temp. Recorded. (Tmax) °C	93	87	81	65	85	69	60	68	68	60
Period to reach Max. Temp. (Hrs)	80	87	91	67	76	59	57	89	56	73
Ambient Temp. (Tam) °C	42	30	41	41	32	40	29	42	31	34
Diff.of Temp.at peak $\Delta T_p = (T_{max} - T_{am})$ °C	51	57	40	24	53	29	31	26	38	26

Having known the peak temperatures, the difference between peak temperatures and the ambient temperatures at that time, designated as ( $\Delta T_p$ ) was calculated. Applying this temperature

difference ( $\Delta T_p$ ) the crack index as per equation (1) (2) and (3) were computed as tabulated in table 6. The probability of crack occurrence was worked out from graph given in Fig.3.

**Table 6 :** Table showing the Crack index and probability of cracking for  $\Delta T_p$  in concrete

Location	C			X		Y		P	Q	
Thermo Couple	C'	C2	C3	X2	X3	Y1	Y3	P3	Q2	Q3
Diff.of Temp.at peak $\Delta T_p = (T_{mx} - T_{am})$	51	57	40	24	53	29	31	26	38	26
Crack Index - - korean spcs. $I_{CR(K)} / 15 / \Delta T_p$	0.29	0.26	0.38	0.63	0.28	0.52	0.48	0.58	0.39	0.58
Probability of crack occurrence. %	95%	96%	94%	84%	95%	91%	92%	88%	94%	88%
Crack Index - - elastic analysis $I_{CR(e)} = 15.4 / \Delta T_p$	0.3	0.27	0.39	0.64	0.29	0.53	0.5	0.59	0.41	0.59
Probability of crack occurrence. %	95%	95%	93%	84%	95%	91%	92%	88%	94%	88%
Crack Index - - Hypoelstic analysis. $I_{CR(h)} = 25 / \Delta T_p$	0.49	0.44	0.63	1.04	0.47	0.86	0.81	0.96	0.66	0.96
Probability of crack occurrence. %	92%	94%	84%	50%	92%	58%	76%	54%	83%	54%

## 5. EXPERIMENTAL OBSERVATIONS AND DISCUSSIONS

The equations tabulated in Tables 4 could be used to predict the temperature rise for structures with similar geometry, cement contents, mix proportions, ambient temperature conditions, curing conditions etc.

The temperature rise could be used to assess the thermal gradients and the effects such as cracking index and the tensile stresses when the internal restraint is dominant specially in the early ages say up to 3 days. As can be seen the peak temperatures are reached within about 55 to 90 hrs., and the

temperatures were getting stabilized well within 14 days with the rate of cooling being very low.

From the derived equations for the actual temperature rise it could be seen that for 14 days the Coefficient of correlation (r) values are in the range of 0.88 – 0.98 which is a strong correlation and could be used to predict the temperature in concrete at given time but should be used for early periods say up-to 3 days as the use and significance of these equations diminishes as the concrete is cooling with slow rates, and peak temperatures being achieved within 4 days.

Based on the temperature difference ( $\Delta T$ ) the crack index as per the Korean formula gives a high crack probability and hence this equation was observed to be too conservative and gives high risk of cracking occurrence. The elastic model crack index is also very much similar to the crack index as per Korean formula. The practical formula of crack index based on hypoelastic model gives better assessment of the probability of crack occurrence. For example, for a temperature difference of 20°C the elastic and hypoelastic model gives a crack index as 0.77 & 1.25 and accordingly this fall into the category of limiting harmful cracks under elastic model whereas the hypoelastic model indicates that it falls into category of limiting the cracks. The effect of these different results on the overall construction scheme and its economics could be significant.

## 6. CONCLUSION

The derived temperature rise equations with strong “r” values could be used to predict the early age temperature rise in structures with similar geometry, weather conditions, curing and form removal.

The temperature-based assessment of cracking which is based on crack index is a good and handy tool to quickly assess the probability of cracking. However, it should be used with caution and restraint since it is too conservative. In the present study even though the probability of crack occurrence as per Korean specification and elastic analysis is more than 50%, actually no cracks were observed, this could be due to heavy reinforcement and the use of vertical pins and temperature(skin) reinforcement in the structure.

The more realistic equation of crack index based on hypoelastic model can be used which nearly matches with the existing limiting temperature difference namely 15°C - 20°C for the elimination of cracking that has been adopted the world over.

## ACKNOWLEDGEMENT

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