CRACKING DUE TO TEMPERATURE GRADIENT IN CONCRETE

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Abstract: Mass concrete is used in many projects related to the massive construction such as raft foundations, pile caps, thick beams, walls and dams. Since cement hydration is an exothermic reaction, the temperature rise within a large concrete mass can be quit high. As a result, significant tensile stresses and strains may be developed from the volume change associated with the increase and decrease of temperature within the mass concrete which will lead to crack the concrete. Cracks caused by thermal gradient may cause loss of structural integrity and monolithic action or shortening of service life of the structures. The objective of this research is to determine the thermal strain variation from arisentemperature datawhich in turn can be used to predict, whether the relevant concrete section is going to be cracked or not by comparing with tensile strain capacity values.

Keywords: Surface Gradient Analysis, Balanced Temperature, Tensile Strain Capacity

1 Introduction

According to ACI 207[1], “Mass Concrete (MC)is any large volume of concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and attendant volume change to minimize cracking.”

The most important characteristic of mass concrete is thermal behavior. When Portland cement combines with water, the resulting exothermic (heat-releasing) chemical reaction causes a temperature rise in the concrete mass. The actual temperaturerise inmass concrete structures depends upon the heat generating characteristics of the concrete mixture, its thermal properties, environmental conditions, geometry of the MCstructure, and construction conditions. Since concrete has a low conductivity, a great portion of generated heat is trapped in the center of mass concrete element and escapes very slowly. This situation leads to a temperature gradient between center and outer part of the mass concrete element. Temperature gradient is a cause for tensile stresses, and when stress exceeds the tensile strain capacity of concrete,“Thermal Cracks”are formed in the concrete structure.

Usually the peak temperature is reached in a few days to weeks after placement, followed by a slow reduction in temperature. A change in volume occurs in the MC structure proportional to the temperature change and the coefficient of thermal expansion of the concrete. If volume change is restrained during cooling of the mass, by the foundation, the previously placed concrete, or the exterior surfaces, sufficient tensile strain can develop to cause cracking. Cracking generally occurs in the main body or at the surface of the MC structure. These two principal cracking phenomena are termed Mass Gradient and Surface Gradient cracking, respectively [1].

In this study, Tensile Strain Capacity (TSC)of concrete is used with the results of temperature analysis to determine the risk of forming cracks in MC.

2 Literature Survey

ACI207.1R contains detailed information on heat generation, volume change, restraint, and cracking in concrete. The analysis procedure for Surface Gradient was carried out according to the method given in technical report by U.S. Army Corps of Engineers [1]. Surrounding data was taken from “CIRIA Report 91 – Early age thermal crack control in concrete” [3].

2.1 Surface Gradient Analysis

Surface gradient cracking occurs due to the “Internal Restraint”,in which changes in thetemperature profile across the element can cause one part (exterior) of the section to restrain the movement of another part (interior) of same section. Strain was used as a basis for the surface gradient cracking analysis, sinceit is not suitable to rely upon the constant Modulus ofElasticity as it varies with age & temperature of the concrete.

The strain due to thermal gradient in concretecan be determined by equation (1) given inACI 207.2R,

$$\varepsilon = (C_{th})(dT)(K_R) \tag{1}$$

Where,

ϵ= induced tensile strain (x 10^{-6})
C_{th}= coefficient of thermal expansion - x $10^{-6}/^{0}$ C
dT= temperature difference with respect to interior temperature - deg C
K_R = internal restraint factor

Typical values for the coefficient of thermal expansion for mass concrete are in the range 5-14 x $10^{-6}/^{0}$C. Fora constant value of 10.5 x $10^{-6}/^{0}$C coefficient of thermal expansion was considered for this study.

2.1.1 Surface gradient restraint factor (K_R)

The degree of restraint cannot bedetermined exactly but can be estimated based on the thickness of the exterior surface layer being restrained. The restraint factor, K_R, is computed from following equations depending upon the value of *L/H*, where *L* is the monolith width (between joints or between ends of the monolith) and H is the distance from the interior strain and stress-free surface (Thermal neutral surface) to the exterior surface, called “Tension Block Width” as shown in Figure 2.1

For *L/H* greater or equal to 2.5

For *L/H*lessthan 2.5

$$K_R = \left[\frac{L/H - 2}{L/H + 1}\right]^{h/H} \qquad K_R = \left[\frac{L/H - 1}{L/H + 10}\right]^{h/H} \tag{2}$$

The K_R can be determined from equation (2)

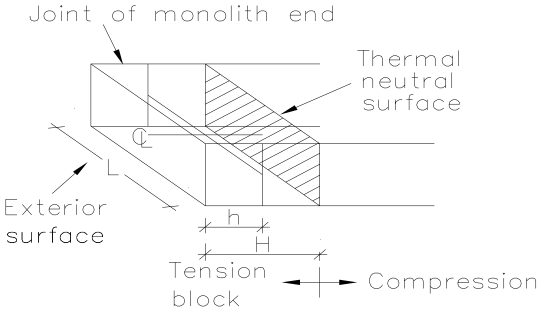

Figure 2.1: *Surface Gradient Restraint Model*

2.1.2 Determination ofdT andH

The temperature distribution can induce tension near the surface and compression within the interior of concrete. ACI 207.2R states that for sectional stability, the summation of tensile stresses (and strains) induced by a temperature gradient in a gross section must be balanced by equal compressive stresses (and strains).

Therefore,thetemperature differences (dT) are arranged to provide equal tension and compression in the section, providing a graphical representation of the surface gradient restraint model (Figure 2.1).

While Negative temperature differences are producing tensile stresses, positive temperature differences produce compressive stresses (Figure 2.2). The location of dT=0 determines the location of the tension block relative to the exterior surface (H). By equating the shaded positive and negative areas in Figure 2.2, H can be calculated.

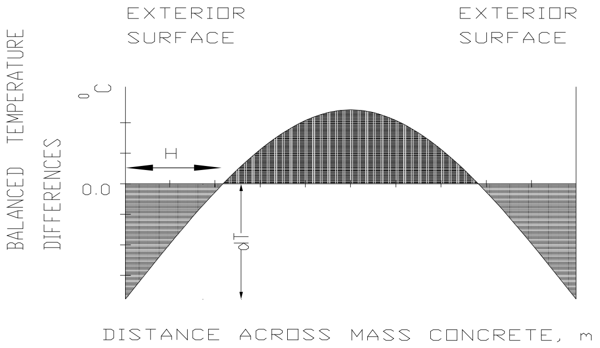

Figure 2.2: *Shape of the Balanced TemperatureDistribution*

The main steps in calculating tensile strain due to temperature distribution are given in Figure 2.3 and the detailed description is included in “Case Study”.

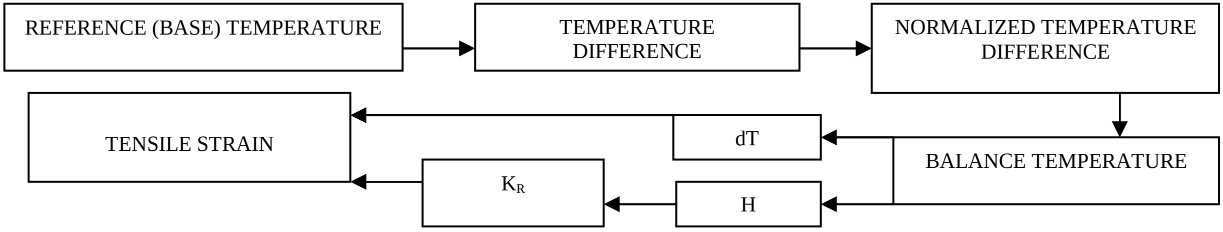

Figure 2.3: *Method of Finding Tensile Strain*

Reference (Base) temperatures for a surface gradient analysis are defined as the temperatures in the structure at the time when the concrete begins to harden and material properties begin to develop. It wasassumed that concrete begins to gain elastic form at 2 hrs after mixing.

3 Experimental Investigation

3.1 Temperature Rise in Concrete Cube

A 1.5m concrete cube was cast on ground with plywood formwork on sides and bottom. Top surface was insulated with a polystyrene sheetand a sand layer.

In order to obtain temperature distribution fixed thermo couples (TC1 to TC6) were embedded at the centre of the block as shown in Figure 3.1.

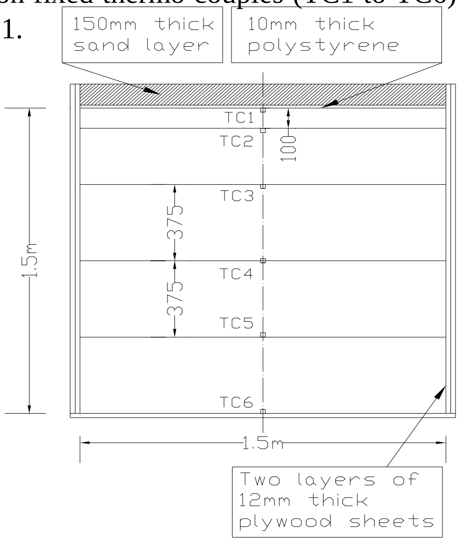

Figure 3.1: *The Typical Concrete Mass*

Temperature data obtained from thermo couples are shown in Table 3.1. Temperature changes or differences have been determined by taking the base temperatures as temperatures at the concrete age of 2 hr.

		Temperature distribution – C							
Location	distance(h)	2 hr	12 hr	18 hr	24 hr	48 hr	72 hr	96 hr	120 hr
TC1	0.000	30.39	49.28	57.84	60.00	57.53	49.20	43.12	37.76
TC2	0.100	31.12	52.8	62.16	64.32	61.74	52.56	45.28	39.46
TC3	0.375	31.20	59.44	68.56	71.84	68.96	58.72	49.84	42.72
TC4	0.750	31.15	60.64	70.72	74.32	71.92	60.80	51.36	43.92
TC5	1.125	31.17	59.6	68.96	71.52	67.70	57.68	49.28	42.64
TC6	1.500	30.46	50.16	56.4	57.28	54.86	48.08	42.48	37.96

Table 3.1: *Temperature Data*

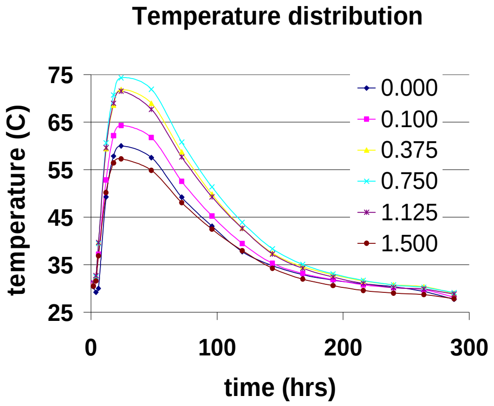

Figure 3.2: *Temperature Variation of the Concrete Section with Time*

Temperature differences relative to the base temperatures are shown in Table 3.2.

Table 3.2: *Temperature Difference*

h	2.0	12.0	18.0	24.0	48.0	72.0	96.0	120.0
0	0.00	18.89	27.45	29.61	27.14	18.81	12.73	7.37
0.1	0.00	21.68	31.04	33.20	30.62	21.44	14.16	8.34
0.375	0.00	28.24	37.36	40.64	37.76	27.52	18.64	11.52
0.75	0.00	29.49	39.57	43.17	40.77	29.65	20.21	12.77
1.125	0.00	28.43	37.79	40.35	36.53	26.51	18.11	11.47
1.5	0.00	19.70	25.94	26.82	24.40	17.62	12.02	7.50

Firstly, Normalized temperature differences are obtained by subtracting the surface temperature differences from the corresponding interior temperature differences at the same time intervals (seeTable 3.3).

Table 3.3: *Normalized Temperature Difference*

h	2.0	12.0	18.0	24.0	48.0	72.0	96.0	120.0
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.1	0.00	2.79	3.59	3.59	3.48	2.63	1.43	0.97
0.375	0.00	9.35	9.91	11.03	10.62	8.71	5.91	4.15
0.75	0.00	10.60	12.12	13.56	13.63	10.84	7.48	5.40
1.125	0.00	9.54	10.34	10.74	9.39	7.70	5.38	4.10
1.5	0.00	0.81	-1.51	-2.79	-2.74	-1.19	-0.71	0.13

ThenBalanced Temperature (dT)can be calculated by equating positive and negative areas (by integrating) of normalized temperature difference distribution. Those Balanced temperature values are shown inFigure 3.3.Consequently, Tension Block Widths (H)that underwent tensile stresses at each age of the concrete,were calculated (table 3.4).

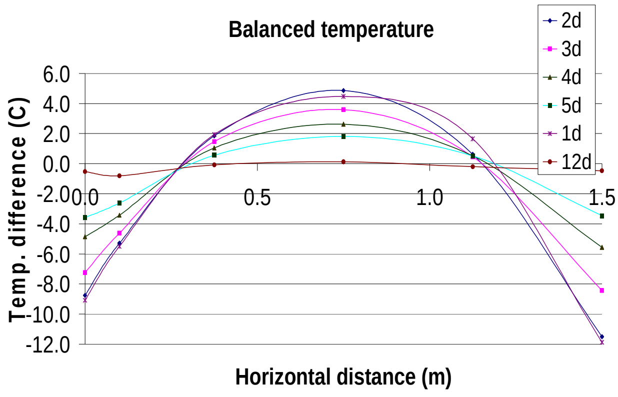

Table 3.4: *Tension Block Widths*

Time(hr)	12.0	18.0	24.0	48.0	72.0	96.0	120.0
Top(m)	0.318	0.280	0.284	0.287	0.295	0.305	0.327
Bot. (m)	0.298	0.310	0.332	0.354	0.331	0.340	0.327

Figure 3.3: *Balanced Temperatures*

K_R(Restraint factors) were calculated according to the equation (2) and given in Table 3.5.

Table 3.5: *Restraint Factors*

	12.000	18.0	24.0	48.0	72.0	96.0	120.0
Top surf.	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1m from top	0.791	0.796	0.796	0.795	0.794	0.793	0.790
Bot. surf.	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Out of interior nodes, only a node which was located 0.1m below from the top should be considered, because all other nodes are located in compression zone. Assuming the Coefficient of thermal expansion as 10.5 x $10^{-6}/^{0}C$, induced tensile strainswere found by using equation (1) and are shown in Table 3.6.

Table 3.6: *Induced Tensile Strain values in millionths*

time	12.0	18.0	24.0	48.0	72.0	96.0	120.0
top surface	86	87	95	92	76	51	38
0.1m from top	45	40	46	44	38	29	22
bottom surface	77	103	125	121	89	58	36

Figure 3.4 shows thetensile strain variation with time for top, bottom and 0.1m below top surface.

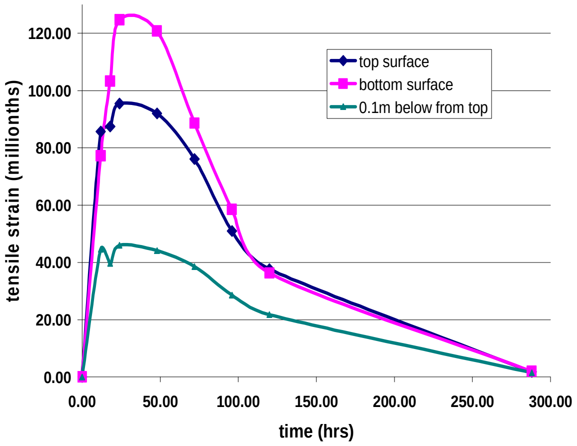

Figure 3.4: *Tensile Strain Variation with Time*

It can be seen that maximum tensile strains were develop at the age of 24 hrs.

3.2 Tensile Strain Capacity of Concrete

Tests were carried out to obtain the tensile strain capacity of Gr 40 concrete.Three types of tests were conducted,*Rapid load flexural beam test, Compressive strength test andSplitting tensile test*.Since the strains due to surface gradients develop more rapidly, the Rapid-load beam test was conducted.

3.2.1 Rapid Load Flexural Beam Test

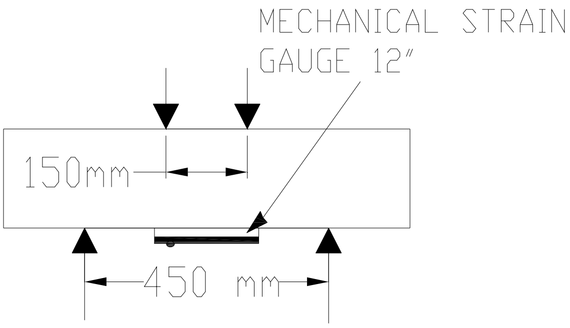

Figure 3.5: *Loading Arrangement of Rapid Load BeamTest*

Test Specimens and mix design properties

Table 3.7 gives No. of beams tested at each age whereas Table 3.8 gives the mix proportions of Gr 40 concrete (Slump – 180 mm)used in the test series.

Table 3.7: *No of Test Beams*Table 3.8: *Mix Proportions of Gr 40 concrete*

17.5 hrs	24 hrs	42 hrs	144 hrs
3 nos of beams	2 nos of beams	2 nos of beams	2 nos of beams

Material	Quantity
Cement	485 kg
Sand + Quarry dust (1:1)	762 kg
Machine crushed Aggregate	1009 kg
Admixtures (Super Crete)	4800 ml
Water	160 kg

Test Method

Loading of the beams was done in accordance with the procedure given in CRD-C 16 [2]. For each loading age, beams were loaded at a rapid loading rate of 0.28 MPa/min.The loading arrangement is shown in Figure 3.5.

A continuous record of load and strain was obtained throughout the test by a “Mechanical strain gauge”untilthe beam failure.

Results

Ultimate tensile strain capacities at each age are given in Table 3.9.

Table 3.9: *Tensile Strain Capacities*

Time	17.5 hr	24 hr	42 hr	144 hr
Failure Load (kN)	21.7	24.7	30.0	32.9
Strain Capacity (millionths)	156	168	213	228

Compressive strength andsplitting tensile strength of concrete at critical ages are given in Table 3.10.

Table 3.10: *Strength Results*

Age of the concrete (hrs)	17.5	24.0	42.0
Compressive Strength (N/mm2)	18.1	21.2	43.5
Tensile Strength (N/mm2)	1.647	2.147	2.563

4 Analysis of Results and Discussion

4.1 Backward Analysis

Based on equation (1), for a given tensile strain capacity, maximum temperature difference (dT) can be calculated at maximum restraint of K_R=1 (See Table 4.1)

Table 4.1: *Temperature Differences for K_R=1*

Strain capacity €(millionths)	C_{th}, millionths/deg C	*Kr*	*dT*
156	10.5	1	14.86
168	10.5	1	16
213	10.5	1	20.29
228	10.5	1	21.71

The determination of the variation betweennormalized temperatures vs. distance is a trial and error process. The variation should be a polynomial function of fourth degree. Tension block width was assumed and therefore, the known coordinates are as follows (Table 4.2). According to those coordinates, a relevant graph could be drawn.

Table 4.2: *Coordinates of graph for K_R=1*

X	0	H	1.5-H	1.5
Y	0	***dT***	***dT***	0

The area of the graph should be equated by the Y = dTas to satisfy tension and compression stresses equal. The final graphs obtained from the above process are given inFigure4.1.

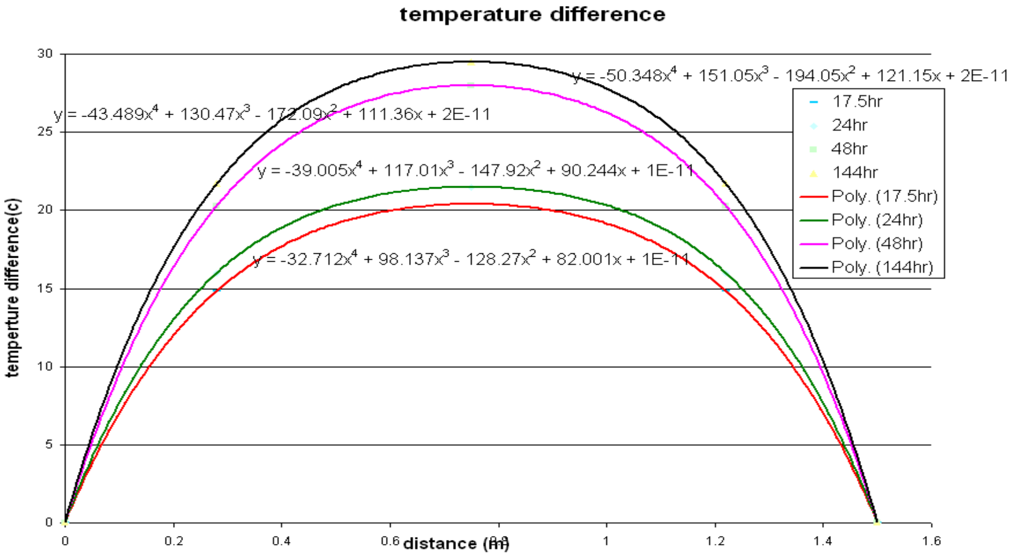

Figure 4.1: *Balanced Temperature curves for K_R=1*

Therefore maximum temperature differences are as given in Table 4.3,

Table 4.3-*Maximum Temperature differences*

Age	17.5	24	42	144
Maximum normalized temperature	20.4	21.5	28	29.5
Max. Norm. temp. for slow load test	28	30	38	41

Since the tensile strain capacity values should be multiplied by 1.4 [1], to determine the tensile capacity values under the slow loading, the temperature differences are also varying as given in Table 4.3.

These normalized temperature differences are developed by subtracting the surface temperature differences from the corresponding interior temperature differences at the same time intervals.

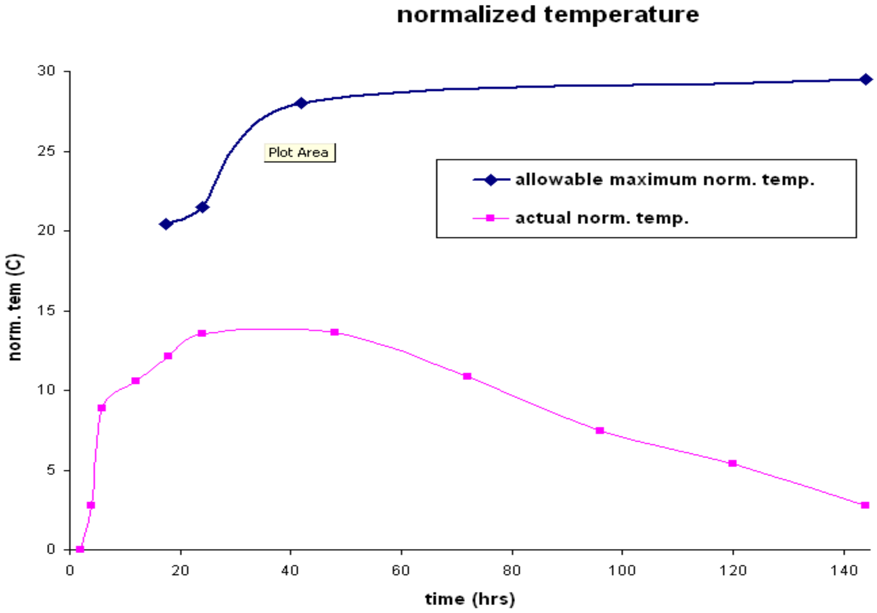

Figure 4.2: *Comparision of Temperature values*

Figure 4.2 shows that allowable maximum tensile capacities are clearly much higher than the actual ones. The allowable maximum temperature differences cannot be determined before 17.5 hrs accurately, because actual strain capacities cannot be obtain through an experiment due to practical difficulties.

4.2 Discussion

In this case, to evaluate induced tensile strain values in surface gradient analysis it has used strain values but not stress values. This is because critical induced strain values would not in the region of elasticity but may be in the region of plasticity. Therefore it is impossible to find Modulus of Elasticity value to convert these strain values to stress values.

Tensile strain capacity values found from this experimental part were lower values than the actual values due to following two errors.

Strain values were not due to the "Pure Bending"

In four point flexural loading test, the length at which the pure bending occurs is 150mm. But strain meter used here had 300mm length. Therefore strain meter reading is not due to the constant pure bending. Hence, actual strain capacity values were greater than the values obtained from the test.

Strain meter could not measure curve length
Since the strain meter was a mechanical one, it is not possible to measure curved lengths

On the other hand, to get more accurate tensile strain capacity values, it is necessary to take measurements through a "Data Logger" by using a calibrated 150mm strain gauge.

When dealing with thermal effect of mass concrete structures, normally maximum temperature difference within the concreteis limited to 20 C. Through a back calculation, it was found that the minimum allowable temperature difference is around 20.5 C at the age of 17.5 hr for rapid load tension test &28.0 C for slow load tension test (modified by 1.4) for this particular concrete block. Furthermore this difference got higher with the increase of the age of concrete. Therefore, from this approach, one can predict the maximum temperature differences exactly at each age for a given concrete section. Placement temperature of the concrete 31 C did not make any effect on thermal stresses according to this analysis. Finally, it can be concluded that maximum lift height of 1.5m can be safely applicable for concreting in the particular project.

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