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An Experimental Study on Thermal Stresses and Effect of Temperature on Thermal Properties of Mass Concrete

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Abstract: Thermal deformation under restrained conditions often leads to early-age cracking and durability problems in mass concrete structures. The principal parameters that considerably affect the performance of mass concrete structures are the cement content, temperature of concrete making constituents, maximum concrete temperature, temperature differential, time and duration of the maximum temperature differential. Hydration process generate heat, if it is not controlled or dissipated properly, thermal damage cause thermal cracking and/or delayed ettringite formation. Therefore it becomes very important to predict temperature rise and thermal stresses developed in mass concrete. The objective of this paper is to predict the maximum placement temperature of concrete for various ambient temperatures to control the occurrence of early age thermal cracks.
Keywords: Temperature Prediction, Mass Concrete, Early Age Thermal Cracks, Delayed Ettringite Formation

I. INTRODUCTION

Mass concrete is defined in ACI 207 as “any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking.” The design of mass concrete structures is generally based on durability, economy, and thermal action, with strength often being a secondary, rather than a primary, concern. The one characteristic that distinguishes mass concrete from other concrete work is thermal behaviour. Because the cement-water reaction is exothermic by nature, the temperature rise within a large concrete mass, where the heat is not quickly dissipated, can be quite high. Significant tensile stresses and strains may result from the restrained volume change associated with a decline in temperature as heat of hydration is dissipated. Cracking due to thermal behaviour may cause a loss of structural integrity and monolithic action, excessive seepage and shortening of the service life of the structure, or be aesthetically objectionable.

To avoid concrete surface cracking caused by the heat generated in the concrete, maximum temperature difference within the concrete mass should not go beyond 20° C (Neville, A.M., 2011) as shown in Fig. 1,

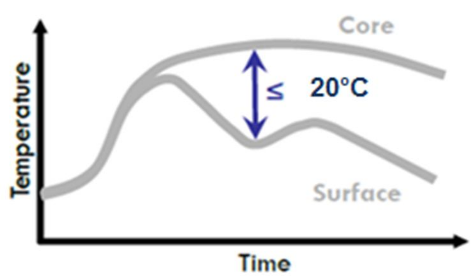

Fig. 1: Pattern of temperature change which causes cracking

But with limestone aggregate, the difference can be permitted up to 31° C (Portland Cement Association). The exact magnitude of temperature gradient depends on a number of factors, including the initial placement temperature of concrete, the ambient temperature around the structure and the thermal properties of the concrete itself. During early age of concrete, a number of factors affect the thermal characteristics of concrete, including heat of hydration of cement, specific heat, thermal diffusivity, thermal conductivity, coefficient of thermal expansion, temperature gradients etc. The temperature profile of concrete component is further affected by environmental conditions such as ambient temperatures, humidity, wind velocity etc.

In addition to thermal cracking, higher internal temperatures may cause deleterious effects in concrete i.e. Delayed Ettringite Formation (DEF). DEF is associated with some concretes exposed to higher curing temperatures and is caused by the melting of ettringite, a cement hydration product, at temperatures above about 70° C. Reformation of the ettringite occurs upon cooling, and when introduced to water, can cause internal volumetric expansion, which could lead to cracking of the concrete at the paste to aggregate or reinforcing steel interface. However there are specific conditions for the initiation of DEF. Even in the presence of high temperatures and moisture, it only occurs within cements with large amount of sulphur trioxide (SO_3), alkalies or magnesium oxide (MgO).

II. LITERATURE REVIEW

In mass concrete, thermal strains and stresses develop by a change in the mass concrete volume. The two primary causes of such a volume change are from the generation and dissipation of the heat of cement hydration and from periodic cycles of ambient temperature.

A. *Restraint and Thermal Stress*

If concrete element is free to move, tensile strain or stress caused by restraint would not develop. However, movements of concrete mass are restrained to some degree by the supporting elements or by different parts of the element itself. These restraints induce tensile and compressive stresses commonly due to temperature differential. Tensile stresses in concrete can lead to cracking because concrete has the ability to withstand compressive stresses. There are internal restraint and external restraint. Both types are interrelated and usually exist to some degrees in all concrete elements (ACI 207.2R-07).

1) *Internal Restraint:* When concrete is placed, the internal temperature increases due to heat of hydration while the surface of concrete lose heat to the atmosphere, there develops a temperature differential between the cool exterior and the hot core of the concrete element, the heat not being dissipated to the outside fast enough in consequence of the low thermal diffusivity of the concrete. As a result, the free thermal expansion is unequal in the various parts of the concrete element. Restraint of the free expansion results in stresses, compressive in one part of the element and tensile in the other. If the tensile stress at the surface of the element due to the expansion of the core exceeds the tensile strength of concrete or if it results in the tensile strain capacity being exceeded (see Fig.2), then surface cracking will develop. Internal restraint can occur also when concrete is placed against a surface at a much lower temperature, such as cold ground or uninsulated formwork in cold weather. In such a situation, different parts of the concrete element set at different temperatures. When subsequently, the core of the concrete element cools, its thermal contraction is restrained by the already cool external part and cracking in the interior may occur (Neville, A.M., 2011).

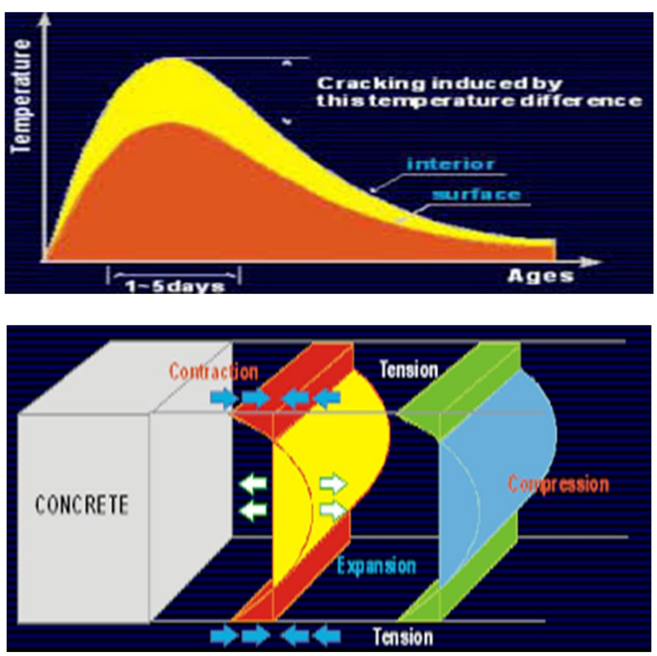

Fig. 2: Crack formation mechanism due to internal restraint (Adapted from Cha. 2009)

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2) *External Restraint:* At some later age, an internal section of concrete enters a cooling phase controlled by the same ambient temperature after the peak temperature has been reached. This temperature decrease induces a contraction of concrete volume, but rigid structures such as a foundation or adjoining older concrete elements not experiencing temperature changes constrain moving. This mechanism known as an external restraint results in cracks as shown in Figure 3. The external restraint develops compressive stress at early age and tensile stress later. The degree of restraint depends primarily on the relative dimensions, strength, and modulus of elasticity of the concrete and restraining material (ACI 207.2R-07).

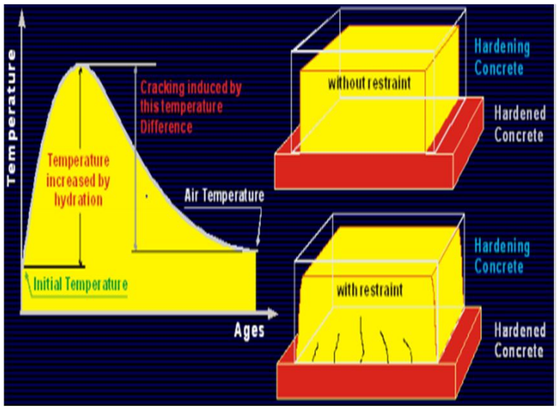

Fig. 3: Crack formation mechanism due to external restraint (Adapted from Cha. 2009)

B. Thermal Properties of Concrete

The thermal properties of concrete are coefficient of expansion, conductivity, specific heat, and diffusivity. The relationship of diffusivity, conductivity, and specific heat is defined by

$$h^2 = \frac{K}{C\rho}$$

h^2 = Thermal diffusivity (m^2/h);
K = Thermal conductivity, (J/m·h·°C);
C = Specific heat, (J/kg·°C); and
ρ = Density of the concrete (kg/m^3),

1) *Thermal Diffusivity (h^2):* Diffusivity represents the rate at which temperature changes within a mass can take place, and is thus an index of the facility with which concrete can undergo temperature changes. The range of typical values of diffusivity of ordinary concrete is between 0.002 and 0.006 m^2/h, depending on the type of aggregate used. The following rock types are listed in order of increasing diffusivity: basalt, limestone, and quartzite.
2) *Thermal Conductivity (K):* It is the rate of heat flow per unit area under a unit temperature difference between the two faces of material of unit length. In general terms, basalt and trachyte have a low conductivity, dolomite and limestone are in the middle range, and quartz exhibits the highest conductivity.
3) *Specific Heat (C):* It is the amount of heat required to raise the temperature of unit mass of concrete by one degree Celsius. Specific heat increases with an increase in temperature and with a decrease in the density of the concrete. The common range of values for ordinary concrete is between 850 and 1050 J/kg per °C.

III. PRESENT STUDY

The overall objective of the study was to have an understanding of thermal stresses and effect of temperature on thermal properties of mass concrete. In this study, a literature and specification survey was conducted to identify conditions that typically have the largest impact on the thermal development of mass concrete. In this paper, laboratory studies were conducted in Central Soil and Materials Research Station.

The scope of laboratory studies involves: mix design of M15A80 grade concrete. For the mix, Portland Pozzolana cement, for fine aggregate natural river sand and aggregates obtained from charnokite group rock of dark grey in colour and coarse to medium grained rock were used. The study involved estimation of compressive strength, modulus of elasticity, specific heat, thermal diffusivity, thermal conductivity and coefficient of thermal expansion by testing concrete cube samples after proper curing. The input data from these tests was further utilised for calculation of placement temperature, lift height, lift interval and assess pre-cooling requirements of ingredients of mass concrete to meet the codal provision as per IS 14591-1999 (Reaffirmed 2015).

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Table 1: Concrete Mix Proportion

Mix Type	M15A80
Cement content (kg/m^3)	210
Coarse Aggregate (kg/m^3)	1647
80-40 mm	626
40-20 mm	428
20-10 mm	330
10-4.75 mm	263
Fine Aggregate (kg/m^3)	614
Water (Kg/m^3)	126
Admixture (kg/m^3)	3.57

A. Determination Of Compressive Strength And Modulus Of Elasticity

For assessing compressive strength 30x30x30 cm cube were cast as per Table 1. These specimens were cured in water till the curing age of 7 and 28 days and compressive strength of these specimens were then determined.

Table 2: Average compressive strength of cube

Age	7 days	28 days
Cube compressive strength (N/mm^2)	23.85	29.04

For evaluating the modulus of elasticity of concrete, 30x30x30 cm cubes were cast and cured for 7 and 28 days. Linear strain gauges of suitable sizes for measurement of strains were installed on these cube specimens before loading in the compression testing machine. The specimen was loaded up to one third of its compressive strength. A graph was then plotted between axial stress and corresponding strain value and modulus of elasticity has been computed at 7 and 28 days.

Table 3: Average modulus of Elasticity of design mix

Age	7 days	28 days
Modulus of Elasticity (N/mm^2)	1.64×10^4	2.0×10^4

B. Determination Of Thermal Properties Of Mass Concrete

For evaluating the thermal properties of mass concrete, cubes of 15x15x15 cm cubes after wet sieving were casted as per Table 1 and cured in water for 28 days... The cubes are then cut in two halfs equally with the help of concrete cutting machine in the laboratory. The tests were carried out with a Hot Disk TPS 2500 S system shown in Figure 4.

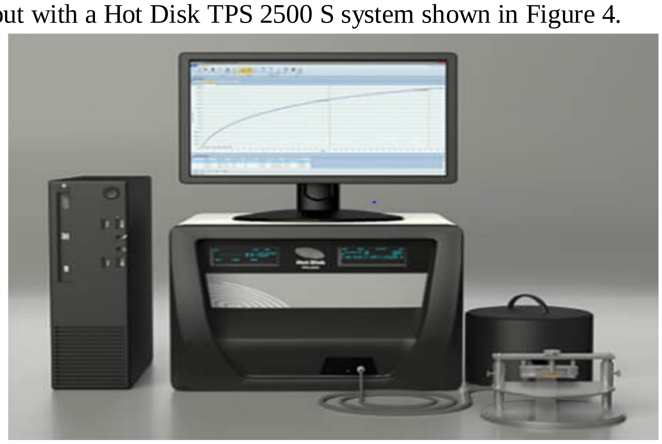

Fig. 4: Hot Disk TPS 2500 S

1) *Principle of Working of Hot Disk TPS 2500S:* The Hot Disk TPS 2500 S system works on Transient Plane Source technique which employs two samples halves, in-between which the sensor is sandwiched as shown in Figure 5.

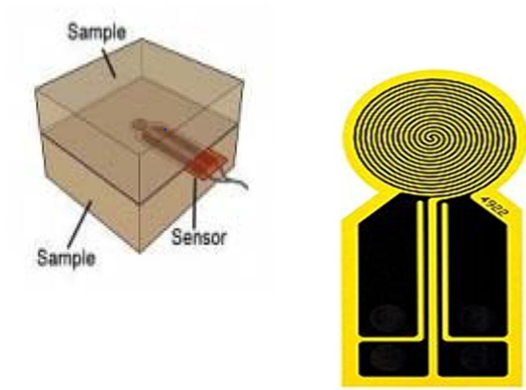

Fig.5: Placing of sensor between two halves of sample halves and sensor

The flat sensor consists of a continuous double spiral of electrically conducting nickel (Ni) metal, etched out of a thin foil. The nickel spiral is situated between two layers of thin polyimide film Kapton. The thin Kapton films provide electrical insulation and mechanical stability to the sensor. The sensor is placed between two halves of the sample to be measured. During the measurement a constant electrical effect passes through the conducting spiral, increasing the sensor temperature. The heat generated dissipates into the sample on both sides of the sensor, at a rate depending on the thermal transport properties of the material. By recording temperature vs. time response in the sensor, the thermal conductivity, thermal diffusivity and specific heat capacity of the material can be calculated.

2) *Measurements and Results:* A sensor of radius approximately 6.4 mm is placed between two halves as shown in Figure 6 of the samples and given a power of 800 mW for 80 seconds.

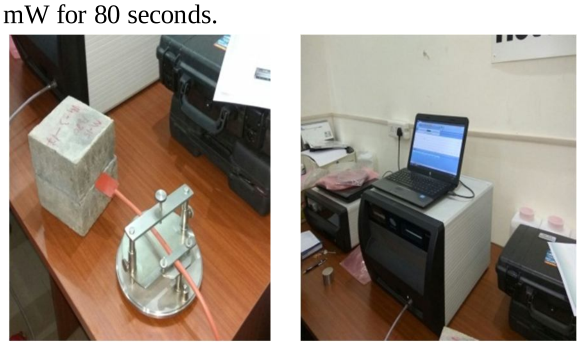

Fig.6: Placing of sensor between two halves of sample and recording of measurements

The measurements are recorded automatically and graphs are plotted on the software as shown in Figure 7.

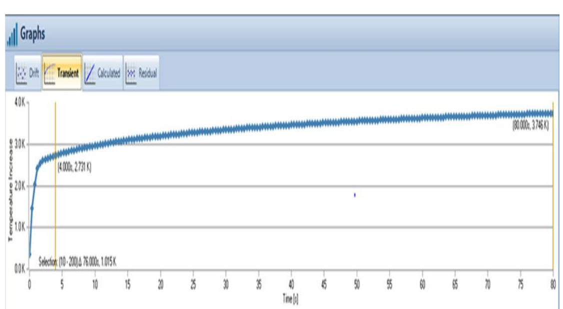

Fig.7: Graphs plotted by software

The thermal conductivity, specific heat, and thermal diffusivity of three samples are recorded in Table 4.

Table 4: Thermal properties of M15A80 grade concrete

S. No.	Cube ID	Thermal Conductivity (*K*) in J/m·h·°C	Specific Heat (C) in J/kg·°C	Thermal Diffusivity (h^2) in m^2/h
1	P/CSM/1	10252.80	930	0.0043
2	P/CSM/2	10605.60	915	0.0045
3	P/CSM/3	10602.00	945	0.0044
Average value		10486.80	930	0.0044

With these values calculation was being done as per Annexure A of IS 14591-1999 (Reaffirmed 2015) for calculating placement temperature, lift height, lift interval and assess pre-cooling requirements of ingredients of mass concrete for Zone I and Zone II. The results of the same are recorded in Table 5 and Table 6 respectively.

Table 5: Mass Concreting in Dam Foundation Interface and up to 0.15 B (B = Base width of Dam at Foundation level) above Foundation Level, where B is the Base Width of the dam at Foundation Level and at a Level where Concreting is interrupted for a period of more than two weeks (Zone I).

Ambient Temperature ºC	Concrete Placement Temperature ºC (DPT)	Time Interval between lifts	Lift Height	Temperature Requirements		Thermal Stress at final stable temperature in MPa	Thermal Stress at ambient temperature in MPa	DPT + Adiabatic rise - Atmospheric Temp	Remarks
				Mixing Water ºC	Ice %				
21	20	3 days (72 hrs)	0.5 m	4	40	-0.32	1.12	26.30	Adiabatic rise – 27.3 ºC Temperatures of CA : ≤ 18 ºC FA : ≤ 25 ºC Pozzolana = 22% Restraint Factor = 1
22						-0.16	1.10	25.30	
23						0.01	1.07	24.30	
24						0.17	1.05	23.30	
25						0.33	1.03	22.30	
26	17				50	0.43	0.95	18.30	
27						0.60	0.93	17.30	
28	15				60	0.72	0.86	14.30	
29						0.88	0.84	13.30	
30	12				70	0.98	0.76	9.30	
31						1.14	0.74	8.30	
32						1.31	0.72	7.30	
33						1.47	0.70	6.30	

Table 6: Mass Concreting above Foundation Level beyond 0.15 B (B = Base width of Dam at Foundation level) and at a Level where Concreting is not interrupted for a period of more than two weeks (Zone II)

Ambient Temperature °C	Concrete Placement Temperature °C (DPT)	Time Interval between lifts	Lift Height	Temperature Requirements		Thermal Stress at final stable temperature in MPa	Thermal Stress at ambient temperature in MPa	DPT + Adiabatic rise - Atmospheric Temp	Remarks
				Mixing Water °C	Ice %				
23	16	3 days (72 hrs)	1.5 m	4	40	0.92	1.45	20.30	Adiabatic rise – 27.3 °C Temperatures of CA : ≤ 18 °C FA : ≤ 25 °C Pozzolana = 22% Restraint Factor = 0.5
24	15				45	0.90	1.35	18.30	
25						0.00	1.29	17.30	
26						0.98	1.24	16.30	
27						1.02	1.19	15.30	
28						1.06	1.13	14.30	
29						1.10	1.08	13.30	
30	14				55	1.08	0.97	11.30	
31						1.12	0.92	10.30	
32						1.16	0.87	9.30	
33						1.20	0.81	8.30	
34	13				60	1.18	0.71	6.30	
35						1.22	0.65	5.30	
36						1.26	0.60	4.30	
37						1.30	0.55	3.30	
38	12				70	1.29	0.44	1.30	
39						1.32	0.39	0.30	
40						1.36	0.33	-0.70	
41						1.40	0.28	-1.70	

IV. CONCLUSION

The following conclusions were generated on the basis of the above study:

A. Mass concrete is prone to cracking due to thermal stresses; therefore effective temperature control and monitoring is required at site.
B. For higher ambient temperature, concrete placement temperature has to be kept low so as to keep the thermal stresses under limits.
C. For Zone I and II, Thermal stresses increases with the increase in DPT + Adiabatic rise - Atmospheric Temp.
D. For Zone I and II, as per IS 14591: 1999 (Reaffirmed 2015) thermal stresses are decreasing with the increase in DPT + Adiabatic rise - Atmospheric Temp which is calculated at stable temperature of concrete which would be achieved in eight to ten years or even more depending upon the reservoir water temperature and the mean annual ambient temperature whereas as per our study for calculation of thermal stresses present ambient temperature has been taken.
E. For Zone II, Though the thermal stresses are within the limits for ambient temperature of 41 ºC but as per IS 7861 Part 1: 1971 (Reaffirmed 2016), any operation of concreting above 40 ºC then the guidelines of hot weather concreting needs to be followed.
F. Higher the ambient temperature, lower will be the placement temperature, higher will be requirement of ice.
G. More the time interval between lifts more will be dissipation of heat and temperature loss.
H. Lower the lift height more will be the heat dissipation and temperature loss

V. ACKNOWLEDGEMENT

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