Thermal Analysis of Dyraaba Roller Compacted Concrete (RCC) Dam Using Finite Element Method

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Abstract

Cracking of dam body due to trapped heat is one of the probable phenomena in concrete RCC dams that can cause several instability and leakage problems and consequently will increase costs of the project. Thermal analysis is conducted to evaluate the responses of dams in both design and construction stages under thermal loads. The main core of this problem is cement hydration process that is an exothermic chemical reaction causing heat increase. Therefore, for more precise analysis, effect of heat on hydration rate should be considered in calculations. Determination of the heat transfer is a complicated process due to layer by layer construction method. In this paper, Dyraabadam thermal analysis has been performed to ensure there will be no damage in the dam body due to the heat generation of cement and fly-ash. Dyraabadam is an RCC dam with 50 m height that is located in Sri Lanka as a part of Uma Oya project. A finite element model has been developed using ANSYS software, with consideration of different time intervals between two successive layers, different placing temperatures and maturity effect on heat on hydration rate. In this paper mass gradient cracking risk has been calculated which shows that no serious cracking risk exists.

Keywords: Thermal Analysis, RCC dam, Heat generation, Finite element method, Dyraabadam

1. INTRODUCTION

Thermal analysis is conducted in concrete dams to ensure thereliability of the dam body's stability and serviceability during changing itsinternaltemperature. Concrete dams' thermal analysis is divided into two categories:

First type is the study of the service thermal analysis which is the analysis of thermal loads due to thewater,ambient and other loads that will be applied to the dam body.These loads can affect thestability of the dam body and inner stress conditions.The Second type is the construction thermal analysis, which tensile stresses and subsequent cracking (in different elevations in dam body) due to the cement heat of hydration, convection and other related items coming from construction method or ambient condition is calculated. In concrete dams, thermal analysis is performed for below reasons:

- Definition of a safe maximum placing temperature for fresh concrete
- Definition of precooling and post cooling system capacity
- Definition of concrete blocks length
- Definition of the optimum lift thickness
- Definition of safe time interval between successive lifts with consideration of probable stops during concrete placing
- Definition of the best time for start of the dam body
- Definition of the best arrangement of instrumentation

2. HEAT DISTRIBUTION IN MASS CONCRETES

Mass concrete is any volume of concrete with dimensions large enough to require that measures be taken to cope with the generation of heat from hydration of the cement and attendant volume change to minimize cracking [1].Increasing heat in mass concrete finally will cause its contraction and cracking. Therefore,to satisfy the engineering requirements the thermal control is a mandatory. Heat distribution calculation is a complicated process because mass concrete structures are placed layer by layer. Time interval between two successive lifts will make it even more complicated. Total heat distribution equation could be expressed as below:

$$k_{xx}\frac{\partial^2 T}{\partial x^2}+k_{yy}\frac{\partial^2 T}{\partial y^2}+k_{zz}\frac{\partial^2 T}{\partial z^2}+w=\rho c\frac{\partial T}{\partial t} \tag{1}$$

WhereT is body temperature, k is thermal conductivity, ρis specific gravity, c is specific heat and w is heat generation. What is important in this equation is correct boundary conditions. Boundary conditions are points with constant temperature, convection or radiation.

3. EFFECTIVE FACTORS IN CEMENT HYDRATION

Hydration depends on different factors e.g. cement chemical composition, water cement ratio, fineness and size distribution of cement grains.Hydration is a thermoactivated reaction which means that reaction rate will be increased with increasing in temperatureand vice versa. (See Figure 1). For cement increasing the temperature will increase rate of reaction and so increase heat generation. Since generated heat depends on heat generation rate, so for a more precise analysis, heat generation rate shall be considered in the finite element model of the dam body.

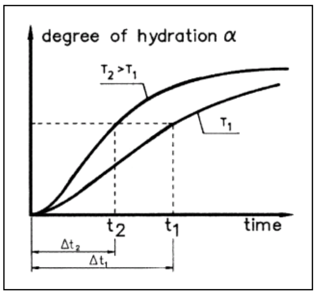

Figure 1. Time and temperature effects on hydration rate

Effect of heat on hydration rate is explained as below [2]:

$$H(T)=e^{\frac{Ea}{R}(\frac{1}{T0}-\frac{1}{T})} \tag{2}$$

T is concrete temperature at time of calculation and T0 is datum temperature of reaction (equals to 293 Kelvin) and for Portland cement R is 8.31J/mol.K. Ea is activation energy and could be expressed as below expression [2]:

$$Ea(Kj/mol)=\begin{cases}33.5 \therefore T>20°C\\ 33.5+1.47(20-T)\therefore T<20°C\end{cases} \tag{3}$$

Many expressions have been presented for mass concrete heat generation which one of them is proposed by USBR [3].

$$Q=Q_m(1-e^{-m.te}) \tag{4}$$

In above expression, Q_m and m are coefficients that depends on cement type and its heat generation. te is equal age or maturity which will increase withincreasing time and temperature.Therefore, heat generation rate relationship with time can be expressed as 6.

$$te=\int H.dt \tag{5}$$

$$Q^{\cdot} = \frac{\partial Q}{\partial te} \cdot \frac{\partial te}{\partial t}$$

$$Q^{\cdot} = (me^{-mte}).H \qquad (6)$$

4. CRACKING TYPE IN MASS CONCRETE STRUCTURES

Cracking types in mass concrete structures which is created due to thermal stresses are divided into two types:

4.1 SURFACE GRADIENT THERMAL CRACKING

This type of cracking occurs during cold months due to surface thermal gradient in concrete structure and will be visible in first few days after concreting. For prevention of this type of cracking,temperature difference between internal and external temperature of concrete shall be limited. Technical specifications generally advise to increase time of demolding in comparison with normal conditions or use suitable insulation. This type of cracking has a lower degree of importance because of lower depth and opening. After diminishing thermal gradient between internal and external part of the concrete structure, cracks are almost closed. This type of cracks has no harmful effect of watertightness or structural behavior of the dam body.

4.2 MASS GRADIENT THERMAL CRACKING

The mass gradient thermal cracking is created while concrete is placed in the warm months and cools down to final stable temperature. These cracks are generally visible at later ages after cooling of concrete(e.g. cooling concrete to closure temperature in concrete dams). Probability of occurrence of this type of cracking is higher in areas near foundation rock because of higher restraint. These cracks could be prevented by decreasing concrete peak temperature or cooling rate. These types of cracks are wide enough and will harm permeability of structure and generally penetrate into dam body.

5. PARAMETERS HAVE BEEN USED IN THERMAL ANALYSIS

There are several effective parameters that is effective on this analysis results. In this section the most important ones such as materials and assumptions were presented.

5.1 DAM BODY GEOMETRY

Dyraabadam is an RCC dam with 50m height and 165 m crest length. Figure 2 shows Dyraabadam cross section.

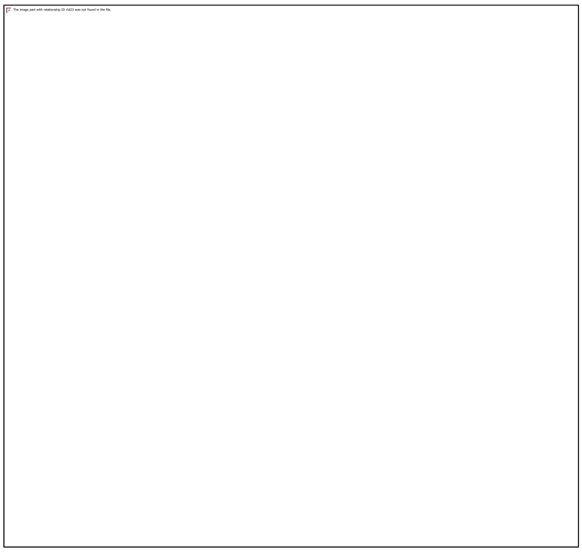

Figure 2. Dyraabadam cross section

5.2 AMBIENT CONDITION

UmaOya project is a combination of connected projects including access tunnel to powerplant cavern, connection roads and a link tunnel between Dyraabaand Pahulpola dams with 3.75 km and a 15km water transmission tunnel to the powerplant and also Dyrabaa and Pahulpola RCC dams. DyraabaRCC dam is one of the dams providing water for powerplantand is larger than another dam. Thisdam is located in Sri Lankain a distance of 10 km from Bandarawela. Pahulpola water is transmitted to Dyraabadam. The average monthly temperatures are shown in Figure 3.

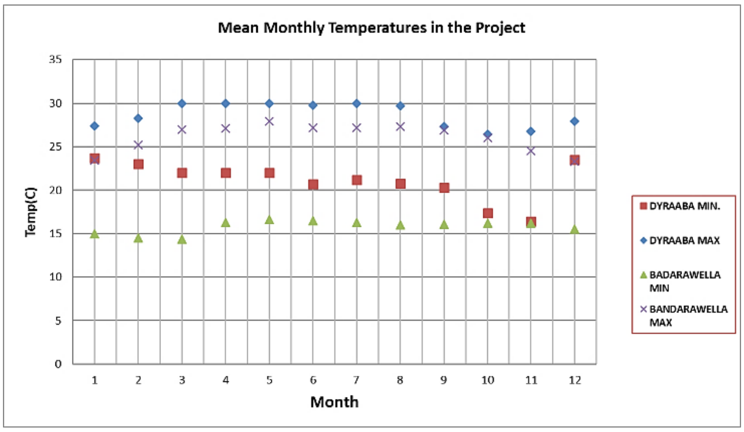

Figure 3. Monthly temperatures in the project area

5.3 MIX DESIGN AND CEMENT CONTENT

Based on mix design studies of RCC and test pad test results, cement content in RCC mix designs are 190kg and 230kg in core and facing concretes, respectively.In the mixes Holcim-extra pozzolanic(25%flyash) cement have been used. Based on tests results on Holcim cement hat generation is 41.14 Cal/gr and 62.25 Cal/gr at 7 & 28 days age respectively. ACI 207.2R-07 states that each gram of cement produces heat two times of each gram of pozzolan [5]. Therefore,heat generation of neat cement will be 47 cal/gr and 71 cal/gr at 7 days and 28 days respectively. Because of using 62.5 percent flyash in cementitious materials (cement+ pozzolan), heat generation of total cementitious materials will be 32cal/gr and 52 cal/gr.In thermal analysis7 days and 28 days heat generation have been assumed 35 cal/gr and 52 cal/gr at 7 and 28 days conservatively.

5.4 THERMAL AND STRUCTURAL PROPERTIES OF RCC

Other assumptions for Thermal and structural properties of Roller compacted concrete in Dyraabadam have been shown in Table1.

Table 1- Properties of RCC in the analyses

Property	RCC
Diffusivity (m^2.day)	0.096
Specific heat(J/kg.°C)	950
Density (kg/m^3)	2450
Surface TransmissionCoefficient ($Kcal/m^2$.h.°C)	60
Thermal expansion coefficient (1°C)	9.3×10-6
Elasticity Modulus (GPa)	16
Rapid rate tensile strain capacity	-
Slow rate tensile strain capacity	80 µ
Poisson's ratio	0.2

5.5 FINITE ELEMENT MODEL

Finite element model has been constructed using Ansys 5.4. Figure 4 shows this model for thermal analysis of Dyraabadam.It should be mentioned that based on UsarmyETL1110-2-542, Only a middle strip of dam body can be modelled for calculation of mass gradient cracking risk in concrete dams [4].

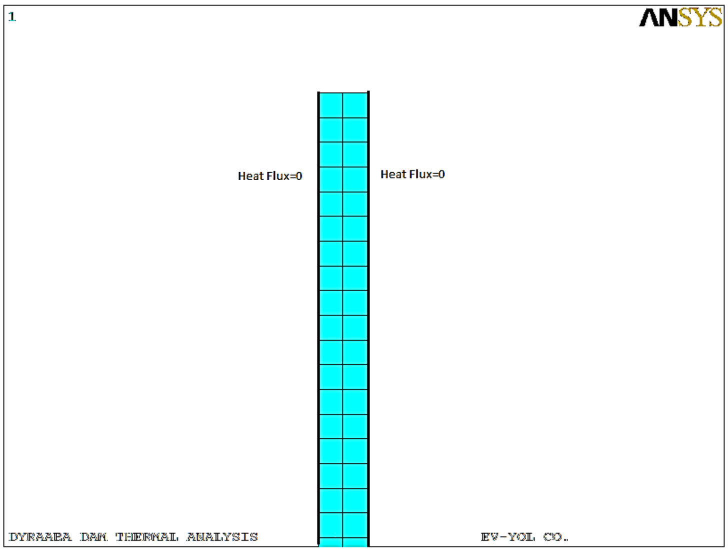

Figure 4.Finite elementmodel for thermalanalysis of Dyraabadam

5.6 SENSITIVITY ANALYSIS OF PLACING TEMPERATURES AND SCHEDULE OF PROJECT

A sensitivity analysis was conducted in four steps to evaluate the cracking risk in dam body. These analyses have done based on presented data in Table 2. The main aim of these analyses isinvestigation of cracking situation of dam body with 4 probable RCC placing rate in the project i.e. 0.5, 1, 1.5 and 2 layers per day. In the A1 and A2 analyses, placing temperature is 30℃. Ambient temperature with consideration of solar radiation has been considered 32℃. Facing Concretes because of lower thickness higher volume to surface ratio and also contacting with ambient will not effective in mass gradient cracking.

Table 2-Performed analyses on dam body core

	Fresh Concrete Temp.	Cement Content	Placing rate (m/day)
A1	30	190	0.6
A2	30		0.45
A3	32		0.3
A4	32		0.15

6. ASSUMPTIONS IN DYRAABA THERMAL ANALYSIS

In Dyraabadam thermal analysis, below assumptions have been considered:

1. Concrete is considered isotropic and homogeneous. On the other hand, conductivity, diffusivity and other properties are considered equal in all directions.
2. Thermal and structural properties of concrete are consideredto be constantrelated to temperature variations. Also, thermal properties of concrete are considered constant at all periods of time and during progress of hydration.
3. Effect of heat of hydration rate (Maturity) have been considered on calculations. This means that by increasing the temperature hydration rate will be increased.
4. Due to the lack of precise and tested parameters, exhaust of the temperature perpendicular to plane has been neglected. Therefore,the model shows the highest probable temperature in the middle part of layers and Middle part of the dam.

5. The Number of Layers has been picked up in a manner to gain the maximum probable temperature in the dam body. Also, the assumption for foundation initial temperature has minimum effect on peak temperature in dam core.
6. For consideration of sun radiation on concrete surface, ambient temperature has been increased 2℃ (according to Us. Army-ETL 1110-2-542)
7. Effect of temperature fluctuations during the day have been neglected and analysis is performed with maximum monthly temperature. So, it is predicted that actual peak temperature be less than this analyses results.
8. Cooling rate of concrete depends on many factors such as layer thickness, exposure duration and ambient temperature changes. In the analyses the main aim is calculation of maximum temperature difference between peak and minimum temperature and also applied strain to the concrete.
9. Based on strain method, the compressive strains in the dam body is neglected conservatively
10. Water spraying on concrete surface for curing will decrease temperature of hardened concrete (surface post cooling) and increase surface transmission coefficient. But this effect has been neglected conservatively.
11. Due to the mild ambient temperatures of the site, surface gradient risk is very low so will not be calculated in this analysis.

7. CRACKING ANALYSES

Based on above assumptions, a thermal numerical model has been developedwith 100 lifts and peak temperature of hardened RCC and temperature change in concrete have been calculated. Due to the using of maximum air temperature in the warm months, it is predicted that peak temperature in concrete will be less in real condition.
Table 3shows the results of calculations of cracking risk due to the mass gradient. Dyraabadam mean annual temperature is 22.5℃. Restraint factor has alsobeen calculated by consideration of foundation deformation modulus of 14GPa. It is evident that due to the probable increasing strength and elasticity modulus of concrete in later ages, the restraint factors in this calculation is conservative. For cracking analysis crack opening has been considered 2mm.

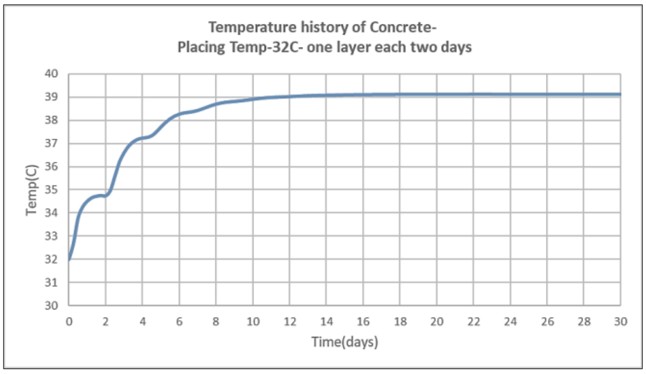

Figure 5.Calculated temperature history of Concrete Placing Temp. = 32℃- One layer each two days

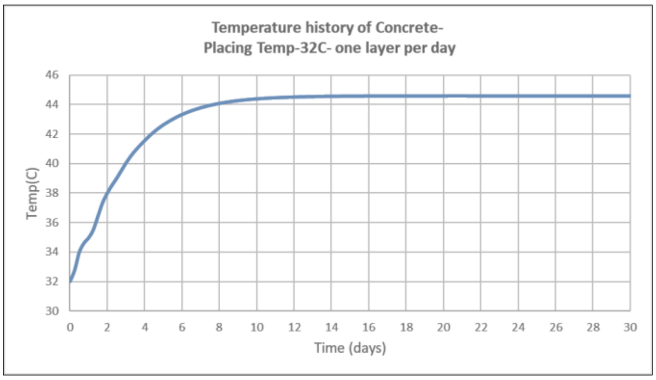

Figure 6.Calculated temperature history of Concrete Placing Temp. = 32℃- One layer per day

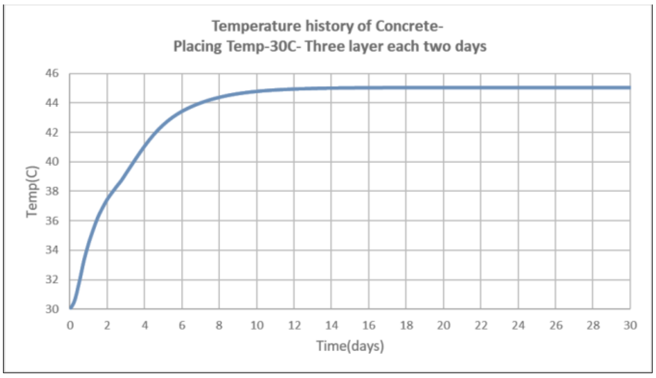

Figure 7.Calculated temperature history of Concrete Placing Temp. = 30°C- One layer per day

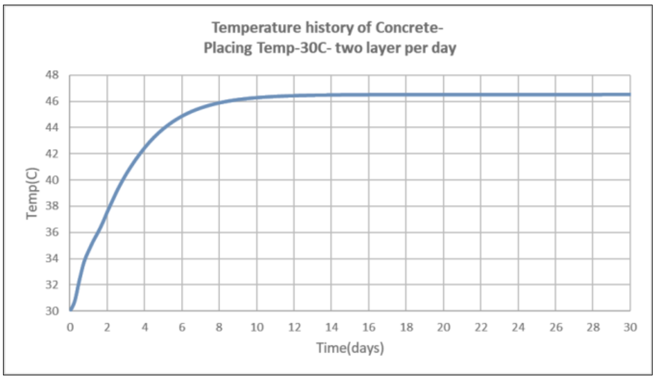

Figure 8.Calculated temperature history of Concrete Placing Temp. = 30°C- Two layers per day

In mass gradient cracking risk analysis, restraint reduction by increasing the height has not been considered and 100% of restraint have been considered. It is evident that in higher elevation of the dam body restraint is reduced. In A1 thermal analysis placing of two layers per day up to crest elevation has been modeled and peak temperatures have been calculated. Placing RCC in the main dam body will be a combination of A1 to A4 with different placing rates. Although in A1 (2 layers per day) crack spacing is more than contraction joint spacing and no cracking risk exist in this condition. However, it is advisable to keep placing rate less than two layers per day.

Table 3-Final Results and Cracking analysis

Analysis	Peak Temperature (°C)	Final Temperature (°C)	Restraint	Strain(μ)	Crack Spacing (m)	Result
A1	46.5	22.5	0.7	156.24	26.2	**Not Recommended**
A2	45.05	22.5	0.7	146.8005	29.9	**No Crack**
A3	44.6	22.5	0.7	143.871	31.3	**No Crack**
A4	39.1	22.5	0.7	108.066	71.3	**No Crack**

8. CONCLUSION

In this paper, thermal analysis of Dyraabadam body have been presented. Four different placing rates of 0.5, 1, 1.5 and 2 layers (0.3m thickness) have been analyzed. It is tried that the results be independent to a specific construction methodology and also be conservative. Based on strain method, compressive strains have been neglected. The below results are presented[6]:

1. Performed analyses shows that even with a placing temperature of 32℃, at placing rates of one layer per day or less, no cracking will exist. For higher placing rates (1.5 layers per day) placing temperature shall be decreased to 30℃. two layers per day is not recommendedbecause of higher cracking risk.
2. Continuous placement of 100 layers have been modeled, so the results of analyses are conservative. In real condition, time lapse between layers are more and maximum temperature is lower.
3. In calculation of mass gradient cracking risk, restraint factor reduction in higher elevation of dam body which will decrease thermal strain and has been neglected (K_R=1.0).
4. Surface post-cooling (water spraying) will help reduction of peak temperature and also will prevent from direct sunlight to concrete.

9. REFERENCES

1. ACI 207.1R-05-Guide to Mass Concrete
2. APPARENT ACTIVATION ENERGY An example of determination from adiabatic hydration tests (IPACS Report), Paolo Morabito,2001
3. Control of Cracking in Mass Concrete Structures, United States Department of The Interior Bureau of Reclamation,1981
4. Us. Army-ETL 1110-2-542- Thermal Studies of Massive Concrete Structures, 30May1997
5. ACI 207.2R-07- Report on Thermal and Volume Change Effects on Cracking of Mass Concrete
6. Dyraaba Thermal Analysis, Evyol Company,2013