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Construction Stage Thermal Analysis of a Roller Compacted Concrete Gravity Dam Using Three-Dimensional Finite Element Modelling

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Abstract: Temperature rise due to cement hydration is a critical concern during the construction of Roller Compacted Concrete (RCC) gravity dams, as it can induce thermal stresses and increase the risk of early-age cracking. This study presents a three-dimensional finite element analysis of a Non-Overflow (NOF) block of the proposed Garai RCC Gravity Dam using MIDAS software. Construction-stage thermal analysis was performed considering heat of hydration, ambient temperature variation, convection boundary conditions, and age-dependent material properties. A construction schedule commencing in January was evaluated to investigate temperature development during construction due to seasonal effects. The results showed peak temperatures of 39.63°C for the January schedule respective. Crack ratio assessment indicated satisfactory thermal safety for case at a placing temperature of 22°C. The study demonstrates that three-dimensional finite element modelling is an effective tool for predicting temperature rise and assessing the influence of construction season on RCC dam performance during construction.

Keywords -. Roller Compacted Concrete Dam, Finite Element Analysis, Temperature Rise, Construction Stage Analysis, Heat of hydration, Seasonal Effect, RCC Gravity Dam.

NOTATION

$Q(t)$	Adiabatic temperature rise at time t
Q_{int}	Maximum adiabatic temperature rise
r	Reactive velocity coefficient
t	Age of concrete
t_0	Start time of heat generation
$F(t)$	Ambient temperature at time t
T	Temperature amplitude (half of daily temperature variation)
t_0	Delay time or phase shift
T_0	Mean daily temperature
h	film coefficient
v	wind velocity

I. INTRODUCTION

Roller Compacted Concrete (RCC) gravity dams have gained widespread acceptance in modern hydraulic engineering due to their rapid construction, cost-effectiveness, and superior performance compared with conventional mass concrete dams. RCC consists of a low-slump concrete mixture placed in thin layers and compacted using vibratory rollers, allowing faster construction and reduced project costs. Owing to the large volume of concrete involved, RCC dams behave as mass concrete structures, where self-weight provides resistance against hydrostatic and other external loads. Despite their advantages, temperature control during construction remains one of the most important challenges affecting the safety and durability of RCC dams.

During construction, a significant amount of heat is generated as a result of cement hydration. Since the concrete mass is large, the generated heat dissipates slowly from the interior regions of the dam, leading to a rise in core temperature. The exposed surfaces, however, cool more rapidly due to interaction with the surrounding atmosphere. This non-uniform temperature distribution causes thermal strains and stresses within the structure, particularly during the cooling phase when the concrete tends to contract. If the induced tensile stresses exceed the tensile strength of young concrete, thermal cracking may occur, resulting in increased permeability, seepage, and reduced structural durability.

The proposed Gargai RCC Gravity Dam in Maharashtra is an important water supply project intended to meet the future water demands of Mumbai. Considering the massive concrete volume and staged construction sequence involved in the project, understanding temperature development during construction is essential for ensuring thermal safety. In this study, a three-dimensional finite element model of a selected Non-Overflow (NOF) block of the proposed Gargai RCC Gravity Dam was developed using MIDAS software. Construction-stage thermal analysis was performed to evaluate temperature rise and investigate the influence of different construction schedules starting in January. The findings provide valuable insights into the thermal behaviour of the dam and support the development of safe construction practices for RCC gravity dams.

II. LITERATURE REVIEW

Lu et al. (2024) investigated the feasibility of temperature-control measures during the construction of large-volume concrete gravity dams in cold regions. Using numerical simulation and field monitoring data, the study demonstrated that cooling pipes, insulation systems, and optimized construction schedules effectively reduce peak temperatures and thermal cracking risks.

Mousavi and Khiavi (2022) developed a probabilistic thermal analysis framework for RCC dams and reported that thermal conductivity and modulus of elasticity are among the most influential parameters affecting temperature distribution, stress development, and structural deformation.

Mirković et al. (2022) conducted a long-term three-dimensional thermal stress analysis of concrete gravity dams and found that reducing contraction-joint spacing significantly decreases thermal tensile stresses and crack-prone zones, thereby improving dam safety.

Aniskin and Nguyen (2021) employed three-dimensional finite element modelling to predict thermal stresses in RCC dams. Their study showed that cement content, construction rate, and placing temperature have a significant influence on temperature development and cracking potential.

Zhao et al. (2019) proposed an equivalent inverse-analysis method for determining thermodynamic parameters of compacted RCC layers. The study improved the accuracy of thermal stress simulations by accounting for the interaction between individual concrete lifts and the dam mass.

Hagos et al. (2019) evaluated the influence of lift thickness on temperature and thermal stresses in RCC gravity dams. The results indicated that larger lift thicknesses lead to higher temperatures and greater cracking potential.

Malkawi et al. (2003) carried out coupled thermal–structural finite element modelling of an RCC gravity dam and demonstrated that hydration heat plays a major role in temperature rise and thermal stress development during construction. The study emphasized the importance of temperature control measure for thermal cracking.

Although previous studies have contributed significantly to understanding the thermal behaviour of RCC dams, many investigations are limited to simplified construction sequences or specific case studies. Comprehensive three-dimensional analyses incorporating realistic construction-stage simulation and seasonal construction schedules remain relatively limited. Therefore, the present study focuses on a detailed three-dimensional construction-stage thermal analysis of the proposed Gargai RCC Gravity Dam and evaluates the influence of January construction schedule on temperature development and thermal safety.

III. METHODOLOGY

The overall methodology adopted in this study enables a realistic assessment of the thermal performance of the proposed Gargai RCC Gravity Dam during construction. The sequence of analysis followed in the present investigation is illustrated in the methodology flow chart presented in the subsequent section.

A three-dimensional finite element model of the selected NOF block was developed in MIDAS software.

1. Geometry

A three-dimensional finite element model of the selected Non-Overflow (NOF) block of the proposed Gargai RCC Gravity Dam was developed in MIDAS software. The NOF block has a height of 64 m, a base width of 56 m, and a crest width of 8 m. To realistically represent the construction process, the dam block was divided into 43 construction lifts. The first 42 lifts were modelled with a height of 1.5 m each, while the top lift was assigned a height of 1.0 m. A foundation rock block was included beneath the dam section to account for dam–foundation interaction and provide realistic restraint conditions during thermal analysis. Sequential activation of these lifts was used to simulate the actual construction procedure adopted in RCC dam construction.

2 Material Properties

Mechanical Properties

The mechanical properties of RCC concrete significantly influence the structural response of the dam during construction. Parameters such as modulus of elasticity, Poisson's ratio, and unit weight govern the stiffness, deformation behaviour, and load-carrying capacity of the concrete mass. A higher modulus of elasticity increases resistance to deformation and results in greater restraint against thermal expansion and contraction, which can lead to higher thermal stress development within the dam body. Similarly, the self-weight of the concrete contributes to the overall stress state of the structure, while Poisson's ratio affects the lateral deformation characteristics. Therefore, accurate representation of mechanical properties is essential for predicting stress distribution and assessing the structural stability of RCC dams.

In present study, The dam body was assumed to be constructed using M20 grade Roller Compacted Concrete (RCC). The mechanical properties adopted in the finite element model included a modulus of elasticity of 25 GPa, Poisson's ratio of 0.20, and a unit weight of 24 kN/m³. These properties were used to evaluate stress development and structural response during the construction stage.

Thermal Properties

The thermal behaviour of RCC concrete was characterized using thermal conductivity, specific heat, and coefficient of thermal expansion. These properties govern heat storage, transfer, and thermal strain development within the dam body and directly influence peak temperature rise during construction. These properties directly influence peak temperature rise and the resulting thermal strains developed within the dam body. Consequently, proper characterization of thermal properties is necessary for accurately simulating temperature evolution and evaluating the thermal performance of RCC dams during construction. In present

study, a thermal expansion coefficient of $1 \times 10^{-5}/^{\circ}\text{C}$ was adopted. Thermal conductivity and specific heat were specified to simulate heat transfer and temperature evolution resulting from cement hydration within the RCC mass.

Table 1 Properties of material

Property	Value
Grade of Concrete	M20
Modulus of Elasticity (E)	25,000,000 kN/m ²
Poisson's Ratio	0.20
Unit Weight	24 kN/m ³
Coefficient of Thermal Expansion	$1 \times 10^{-5} /^{\circ}\text{C}$
Thermal Conductivity	112,320 J/(m·day·°C)
Specific Heat	836,800 J/(ton·°C)

Time-Dependent Properties

Since concrete properties evolve with age, time-dependent material behaviour was incorporated in the analysis. An age-dependent modulus of elasticity function was used to represent the gradual increase in stiffness with concrete maturity. The modulus of elasticity of concrete is not constant and increases gradually with age due to the progress of cement hydration and strength gain. The modulus of elasticity function is used to represent this age-dependent increase in concrete stiffness during construction. Newly placed RCC possesses lower stiffness and therefore experiences larger deformations under thermal loading. As the concrete matures, its stiffness increases, resulting in higher restraint against thermal deformation and greater thermal stress development. Therefore, incorporating the modulus of elasticity function enables more realistic prediction of the structural response of the dam during construction.

In addition, creep and shrinkage functions were considered to account for stress relaxation and volumetric deformation during construction. Creep and shrinkage are important time-dependent properties that influence the long-term behaviour of mass concrete structures. Creep represents the gradual increase in concrete strain under sustained loading and helps in relieving or redistributing thermal stresses developed within the dam body. Shrinkage refers to the gradual reduction in concrete volume due to moisture loss and hydration processes, which can contribute to tensile stress development. The creep and shrinkage function is incorporated in the analysis to account for these time-dependent deformations and to obtain a more realistic assessment of thermal stress and cracking potential in the RCC dam. Inclusion of these parameters enabled a more realistic prediction of temperature-induced stress development in the dam body.

3. Finite Element Meshing

The three-dimensional geometry of the dam and foundation system was discretized using solid finite elements. A hybrid meshing of 2m size approach was adopted to ensure adequate representation of the geometry while maintaining computational efficiency. Special attention was given to mesh compatibility between adjacent construction lifts and at the dam–foundation interface. The mesh density was selected to capture temperature distribution and stress concentrations accurately throughout the structure. Each construction lift was meshed separately and activated sequentially during construction-stage analysis, allowing realistic simulation of heat generation and structural response.

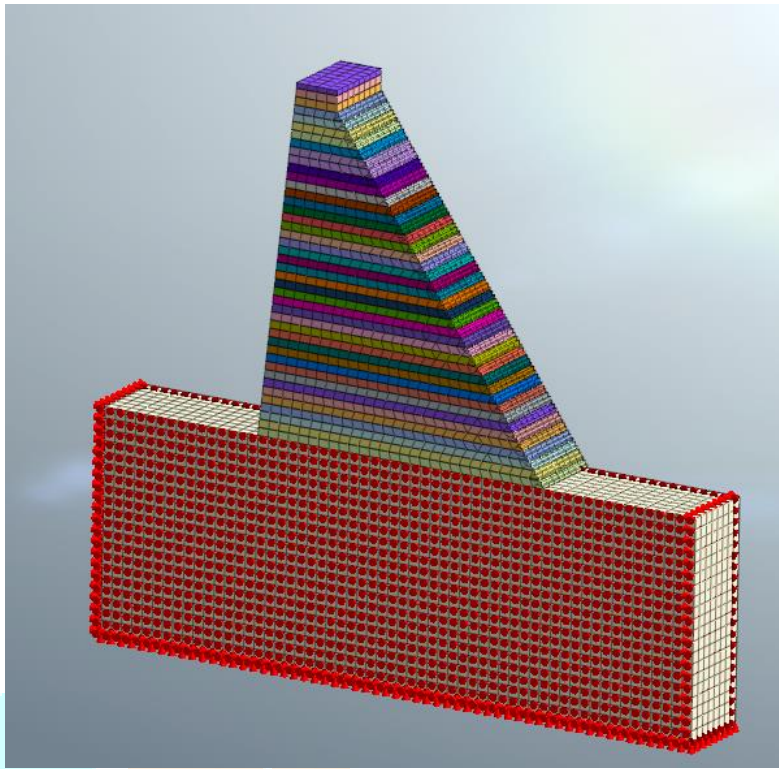


Figure 1 Modelling of NOF Block in MIDAS

Thermal Parameters Heat of Hydration Function

Heat generated during cement hydration causes a progressive increase in the internal temperature of the RCC dam. Successive lift placement leads to heat accumulation within the concrete mass, influencing peak temperature development during construction.

The heat generated at any time t is calculated using the exponential heat generation function:

$$Q(t) = Q_{int} \left[1 - e^{-r(t-t_0)} \right] \quad (1)$$

In the present study, the parameters of the heat source function were adopted based on values reported in published literature on RCC dams and mass concrete thermal analysis. The values considered for M20 RCC concrete

Maximum adiabatic temperature rise, $Q_{int} = 22^\circ\text{C}$

Reactive velocity coefficient, $r = 0.442 \text{ day}^{-1}$

Start of heat source, $t_0 = 0 \text{ day}$

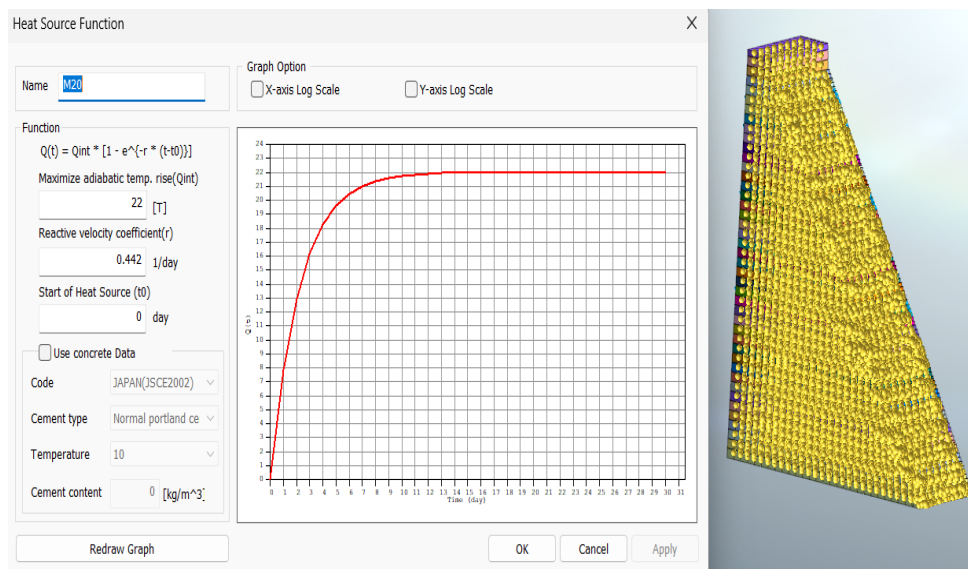


Figure 2 Heat of hydration function

Ambient Temperature function

In addition to the internal heat generated due to cement hydration, the temperature of the concrete is continuously influenced by surrounding atmospheric conditions. Therefore, realistic environmental thermal loading must be applied to accurately simulate temperature development within the dam body. In the present study, thermal loading was applied through an Ambient Temperature Function in MIDAS software. The ambient temperature data were obtained from meteorological records and incorporated into the model according to the adopted construction schedule.

The variation of ambient temperature with time was represented using the sinusoidal function available in MIDAS:

$$F(t) = T \sin \left(\frac{2\pi}{24} (t + t_0) \right) + T_0 \quad (2)$$

Table 2 Ambient temperature data

Month	Mean Temp (°C)	Min Temp (C)	Max Temp (C)	T-MAX TEMP	MEAN
January	23.9	18.8	29.4	5.3	24.1
February	24.7	19.6	30.2	5.3	24.9
March	26.7	21.7	32	5.15	26.85
April	28.2	24	32.8	4.4	28.4
May	29	26.2	32.4	3.1	29.3
June	27.4	25.9	29.5	1.8	27.7
July	25.9	24.9	27.3	1.2	26.1
August	25.6	24.5	27.2	1.35	25.85
September	26.1	24.4	28.2	1.9	26.3
October	27.3	24	31	3.5	27.5
November	27	22.4	31.8	4.7	27.1
December	25.1	20.1	30.5	5.2	25.3

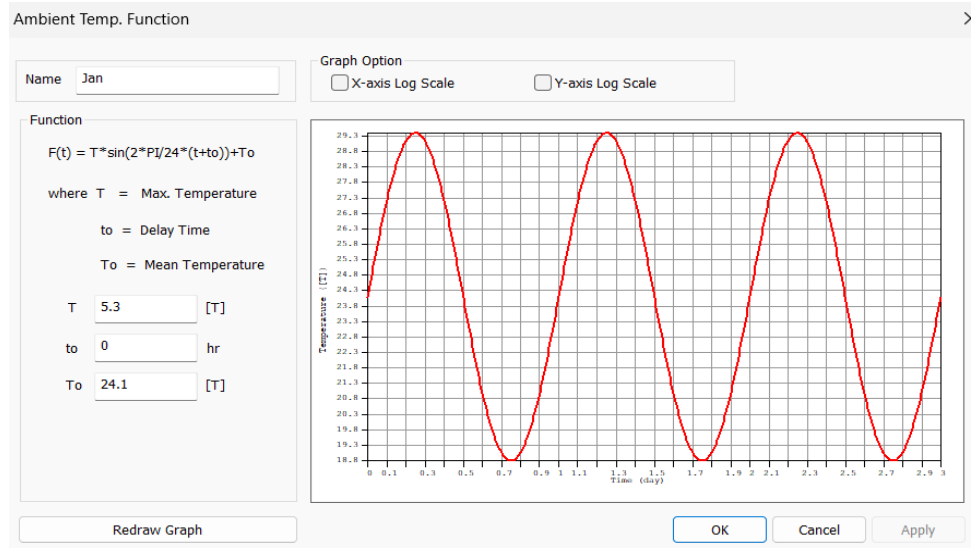


Figure 3 Ambient temperature function

Film coefficient

To simulate heat transfer between the concrete surfaces and surrounding air, the convection phenomenon was considered as the primary boundary condition. Convection heat transfer was defined using film coefficients calculated from local wind speed data corresponding to the selected construction period. Month-wise atmospheric temperatures and wind speeds obtained from meteorological sources were used to determine the appropriate convection coefficients for each construction stage. These coefficients were then assigned to exposed dam surfaces throughout the analysis.

The following equations are from the ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) Handbook and Product Directory-1977 Fundamentals (1977). These equations may be used for computing the film coefficients to be included in MIDAS for modelling convection. For surfaces without forms, the coefficients should be computed based on the following:

$$\begin{aligned}
 h &= 0.1132V^{0.8} \\
 &\text{for } V > 10.9 \text{ mph} \\
 \text{and} \\
 h &= 0.165 + 0.0513(V) \\
 &\text{for } V < 10.9 \text{ mph} \\
 \text{where,} \\
 h &= \text{film coefficient} \left(\frac{\text{Btu}}{\text{day-in.}^2\text{-}^\circ\text{F}} \right) \\
 V &= \text{wind velocity (mph)}
 \end{aligned}
 \tag{3}$$

The equation indicates a direct relationship between wind speed and convective heat transfer. As wind velocity increases, the film coefficient also increases, resulting in greater heat dissipation from the concrete surface. Consequently, the temperature difference between the core and surface of the dam may increase, leading to higher thermal stresses.

4. Construction Schedule

To investigate the influence of seasonal climatic conditions on thermal behaviour, construction schedules were developed. The schedule assumed a construction start date of 1 January with same stage durations however, the ambient temperature functions and film coefficients assigned to each stage differed according to the corresponding monthly environmental conditions. At the time of activation of a new lift, the corresponding heat of hydration function, initial placing temperature, and material age-dependent properties were assigned automatically to that stage. Simultaneously, convection boundary conditions were applied to

all surfaces exposed to the atmosphere. The ambient temperature function corresponding to the month of construction and the associated film coefficient calculated from the monthly wind speed data were assigned to the exposed element faces.

In the present study, an initial placing temperature of 22°C was adopted for the January construction schedule, reflecting winter construction conditions. The temperature fields generated from these loading conditions were subsequently used in nonlinear thermal–stress analysis for determination of crack ratio and assessment of thermal safety of the structure.

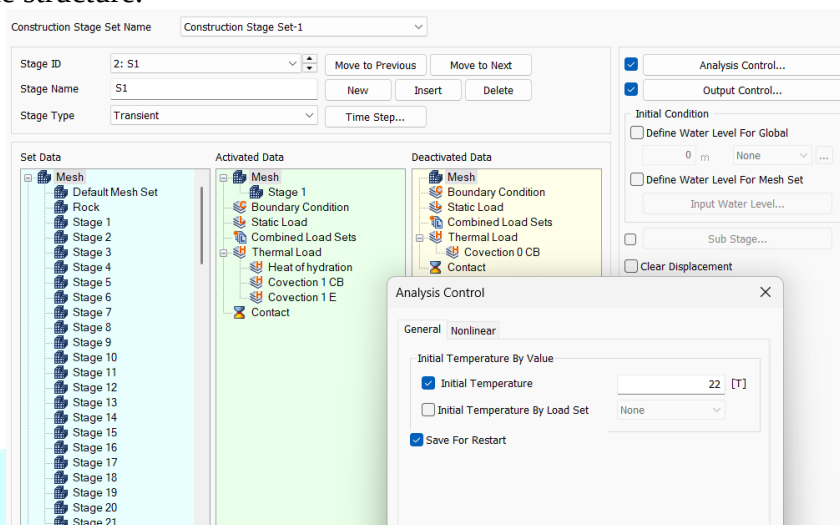


Figure 4 Application of construction stage in MIDAS

The complete construction schedules adopted for January is presented in the table below:

Table 3 Construction Schedule

Height above foundation (h)	Lift Height	Day	Construction scheme	Stages	Month	Film coefficient
1.5	1.5	8	8	1	January	1754157
3	1.5	16	8	2	January	1754157
4.5	1.5	24	8	3	January	1754157
6	1.5	32	8	4	January	1754157
7.5	1.5	40	8	5	February	1739056
9	1.5	48	8	6	February	1739056
10.5	1.5	56	8	7	February	1739056
12	1.5	64	8	8	March	1723956
13.5	1.5	72	8	9	March	1723956
15	1.5	80	8	10	March	1723956
16.5	1.5	88	8	11	March	1723956
19.5	1.5	104	8	13	April	1784359
21	1.5	112	8	14	April	1784359
22.5	1.5	120	8	15	April	1784359
24	1.5	128	8	16	May	2186142
25.5	1.5	136	8	17	May	2186142
27	1.5	144	8	18	May	2186142
28.5	1.5	152	8	19	May	2186142
30	1.5	160	8	20	June	2641242
31.5	1.5	168	8	21	June	2641242
33	1.5	176	8	22	June	2641242
34.5	1.5	184	8	23	June	2641242
36	1.5	192	8	24	July	2939015

37.5	1.5	200	8	25	July	2939015
39	1.5	208	8	26	July	2939015
40.5	1.5	216	8	27	July	2939015
42	1.5	224	8	28	August	2641242
Height above foundation (h)	Lift Height	Day	Construction scheme	Stages	Month	Film coefficient
48	1.5	256	8	32	September	1859862
49.5	1.5	264	8	33	September	1859862
51	1.5	272	8	34	September	1859862
52.5	1.5	280	8	35	October	1542747
54	1.5	288	8	36	October	1542747
55.5	1.5	296	8	37	October	1542747
57	1.5	304	8	38	October	1542747
58.5	1.5	312	8	39	November	1572948
60	1.5	320	8	40	November	1572948
61.5	1.5	328	8	41	November	1572948
63	1.5	336	8	42	December	1663553
64	1	344	8	43	December	1663553

5. Thermal analysis

In the present study, temperature development within the dam was determined using Transient Heat Transfer Analysis. Transient heat transfer analysis was employed to evaluate the variation of temperature within the RCC dam with respect to time during the construction period. Unlike steady-state analysis, transient analysis accounts for continuous changes in temperature caused by hydration heat generation, environmental conditions, and construction-stage activation of concrete lifts. The method enables simulation of heat accumulation and dissipation throughout the dam body as construction progresses. By considering the time-dependent nature of temperature development, transient heat analysis provides a realistic prediction of peak temperatures during construction. The temperature fields obtained from this analysis were subsequently used to assess the thermal behaviour of the RCC dam under different construction schedules.

The temperatures calculated from the thermal analysis are subsequently applied as loads in a Nonlinear Incremental Thermal–Stress Analysis. The term incremental analysis refers to the application of loads stage by stage according to the actual construction sequence. Each newly placed concrete lift contributes additional stiffness, internal heat generation, and restraint to the structure. Therefore, the structural response continuously changes during construction and must be evaluated incrementally. This help to calculate the crack ratio for the stages which signifies safe placing temperature of concrete.

$$\text{Crack Ratio} = \frac{\text{Concrete Tensile Strength}}{\text{Maximum Principal Tensile Stress}}$$

The crack ratio provides a measure of the resistance of concrete against temperature-induced cracking. A crack ratio greater than unity indicates that the available tensile strength of concrete is sufficient to resist the generated thermal tensile stresses, whereas a crack ratio less than unity indicates the possibility of thermal cracking.

The complete analysis procedure therefore consists of data collection, finite element modelling, assignment of thermal and mechanical properties, definition of hydration heat and convection boundary conditions, transient thermal analysis, nonlinear incremental thermal–stress analysis, and assessment of crack ratio. This methodology enables realistic simulation of temperature development, stress generation, and cracking tendency during staged construction of the selected NOF block.

IV. RESULTS AND DISCUSSION

4.1 Temperature Development

The transient heat transfer analysis indicated a continuous increase in temperature within the NOF block during construction due to the cumulative effect of hydration heat generated in successive RCC lifts. The highest temperatures were observed in the interior region of the dam where heat dissipation was relatively slow compared to the exposed surfaces. As construction progressed, the newly placed concrete contributed additional heat, resulting in gradual temperature accumulation within the structure. The elevated ambient temperatures prevailing during this period reduced the rate of heat loss from exposed surfaces and influenced the overall temperature development within the concrete mass. However, the peak temperature remained within acceptable limits for RCC dam construction, indicating satisfactory thermal performance of the structure during the construction stage. For the January construction schedule, the maximum temperature developed in the NOF block was **39.63°C**. Considering an initial placing temperature of **22°C**, the peak temperature rise was found to be **17.63°C**, primarily due to the cumulative effect of hydration heat generated in successive RCC lifts.

2. Safe Placing Temperature

To evaluate thermal safety, the January construction schedule was analyzed with a concrete placing temperature of 22°C. The results indicated that the temperature rise developed during construction did not produce critical thermal stresses within the NOF block. The thermal safety of the structure was assessed using the crack ratio, which compares the tensile capacity of concrete with the induced thermal tensile stress. The analysis showed that the crack ratio remained greater than 1.0 in all critical regions of the dam, indicating that the available tensile strength of concrete was sufficient to resist the developed thermal stresses. Since a crack ratio greater than 1.0 signifies a safe condition against thermal cracking, the construction scenario satisfied the thermal safety requirements. Therefore, a placing temperature of 22°C was found to be safe and suitable for construction commencing in January, ensuring acceptable temperature development and minimizing the risk of temperature-induced cracking during construction and indicating sufficient tensile capacity of concrete throughout the construction period.

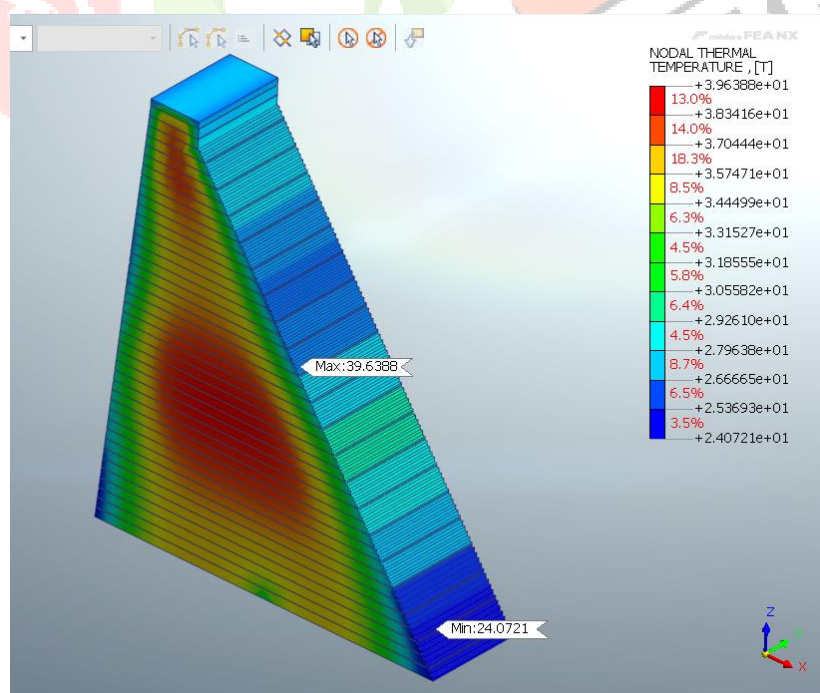


Figure 5 Maximum and minimum temperature development during construction

V. CONCLUSION

Based on the results obtained from the three-dimensional finite element thermal analysis, the following conclusions are drawn:

1. Three-dimensional finite element model successfully captured the construction-stage temperature development of the RCC gravity dam and provided a realistic assessment of thermal behaviour during staged construction.
2. Heat generated due to cement hydration was identified as the governing factor influencing temperature rise, leading to progressive heat accumulation within the dam body during construction.
3. For the January construction schedule, the maximum temperature within the NOF block reached approximately 39.63°C, with the highest temperatures occurring in the interior region of the dam.
4. The lower ambient temperatures associated with January construction enhanced heat dissipation from exposed surfaces and contributed to maintaining acceptable temperature levels throughout the construction period.
5. Thermal safety assessment indicated that a placing temperature of 22°C is suitable for the January construction schedule, with the crack ratio remaining greater than 1.0, confirming a low risk of temperature-induced cracking.

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