Gibe III dam: project summary, mixes, properties, thermal issues and cores

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Introduction

The Gibe III Hydroelectric Project is one of the most important steps in the Ethiopian Government's planned commitment to meet the present and future power requirements of the country by utilizing available renewable resources that will help answer to the socio-economic demands of the nation.

The Ethiopian Electric Power Corporation Company (EEPCo) is responsible for power generation, transmission, distribution and sales of electricity all over the nation. They entrusted Salini SpA with the engineering, procurement, construction and commissioning of the Project in July 2006. The design of the Gibe III was conducted for Salini by Studio Ing. G. Pietrangeli s.r.l.. The Gibe III dam and hydropower plant are currently under construction.

The Gibe III site is located in the Southern Nations and Nationalities Peoples Region Administration (SNNP) within Bolaso Sore Woreda of the Wolayta Zone, some 300 km South-West of Addis Ababa.

The project includes a roller compacted concrete (RCC) dam with a maximum height of 243 m and a total volume of RCC of about 6 million cubic meters. The 1,870 MW installed power will be generated by 10 Francis turbines in an outdoor power plant for the production of 6,500 GWh/year to be distributed by means of a 65 km long high voltage transmission line. The project also includes 7 chute spillways, 2 headrace tunnels, 3 river diversion tunnels, and a temporary rockfill dam with an impermeable membrane (see Figure 1).

The Gibe III project is part of far more prodigious venture. It is the third part of the Omo-Gibe cascade series that includes two plants already operating upstream, namely, the Gilgel Gibe I (IP = 200 MW) and Gibe II (IP = 420 MW).
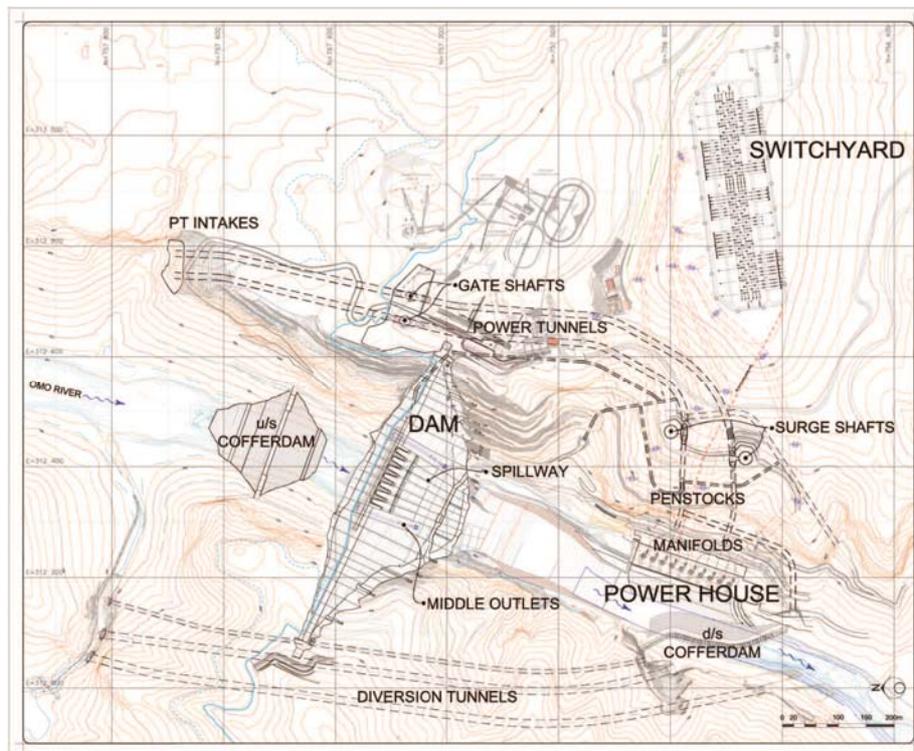
Fig. 1. Gibe III hydroelectric project, plan view.

This paper, focused on the RCC dam, presents basic project information, a summary of RCC mix designs and basic properties, the two-dimensional dam thermal analysis and a sample of cores recently extracted from the dam.

1. Dam site climatic data

The dam site is located in a tropical sub-humid region with an annual average temperature of 27°C. Five meteorological stations (three are still in operation) have been installed at Gibe III site from March 2006, three on different plateaus around elevation 1050 m a.s.l. and two at the Omo river level of 695 m a.s.l. All stations record simultaneously, with a set recorded frequency of an hour for air temperature, relative humidity, rain, wind speed and solar radiation.

Figure 2a shows the hourly monthly average temperature reordered at Gibe III site (elev. 695 m a.s.l.). As illustrated in the figure the maximum monthly average temperature is 31°C in February and the minimum monthly average temperature is 25°C in July.

Figure 2b shows the monthly rainfall measured at the dam site. Two climatic seasons characterize the project area: the dry season that prevails from November through February and the wet season that prevails from March to October. The maximum monthly precipitation ranges from about 300 to 500 mm. The heaviest monthly precipitation of 515 mm was recorded in April 2006.
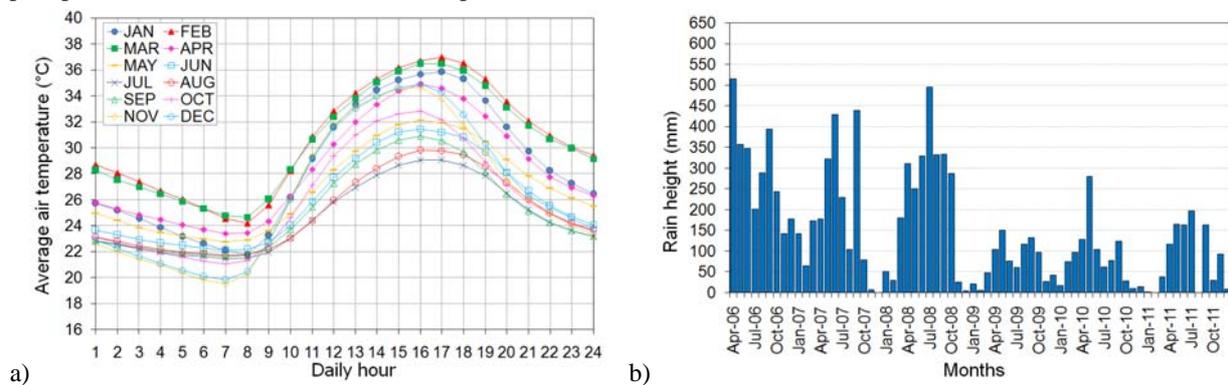
Fig. 2. Gibe III meteorological station: a)Hourly average temperature; b)Monthly rain

2. Dam characteristics and zoning

Gibe III is a 243 meter high roller compacted concrete gravity dam with a crest length of 670 m at elevation 896 m a.s.l. and a total volume of about 6 million cubic meters. The upstream face has a 0.25:1 (H:V) slope in the lower portion (below elev. 770 m a.s.l.) and a 0.2:1 (H:V) slope in the upper portion. The stepped downstream face has an average slope of 0.65:1 (H:V) with a local slope decrease at the toe below elev. 700 m a.s.l.. The dam has 35 monolith blocks separated by cutting joints into the freshly RCC after compaction. The construction joint spacing along the dam axis varies from 11 to 24 m. The dam body is crossed by 6 main longitudinal galleries every 40 m of height (at elevations 660, 700, 740, 780, 820 and 860 m a.s.l.). Most of these extend into the abutments for about 40-50 m.

Figure 3 illustrates the main section of the dam with the cement content zoning and the extent of bedding mix at lift joints for different elevations. As shows in the figure the dam is divided in different zones based on the RCC mixes and also the presence (or not) of systematic bedding mix. The cement dosages range from 70 to 120 kg/m^3 according to the design strength demand. A higher cement content is used in the lower part of the dam to meet the upstream dynamic tensile strength and permeability requirements, and at the downstream toe for compressive strength requirements. The extent of bedding mix is primarily established by consideration for impermeability at lift joints in the upstream portion of the dam and to assure adequate safety against sliding on any horizontal lift within the structure. The extreme upstream face uses grout enriched RCC (GERCC) with variable width of 80 cm below elev. 750 m a.s.l., 60 cm between 750 and 800 m a.s.l. and 40 cm in the remaining portion. A GERCC layer, 50 cm wide is used at the downstream slope to enhance the face appearance and durability.

The spillway is incorporated in the central part of the dam on the downstream face. It includes an overflow crest at el. 875 m a.s.l. with a length of 124 m and height of 93 m, divided into seven bays controlled by radial gates. The chute on the d/s slope is divided into seven rectangular canals slightly convergent, with three different types of deflector buckets designed for partly dissipating the energy in air and impacting the plunge pool between the d/s toe of the dam and the Power House. The design flood for the spillway is Q = 10,600 m^3/sec (10,000 years return period through 5 bays) as well as the routed exceptional flood Q = 18,000 m^3/sec (Probable Maximum Flood through 7 bays). Two middle outlets are symmetrically located in the dam body, with inlet invert elevation of 750 m a.s.l., to allow the control of the reservoir impounding, allow a safe drawdown of the reservoir up to the power tunnel intake elevation about 780 m a.s.l. and allow controlled flood release for environmental purposes.

ZONE	f_C [MPa]	CEMENT [kg/m³]	Systematic BEDDING
A	15	120	Y
B	15	105	Y
C	10	90	Y
D	10	90	N
E	10	90	Y
F	18	105	Y
G	10	70	Y
H	10	70	N
I	15	90	N
J	15	90	Y
K	8	70	Y
L	8	70	N
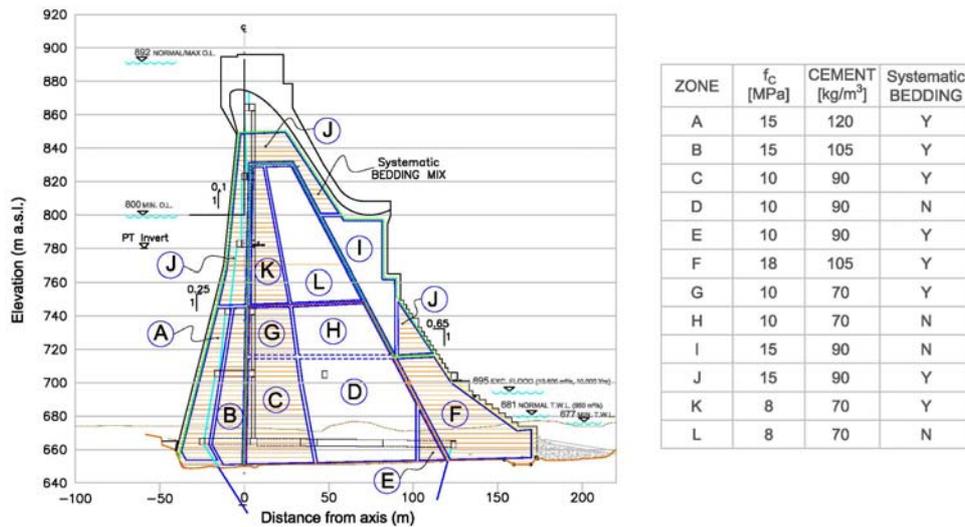
Fig. 3. Gibe III main section (geometry, cement content zoning, extension of lift bedding mix).

3. Mix design, thermal and mechanical properties

3.1 General

Extensive mix designs and testing were undertaken to develop credible site specifc mixes e mechanical and thermal parameters necessary to perform thermal analyses in addition to structural analyses. Particular attention has been paid to the methodology used to establish the adiabatic temperature rise and time-dependent values of tensile strain capacities for each zone.

Considering the importance of the project, the mix design program started more than 3 years ago at the Gibe III site laboratory. During the different design mix phases, in addition to the basic variable of cement type and content, other variables in the mix programs included the type and dose of admixture, the amount and source of ignimbrite fines passing 0.075 mm, the size and amount of ignimbrite aggregates, the proportions and percentages of crushed gravel and basalt, and water content. The site test program includes compressive and split tensile strength at 3, 7, 14, 28, 56, 90, 180 and 365 days using standard cure, and 14 day accelerated cures. The density of each cylinder was determined by weighing in air and water. The mix program also included complete stress-strain curves of the compressive cylinders, with the secant modulus reported at 25%, 50%, 75%, and 100% of ultimate load. Fresh mix properties were also determined including VB time, temperature, fresh compacted unit weight, and air content. Special tests (i.e. adiabatic temperature rise, creep and direct tensile tests) have been performed at Levelton Laboratory in British Columbia (Canada). The test results of different trial mix phases were used along with experience at other projects and relationships that have been established for both RCC and conventional concrete to estimate a complete set of probable time dependant and load dependant material properties.

3.2 Mechanical properties

Space does not allow presentation of all the extensive mix design studies carried out at project site laboratory, so this paragraph presents mainly the results of tests performed on the mixes finally used for the dam construction to date. The final design mixes include:

- o   cement: Cementir Slag cement from Italy;
- o   total aggregate: 72% crushed river gravel, 25% crushed basalt, 3% crushed ignimbrite;
- o   aggregate fines: 6%
- o   filler: Ignimbrite powder

Figures 4a shows the average compressive strength for all the RCC mixes placed in the dam since December 2011. As shown in the figure the results of the test cylinders through 365 days are only available now for the mixes with cement content of 105 kg/m³ and 120 kg/m³. Results through only 90 days are currently available for the other mixes (70 kg/m³ and 90 kg/m³). Figure 4b shows the stress-strain curve of the mix with 125 kg/m³ of cement at two different ages (28 and 365 days). The relationship between the measured values of compressive and split strength for all the mixes are reported in Figure 4c. The direct tensile strength for the RCC mass and for RCC lifts with bedding were estimated from values of the indirect split tensile strength using the formula developed by Dr. Schrader [1]. The values agree reasonably well with the limited direct tension tests of cores, including the full stress-strain curves, at Levelton Lab.
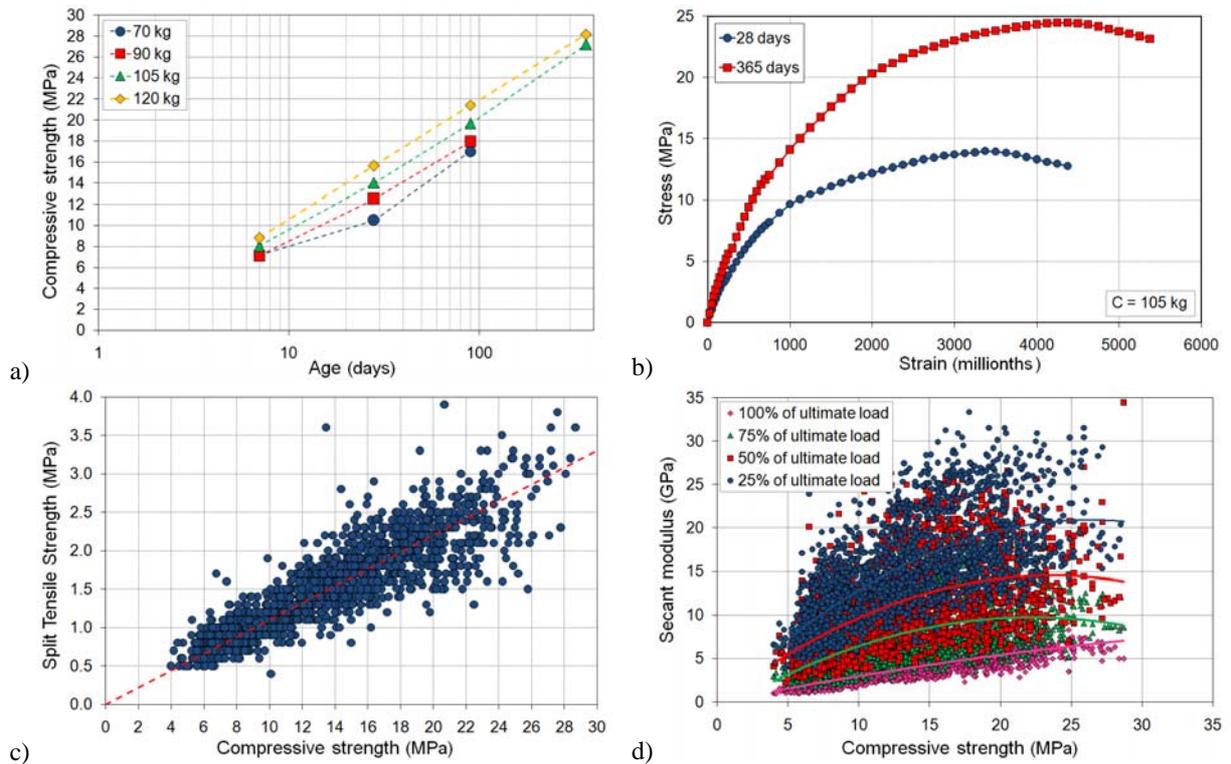
Fig. 4. Mechanical properties of RCC placed at the dam to date: a) Compressive strength vs. age; b) Stress-strain curve of the mix with 105 kg per cubic meter of cement (28 and 365 days); c) Split tensile strength vs. compressive strength; d) Secant elastic modulus at various levels of stress vs. compressive strength.

It is significant that the stress-strain curves are not linear. This is very beneficial. There is considerable "strain softening" that occurs at higher levels of load. Accordingly, the secant modulus of elasticity decreases signify as the load is increased. Results at 25%, 50% 75% and 100% of ultimate load are shown in fig 4d.

Figure 5a shows results of tests to determine the creep factor for Gibe III mixes, compared to global data from other projects with various mixes (different cement contents, different cements, different pozzolan contents, different pozzolans, different water contents, different w/c, different aggregates and msa, etc.). The chart shows the average curve of the Gibe III data. The creep values were used in conjunction with the modulus of elasticity values to establish sustained modulus (E_{SUS}) values for different time periods. The sustained modulus takes into account the change of modulus during the time of loading (the time period of cooling), along with creep relaxation for that time period. The sustained modulus values were then used in conjunction with the direct tensile strengths to develop "slow load" tensile strain capacities (TSC). The values of tensile strain capacity for different mixes vs. RCC age at the time of initial loading are reported in the figure 5b. This example is for situations where the total time period is 365 days past the age of initial loading..
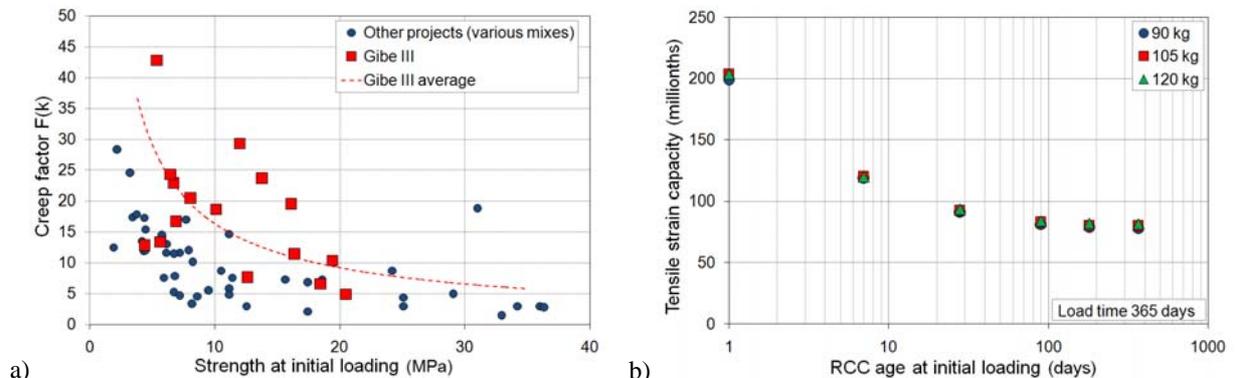
Fig. 5. a) Creep factor vs. strength at initial loading; b) Slow load tensile strain capacity vs. RCC age at initial loading

3.3 Thermal properties

Thermal properties of the RCC mixes, including the specific heat (C_h), the thermal diffusivity (h^2), coefficient of thermal expansion (CTE) and the adiabatic temperature rise (ΔT_{ad}) were investigated at the Levelton laboratory in Canada. Table 1 summarizes the thermal properties of the different RCC mixes used in the dam.

Parameters	Unit	Cement content (kg/m^3)				
		70	90	105	120	200
Specific heat (C_h)	kJ/kg - °C	0.82				
Diffusivity (h^2)	m^2/hr	0.0016				
Conductivity (k)	W/m - °C	0.89				
Coeff. Of thermal expansion (CTE)	x10^{-6}/°C	7.6	7.7	7.8	7.9	8.1
Adiabatic T-rise (ΔT_{ad}) @365 days	°C	11.0	13.6	15.6	17.5	27.4

Tab. 1. RCC mixes thermal properties

Four laboratory tests, on the same mix at different ages (approx. 28 and 90 days), were carried out to estimate the value of thermal diffusivity. Because the value measured, equal to 0.0016 m^2/h, was unusually low, the test was repeated at a second laboratory (CTL laboratory in USA) and similar result was obtained. This low value of thermal diffusivity means slow migration of heat through the mass and, therefore, a longer time than normal to reach the final stable temperature.

The adiabatic rise for different mixes, including GERCC, was first calculated considering the chemistry and heat of hydration tests for the specific cements, the specific heat of the RCC, the cement content of the mixes, and established adjustment factors for admixture, pozzolan, and total cementitious content. The heat of hydration for Cementir cement was measured at CTL laboratory in USA and is equal to 50 cal/g at 7 days and 57 cal/g at 28 days. Two adiabatic temperature rise tests were then performed at Levelton laboratory, using the gradation and composition of aggregate planned for the dam and 120 kg/m^3 of Cementir cement. These tests did not agree with results of the laboratory hydration tests which indicate that the adiabatic temperature rise would stop producing heat (flatline) after 14 days. This is not considered realistic. The results of adiabatic tests were therefore taken into account only to calibrate the estimated adiabatic temperature rise curve in the first stretch between 0 and 14 days (see Figure 6a). Figure 6b shows the magnitude of the adiabatic temperature rise and the shape of the curve for the different mixes used in the dam.
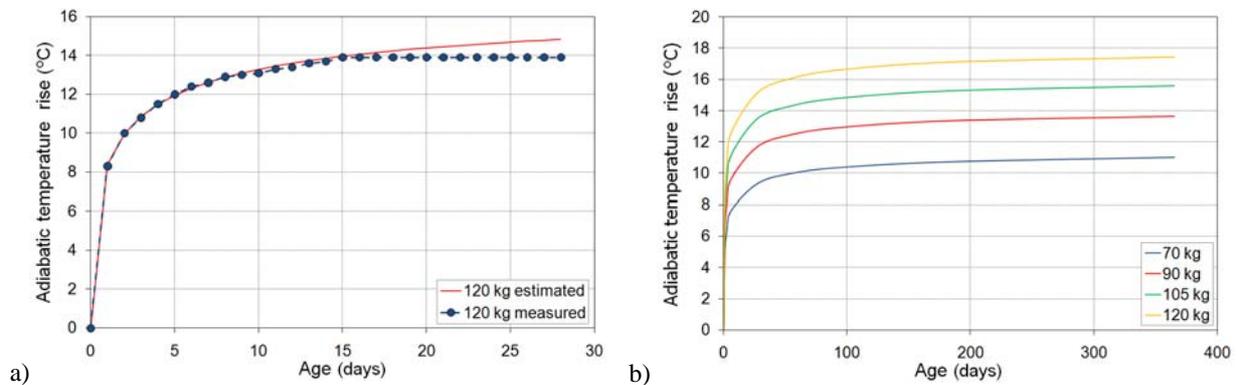
Fig. 6. a) Comparison between measured and estimated adiabatic T-rise; b) RCC mixes adiabatic temperature rise vs. age.

4. Thermal analysis

4.1 General

Several thermal simulations have been performed in order to assess the thermal behaviour of the dam during and after the end of construction and establish the degree of pre-cooling (i.e. placing temperature of RCC) required to avoid the thermal cracks.

4.2 Calculation methodology and assumptions

The thermal study is articulated in two steps: the first is the transient thermal analysis where a finite differences method is utilized on a mathematical model expressly built for the specific case of Gibe III to evaluate the temperature distribution histories in the dam; the second is the gradient cracking analysis, where results of the first step together with the thermo-mechanical properties and degree of restraint present in the different locations of the dam are used to evaluate mass and surface cracking in the RCC mass and upstream face.

The main assumptions of the analysis are: 1) bi-dimensional analysis; 2) node spacing equal to 15 cm (approx. 1,000,000 nodes) in order have at least two elements per 30 cm lift height with 740 lifts, time step equal to 3.5 hours; 3) RCC is assumed homogenous and isotropic; 4) the rock foundation is modelled only under the RCC (no heat flow occurs out the vertical faces of the foundation); 5) conservatively, and in keeping with typical industry practice, compressive strain in the initial expansion phase is neglected; 6) spillway and drainage galleries are not considered.

The calculation methodology considers the main parameters that influence thermal behaviour of an RCC dam, including the effect of daily and monthly fluctuation of air temperature and solar radiation, the effect of the heat transfer by convection from the external surface of RCC lift, the time-varying thermo-mechanical properties of the RCC/GE-RCC mixes (adiabatic temperature rise, elastic modulus, creep, drying shrinkage, tensile strain capacity, etc.), the placing temperature and the construction program (i.e. construction start, lift height and lift placement rate).

In the analysis two types of restraint have been considered; the first one is related to the ratio between the foundation and the dam stiffness, the other one is related to the geometry of the structure. Considering the low value of elastic modulus of the foundation (ranging between 3-10 GPa) the foundation restraint factor was fixed at 0.82. The structure restraint factor is estimated on the basis of the geometry of the dam (height 243 m, base length approx. 200 m, max joint spacing 30 m) as a function of the distance above the foundation. It is equal to 1 at the foundation and equal to 0.1 respectively at 130 m above the foundation in the longitudinal direction and at 25 m above the foundation in the transversal direction.

Several theoretical construction schedules have been adopted in the simulations in order to study the influence of the lift placement rate and construction start on the peak temperature in the RCC mass. In this paper the results of the simulation are reported relevant to the following construction program: construction start at 1st December; RCC lifts height 0.3 m; dam built in two blocks; rate of RCC placing of 2 lifts per day with an average interval of ten lifts between the two blocks.

The maximum placing temperatures were based on different factors: the most important being the cement content (i.e. adiabatic temperature rise) and the location in the structure (i.e. degree of restraint function of the distance from the foundation). The purpose of the study is to establish the maximum allowable placing temperatures for different mixes and locations in the dam to control the RCC peak temperature and the consequent thermal strains so that the tensile strain capacity is not exceeded and cracking is avoided.

4.3 Results

The main results of the thermal analysis are summarised hereafter:

1) The temperature contour into the dam at six different times during RCC placement and after the end of construction are shown in Figure 7. The temperature history, for several nodal points at different distances from the foundation, along two typical sections are shown in Figure 8: section A on the zone of the dam with the mixes with the highest cement content; section B in the central part of the dam.

2) The maximum temperature reached in the dam body is 47°C, located approximately 30 m above the foundation in the mix with higher cement content. The temperature increment is about of 20 °C.

3) The maxima values of tensile strain, equal to about 70-80 millionths, are located in the lower part of the dam (first 15 m from the foundation) where the restraint is the highest. The critical area in terms of thermal stresses is the upstream toe (< 15 m from the foundation) where there are mixes with the highest cement content (105 and 120 kg) and high restraint. The most critical location is 5 m above the foundation, where the restraint factor is highest and the effect of heat loss from the foundation begins to decrease significantly. In order to avoid thermal cracks in this zone the maximum placing temperature cannot exceed 20-23°C (in function of the different assumptions of RCC placement rate and the effectiveness of surface protection).

4) Because both the foundation restraint factor and the internal restraint factor decrease at higher levels above the foundation, tensile strains in these upper regions decrease substantially. For example, at a height of 100 meters in the tallest monoliths of the dam, the tensile strain is less than 20 millionths.

5) The temperatures measured to date by the thermocouples and optic fibres installed within the lower part of dam body (from el. 660 to 680 m a.s.l.) are some degree less than the calculated temperatures; this is attributable to the difference between the theoretical RCC placement rate assumed in the model (2 lifts per day, 365 days per year) and the effective speed of placement (in the first part of the dam the RCC placement rate was, also because of rainy season, less than 2 lift per day and the working days in wet season are in the range of 20 over 30 days per month, instead of the theoretical 30 days per month assumed in the calculations). Therefore the results of the analyses and the relevant prescriptions have safety margins due to specific construction constraints conservatively not accounted in the simulations.
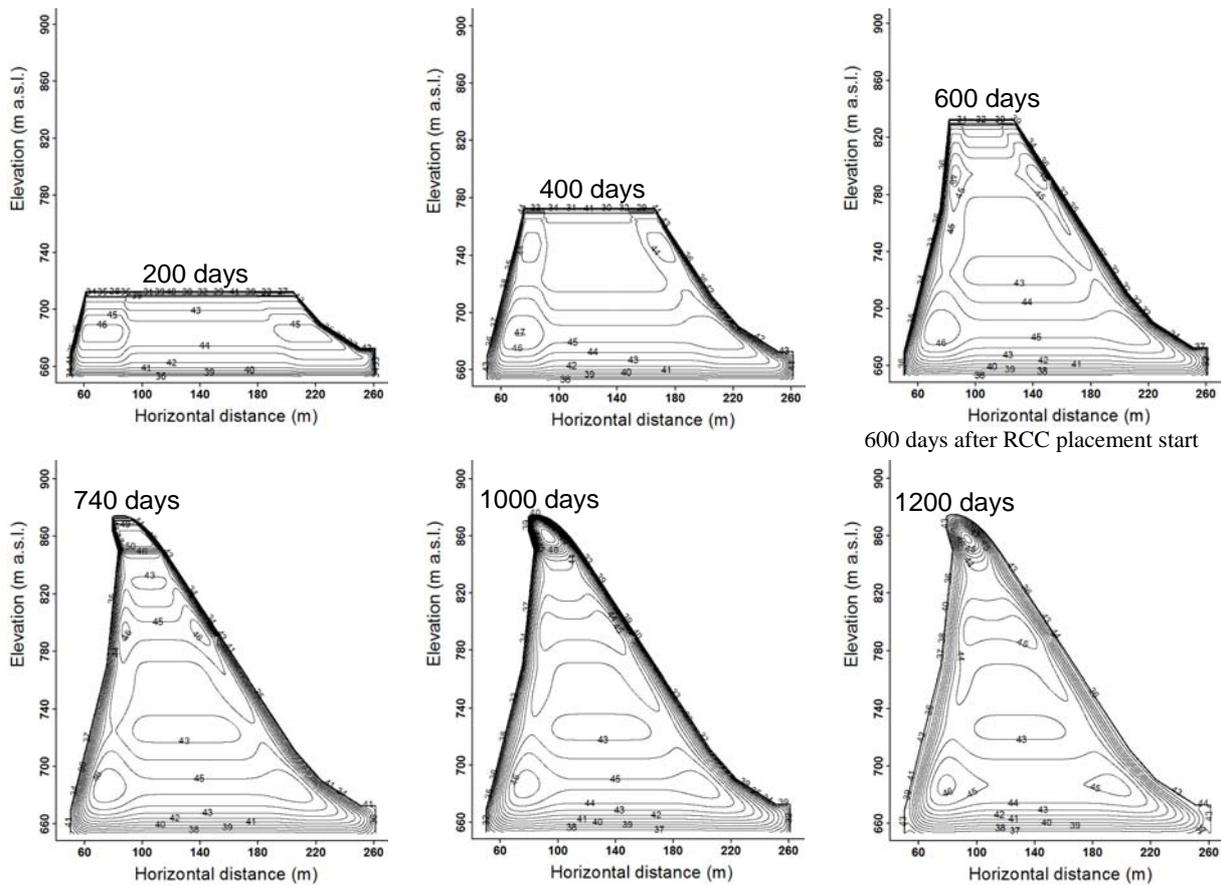
Fig. 7. Temperature contours values into the dam at six different times after the RCC placement strart.
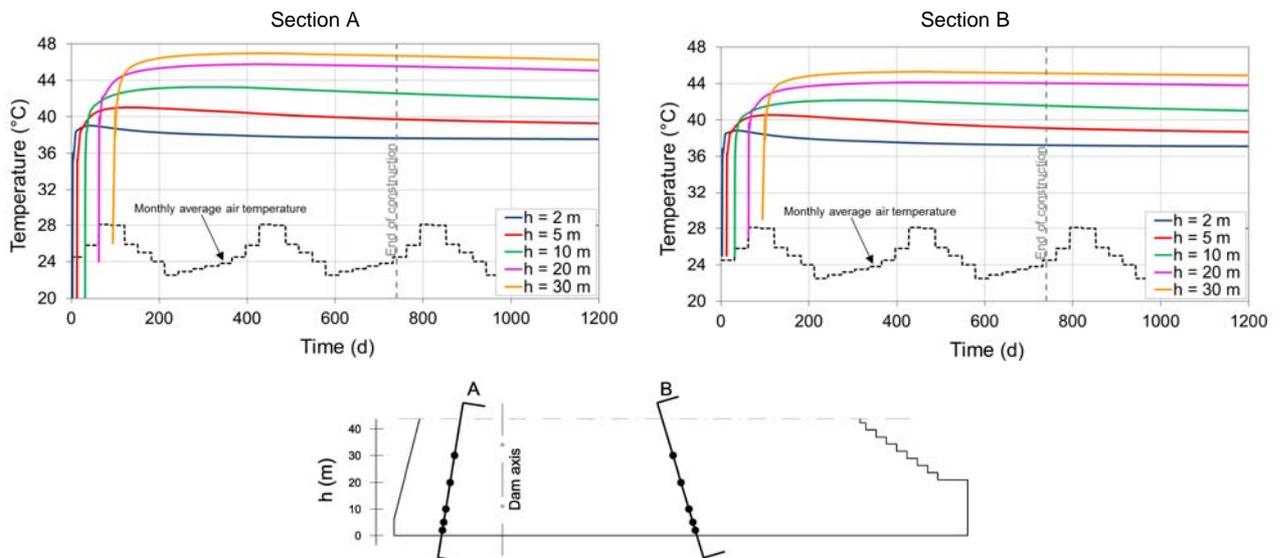
Fig. 8. RCC temperature history along sections A and B at different distances from the foundation (h).

5. Conclusions and current cores

More than 1 million of the total 6 million cubic meters in the dam has been placed. An extensive coring and evaluation program is continually underway as the dam is being built. So far (December 2012) it has consisted of 37 core holes and 550 meters of drilling. The cores are inspected, logged and tested. The holes are then pressure tested. The cores are logged and inspected as they are extracted. It is necessary to break the cores in order for them to fit into the core boxes, with some intermediate breaks also occurring due to handling, so viewing the cores after boxing

can be misleading. Fig. 9 shows typical recent cores being extracted and also after the same core has been boxed. Tests of the cores show no problem with strength or density. Tests of lift joints that were separated for any reason resulted in friction angles of 46-48 degrees, which is in excess of design requirements. Shear tests of large blocks sawn from the gallery floor showed good cohesion and friction, exceeding design requirements.

Fig. 9. Example of retrieved cores from the dam body and relevant core box

Acknowledgments

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