SIMULATION OF CONSTRUCTION OF RCC DAMS. I: TEMPERATURE AND AGING

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ABSTRACT: The increasing number of roller compacted concrete (RCC) dams being built around the world demands accurate methodologies for the realistic short- and long-term evaluations of the risk of thermally induced cracking in these constructions. In this work a numerical procedure for the simulation of the construction process of RCC dams is presented. It takes into account the more relevant features of the behavior of concrete at early ages, such as hydration, aging, creep, and damage. A 2D model of the Urugua-í RCC Dam, built in Argentina, is used to perform the corresponding analyses. In this first part only the thermochemical aspects of the simulation of the construction process are presented. The temperature distribution and evolution inside the dam are obtained before and after the completion of the dam. The evolution of the compressive and tensile strengths and elastic moduli and their final distribution inside the dam can also be predicted. Results from 2D and simplified vertical 1D models are compared to assess the validity of the latter, and several parametric studies are carried out. The simulation and discussion of the mechanical aspects of the construction process are relegated to a companion paper that follows.

INTRODUCTION AND MOTIVATION

During the last 30 years great effort has been made to find an alternative to embankment dams for large gravity constructions that would, on one hand, overcome the risk of failure due to overtopping or internal erosion (piping) and, on the other hand, be economically competitive. Currently, the answer to this technological challenge is roller compacted concrete (RCC) dams. RCC is a relatively lean no-slump concrete that can be spread horizontally and compacted using earthworking machinery such as dozers and vibratory rollers. The first evaluations on place-in unit costs for several RCC dams built in the United States showed that these represented savings ranging from 30 to 70% of the cost of conventional concrete dams (Schrader and Naminas 1988).

RCC dam construction has the following features:

- The dam body is constructed by placing concrete, in the same placing cycle, over a wide area encompassing several blocks.
- Transverse joints are cut after the placement of concrete.
- No longitudinal joints are made.
- Pipe cooling is not (generally) used.

These features allow a high production rate, reducing the construction time. On the other hand, to achieve this, particular attention must be devoted to design aspects such as

- The distance between transverse contraction joints (typically, a distance of at least 30–45 m)
- Reduction of the number of special elements such as galleries, drains, or spillways
- Limitation of the use of non-RCCs in the facing or elsewhere

The main difference between RCC and conventional concrete is its low cement content and no-slump consistency. Usually, high admixture contents (e.g., fly ash) are used. Consequently, the RCC hydration process is slower, its density is higher, and its stiffness is lower than for ordinary concrete. On one hand, the low water content in the mixture leads to less shrinkage, and, on the other hand, the low cement content makes the hydration heat considerably lower, up to three times smaller than for conventional concretes. Nevertheless, the high concreting rate used in RCC dams may lead to significant temperature rises.

This increase in temperature occurs during the first days after placing, when the stiffness of concrete is still quite low, and creep (viscous) effects are significant; therefore, it usually leads to moderate, and mainly compressive, stresses. However, months later, when the stiffness has significantly increased, the concrete starts to cool down. The low thermal conductivity of the material, differential effects due to the evolutionary construction process, and convection phenomena with the environment may generate considerable thermal gradients. These, together with geometrical aspects and external restraints may develop relatively important tensile stresses, and thermally induced cracking may appear. This may result in structural damage even before the reservoir is filled, and, in any case, it may affect significantly the durability and serviceability of massive concrete dams.

Fortunately, the RCC dam construction method is advantageous in thermal stress control due to the following:

- The placement of thin lifts allows for heat losses by convection and radiation.
- The placement of concrete at constant speed and with regularity helps to produce smooth temperature gradients within the dam body.

For all of these reasons, the determination of the lift schedule and the basic cycle of concrete construction (pouring, curing, and green-cutting) is essential for establishing the construction program for a large RCC dam. The qualitative and quantitative assessment of the influence of major factors such as the composition of the mix, the ambient temperature, the placing temperature, placing speed (lift thickness and placement interval), and time for starting placement must be established.

This paper presents a numerical procedure for the simulation of the construction process of RCC dams. First, a thermochemical model is proposed to simulate the hydration and aging processes of concrete. Second, the case study of the

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Urugua-í RCC Dam in Argentina is described. The actual conditions and concreting schedule that occurred during the construction of the dam are considered as the reference case. Also, results from the 2D numerical simulation are compared to simplified 1D simulations. Finally, some parametric studies are performed to establish the effect of some major variables of the construction process that may influence the temperature distribution and evolution: the placing temperature, the starting date, and the placing speed.

NUMERICAL MODEL

Hydration of concrete is a very complex process that involves a number of chemical and physical phenomena at the microscopic level. In view of this evidence, a macroscopic description of the hydration phenomenon is adopted for engineering purposes. From this point of view, hydration of concrete is a highly exothermic and thermally activated reaction, so that a thermochemical model is necessary for its modelization. The thermochemical model used in this work is described in detail in Cervera et al. (1999), and it will only be sketched here. The proposed procedure is able to accurately predict the evolution in time of the hydration heat production and the main mechanical properties of concrete. The new concept of the aging degree, different from the commonly used maturity concept, is introduced in order to account for the influence of the variable curing temperature in the final values of the mechanical properties.

Thermochemical Model

Hydration of concrete is a highly exothermal process due to the large amount of hydration heat produced during the reaction. An adequate numerical simulation of the associated thermal problem requires the evaluation of the rate of hydration heat liberated at every instant during the process. In the following, Q is the amount of heat liberated per unit volume, and $\dot{Q}$ is its time rate. The thermochemical model must provide an appropriate expression for this last term, acting in the thermal field equation as an internal heat source.

Most authors identify the rate of heat liberation with the actual rate of hydration. In this case, the hydration degree can be defined as $\xi = \bar{Q}/\bar{Q}_\infty$, where $\bar{Q}_\infty$ is the final amount of liberated heat in ideal conditions, that is, with an adequate water content and perfect contact between the water and the cement grains. In practice, complete hydration of the concrete is not achieved during curing, and, therefore, $\xi_\infty < 1$. The final degree of hydration ξ_∞ is related to the water-to-cement ratio of the mixture, and it can be estimated as a function of it.

From these considerations, it is evident that a linear dependency of the following form can be assumed:

$$Q(\xi) = Q_\xi \xi; \quad \dot{Q}(\xi) = Q_\xi \dot{\xi} \qquad (1a,b)$$

where Q_ξ = latent heat per unit of hydration extent, assumed here to be a constant material property.

Because of its thermoactivated character, the evolution of the hydration degree can be defined by an Arrhenius-type expression, in the form

$$\dot{\xi} = \tilde{A}_\xi(\xi)\exp\left(-\frac{E_a}{RT}\right) \geq 0 \qquad (2)$$

where E_a = activation energy of the reaction; and R = constant for ideal gases. The ratio E_a/R can be experimentally determined, and it ranges from 3,000 to 8,000 K for concrete. The function $\tilde{A}_\xi(\xi)$ is a normalized affinity that completely characterizes the macroscopic hydration kinetics for a given concrete mixture. This function can be obtained experimentally from an adiabatic calorimetric test (Ulm and Coussy 1996). Here, we will use the following analytical expression for this function:

$$\tilde{A}_\xi(\xi) = \frac{k_\xi}{\eta_{\xi 0}}\left(\frac{A_{\xi 0}}{k_\xi \xi_\infty} + \xi\right)(\xi_\infty - \xi)\exp\left(-\bar{\eta}\,\frac{\xi}{\xi_\infty}\right) \qquad (3)$$

where k_ξ, $A_{\xi 0}$, $\eta_{\xi 0}$ and $\bar{\eta}$ = material properties. Fig. 1(a) shows the evolution of the temperatures obtained using the proposed thermochemical model in adiabatic tests for two typical RCCs (RCC60 and RCC90) and two conventional portland concretes (CPCs H180 and H220) (see next section on Urugua-í Dam and Table 1 for details). In Fig. 1(a), the dots represent the experimental values, and the solid line represents the prediction by the model. Note that the adiabatic temperature rise as well as the hydration rate are smaller for RCC than for conventional concrete.

Aging Model

During the last several decades, many aging models have been proposed in which the mechanical properties of young concrete were expressed in terms of the hydration degree, or alternatively, of the maturity (Rastrup 1954; Oloukon et al. 1990). However, there is experimental evidence that the evo-

TABLE 1. Material Properties for Urugua-í Dam

Property (1)	H180 (2)	H220 (3)	RCC60 (4)	RCC90 (5)	Rock (6)
w/c	0.50	0.50	1.60	1.00	—
ρ (10^3 kg/m^3)	2.44	2.40	2.50	2.50	2.70
C (10^{-6} J/m^3 °C)	2.35	1.95	2.49	2.44	2.37
k_T (10^3 J/mh °C)	6.81	6.81	6.99	6.11	7.74
α_T (10^{-6})	6.00	8.00	7.40	8.33	—
Q_ξ (10^7 J/m^3)	7.79	9.50	2.57	3.97	—
f_∞^- (MPa)	18.0	22.0	9.0	13.6	50.0
f_∞^+ (MPa)	2.00	2.20	0.87	1.36	5.00
E_∞ (GPa)	31.00	38.00	14.00	22.00	30.00

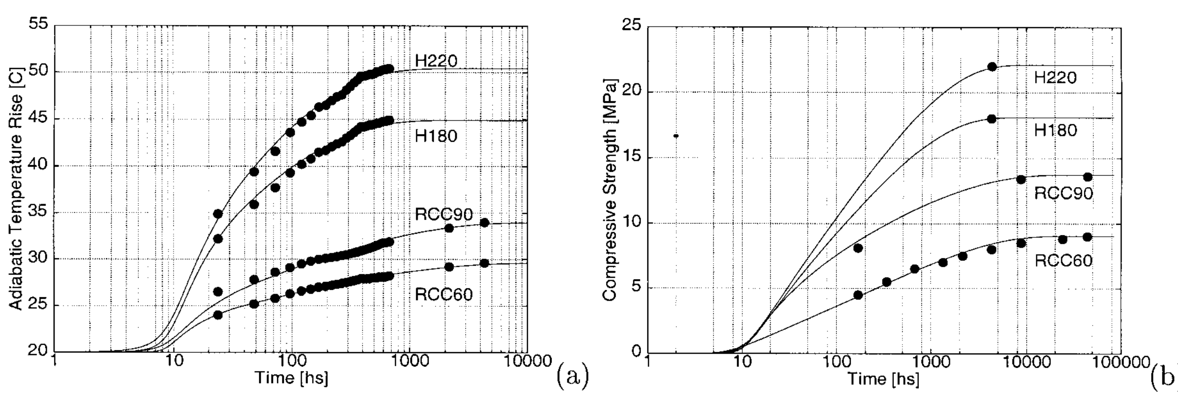

FIG. 1. Comparison with Experimental Data: (a) Temperature Evolution in Adiabatic Tests; (b) Strength Evolution in Isothermal Tests

lution of the concrete strength depends not only on the degree of hydration but also on the kinetics of the hydration reaction (Wild et al. 1995; Tan and Gjorv 1996; Kim et al. 1998). To consider this effect, let us introduce an aging internal variable κ, defined as a normalized strength, in the form

$$f^{-}(\kappa) = \kappa f_{\infty}^{-} \tag{4}$$

where f^{-} = compressive strength; and f_{∞}^{-} = its final value.

The evolution of the aging degree $\dot{\kappa}$ is defined in terms of the evolution of the hydration degree $\dot{\xi}$ and the kinetics of the hydration reaction, so that

$$\dot{\kappa} = (A_f \xi + B_f) \left(\frac{T_T - T}{T_T - T_{\mathrm{ref}}} \right)^{n_T} \dot{\xi}, \quad \dot{\kappa} \geq 0 \tag{5}$$

where A_f and B_f = material constants; T_{ref} = reference temperature for the determination of f_{∞}^{-}; T_T = maximum temperature at which hardening of concrete may occur; and n_T = material property controlling the sensibility to the curing temperature.

According to most codes of practice, other mechanical properties such as the tensile strength f^{+} or the elastic modulus E can be related to the compressive strength, and therefore, to the aging degree (Cervera et al. 1999), in the form

$$f^{+}(\kappa) = \kappa^{2/3} f_{\infty}^{+}; \quad E(\kappa) = \kappa^{1/2} E_{\infty} \tag{6a,b}$$

where f_{∞}^{+} and E_{∞} = final values, when the hydration process is completed.

Fig. 1(b) shows curves of evolution of the compressive strength obtained using the proposed thermochemical model in isothermal tests (at 20°C) for two typical RCCs and two CPCs (see next section on Urugua-í Dam). In Fig. 1(b), the dots represent the experimental values, and the solid line represents the prediction by the model. Note that the compressive strength is smaller for RCCs, because of their low cement content. Also, the strength rate of evolution is slower, as it is related to the hydration rate.

URUGUA-Í DAM

The Urugua-í Hydroelectric Project is located in the Province of Misiones, northeast of Argentina. The dam is owned by Electricidad de Misiones SA, and it has been built at the Urugua-í River, 8-km upstream from the confluence with the Paraná River, 127 m above sea level.

The zone has a hot, subtropical climate, without a dry season. Its annual mean climate values are as follows: temperature, 20°C (ranging from 11°C in winter to 27°C in summer); relative humidity, 80%; wind velocity, 4 km/h; annual rainfall, 1,750 mm; and annual evaporation, 1,168 mm.

The RCC project was approved as an alternative to the originally designed rockfill dam with concrete facing. The change was based on significant savings in time and construction costs. The project represented quite a challenge because it was the first experience of an RCC dam in Argentina while at the same time being one of the largest RCC dams in the world at that moment. Also, the project included some outstanding features such as a very low cement content in the mix and the consideration of a PVC membrane as an impervious barrier.

Information on some of the design criteria used and results from the thermal analyses performed at the design stage, as well as on construction process of the dam, and its behavior during and after its completion can be found in Buchas and Buchas (1991), Lorenzo and Calivari (1991), and Giovambattista (1995).

Geometry

The main dam is a straight RCC gravity structure, 78-m high and 676-m long. In the central part, there is a 170-m-long uncontrolled spillway, with a bridge over it. The total volume of concrete is 600,000 m^3.

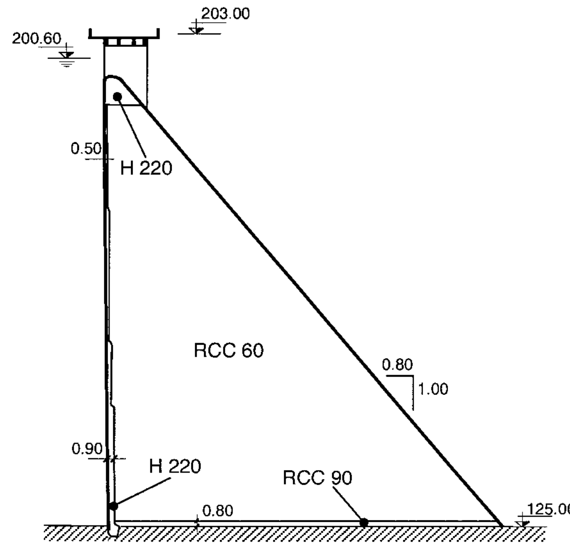

FIG. 2. Cross Section of Urugua-í Dam

Fig. 2 shows a cross-section of the dam. Note that the slope of the downstream face is 1:0.8 (V:H), which is rather common in RCC dams. Crest and base elevations are 203 and 126 m above sea level, respectively. Maximum width at the base is 57 m.

The dam has two main transverse contraction joints placed 227 m apart. Secondary precut joints were placed approximately every 70–90 m above Elevation 182 m.

The upstream facing consists of precast reinforced concrete panels anchored in the mass of the dam, a continuous 2-mm PVC membrane, and 0.50–0.90-m-thick CPC. Facing concrete has contraction joints every 14–20 m. These joints are 1.20-m deep and run into the RCC.

Material Properties

Four different types of concrete were used in the dam:

- The foundation was built in CPC with a cement content of 180 kg/m^3 (H180).
- The upstream facing and the spillway crest was built in CPC with a cement content of 220 kg/m^3 (H220).
- The body of the dam was built in RCC with a low cement content of 60 kg/m^3 (RCC60).
- The interface between the dam and the foundation (0.80-m high) was built in RCC with a cement content of 90 kg/m^3 (RCC90).

All RCC and CPC were made with portland cement similar to Type II ASTM, without pozzolanic admixtures. Table 1 summarizes the relevant material properties for the four types of concrete. The rest of the material properties necessary to perform the numerical simulations have been obtained by calibration of the model parameters to match experimental data obtained from the four types of concrete used in the dam. The comparison between the model performance and the available experimental results is shown in Fig. 1, where the dots represent the experimental values and the solid lines represent the predictions by the model. Fig. 1(a) shows the evolution of the temperatures obtained in adiabatic tests, and Fig. 1(b) shows the evolution of the compressive strength obtained in isothermal tests. Note that good agreement is obtained between the model predictions and the experimental results for the four types of concrete.

Construction Process

Concreting of the foundation and the shear key began in January 1988, in the middle of the austral summer, and was completed in March of the same year. RCC placing began in April 1988 and was finished in March 1989. Therefore, it can be considered that the construction of the body of the dam took approximately 1 year. The reservoir filling started in December 1989 and reached the spillway level in July 1990.

The dam was built with 40-cm-thick lifts. The average placement interval between lifts was 48 h. Therefore, the placing speed can be_estimated as V = 20 cm/day. The relative placing speed is $\bar{V} = V/H$ = 0.96 1/year, where H is the dam height.

THERMAL ANALYSIS

In this section, results from thermal analyses performed on a numerical model of the Urugua-í RCC Dam are presented. First, results from the 2D reference case, simulating the real construction process of the dam, are discussed. Second, results from simplified 1D vertical simulations are presented in order to assess the validity of this type of calculation. Finally, some parametric studies are performed to establish the effect of some major variables of the construction process that may have an influence on the temperature distribution and evolution: the placing temperature, the starting date, and the placing speed.

2D Reference Case

The numerical model used for the 2D thermal analyses consists of a finite-element discretization of the central cross section of the dam. The mesh represents the body of the dam (from Elevation 125 m to Elevation 189 m), plus the foundation (from Elevation 115 m to Elevation 125 m) and some surrounding foundation rock (down to elevation 90 m). The dam is formed by 157 RCC lifts 0.40-m thick. The upstream facing and the spillway crest, both cast in H220 concrete, are also included in the model.

The numerical model used allows simulation of the actual evolutionary construction process of the dam. To this end, the finite elements corresponding to the different concrete lifts are progressively activated at the times corresponding to their respective placing in the dam. Placing of the RCC concrete is simulated by assuming a constant placing interval of 2 days; therefore, lifts are activated one at a time, every 2 days.

The initial temperature of the activated elements is automatically set equal to the corresponding placing temperature. For the reference simulation case the placing temperature of each lift is taken as equal to the ambient temperature corresponding to the placing date +5°C. This increase in the placing temperature is assumed to be due to the stocking conditions and the manipulation operations performed during the production process of the concrete. The initial temperature of the foundation rock is assumed to vary linearly from the ambient temperature at the surface (Elevation 125 m) to 10°C at the bottom of the model (Elevation 90 m).

During the construction of the dam, temperature at the boundaries in contact with the air is automatically set equal to the ambient temperature at the corresponding data. After the completion of the dam, the analysis is continued for the subsequent 11 years, to be able to follow the evolution on the temperatures during the cooling process. To this end, the ambient temperature is automatically adjusted to follow the average cyclic seasonal thermal variation in the area.

In the 2D model, every lift is discretized into 50 four-node elements (25 elements across and 2 elements thick), thus resulting in 7,850 elements in the dam body. The mesh is finer near the upstream and downstream faces to represent the CPC facing and to capture the boundary thermal effects. The total number of elements in the mesh is 9,500 including the foundation.

The time step used in the analysis during the construction of the dam is 12 h, so that once a lift is activated four time steps pass before a new lift is placed above. During this time the temperature of the newly placed concrete varies according to the ambient temperature on top and the temperature of the concrete already placed below. During these 2 days the concrete reaches a significant hydration and aging degree before another lift is placed on top. An automatic subincrementation technique is used within the time step to accurately integrate the evolution of the hydration and aging degrees [(2) and (5)] at these extremely early ages.

Fig. 3 compares the computed temperature evolution for two points, located at Elevation 130 m and distances of 2.00 and 22.00 m from the upstream face, with actual in situ temperature measurements obtained during the construction. It should be noted that agreement between the model predictions and real measured temperatures is remarkable. The ambient temperature throughout the year is also plotted; note that higher temperatures occur between December and February (austral summer), whereas colder weather occurs between June and September (austral winter). Elevation 130 m corresponds to the lower lifts in the body of the dam (RCC60), placed directly over the foundation. Note that the point located closer to the upstream wall reaches a slightly higher temperature just after being placed. This is due to its proximity to the upstream facing, made of H220, and with a higher hydration heat. Note also that this point is quite sensitive to the variation of the ambient temperature. On the other hand, the innermost point is much more isolated by the surrounding concrete. The very smooth temperature decrease that occurs there is due to heat conduction in the vertical direction toward the upper surface and toward the foundation and the rock below.

Fig. 4 shows the temperature evolution for interior points corresponding to lifts placed with 1-month intervals between them. In Fig. 4 the corresponding (placing months) elevations are as follows: (4) 129 m, (5) 135 m, (6) 141 m, (7) 147 m, (8) 153 m, (9) 159 m, (10) 165 m, (11) 171 m, (12) 177 m, (1) 179 m, and (2) 185 m. Higher temperature rises appear at the bottom lifts (April to July), because of the heat coming from the hydration of the H180 concrete in the foundation and in the lifts placed during the austral summer (December to February), between elevations 180 and 190 m. Note the temperature drop that occurs for the lifts placed in December because of the concreting break during Christmas. The temperature is still rising in most of the dam after completion and more steeply in those lifts placed during winter (July to August). This is because heat conduction between vertically ad-

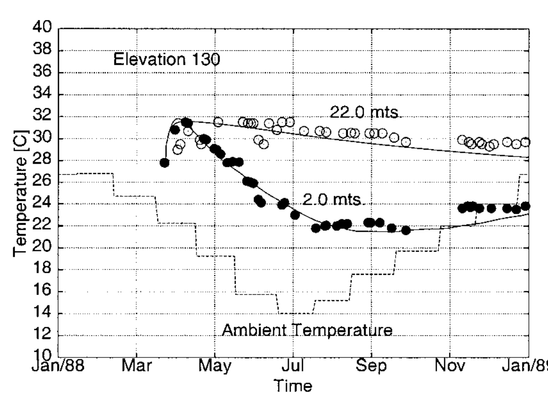

FIG. 3. Comparison between Computed and Measured Temperature Evolution in Dam

joining lifts continues for a long period of time after placement. The bottom layers start to cool shortly after being placed because of the heat conduction toward the foundation rock.

Fig. 5 shows contour plots for the evolution of the temperatures in the body of the dam during the construction process (1 year). The corresponding (months) elevations are (June 1988) 146 m, (November 1988) 175 m, and (June 1989) 196 m [Figs. 5 (a–c), respectively]. As mentioned above, the higher temperatures correspond to the foundation and those lifts located immediately over it, because of the higher hydration heat of concrete used there, and to the lifts located between Elevations 180 and 190 m, placed during the austral summer (December to February), when the ambient (and placing) temperatures are higher. Note also how the ambient temperature varies according to the seasonal oscillation. Due to the low thermal conductivity of concrete, temperature gradients due to the difference between the ambient and inside temperatures are evident, although they are limited to a distance of about 2 m from the exterior faces. These temperature gradients may lead to thermally induced superficial cracking in these faces, and because of this transverse contraction joints are cut in the facing every 14.24 m (1.20-m deep and running inside the RCC).

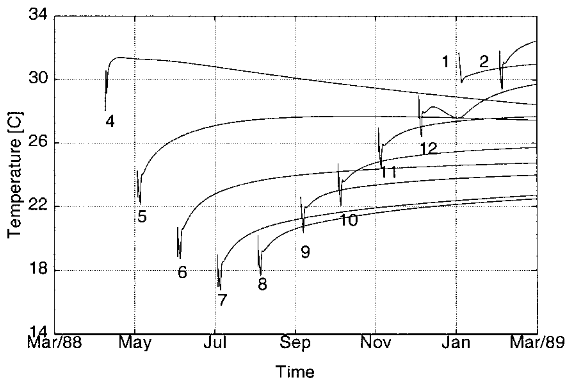

FIG. 4. Temperature Evolution for Different Elevations

Fig. 6 shows contour plots for the distribution of the compressive strength (in MPa) after 1 year, at the time of the completion of the construction. Note that the strength distribution is not homegeneous, because of the different curing conditions that occurred at different locations. Higher strength is attained for concrete placed during the winter, at lower temperatures, at midheight of the dam, whereas lower strength is attained for concrete placed during the summer, at higher temperatures, at the bottom and top parts of the dam. The distributions of compressive and tensile strengths are similar but not identical because of their different dependence on the aging degree [(4) and (6)]. The prediction of the actual distribution of tensile strength is important for the evaluation of the risk of cracking due to thermal straining.

Fig. 7 shows the long-term temperature evolution for three of the interior points monitored in Fig. 4, those located at Elevations 153, 165, and 177 m. The thermal analysis was run for 11 years after completion of the dam. It is clear that the temperature in the interior of the dam decreases progressively,

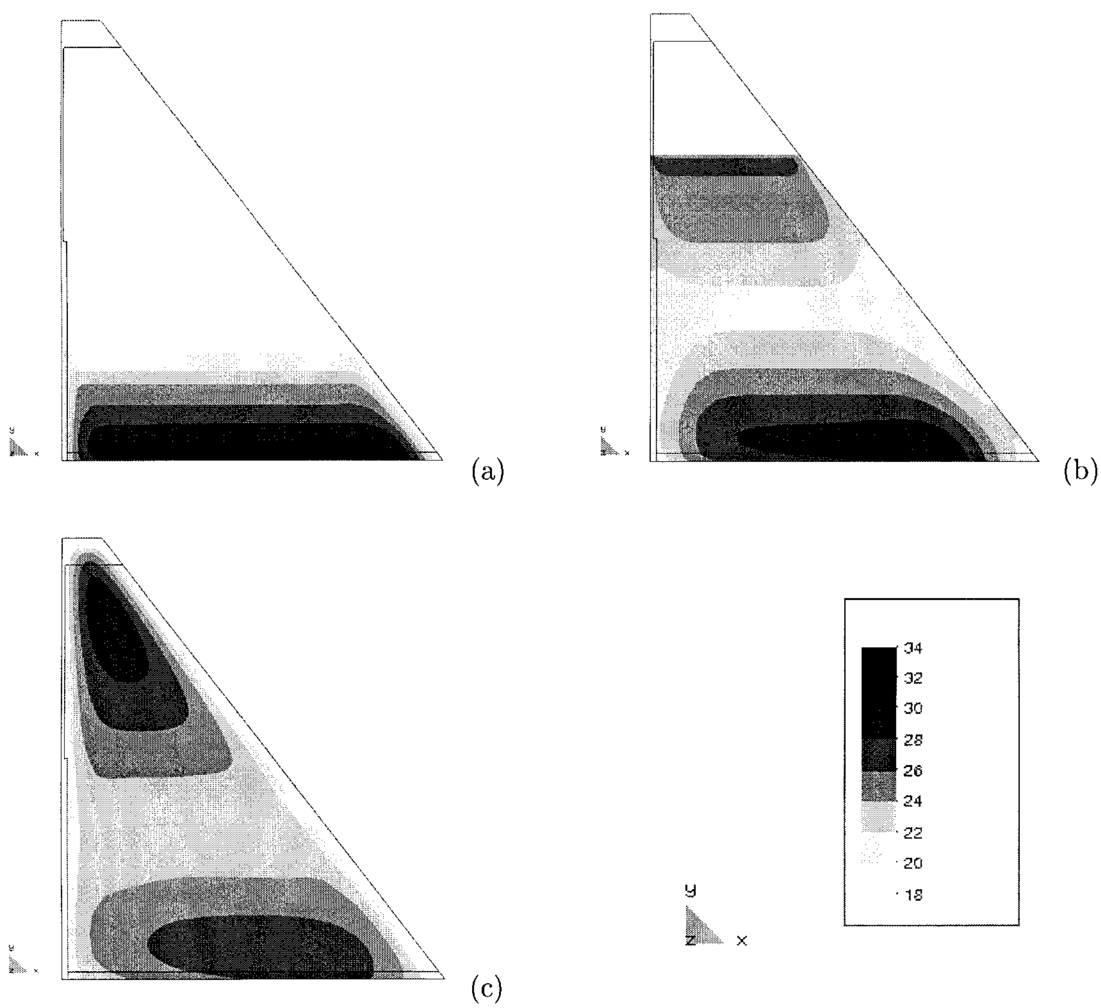

FIG. 5. Short-Term Evolution of Temperatures (°C); Corresponding (Months) Elevations Are: (a) (June 1988) 146 m; (b) (November 1988) 175 m; (c) (June 1989) 196 m

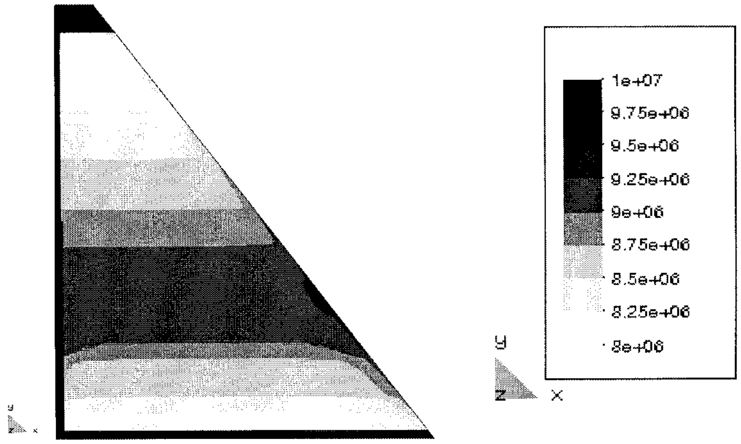

FIG. 6. Distribution of Compressive Strength (MPa) at Completion of Dam (1 Year)

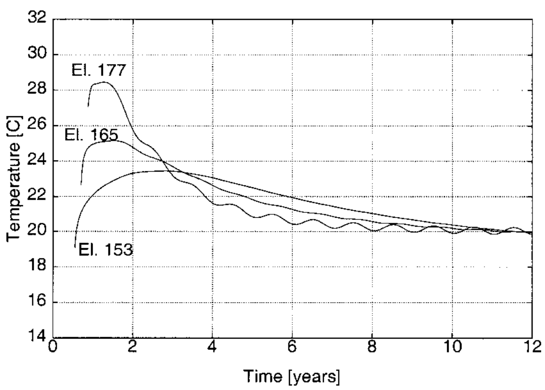

FIG. 7. Long-Term Temperature Evolution for Different Elevations

as the heat generated during the hydration process is released through the upstream and downstream faces. The final stable temperature in the interior of the dam will be approximately equal to the mean annual temperature (20°C). The temperature drop is faster for the upper elevations, because they were placed in the summer and because they are more exposed to the ambient temperature. This temperature drop may lead to thermally induced cracking in the interior of the dam; therefore, the necessity of placing transverse contraction joints every 70–90 m above Elevation 182 m. Note also that the seasonal oscillation of the ambient temperature is only noted for the point located at higher elevations, whereas the bottom part of the dam body is virtually unaffected by it.

Fig. 8 shows contour plots for the evolution of the temperatures in the body of the dam for the first 10 years after completion of the dam. All of the snapshots correspond to the temperature distribution in the winter (June). The corresponding years are 1989, 1991, and 1999 [Figs. 8(a–c), respectively]. Note how the overall temperature is progressively lower, as heat is dissipated to the environment and, to a minor extent, to the foundation rock. The cooling is faster in the upper part of the dam, where the outer surfaces are closer. The upper ''hot spot'' has completely vanished after 2 years. The lower hot spot is still visible after 2 years, although temperature has already dropped more than 5°C. It has also ''migrated'' upward due to heat flux toward cooler parts of the dam body. After 10 years the heat generated during the construction process has virtually disappeared. The dam is then in a thermally stable regime, subjected only to the cyclic seasonal oscillations.

Numerical 1D Simulation

Thermal simulations of the construction process of concrete dams are usually done using simplified 1D models [e.g., Yamazumi et al. (1995)]. The reason for this is that most of the concrete mass in the dam is placed too far away from the upstream and downstream faces to be influenced by the heat losses through them. Therefore, a ID vertical model in which the horizontal heat flux is prevented seems representative of the real conditions inside the dam body.

To validate this approach, a 1D vertical model of the Urugua-í RCC Dam is constructed, following exactly the same guidelines described for the 2D model. Therefore, the vertical size and distribution of the finite elements, the material properties, the initial and placing temperatures, as well as the overall activation strategy for the lifts are the same as described above.

Fig. 9 shows the comparison between the computed evolution of temperatures using the 2D and 1D models, for two different placing (month) elevations: (May) 140 m and (September) 165 m. Points in the 2D model are located halfway between the upstream and downstream faces. In Fig. 9, the solid lines represent the 1D results, and the dashed lines represent the 2D solution.

The plot shows that results obtained using the 1D model virtually overlap with those obtained using the 2D model during the first year, that is, during the duration of the construction process. Later, the 1D model clearly underestimates the temperature drop, as it cannot represent the main thermal dissipation mechanism of the real dam: horizontal heat flux through the facing.

Thus, it can be concluded that 1D vertical thermal models can accurately predict the vertical distribution of the temperature inside the dam body during the construction process, which is in itself very useful information. Obviously, they cannot provide information on the thermal gradients developed near the faces of the dam, nor about the transient of the long-term temperature drop until the final stable temperature distribution is reached.

Parametric Studies

Despite their simplicity, 1D vertical models can be very useful to perform parametric studies on the influence of the major variables in the construction process that may affect the final temperature distribution inside the dam and at an extremely low cost. In this section some of these example simulations will be performed for the Urugua-í RCC Dam.

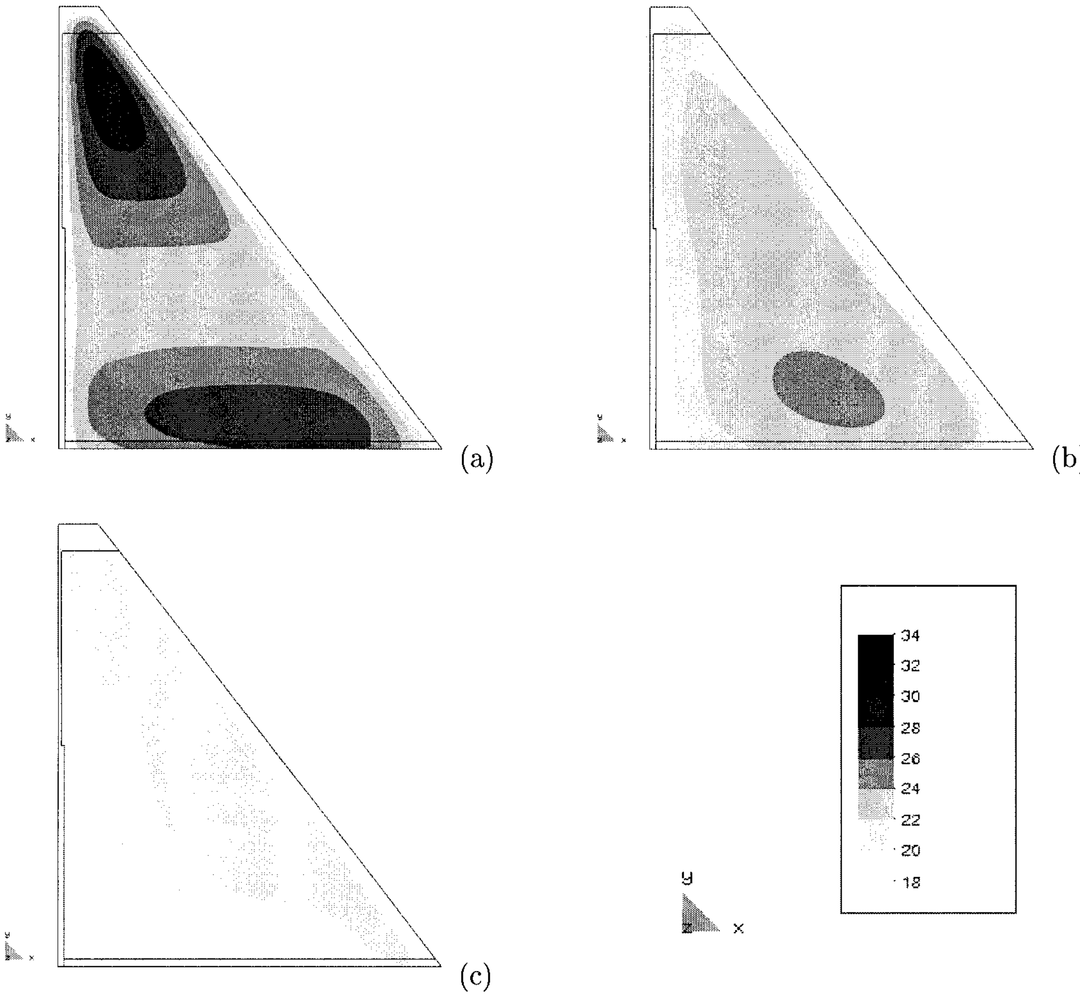

FIG. 8. Long-Term Evolution of Temperatures (°C); Winter Distribution for: (a) 1989; (b) 1991; (c) 1999

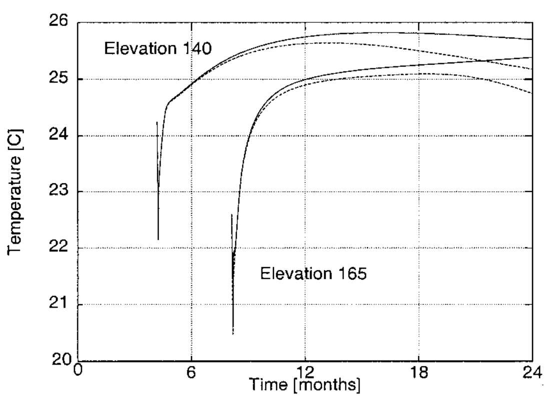

FIG. 9. Long-Term Temperature Evolution for Different Elevations Computed Using ID (Solid Line) and 2D (Dashed Line) Models

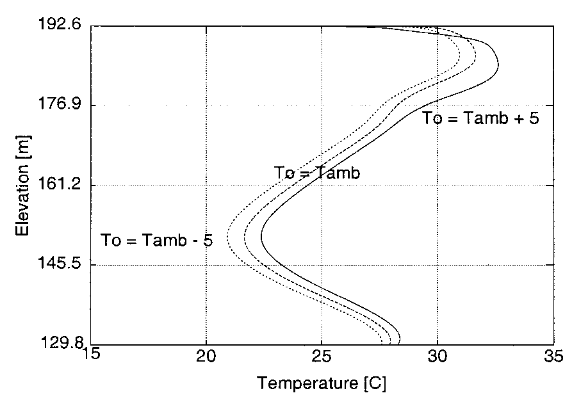

FIG. 10. Influence of Placing Temperature

Influence of Placing Temperature

To investigate the influence of the placing temperature of the concrete T_0 compared to the ambient temperature at the time of placing T_{amb}, three different cases are compared: (1) $T_0 = T_{amb} + 5°C$ (no precooling, reference case); (2) $T_0 = T_{amb}$ (mild precooling); and (3) $T_0 = T_{amb} - 5°C$ (intense precooling).

Fig. 10 shows the comparison between the computed vertical distribution of temperatures for the three cases at the time of the completion of the dam. It can be seen that, although the precooling of the concrete before being placed obviously results in lower temperatures in the final distribution, the efficiency of the procedure is quite limited, and it can be evaluated at about 20% for the studied case. The reason for this is that for the lift thickness used in Urugua-í Dam the heat flux across the exposed upper surface of the lift just being placed is enough to quickly reduce the difference between the concrete and the ambient temperatures. Precooling would obviously be more effective for (1) thicker lifts, due to the low conductivity of concrete; or (2) faster placing speed, as this would reduce the time that a newly placed lift is exposed to the ambient temperature.

Influence of Starting Date

To investigate the influence of the starting date for concreting, four different cases are compared: (1) Starting in April (austral autumn, reference case); (2) starting in July (austral winter); (3) starting in October (austral spring); and (4) starting in January (austral summer).

Fig. 11 shows the comparison between the computed vertical distribution of temperatures at the completion of the dam for the four cases. For Case 1, starting in April, highest temperatures are attained close to the foundation and near the crest. The latter problem can be dealt with providing transverse joints in the upper part of the dam. For Cases 2 and 3, starting in July and October, respectively, highest temperatures are attained at midheight, and, therefore, they would require much deeper transverse joints. Case 4, starting in January, is probably the worst case, as highest temperatures are attained immediately above the foundation, and this would require full section transverse joints.

It is interesting to note that the maximum temperatures attained for all cases are very close, as these mainly depend on the placing and ambient temperatures and the heat released during the hydration process. However, minimum temperatures at the completion of the dam vary from one case to the other, as heat conduction inside the dam tends to raise the temperature of those lifts placed at lower temperatures.

Influence of Placing Speed

To investigate the influence of the relative placing speed of the concrete $\bar{V} = V/H$, where H is the dam height, three different cases are compared: (1) $\bar{V}$ = 1.0 1/year, lift placement interval of 48 h (reference case), (2) $\bar{V}$ = 2.0 1/year, lift placement interval of 24 h (double speed); and (3) $\bar{V}$ = 0.5 1/year, lift placement interval of 96 h (half speed).

Fig. 12 shows results for the three cases analyzed. The solid line in the figure shows the temperature distribution at the completion of the dam for the reference case. The figure also shows results for the second case, where the placing speed is doubled, and the dam is completed in half a year. Now the dam is built between autumn and spring, and the hotter summer season is avoided. Note first that the difference between the placing and the final temperatures is larger than in the previous case. At faster placing speed the loss of hydration heat through the upper lift surfaces is smaller and the temperature rise is closer to the one measured under adiabatic conditions. Also, temperature at the bottom is higher than for the previous case as heat conduction toward the foundation rock is just beginning after 6 months. Note that after 1 year the temperature in the middle part of the dam is still increasing. This means that at the completion of the dam the hydration and aging processes have not been completed yet.

For the third case, where the placing speed is halved and the dam is completed in 2 years, heat conduction plays a significant role. This is quite evident in the final distribution in the bottom half of the dam, where the peaks in the curve have been significantly diminished.

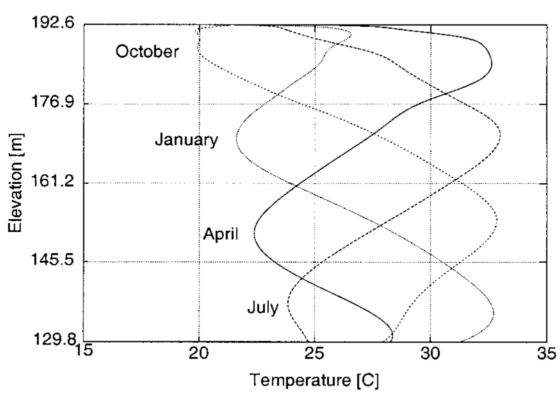

FIG. 11. Influence of Starting Date

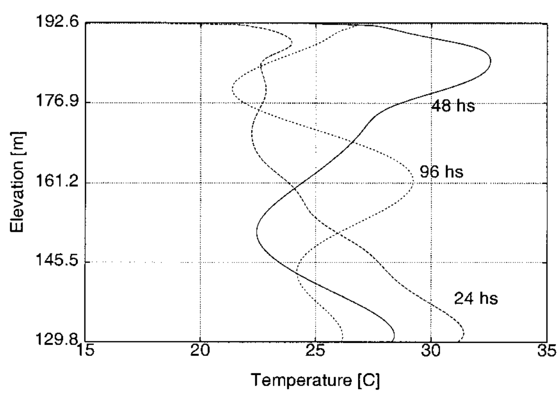

FIG. 12. Influence of Placing Speed

CONCLUSIONS

This work presents a numerical procedure to simulate the thermal analysis of the evolutionary construction process of RCC dams. The proposed procedure is used to perform the corresponding thermal and aging analyses of the Urugua-í RCC Dam, in Argentina. Results obtained from 2D and simplified 1D models suggest the following conclusions:

- The proposed procedure is able to accurately predict the evolution in time of the hydration degree and the hydration heat production.
- The temperature field inside the dam can be computed at any time during the construction process and, almost more importantly, during the first years following the completion of the dam, while the temperature in the dam body decreases to reach the finally stable distribution.
- The new concept of the aging degree, different from the commonly used hydration degree or maturity concepts, is introduced. The evolution of the compressive and tensile strengths and elastic moduli can be predicted in terms of the evolution of this aging degree.
- Vertical 1D thermal models can accurately predict the vertical distribution of the temperature inside the dam body during the construction process, although they cannot provide information on the thermal gradients developed near the faces of the dam, nor about the evolution of the long-term cooling until the final stable temperature distribution is reached.
- The procedure can be applied to perform parametric studies in order to establish the effect of some major variables of the construction process that may have an influence in the temperature distribution and evolution: the placing temperature, the starting date, and the placing speed.

APPENDIX. REFERENCES

Buchas, J., and Buchas, F. (1991). ''Construction of Urugua-í Dam.'' *Proc., ASCE Spec. Conf. on Roller Compacted Concrete 3*, K. D. Hansen and F. G. McLean, eds., ASCE, New York, 258–271.

Cervera, M., Oliver, J., and Prato, T. (1999). ''Thermo-chemo-mechanical model for concrete. I: Hydration and aging.'' *J. Engrg. Mech.*, ASCE, 125(9), 1018–1027.

Giovambattista, A. (1995). ''Urugua-í Dam: Thermal analysis, design criteria and performance.'' *Proc., Int. Symp. on Roller Compacted Concrete Dams, Vol. I: Mat., Plng. and Des.*, Spanish Institute of Cement and its Applications (IECA) and Spanish National Committee on Large Dams (CNEGP), eds., 309–323.

Kim, J.-K, Moon, Y.-H., and Eo, S. -H. (1998). ''Compressive strength development of concrete with different curing time and temperature.'' *Cement and Concrete Res.*, 28(12), 1761–1773.

Lorenzo, A. C., and Calivari, S. C. (1991). ''Behavior of Urugua-í Dam.'' *Proc., ASCE Spec. Conf. on Roller Compacted Concrete 3*, K. D. Hansen and F. G. McLean, eds., ASCE, New York, 272–290.

Oloukon, F. A., Bourdette, E. G., and Deatherage, J. H. (1990). ''Early-age concrete strength prediction by maturity—another look.'' *ACI Mat. J.*, 87(6), 565–572.

Rastrup, E. (1954). ''Heat of hydration in concrete.'' *Mag. of Concrete Res.*, 6(17), 2–13.

Schrader, E. K., and Naminas, D. (1988). ''Performance of roller compacted concrete dams.'' *Proc., 16th Congr. on Large Dams*, ICOLD, ed., Vol. 3, 339–363.

Tan, K., and Gjorv, O. E. (1996). ''Performance of concrete under different curing conditions.'' *Cement and Concrete Res.*, 26(3), 355–361.

Ulm, F. J., and Coussy, O. (1996). ''Strength growth as chemo-plastic hardening in early age concrete.'' *J. Engrg. Mech.*, ASCE, 122(12), 1123–1132.

Wild, S., Sabir, B. B., and Khatib, J. M. (1995). ''Factor influencing strength development of concrete containing silica fume.'' *Cement and Concrete Res.*, 25(7), 1567–1580.

Yamazumi, A., Harita, K., Jikan, S., and Kido, K. (1995). ''A study of thermal control on rcd dams.'' *Proc., Int. Symp. on Roller Compacted Concrete Dams, Vol. I: Mat., Plng. and Des.*, Spanish Institute of Cement and Its Applications (IECA) and Spanish National Committee on Large Dams (CNEGP), eds., 493–507.

APPENDIX II. NOTATION

The following symbols are used in this paper:

$\tilde{A}_\xi$ = normalized chemical affinity;
C = heat capacity per unit volume;
E, E_∞ = elastic modulus and final elastic modulus, respectively;
f^+, f^+_∞ = tensile strength and its final value, respectively;
f^-, f^-_∞ = compressive strength and its final value, respectively;
k_T = thermal conductivity;
Q = hydration heat per unit volume;
$\underline{Q}_\xi$ = hydration heat per unit of hydration degree;
Q_∞ = final amount of liberated heat (in ideal conditions);
T, T_0 = temperature and initial (or placing) temperature, respectively;
T_{amb} = ambient temperature;
T_{ref} = reference temperature;
$T_{\underline{T}}$ = maximum temperature for strength evolution;
V, V = placing speed and relative placing speed, respectively;
w/c = water-to-cement mass ratio;
κ = aging degree;
ξ = hydration degree;
$\underline{\xi}_{\mathrm{set}}$ = hydration degree at setting;
ξ, ξ_∞ = final hydration degree and idem in ideal conditions, respectively;
ρ = density; and
$(\dot{\ })$ = time derivative or rate.