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Numerical Modeling of Early-age Effects on the Mechanical Behavior of Concrete Gravity Dams

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Abstract
The control of thermal cracks induced by the effect of early age are the main concerns in concrete dam during the construction stage. Despite its importance, detailed thermal analysis of concrete gravity dams during the construction period is relatively rarely in the literature, eventually because prediction the behavior of concrete gravity dam on early stage requires taking into account the several phenomena and interaction, demands a considerable computational effort. To overcome this drawback, the present paper proposes a numerical modeling strategy to predict the thermo-mechanical behavior of concrete gravity dams during construction periods considering the effect of early age and the construction schedule. The proposed strategy is also used to study the effect of pre-cooling methods on the thermal-mechanical fields on concrete gravity dam during construction process. For this purpose, a Chemo-Thermo-Mechanical model is developed for predicting the behavior of a gravity dam at early stages. Firstly, temperature field model was established and verified with the results reported in the literature. Furthermore, the thermo-mechanical behavior of a concrete gravity dam is performed for two configurations: Early age state with pre-cooling and early age without pre-cooling. Thermal stress analysis was also conducted and results showed that the greatest tensile stresses after construction are developed at the heel of dams and resumption of concreting interface due to the internal restraint imposed by the concrete. The numerical results showed that the pre-cooling methods is an effective way to reduce both the hydration temperature and tensile stress induced by the effect of early age.

Keywords
concrete gravity dams, early age, chemo-thermo-mechanical, precooling method

1 Introduction

In massive concrete structures, the initial state has a crucial role on the structural safety perspective. Throughout the construction of large structures, the internal rise of temperature due to the heat released by cement hydration and its interaction with environmental conditions often result in significant volumetric deformations. When restrained either internally or externally, these deformations may lead to the development of considerable tensile stresses and, consequently, to the cracking of concrete at early stages. The risk of early age cracking of concrete is induced by several factors including, but not limited to autogenous shrinkage, creep which relaxation induced stresses, etc. The premature cracking of concrete at early age has a significant effect on the durability and tightness of structures during the service life and under extreme condition, especially for hydraulic engineering and nuclear containments buildings. The concrete dams are typical examples of massive structures that exhibit very complex behavior during the concreting phases and the operating periods. Concrete dam construction recommends that the self-induced stresses must not exceed the tensile strength [1–3]. In the last 40 years, most of concrete dams were constructed using the Roller Compacted Concrete (RCC). The main advantage of this conceptual trend is the reduction of cost and time of the construction (up to 30–47% decrease compared to Conventional Vibrated Concrete (CVC)). Furthermore, it reduces the thermal constraint which is considered as a challenge for engineers and contractors during construction of these huge structures. The construction of gravity dams with RCC is operated by means of monoliths block to prevent thermal stresses [2]. The longitudinal contraction joints are incorporated between these blocks for controlling the crack induced by thermal stress. Each monolith is plotted

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into horizontal layers with thicknesses of 0.3–0.5 m to ensure the effectiveness of concrete compacting [4, 5]. Reducing thermal cracking in concrete gravity dams can also be achieved by lowering or controlling the temperature rise during the concreting process. Several solutions have been proposed to reduce the maximum temperatures namely: pre-cooling methods (including cooling of aggregate, mixed concrete-MgO…); (ii) post-cooling of concrete (including pipe cooling, curing...); (iii) construction phasing (schedule construction) [6].

Cracks occurring at early stages provide preferential pathways for fluid migration through concrete increasing its permeability and affecting, seriously, its durability (effect of water-fracture interaction). The risk of early age cracking in concrete dams justifies the need to assess the current status, and to estimate the remaining service-life taking the early age behavior into consideration. Hence, predicting the early age behavior of a concrete gravity dams with or without precooling process is the key to assess its behavior during construction. In the last two decades, relevant investigations were made in the context of predicting the early behavior of large concrete dams during the construction process in terms of the thermal stress and damages. In order to study the early age behavior of concrete gravity dams by means of numerical computations, several models are available in the literature [7–10]. Earlier, Cervera et al [11, 12] applied the thermo-chemo-mechanical model to the analysis of a RCC dam's behaviors during construction. They incorporate several phenomena that may occur during the construction and the service life (Aging effect, damage, creep…). The numerical procedure is shown to be able to predict the risk of occurrence of damage at different levels. Lackner and Mang [10] proposed a 3D FE model for the simulation of the early age cracking of RCC dams considering the effect of hydration and construction process. Shen et al. [13] proposed a thermo-mechanical model (TM) in order to investigate the influence of Crack Thermal Resistance (CTR) on the TM coupled behavior of a gravity dam under thermal loadings during the construction periods. A probabilistic numerical model to investigate the effect of some properties of RCC variability on the thermal behavior of a dam has been developed by Gaspar et al. [14]. The results showed that the global sensitivity analysis, performed via RBD-FAST sensitivity test, revealed to be a very useful tool, giving precious information about the influence of each random variable on the model output (thermal fields, stress, cracking). Castilho et al. [15] proposed a transient coupled 3D FE model to the analysis of the thermal behavior of an arch dam considering the effect of hydration and concreting phases. The numerical results show a good agreement with data recorded by auscultation tests throughout the construction phase. Li et al. [16] applied a practical method to predict the thermal deformation and contact behavior for concrete dams combining conventional concrete and roller-compacted concrete. Major phenomena occurring during the construction and the operation life have been taken into account. The numerical results show good coherence between the auscultation tests and the proposed approach. A FEM numerical strategy for simulation of post cooling effect has been proposed in [17]. Authors stressed that the proposed methodology is clearly advantageous to predict the thermal behavior of large structures during the construction process. A new hyperbolic expansive model of Mixed MgO-RCC concrete is proposed in [18]. The authors reveal that the addition of Magnesium Oxide (MgO) may produce expansive strain, compensate the shrinkage stress of concrete and relieve the cracking risk of RCC dams.

The present paper proposes a numerical modeling strategy to predict the thermo-mechanical behavior of concrete gravity dams during construction periods including the schedule construction, including external ambient temperature, concrete hydration heat. For this purpose, a Chemo-Thermo-Mechanical model is proposed to assess the early age concrete behavior. Suitability of this model is verified first on thermal analysis of a massive concrete block at 2D and 3d scales and then comparing the numerical results with existing results re-ported in the literature. Furthermore, the model is performed on thermal-mechanical analysis of a concrete gravity dam during construction. The case study chosen for the present investigation is the Beni Haroun RCC gravity. We also investigate the effect of precooling on the initial stress (thermal-stress fields) of concrete gravity dams. It should be highlighted the present contribution provides scientific basis for relevant prevention and control measures for similar projects in the future.

2 Constitutive laws

2.1 Chemo-thermal model

The hydration of cement paste is a thermo-activated process. This process may be expressed with an Arrhenius type law [19]. Its evolution is achieved by the use of a chemical affinity calculated by means of Eq. (1) [8, 10]

$$\dot{\xi} = \tilde{A}(\xi).\exp(\frac{E_a}{RT}), \quad (1)$$

where E_a is the activation energy [J.mol^{-1}], R is the ideal gas constant [J.mol^{-1}.K^{-1}], T is the temperature in Kelvin [K], ξ [K], ξ is the hydration degree and $\tilde{A}(\xi)$ is the chemical affinity [S^{-1}] given by Eq. (2):

$$\tilde{A}(\xi) = a + b\xi + c\xi^2 + d\xi^3 + e\xi^4 + f\xi^5 + g\xi^6 . \quad (2)$$

a, b, c, d, e, f and g are constant material parameters which could be identified from a semi-adiabatic test. The ratio E_a/R ranges between 3000 K and 8000 K. The evolution of the temperature variable is obtained from the energy balance equation, which includes the release of heat due to the hydration reaction Eq. (3).

$$C\dot{T} = \nabla(k\nabla T) + L\dot{\xi} \quad (3)$$

L is the latent hydration heat k is the thermal conductivity [Wm^{-1}K^{-1}] and C is the volumetric heat capacity [Jm^{-1}K^{-1}] which is assumed constant [20]. The boundary conditions are assumed to be of convective type. The convective heat flux ϕ [Wm^{-2}] is given by the Newton's cooling laws in Eq. (4) [21].

$$\phi = h(T_s - T_{ext}) \quad (4)$$

h is the convection exchange coefficient, T_s is the temperature on the surface and T_{ext} is the ambient temperature.

The thermal strain ε_{th} is related to the temperature variation, due to the release of heat by hydration, and the coefficient of thermal expansion α (considered as constant):

$$\varepsilon_{th} = \alpha\dot{T}I . \quad (5)$$

As concrete hardens, autogenous shrinkage develops. The autogenous shrinkage is related to the evolution of hydration. Experimental results show that the autogenous shrinkage evolution is linear with respect to the hydration degree. The autogenous shrinkage ε_{au} could be described by [22]:

$$\dot{\varepsilon}_{au} = -k\dot{\xi}I \text{ for } \xi > \xi_0 . \quad (6)$$

The evolution of the mechanical parameters (Young's Modulus, Poisson's ratio, Tensile strength…) with respect to hydration process will be discussed after presenting the nonlinear plastic-damage model.

2.2 Plastic damage model for nonlinear behavior of concrete

Concrete damaged plasticity has been widely used and is recognized with high-reliability in the failure analysis of concrete behavior under complex conditions. Several failure analyses of concrete structure have been carried by the concrete damage model coupled with Plasticity in previous researches [23, 24]. Nowadays, relevant development and improving were made in order to control and optimization of plastic deformation in concrete damage plasticity model [25, 26].

The coupled plasticity-damage model formulated by Fichant et al. [27] and was improved in order to allow better consideration of fracture energy regularization [28]. In order to predict the nonlinear behavior of concrete, anon-linear plastique-damage is considered, and the relationship stress-strain is given by Eq. (7):

$$\sigma_{ij} = (1-d)\tilde{\sigma}_{ij} = (1-d)C^0_{ijkl}(\varepsilon_{kl} - \varepsilon^p_{kl}) . \quad (7)$$

σ_{ij} is the stress tensor, $\tilde{\sigma}_{ij}$ is the effective stress tensor and σ^0_{ijkl} is the undamaged elastic stiffness tensor. ε^p_{ij} is the plastic strain tensor. The damage behavior is considered as isotropic and is described by a scalar variable.

The damage evolution is given by Eq. (8):

$$d^t = 1 - \frac{\varepsilon_{d0}}{\tilde{\varepsilon}_e}\exp(B(\varepsilon_{d0} - \tilde{\varepsilon}_e)) . \quad (8)$$

$\hat{\varepsilon}_e$ is the equivalent strain given by:

$$\tilde{\varepsilon}_e = \sqrt{\langle \varepsilon_e{}^1 \rangle^2 + \langle \varepsilon_e{}^2 \rangle^2 + \langle \varepsilon_e{}^3 \rangle^2} . \quad (9)$$

ε_{d0} is the strain threshold. B is the parameter that controls the softening curve under tension loadings.

The plastic part of the model is described by two Drucker-Prager yield surfaces (F_t and F_c). One is used to limit the tensile stress and the other is employed to model the compression and the compression-compression regime in bi-axial stress. The yield function is formulated in three-dimensional space as

$$\begin{cases} F_t = \alpha_t J_2(\tilde{\sigma}_{ij}) + \beta_t I_1(\tilde{\sigma}_{ij}) - w(\tilde{p}) - w_0 \\ F_c = \alpha_c J_2(\tilde{\sigma}_{ij}) + \beta_c I_1(\tilde{\sigma}_{ij}) - w(\tilde{p}) - w_0 \end{cases} . \quad (10)$$

The loading functions are written in terms of the plastic stress. We consider a linear plastic evolution for the hardening variable:

$$w(\tilde{p}) = q_p * \tilde{p} + w_0 . \quad (11)$$

q_p is a model parameter, w_0 represents the elastic domain in the stress space. $\tilde{p}$ is the effective plastic strain. (α_t, β_t, α_c, β_c) are constant parameters. The evolution law of the plastic strain tensor is defined through the normality rule.

$$\varepsilon^p_{ij} = \lambda \frac{dF}{d\tilde{\sigma}_{ij}} . \quad (12)$$

Under tensile loading (Mode I), the softening behavior is governed by the fracture energy parameter. The proposed plastic criterion allows complete damage-plastic regularization [28]. The fracture energy is therefore given by Eq. (13):

$$G_f = h_c \int_0^\infty E\left(\varepsilon_{d0} \exp\left[B\left(\varepsilon_{d0} - \varepsilon + \varepsilon^p\right)\right]\right) d\varepsilon$$
$$G_f = h_c \frac{E\varepsilon_{d0}^2}{2} + h_c \frac{E\varepsilon_{d0}}{B(1-\zeta)} \tag{13}$$

with $\zeta = E / \left(E + \frac{q}{df_t / d\sigma}\right)$; E is the Young's modulus, $f_t = E^*\varepsilon_{d0}$ and h_c the finite element size related to the width of the localized band. This leads to a mesh-independent energy release upon crack propagation in Mode I under tensile stress.

2.3 Effect of hydration on the mechanical properties

The Young's modulus

During the hydration process, the mechanical properties are evolving. For the Young's modulus, the following equation is adopted:

$$E(\xi) = E_\infty \overline{\xi}^\beta , \tag{14}$$

with $\overline{\xi} = \left\langle \frac{\xi - \xi_0}{\xi_\infty - \xi_0} \right\rangle_+$ in which ξ_0 is the mechanical percolation threshold. It is kept constant and equal to 0.1. ξ_∞ is the final hydration degree. E_∞ is the final Young Modulus, β is a constant equal to 0.62. $\langle\ \rangle_+$ is the positive part operator.

Poisson's ratio

The Poisson's ratio is relatively stable for concrete. Neville [29] recommends a value equal to 0.2 for most concrete mixes. However, De Schutter [9] suggests an evolution depending on the hydration degree as follows:

$$\nu = 0.18 \sin\frac{\pi\xi}{2} + 0.5\exp(-10\xi) \tag{15}$$

Tensile strength

$$f_t(\xi) = f_{t\infty} \overline{\xi}^\gamma , \tag{16}$$

where $f_{t\infty}$ is the final tensile strength, γ is taken equal to 0.46. The evolution of the tensile strain threshold is computed from the evolution of f_t and E.

$$\varepsilon_{d0}(\xi) = \frac{f_t(\xi)}{E(\xi)} = \frac{f_{t\infty}}{E_\infty} \overline{\xi}^{\gamma-\beta} = \varepsilon_{d0\infty} \overline{\xi}^{\gamma-\beta} \tag{17}$$

Fracture energy

The fracture energy is represented by the stress-crack opening displacement curve under tension. Using the damage-plastic formulation, the fracture energy is given by:

$$G_f = h \frac{f_t}{B(1-\mathrm{H})} , \tag{18}$$

with

$$\mathrm{H} = \frac{E}{E + \frac{q}{dF_t / d\tilde{\sigma}}} . \tag{19}$$

The length scale which is introduced into the model is the element size h_c. For the numerical simulation, the damage parameter B is function of h_c and controls the slope of the strain softening curve. The parameter B is given by Eq. (20):

$$B = h_c \frac{f_t}{G_f(1-\mathrm{H})} \tag{20}$$

So, using the evolution equation of and , we propose the evolution of as:

$$B(\xi) = B_\infty \overline{\xi}^{\gamma-\alpha} \tag{21}$$

with $B_\infty = h \frac{f_{t\infty}}{G_{f\infty}(1-\mathrm{H})}$, and $\alpha = 8$.

3 Validation

Herein, we present a validation of the Chemo-Thermo-Mechanical model at 2D & 3D approaches. The development of temperature in the massive structures is influenced by several factors such as the initial temperature (which depends on the methods of thermal control), environmental conditions, cement type, formwork type, construction phases and adjacent structural. In this section, the CTM model is validated by comparing the temperature predictions with experimental results from the literature. The effects of initial temperature and the daily variation of ambient temperatures on the evolution of strength properties of concrete at early ages has been investigated in [30]. The reliability of our model is evaluated by predicting the temperature fields in massive blocks at 2D and 3D scale. In Sofi et al. [30], a block of concrete was made and cured under laboratory conditions to monitor the temperature development in the concrete. The concrete block was cured under laboratory conditions with a constant temperature of 20 ± 3 C°, RH = 70%. The concrete temperature development was monitored over time using three sensors at different depths. These temperature profiles have been used for validation of the finite element model proposed by authors. The experimental results obtained in [30] are used to validate the CTM model proposed in the present paper. The concrete block dimensions and the FE mesh 2D-3D are shown schematically in Fig. 1. The sensors are located at different depths of the block concrete, in order to capture the evolution of temperature in the block. Thus, the sensors C1, C2 and C3 are respectively placed at 100 mm, 150 mm and 200 mm. The ambient temperature evolution is shown in Fig. 2. The thermal properties of concrete and the boundary conditions used in the study are presented in Table 1.

The comparison of temperature evolution between experimental values measured in Sofi et al. [30] and the estimated numerical simulation by the present model at the 2D-3D scales are depicted in Fig. 3. As expected, the model is shown to be in good agreement with the experimental results with a maximum temperature difference of about 2 °C.

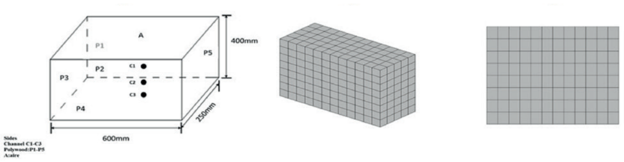

Fig. 1 Concrete block: (a) dimensions and location of the sensors; (b) 3D; (c) 2D

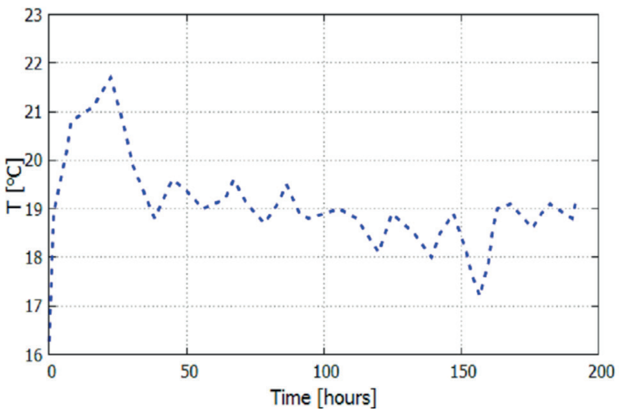

Fig. 2 Experimental ambient temperatures

Table 1 parameters of CTM model

Parameter	Value
Concrete thermal conductivity	2 (W/m K)
Concrete volumetric heat specific capacity	4600 (KJ/m^{3}K)
Convection coefficient between concrete and air	7.5 (Wm^{-2}K^{-1})
Equivalent convection-radiation coefficient between concrete and Framework	6 (Wm^{-2}K^{-1})
Arrhenius constant E_a/R	4000 (°K)
Latent hydration heat	137000 (KJ/)
a	16.62
b	50.81
c	192.21
d	-1173.77
e	602.27
f	1624.42
g	-1367.28

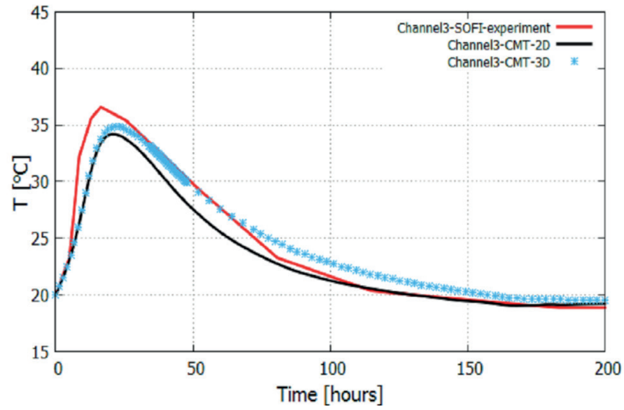

Fig. 3 Validation of the numerical model proposed with the reference results reported in Sofi et al. [30]

4 Structure application: gravity dams during construction

In this section, the objective is to evaluate the influence of early age effect induced temperature redistributions and stresses on concrete dam safety during the operation period.

4.1 Numerical simulation of early age behavior

A numerical investigation of the initial stress conditions of a concrete gravity dam undergoing early age hydration is undertaken. A study on the effect of aggregate cooling temperature control systems is also undertaken with the resultant impact on the thermo-mechanical behavior of concrete. The purpose of this investigation is twofold:

To investigate the effect of aggregate cooling system on concrete behavior at early age.

To study the initial stress state of early age hydration concrete gravity dams with and without temperature controlling systems.

2D Numerical computations are considered and the numerical simulations are performed considering a strain plane condition. The dams are discretized using 3570 QUA4 elements (Square quadrangle with linear interpolation). The sizes of the FE are chosen with regards to the Representative Volume Element (RVE). To deal with localization problem and mesh sensitivity The energetic regularization technique based on the Crack Band approach is used in the present study to deal with localization problem. The fracture energy is injected into a finite element calculation to preserve the energy dissipation and make it FE size-independent which could eliminate the pathological FE-mesh sensitivity [31, 32].

The parameters of concrete damage plasticity model, are given in Table 2.

Table 2 Fracture parameters used for concrete damage plasticity model

E	f_c	f_t	G_f	ε_{d0}	MP1	ALFA
31000	23.8	2.3	200	7,42e-5	40	3100

The dam was divided into 357 layers measuring 30 and 40 cm in thickness to respect the construction process. During the construction periods, the loads and boundary conditions of a concrete gravity dam are in dynamic change. During the construction operation, the environmental temperature, schedule construction, concrete hydration heat and methods of thermal control are primarily used. The main loads and boundary value conditions are briefly presented schematically in Fig. 4. In order to simulate the actual schedule construction, the technology "birth and death" developed by Jaafar et al. [33] has been used in the present study.

The self-weight was loaded dynamically in accordance with the actual pouring process of the dam; the temperature load was determined by taking into account the external air temperature; the pre-cooling method was introduced as the initial temperature of the concrete, and the temperature rise of concrete generated by the exothermic of cement. It should be noted, the hydration process is expected to reach 85% in the five days after concreting. Besides, the formwork was removed after 5 days of pouring. The thermal exchange between the dam surface and air is modeled by convective boundaries, and the thermal exchange between layers is modeled by conduction boundaries. It should be mentioned, the effect of reservoir water temperature and rock temperature were neglected in the present investigation.

Because of the high temperatures at the Beni Haroun site in the summer, cooling of the RCC (and facing concrete) was necessary. A "wet-belt" has been used to cool the coarse aggregate from May to October and flake ice was added in the mixer from June to September. After cooling, average temperature has been recorded.

The monitoring data of average air temperature and initial temperature of concrete for both cases (WPC and PC) are reported in [34]. Regarding the numerical simulation, the parameters used in the CTM model are listed in Table 3 [15, 35]. Some parameters as the activation energy and the chemical affinity, values were adapted from the following references.

The CTM model proposed is used to simulate the early age behavior. As the model is used at macroscale, initial temperature fields resulting from the pre-cooling process are smeared over finite elements. Explicit representation of aggregate cooling needs a mesoscale approach where concrete constituents are explicitly represented. This aspect is outside the scope of the present study.

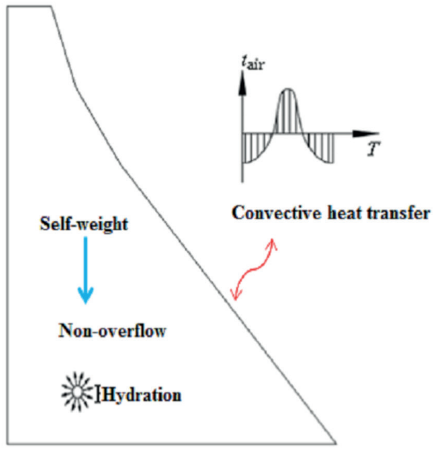

Fig. 4 Loads and boundary conditions during the construction period

Table 3 Set of concrete parameters used in constitutive laws [15, 35]

Parameter	Value
Energy activation E_a	45729.75 (J/mol)
Latent hydration heat L	117840 (KJ/m^3)
Coefficient a	64.417
Coefficient b	18042
Coefficient c	-94620
Coefficient d	215819
Coefficient e	-280172
Coefficient f	208172
Coefficient g	-67901
Coefficient exchange h	20.2 (W/m^{-2} K^{-1}) 2.02 (W/m^{-2} K^{-1})
Thermal conductivity K	2.79 (W/m^2 K)
Specific heat C	2400 (KJ/m^{3}K)
Coefficient of thermal expansion α	10 (µm/(m°C)

4.2 Thermal fields distribution at different elevations of the dam core

Numerical prediction of the temperature for both simulations (WPC and PC) within the core of the dam at different elevations is illustrated in Figs. 5–6. The temperature distributions vary during the dam construction. Two main phenomena could be observed: during cold and moderate season (Elevation 9 m which corresponds to March or elevation 27 m which corresponds to January), the maximal temperature was localized in the core of the dam. On the opposite, during warm periods (Elevation 58.8 m which corresponds to June 2000 or Elevation 63.5 m which corresponds to August), the temperature predicted was

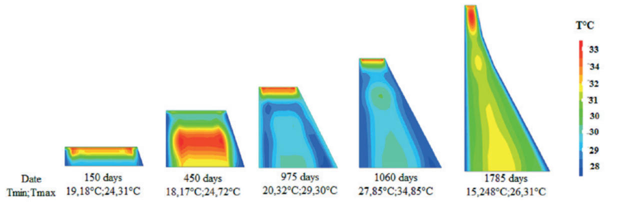

Fig. 5 Evolution of the core temperature: case without precooling (WPC)

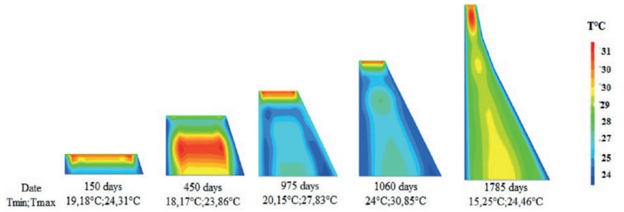

Fig. 6 Evolution of the core temperature: case with precooling (PC)

concentrated in the core of the layer recently poured with some layers below the inferior lift because of the thermal gradient. The maximum temperature generated during the constructions process is recorded during the warmest period at elevation 63.5 m (T_{max} = 34.85 C° for WPC and T_{max} = 30.85 C° for PC). This elevation has been reached during summer (August 2001). Regarding the cooling process, the maximum difference between the extreme temperatures predicted WPC and with PC was about 2 °C. Overall, moderate temperatures have been simulated during the construction process.

4.3 Stress fields distribution at different elevations of the dam core

Horizontal and vertical stresses both for WPC and PC simulations are respectively portrayed in Figs. 7–8. Even if the concrete tensile stress is not exceeded, the initial state predicted would influence the mechanical behavior of the concrete gravity dam. According to the obtained results, the use of pre-cooling method resulted in a diminution of the horizontal stresses induced during the construction process. The greatest tensile stresses were located at the heel of dams and resumption of concreting interface. In addition, the latter were also observed in certain block of the dam. The reason for this concentration can principally be the casting of concrete blocks during Summer. The maximal values of vertical stresses were also observed on both the upstream and downstream of the dam (approximation of air-concrete contact surface). From the results, the pre-cooling method presents a significant effect on the monitoring of stresses state at early age.

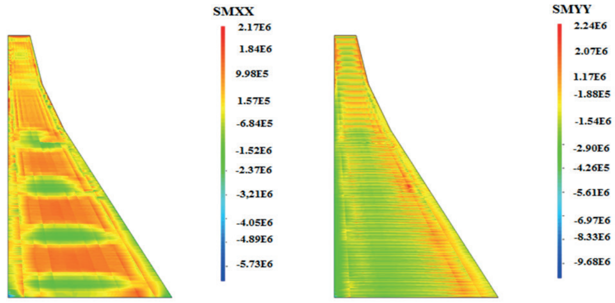

Fig. 7 Stress contours (SMXX stress in direction X- SMYY stress in direction Y) after construction (WPC); Unit (Pa)

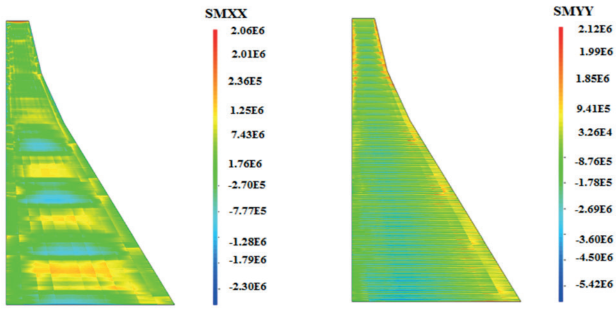

Fig. 8 Stress contours (SMXX stress in direction X- SMYY stress in direction Y) after construction (PC); Unit (Pa)

5 Conclusions

In this investigation, a numerical computational strategy has been proposed to assess the performance of a concrete gravity dams during construction considering the impacts of the early age behavior (exothermic process, environmental conditions) and the effect of the precooling process. The Beni Haroun RCC gravity dam has been taken as a case study. One of the strengths of this study is that it represents a comprehensive examination of a concrete gravity dam behavior from a dam safety perspective considering the construction process (early age, ambient temperature schedule construction…). In order to investigate the effect of early age on the thermal behaviors of concrete gravity dams, a specific chemical-thermo-mechanical is proposed. This model is implemented in CAST3M software, and the implementation is validated with the results from the literature.

In view of the obtained results, the following conclusions could be outlined:

These results validate the capacity of the CTM model to describe the stress and temperature history effect and illustrated the influence of thermo-mechanical interaction in massive concrete structures, particularly in concrete gravity dams.

The greatest tensile stresses after construction are developed at the heel of dams and resumption of concreting interface due to the internal restraint imposed by the concrete. In addition, stresses concentration in certain layers of dams is due to the concreting the lifts during the summer season.

The numerical computations show the usefulness of the precooling process. The effect of the hydration induced early age state on the thermal behavior of concrete dam is still significant with or without introduce the precooling technique.

The numerical strategy proposed in this paper aims to predict the mechanical behaviors for concrete gravity dams during construction considering the effect of early age, helping hence the decision-making of designers and contractor in dams engineering.

Indeed, in seismic analysis, concrete dams are more likely to develop tensile cracks. From a safety point of view, this cracking situation can be more critical in the presence of cracks caused by the thermal behavior of the dam concrete at an early age. The seismic regulation should take into account these initial states due to the effects of early age.

As a summary, some recommendations are suggested in order to improve the thermal stress control for dam engineering.

The maximum temperature for concrete RCC placement is affected by many factors such as the average annual temperature at the site; type of cement; the construction schedules and availability of thermal control method. If all these factors are taken into account, the designers can better plan the cooling method and schedule construction with respect to cooling of aggregates in order to reduce costs, without increasing the cracking risk.

To ensure an efficient control of thermal cracks induced by the effect of early age in concrete gravity dams, the designers need to combine both the thermal control methods pre-colling and post-cooling during the warm season.

The study is limited by the paucity of information of onsite data and the simplified modeling strategy (2D instead of 3D). However, it offers a framework for the exploration of dam's safety during early stages of construction. Further effort would be put on the impact of the initial state (stresses, damage) on the mechanical behaviors of concrete gravity dams under seismic condition. Also, the present analysis should be extended to 3D analysis in order to investigate the effect of transverse joints on the control of premature cracking of concrete gravity dams induced by the effect of early age.

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