Thermal Analysis of Roller Compacted Concrete Dams

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Abstract

Concrete is a material with weak against tension strength. Due to the change in the volume caused by the temperature variations, tensile stresses appear that cause cracks in critical situations. For this reason, the issue of thermal stresses and cracks have great importance in design of roller compacted concrete (RCC) dams. In this paper, thermal analysis of RCC dams is considered to show the effect of temperature change which induced the tension stresses in the body. For modeling and transient analysis of case model of RCC dams, Ansys Workbench software based on finite element method has been used. Different conditions of concreting such as beginning in hot and cold seasons and stopping in hot and cold months of year, pre-cooling of materials are considered as effective conditions. Obtained results illustrate the distribution of temperature and induced stresses in dam body.

Keywords: RCC dams, environmental conditions, finite element, tensile stress.

1.   INTRODUCTION

In the building of RCC dams, the concreting of the dam body is carried out on a vast surface containing several blocks. After pouring concrete, transverse joints are performed. The roller compacted concrete dams do not carry longitudinal joints and usually do not have cooling system. In implementing of RCC dam, precise and continuous monitoring of parameters such as concreting speed, bonding between layers, thickness of layers, concrete start time and time interval between layers is considered.

The basic requirement in the design of concrete dams is to ensure the integrity, sealing and durability of the dam structure. Concrete cracking is a factor that threatens the above cases. Therefore, new methods in building of dam should include measures to limit the possibility of cracking, especially cracks resulted by heat.

The Simulation of the thermal behavior of the dam during construction and operation years are done with the using of a set of mathematical models based on finite element method. Therefore, one, two, and three-dimensional models have been used in different length of time and place for different purposes for the study and thermal analysis of dams.

The effect of environmental heat and cement hydration on a roller concrete dam was conducted by Ahmadi and Heidari (2011). In their study, besides the changes in the properties of the concrete relative to the time, the dam construction process is also modeled. For different levels, the boundary conditions for radiation, convection and solar radiation and for the adiabatic boundary threshold are considered.

Thermal cracking of concrete dams has been done by finite element method by Nurzad and Nemati Chari (2006). In their research, the application of the finite element method in the calculation of the risk of thermal cracking of the bulk dam structure has been investigated. Also, production and distribution of heat in bulk concrete have been investigated. By describing of induced thermal stresses and effective factors, the method of control of conventional thermal stresses, especially the use of post-cooling pipes in concrete was defined. The results showed that preventing thermal cracking can be obtained by appropriate pre-cooling and post-cooling.

The thermal analysis for RCC roller concrete dam was performed by Malkawi (2003) using the Ansys finite element program. The purpose of research was to provide the distribution of temperature in the body of the gravity dam and to investigate the thermal response of the dam using the Ansys software.

In the following, Luna and Yong Wu (2000) considered the properties of concrete as a time function and suggested that if the dam was constructed in cool seasons, the maximum temperature of the dam will be reduced. Also, according to the Hinks and Copley models (1999) that take into account the effect of solar radiation, the speed of execution is lower than the planned speed in hot air, causing a higher temperature than the predicted temperatures, and by reducing the length of the concreting blocks, there is no rapid drop in maximum stresses. Servera (2002, 2003) illustrated that although the pre-cooling of the concrete before pouring in specified location,

the temperature clearly will be lower than the final distribution. But the efficiency of this method is very limited. For the case model, only 20% is evaluated, and the worst possible scenario is the start the project in the summer. Among the factors that affect the cracking of concrete dams are environmental factors. Therefore, an analytical model by Aguado and et al. (1995) simulated the thermal behavior of dams that are exposed to environmental conditions during operation.

2. HEAT TRANSFER

2.1. EFFECTIVE ENVIRONMENTAL PARAMETERS AFFECTING TEMPERATURE VARIATIONS IN THE DAM BODY

The environmental parameters affecting temperature variations in the dam body are: Ambient temperature, wind speed, radiation, insulation and rainfall. The most important of which is the ambient temperature which is investigated by thermal analysis. Lack of data about other parameters and the impossibility of their accurate prediction cause the effects of phenomena such as displacement or wind speed can't be predicted in models. However, their effect on the final results is lower than the ambient temperature. In model simulation, cooling during construction as well as future years, the temperature curves of the environment are always used, which is the result of statistical work on the data obtained from the dam site.

2.2. HEAT EFFECTS IN CONCRETE DAMS

The concrete dams are the largest bulky concrete structures exposed to cracking caused by various phenomena. It is difficult to find a gravity dam that is not in some way affected by cracking. Extreme cracks in dams, other than those caused by earthquake loading, have resulted by climatic conditions. The Daniel Johnson dam in Quebec, Canada, is an example of a large dam that has been damaged by thermal cracking. In this dam, due to temperature changes, thermal cracks appeared at a time when the dam was not yet intact.

The FONTA dam in the U.S is another example of heat cracking. In the finite element analysis performed on this dam, the cracking mechanism was changed due to the combination of two following phenomena. One is the thermal expansion of the concrete in the downstream side and the second is the increasing of concrete temperature due to the hydration of the cement. Department of pathology of dam and reservoir of the great Dams committee announced in a report, temperature variations in the environment and the periods of freezing and melting are one of the most important deterioration factors in concrete dams. In a gravity concrete dam, the upstream procedure is affected by seasonal variations in water temperature variation, which changes with the depth of water in the reservoir. Usually the above temperatures are stabilized at the bottom of the reservoir at 4 C. The downstream side of the dam is affected by seasonal and daily changes in temperature.

Finally, during the process of fixing and hardening of new concrete, the heat caused by hydration will increase the internal temperature of the concrete, which will start to cool over time. The above temperature changes lead to non-uniform volumetric changes in the concrete, which is proportional to the thermal gradient between the core of the dam and its surfaces. When the thermal stress exceeds the capacity of concrete tensile strength, the cracks form in the dam that can cause further damage to the structure. Weather conditions can be damaged during the useful life of the dam, even when the effect of the heat of hydration has been lost.

2.3. THERMAL ANALYSIS

In this research, Ansys workbench software is used for analysis and modeling. The software is based on finite element method for modeling and analysis. The finite element method has been developed to solve complex problems with the geometry, type of material, and custom loading.

2.4. GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

A conduction heat transfer for a two-dimensional, transient and isotropic state can be described mathematically in the Cartesian coordinates as described below.

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z}\right) + Q = \rho C \frac{\partial T}{\partial t} \tag{1}$$

T   :District temperature $\left[{}^{\circ}{}_K\right]$

ρ : Density $\left[kg/m^3 \right]$

C : Specific Heat $\left[J/kg°_K \right]$

K_x , K_y , K_z: Thermal conductivity coefficient $\left[w/m^{2°}_K \right]$

Q : The internal heating rate for the unit volume $\left[w/m^3 \right]$

Equation (1) must be solved under the initial conditions and appropriate boundary conditions. The boundary conditions for this equation are given in the form of the following equations.

$$T = \overline{T} \tag{2}$$

$$-\left(K_x \frac{\partial T}{\partial x} n_x + K_y \frac{\partial T}{\partial y} n_y + K_z \frac{\partial T}{\partial z} n_z \right) = -q_a + q_c + q_r \tag{3}$$

q_a :The intensity of the heat flow is entered $\left[w/m^2 \right]$

q_c : Condensation current intensity $\left[w/m^2 \right]$

q_r : Intensity of the radiation flux $\left[w/m^2 \right]$

n_x, n_y , n_z are Normal surface vectors in the present study. Q, Γ_T, Γ_q , $\overline{T}$ Accordingly, the representative of the rate of heat output of hydration, the common boundary of the dam and concrete, the open-air boundary, the temperature of dam's foundation and the intensity of the thermal current input from the solar radiation and q_c Condensation current intensity and q_r The intensity of the radiation flux is output from the surface.

2.5. HEAT TRANSFER THROUGH CONVECTION

The heat exchange carried out by convection resulting from the temperature difference between Γq and the ambient air temperature is obtained by Newton's cooling law as follows:

$$qc = hc(T - T_a) \tag{4}$$

hc : Convection coefficient $\left[w/m^{2°}_K \right]$

T : Boundary temperature Γ_q $\left[°_K \right]$

T_a : Ambient temperature $\left[°_K \right]$

V : Air velocity in the surroundings $\left[m/sec \right]$

3. MODELING AND CASE STUDY

3.1. MODEL GEOMETRY AND MATERIALS SPECIFICATIONS

To conduct this analysis, the Jhave roller compacted concrete dam has been selected as case study. This dam is located in Kurdistan province on the Jhave river.

In the mixing plan of the Jhawe RCC dam, Portland cement of Urmia has been used. The diagram of increasing adiabatic temperature of the dam mix with 25% of the pozzolan is figure 1.
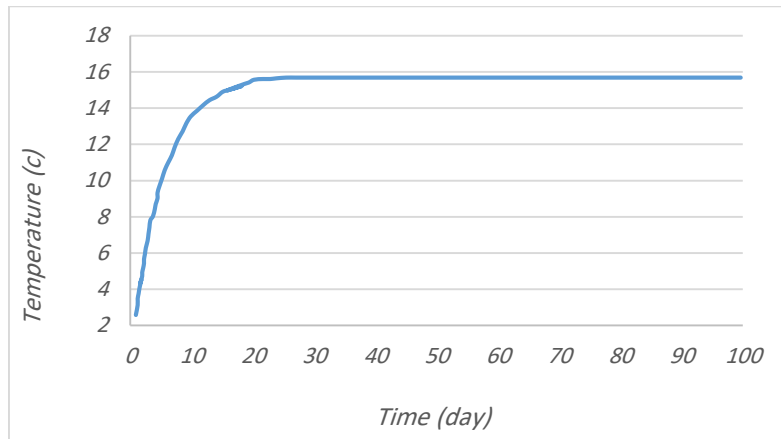
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Fig.1.Adiabatic temperature rise due to hydration heat.

The temperature of the dam in the site, according to the reports of the Mashanir Water Resources Department, has been illustrated in figure 2.
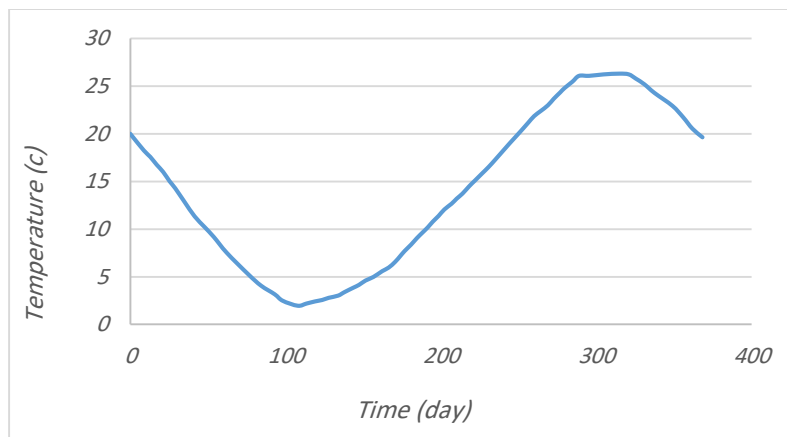

Fig.2.Air temperature in place of construction.

In this research, the initial temperature of the concrete is $15°\text{C}$ and the average annual temperature is $13.8°\text{C}$ and The interval time between two consecutive layer 3-day runs is considered.

To solve and analyze the considered model, concrete dam and foundation materials are assumed to have homogeneous , linear and isotropic behavior. All dimensions are based on the SI system. The bulk modulus of elasticity, concrete density and Poisson ratio are 25 GPA, 2450 kg / m², 0.37 respectively. The parameters required to define the thermal behavior of the materials are summarized in Table1.

Tab.1.Proprties of the materials considered

Variable	Value	Unit
Isotropic Thermal Conductivity	2.96	$W/_{m * °C}$
Specific Heat	970	$J/_{kg * °C}$
Film Coefficient	1500000	$J/_{m^2 * day * °C}$
Thermal Conductivity	10670	$J/_{m * h * °C}$

4.   Thermal Analysis Results

The Ansys workbench software based on finite element method has been used for thermal analysis. To do this analysis, first the layering was carried out according to the criteria for the implementation of the dam then the time step was set for each layer. In this analysis, the weight of layers was not considered and only the effect of heat and its tensions was investigated. Figure 4 shows that the concrete temperature is not even higher at 21 ° C even mid-time during construction.
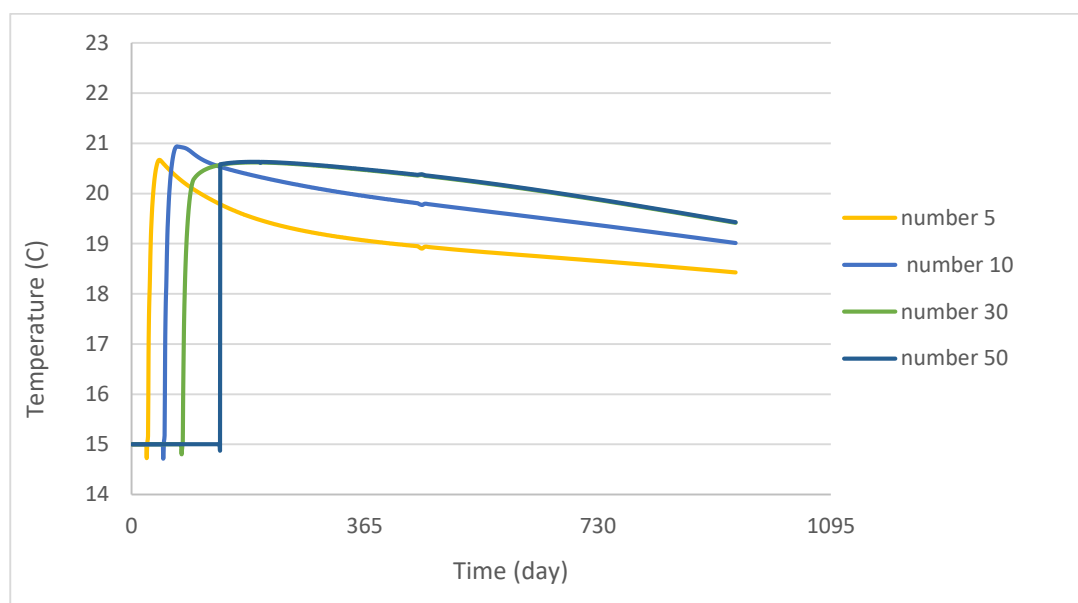
Fig.4. Rcc temperature at different layers during construction

Figures 5 to 9 show how to create and change temperature during construction and concreting of different layers of the dam. It is observed that the body of the dam begins to cool with the passage of time and to the concrete, the new layers from areas exposed to the environment. By the end of 05/03/2009, the end of the concreting and construction work, all the outer parts of the dam begin to decrease the temperature. This decreasing in the following days is the completion of the construction process it continues.
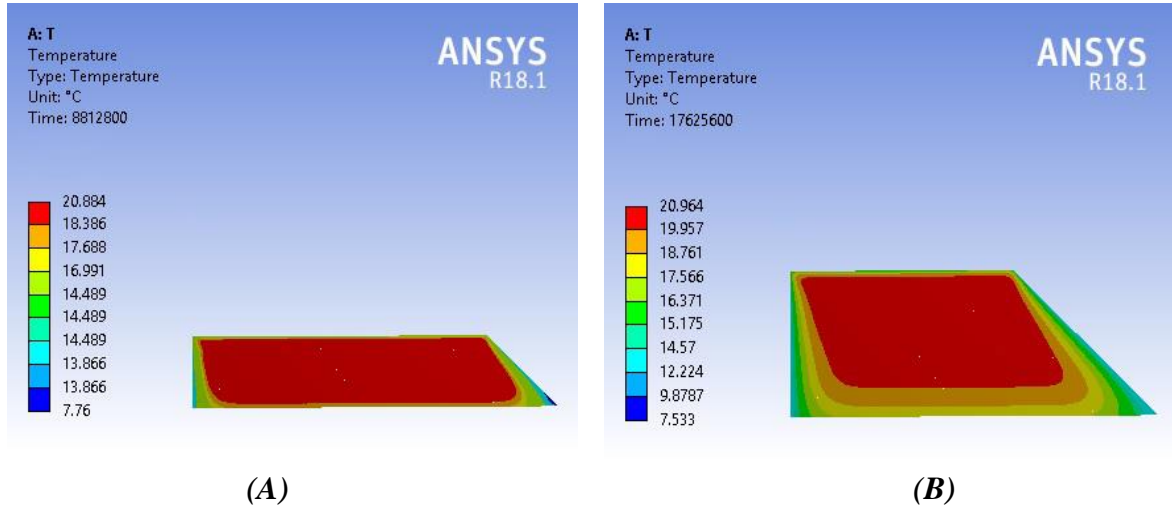
(A) *(B)*

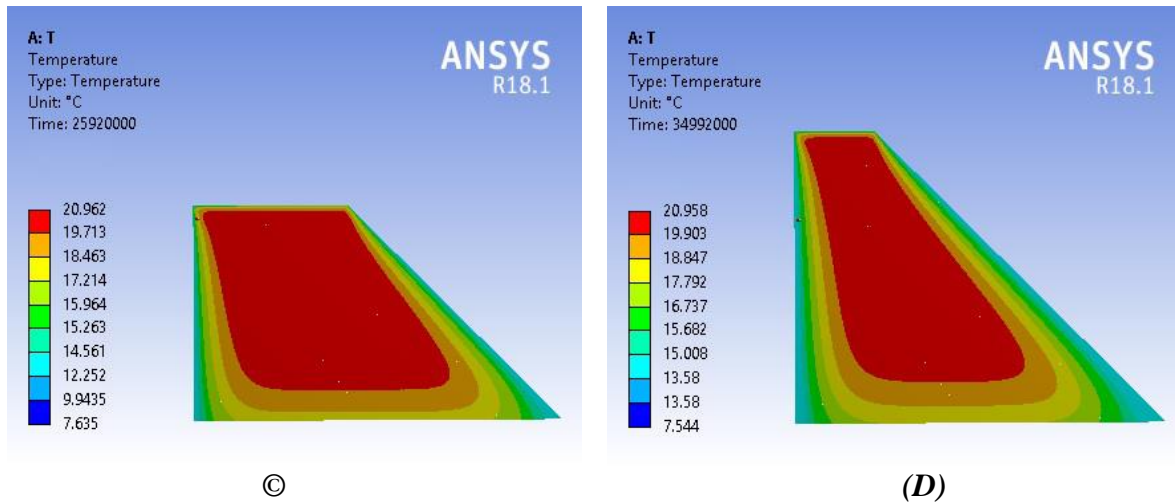**Fig.5. Temperature in ℃ during construction on 02.01.2008 (A) and 13.04.2008 (B)**

© *(D)*

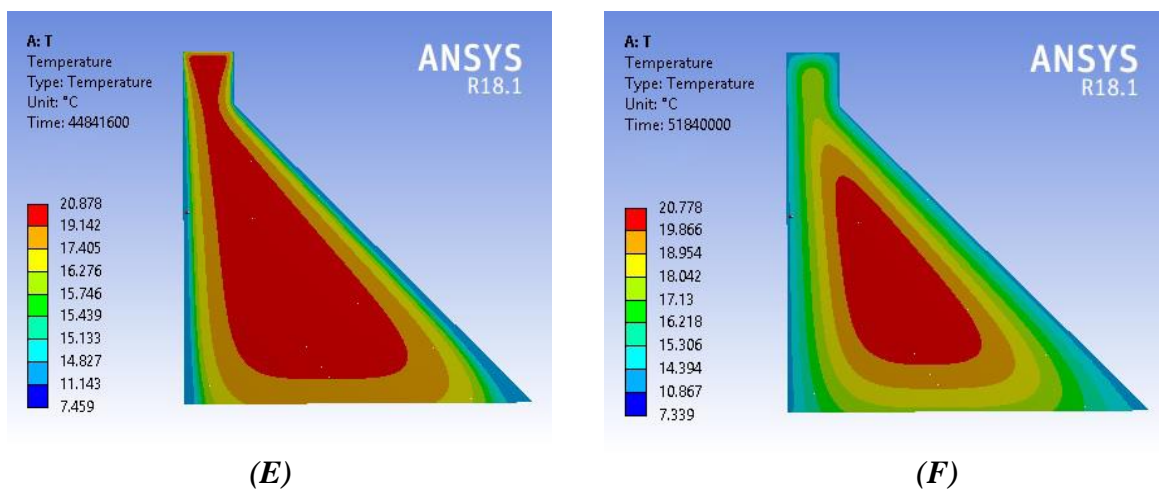**Fig.6. Temperature in ℃ during construction on 22.07.2008(C) and 05.10.2008(D)**

(E) *(F)*

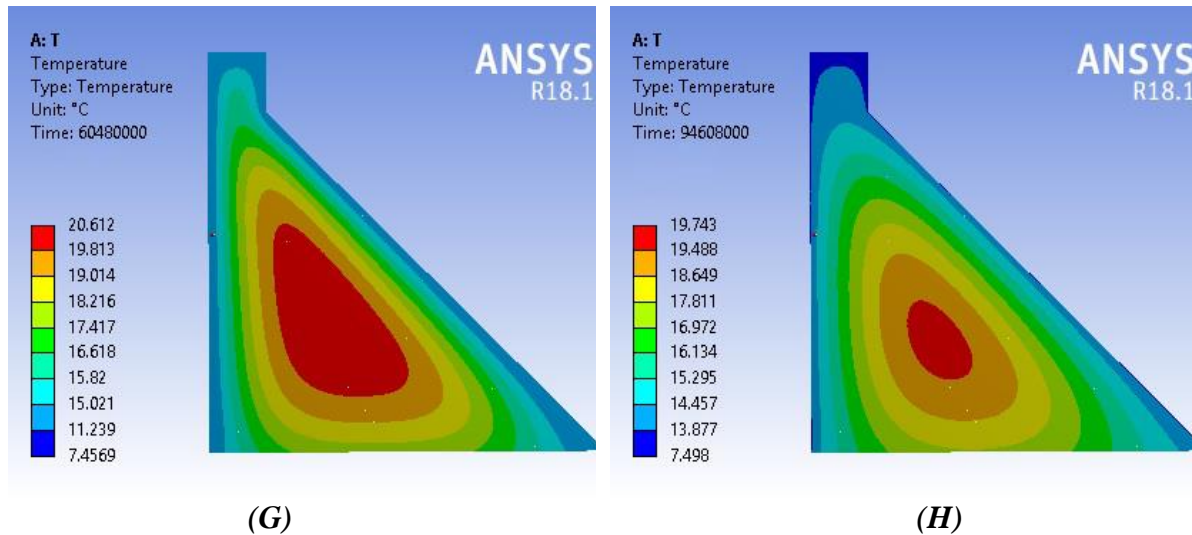**Fig.7. Temperature in ℃ during construction on 27.01.2009 (E) and 16.05.2009 (F)**

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(G)   *(H)*

Fig.8. Temperature in ℃ during construction on 25.08.2009 (G) and 02.04.2010 (H)
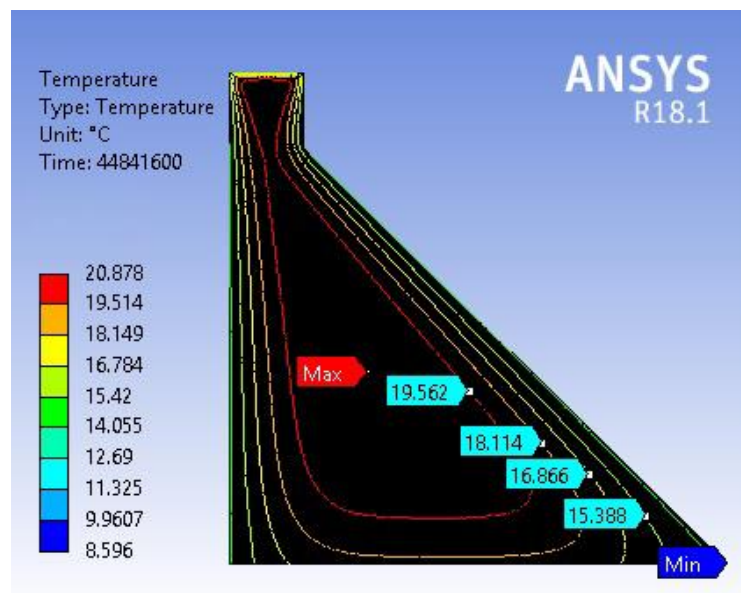

Fig.9. Temperature in ℃ during construction on 27.01.2009.

5. Stress Analysis Result

Figures 10 and 11 show the amount of tension stresses and how it changes in the dam body. These tensions are solely due to the heat created during the dam. And the weight of the dam is not considered. The maximum amount of tension occurs at the points located on the heel and the toe of the dam. And as we move towards the center of the dam, the tensions are reduced.
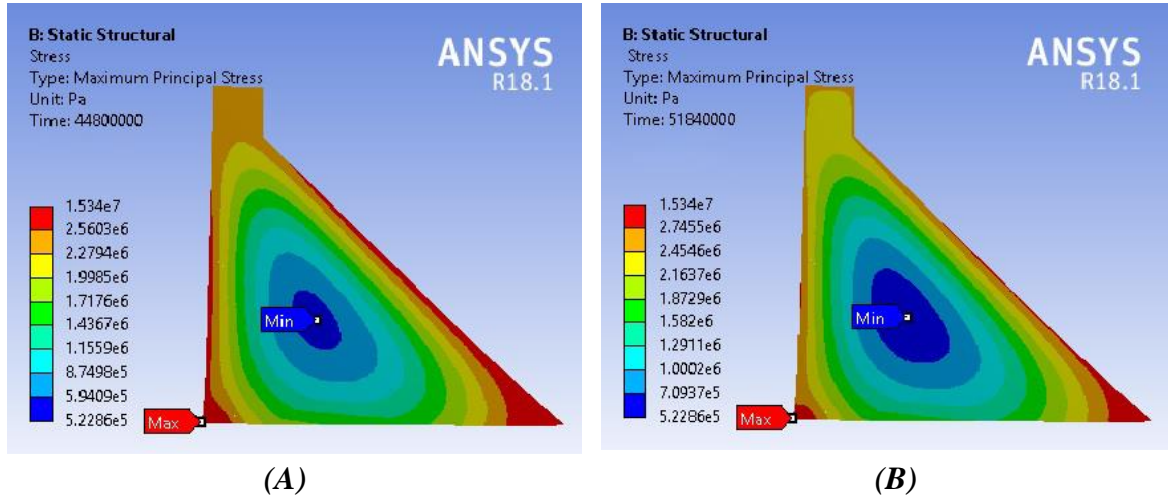
(A)   *(B)*

Fig.10. Maximum principal stress distribution (Pa) on 27.01.2009(A) and 16.05.2009 (B)
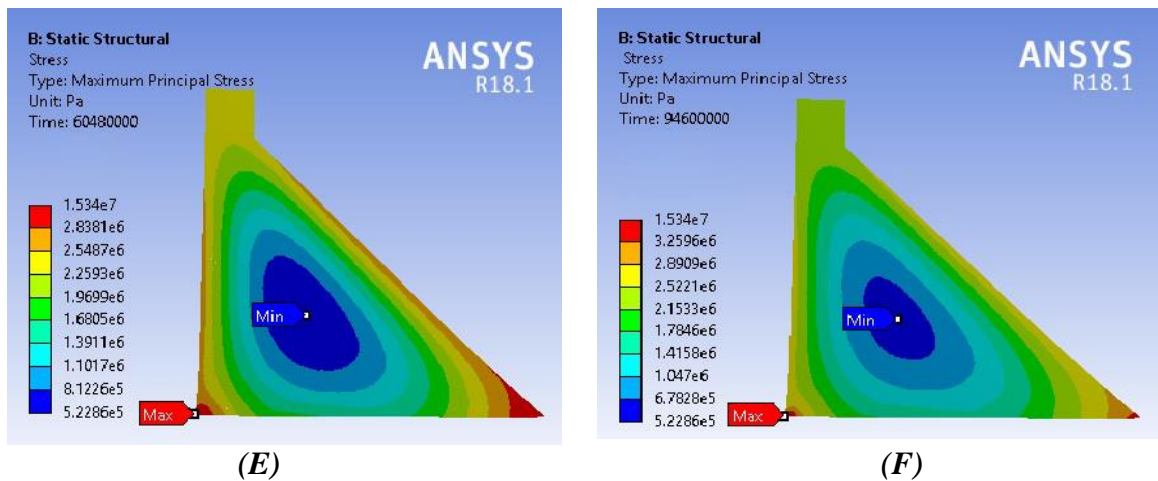

(E)   *(F)*

Fig.11. Principal stress distribution (Pa) on 25.08.2009 (E) and 02.04.2010 (F)

As expected, the maximum deformation of the dam is due to heat during the concrete (Regardless of the weight of the layers) there is a crown dam in the crater and equal to 12 mm.
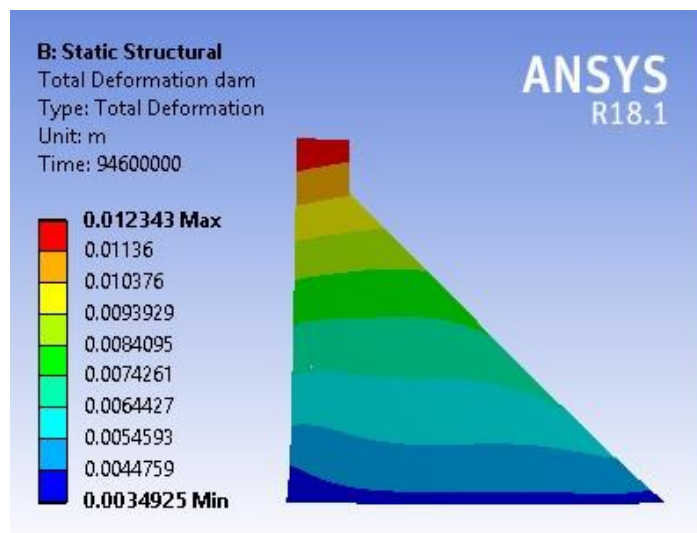

Fig.11. Total deformation rate (m) in the end of construction

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6. CONCLUSIONS

In this research thermal analysis of case model of RCC dam with 86.5m height during and after construction. The following conclusions may be stated:

- For RCC dams the temperature of each thin layer after its placement can be significantly reduced by the water evaporating on the upper face. For conventional dams, this phenomenon is of lesser importance due to the greater thickness of the layers and because of the limited extension in space of its influence.

- RCC dams are hardly subjected to thermal cracking if the external temperature is more or less constant, as in tropical climate, and the initial concrete temperature is not very different of the air.

- Obviously, by significant seasonal variation, crack may appear at the faces of a thick RCC gravity dam during the following winter if the placing occurred at summer time. The cracking is caused by the temperature increase in the interior of the dam combined with the fast cooling of the surface in winter.

- The temperature of the core of the thick gravity dam requires a long time to drop to the final equilibrium state.

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