

TEMPERATURE MODELLING IN ASPHALTIC CONCRETE FACINGS, THE REFLECTIVE SURFACE EFFECT SIMULATION CASE STUDY: GHRIB DAM (AIN DEFLA, ALGERIA)

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ABSTRACT

The asphaltic concrete facing is one of the most widely used components for waterproofing rockfill dams. It is, particularly in the case of hydroelectric pumped storage facilities, often highly exposed to significant temperature fluctuations, which are caused by solar radiation, variation in the water level in the reservoir, frost in the winter season, as well as wind speed and direction, and precipitation. To better explain the heat transfer phenomenon, it is necessary to know the temperature variations in the different layers of the asphaltic concrete facing. This study describes the measurement of the temperature in the asphaltic concrete facing (raw and protected) of the Ghrif dam (Ain Defla, Algeria) and its evaluation using a numerical model of the heat flow using the Fluent software. First, a validation of the model by comparison with experimental measurements, in the case of a daily variation in ambient temperature, the comparison of the results of the calculation of the numerical model with the real measurements shows an excellent similarity. Then we simulate the application of thermal protection by adding a reflective paint to the facing surface. The results of this simulation show that the reflection of solar radiation by the reflective surface has the potential to cool the asphaltic concrete facing and reduce the temperatures significantly, the temperature peak as well as reduce it to 11.47 °C, this happens at noon when the heat is very high, which is significant for our asphaltic concrete facing, where the temperatures reach their maximum values (49°C) in the raw case (without protection).

KEYWORDS

Asphaltic concrete facing, Heat transfer, Ghrif dam, Reflective surface, Modelling, Fluent

INTRODUCTION

The waterproofing performance of asphalt has been known since ancient times. Even today, we can still see 3000-year-old asphalt based hydraulic structures, such as the Tiger dikes in Ashur, Mesopotamia, still in good condition [1].

Asphalt mixes are impermeable, durable, insensitive to water, resistant to most common chemical agents and microorganisms, have a high ability to solve many hydraulic problems, and the flexibility of asphalt waterproofing allows them to adapt to settling of their substrate without cracking or losing their properties [2,3].

The problem of waterproofing embankment dams arises whenever the calculation of superstructure infiltrations indicates unacceptable losses; these losses can either lead to the ruin of the structure by fox formation or, without affecting its safety, be disturbing for the operation of the dam [4, 5, 6].

Temperatures and atmospheric conditions have multiple impacts on hydraulic structures; these impacts are mainly related to changes in temperatures within the structure and its foundations. Air temperatures directly influence temperatures in the asphalt concrete facing, while atmospheric conditions (solar radiation, UV radiation, clouds, etc.) can exacerbate these phenomena [7].

MATERIAL AND METHODS

The originality of this study lies in the consideration of the cooling effect by adding a reflective surface. Using the Fluent software, we tried to model the transient thermal problem including solar radiation and natural convection on the surface of the asphalt concrete facing for a period of 17 hours. The work is organized in two parts:

The first consists in validating the numerical results by comparing them with the experimental values measured at the Ghrib dam asphaltic concrete facing.

The second, consists in protecting the asphaltic concrete facing by a reflective surface against the effects of solar radiation, this surface allows reflecting the radiations by its light colour in order to cool the asphaltic concrete facing.

The energy accumulation of the surface of the asphaltic concrete facing differs considerably from that of the natural soil due to the different properties of thermal radiation. The asphaltic concrete layers absorb large amounts of radiation during the day, which produces heating on the surface of the asphaltic concrete facing that is rapidly transmitted to the lower layers producing an increase in temperature inside them (Figure 1) [8].

Understanding and correctly determining the behaviour of energy accumulation helps in the process of making decisions about asphalt concrete facing construction technologies and studying the relative phenomenon of heat as a serious environmental problem [5,9].

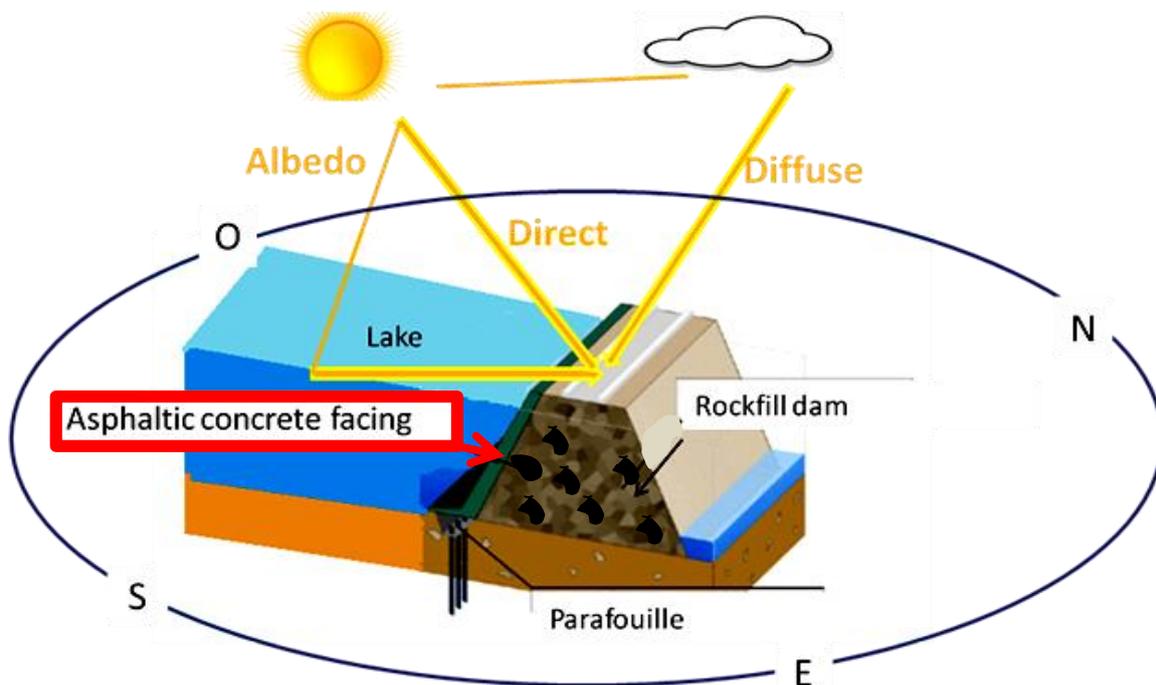


Fig. 1 - The solar components around the dam

Case study

The basic model on which the whole study will be based concerns the Ghrib dam, located in western Algeria in the commune of Oued Chorfa wilaya of Ain Defla (Figure 2a, 2b, 2c). It is located on the upper reaches of the Chelif River and is used for irrigation, drinking water supply and power generation.

The Ghrib dam was built in a poor support area. In order to avoid the risk of settling, a flexible dam capable of adapting to ground movements has been built. This structure is one of the first rockfill structures built with an upstream asphaltic concrete facing, it consists of a stowed rockfill dike, built between 1926 and 1938. Its capacity is 280 millionm³ [6,10].

On the dam we can distinguish two parts: the dam and the asphaltic concrete facing (Figure 3), on the asphaltic concrete facing thermocouples have been placed at three strategic locations, corresponding to the three parts of the experimental model (at 1cm, at 6 and at 10 cm counted from the surface of the surface), each zone includes 3 thermocouples spaced at irregular intervals.

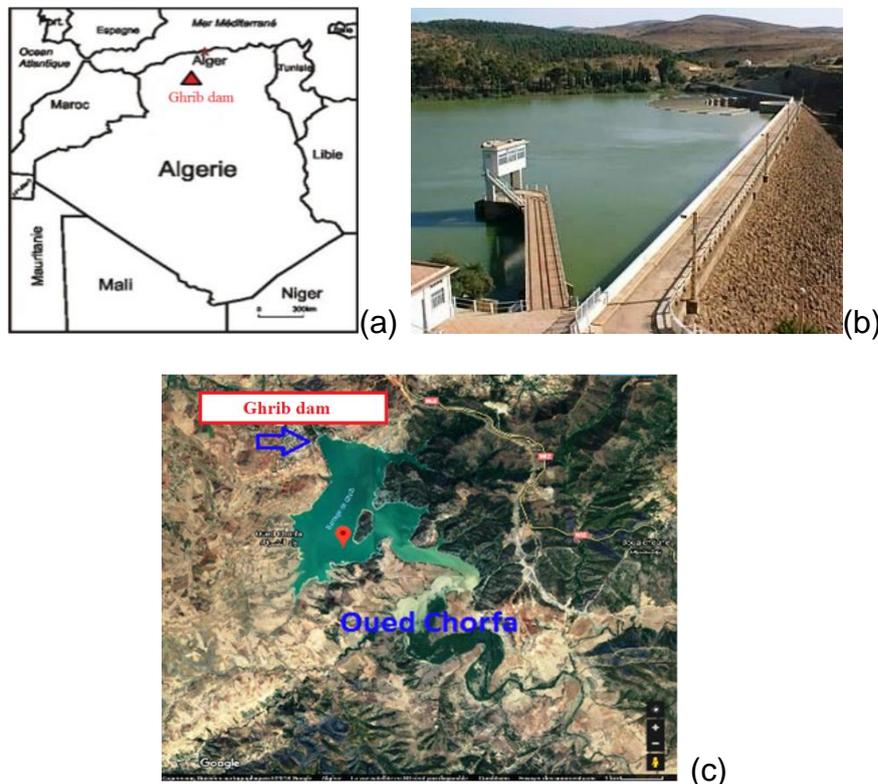


Fig.2 - Ghrib dam location (Ain Defla / Algeria): (a) Ghrib dam on Algeria map. (b) pic of Ghrib dam. (c) Ghrib dam water surface

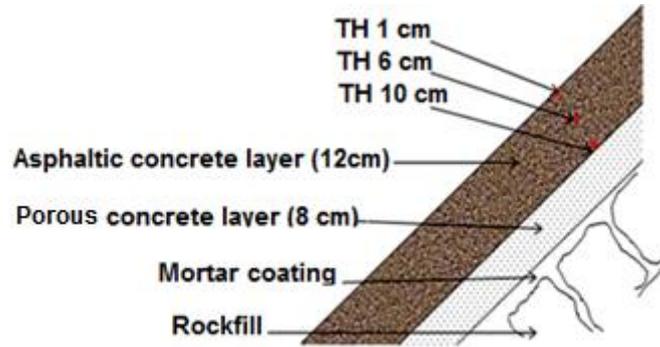


Fig.3 - Sketch of the asphaltic concrete facing of Ghrib, and the location of the sensors for temperature measurement (TH).

Configuration of the model and simulation

The simulated geometry is shown in Figure 4, where we observe the raw asphaltic concrete facing, which consists of two layers: a 12 cm thick asphalt concrete waterproof layer and an 8 cm thick porous concrete draining layer, resting on a rockfill dike (massive limestone).

Mesh geometry, where each layer represents a different material with different physical and thermal properties (Table 1). The structure represents a constant slope of 1/1. An unstructured mesh of quadrilateral and triangular type was used, 0.25 m in the rock slope and 0.01 m in the other layers. Temperatures are measured at the three digital thermocouples (TH) at initially defined positions of 1cm, 6cm and 10cm, with a time chronology of 60 seconds (time step); the maximum number of iterations has been set at 20.

Tab. 1 - Properties of the materials used [6]

Layers	Materials	Thermal conductivity (λ) (W m ⁻² °C ⁻²)	Weight density (ρ) (kg m ⁻³)	Specific heat (Cp) (W s kg ⁻² °C ⁻²)
1	Rockfill	2.8	2700	920
2	Asphaltic concrete	1.165	2230	930
3	Porous concrete	1.27	2310	942

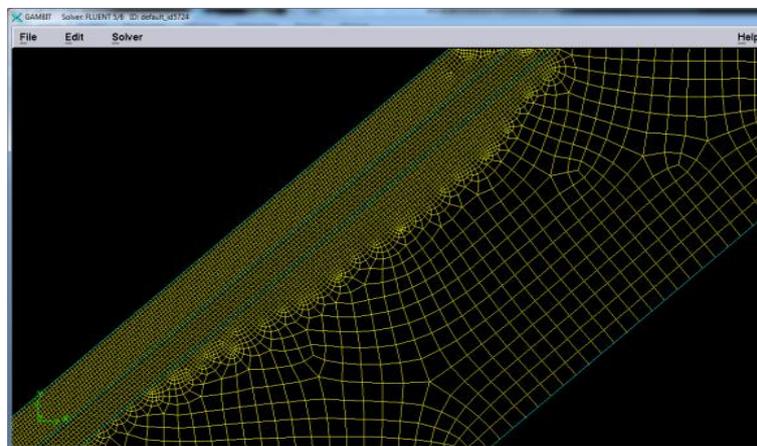


Fig.4 - Example of simulated geometry (raw asphaltic concrete facing)

Mathematical model

For the initial model, the various heat exchanges will be simplified. Thus, it is assumed that thermal transfer throughout the mask is dominated by conduction.

The temperature profile in the asphaltic concrete facing is therefore of the form $T(z,t)$. The heat propagation in the thermal diffusivity asphaltic concrete (a) (2), will be described by the heat equation (1) [10, 11,12]:

$$\frac{\partial T}{\partial t} = a \left(\frac{\partial^2 T}{\partial z^2} \right) \tag{1}$$

$$a = \frac{\lambda}{\rho C_p} \tag{2}$$

Where T is the temperature, λ is the thermal conductivity, C_p is the specific thermal capacity, ρ is the density of the material, z is the distance measured perpendicular to the facing towards the dam body and t is the time.

In the second case of simulation, the asphalt concrete facing is protected against the effects of solar radiation by a white reflective surface, taking into account the convective and radiative exchanges between this surface and the outside air (Figure 5), so in this step the heat transfer model changes from conduction alone to conduction, convection and radiation transfer (Figure 5), so equation 1 takes the following form [9,13]:

$$\frac{\partial T}{\partial t} = a \left(\frac{\partial^2 T}{\partial z^2} \right) - h(T_s - T_{ext}) - \epsilon \sigma (T_s^4 - T_{melody}^4) - \alpha q_{sun} \tag{3}$$

Where:

h is the convective exchange coefficient of the air taken equal to $20 \text{ Wm}^{-2}\text{°C}^{-1}$, T_s is the temperature at the surface of the asphalt concrete facing and T_{air} is the air temperature.

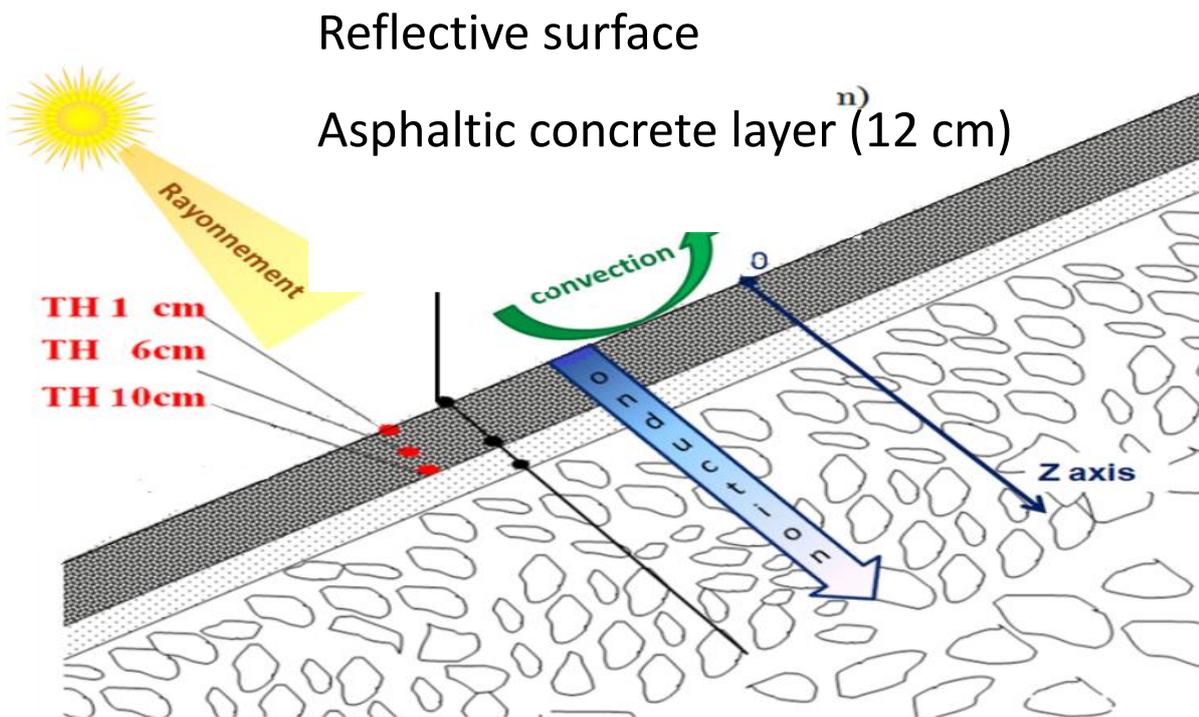


Fig.5 - Schematic section of the asphaltic concrete facing protected by reflective surface

Boundary and initial conditions

The purpose of the numerical model is to determine, from conditions at the limits imposed on its contour, the temperature profile inside the asphaltic concrete facing is simulated for the following two cases.

The first case is conduction only: a Dirichlet condition is introduced on the surface of the asphalt concrete facing is a temperature profile constructed from the experimental readings (Fr. Agence Nationale des Barrages et Transferts - ANBT) imposed on the surface of the Ghib asphaltic concrete facing (4).

$$T(z = 0, t) = T_{\text{experimental}}(t) \quad (4)$$

The second case requires the consideration of heat transfer by convection and radiation. In this case, the heat flux transmitted to the surface of the asphalt concrete facing towards the outside follows the following equation (5) [9].

$$q'' = h(T_s - T_{\text{air}}) + \varepsilon\sigma(T_s^4 - T_{\text{air}}^4) - \alpha q''_{\text{sun}} \quad (5)$$

Where: ε corresponds to emissivity and σ corresponds to the Stefan-Boltzmann constant ($\sigma=5.67 \cdot 10^{-8} \text{ Wm}^{-2}\text{C}^{-4}$) [INCROPERA and DE WITT 2002]. α corresponds to the absorbance of the asphaltic concrete facing surface to solar radiation, it is 0.95 [DJEMILI 2006; CHIBLAK 2005; CHATAIGNER 2008]. q''_{sun} represents the solar radiation flux reaching the surface in Wm^{-2} .

One of the difficulties of modelling comes from the fact that we do not know the precise value of the solar radiation flux as a function of time q''_{sun} . Indeed, the latter is influenced by the alternation of day and night, the inclination of the receiving surface, the presence of shadows, clouds, rain, etc. It can be calculated using the following formula (6):

$$q''_{\text{sun}}(t) = G_{\alpha}(t) + G_w(t) - A(t) \quad (6)$$

With:

$G_{\alpha}(t)$: Global radiation on a surface inclined as a function of time (Wm^{-2});

$G_w(t)$: Atmospheric radiation as a function of time (Wm^{-2});

$A(t)$: Reflected radiation as a function of time (Wm^{-2});

The solar radiation flux will be calculated for the day in question (clear sky), and the place in question by a sub-programme carried out under Matlab.

The temperature profile imposed on the surface asphaltic concrete facing take into account the air temperature, but also the effect of solar radiation. To do this, it will follow the following equation (7) [14, 9]:

$$T_{\text{air}}^*(t) = T_{\text{air}}(t) + \frac{\alpha}{U} q''_{\text{sun}}(t) \quad (7)$$

Where:

T_{air}^* : Modified air temperature taking into account solar radiation $^{\circ}\text{C}$;

U : corresponds to the thermal transfer coefficient between the outside and the interface, which takes into account the external convection coefficients and the equivalent thermal resistance on the interface equal to $20 \text{ Wm}^{-2}\text{C}$ [9].

For the boundary to the left of the models (in the dam body) and at a sufficiently high depth, the temperature of the structure is no longer influenced by the thermal input of the asphaltic concrete facing, this depth is, by hypothesis, equal to 1 m, located in the embankment dike, it is a Neumann condition representing a zero heat flux (8) [9,10 ,11,15].

$$\frac{\partial T(z=1,t)}{\partial z} = 0 \quad (8)$$

$$\text{The initial condition at the time } t=t_0: T(z, t_0) = T_0(z) \quad (9)$$

RESULT AND DISCUSSIONS

Validation of the model by experimental tests

On the graphical representations (Figure 5a, 5b and 5c), very close numerical and experimental values are observed with very significant correlation coefficients exceeding 0.97 for the three thermocouples. The relative difference of 0.19%, 0.35% and 0.48%, on average, respectively for TH 1cm, TH 6cm and TH 10cm. It should be noted that the maximum deviation for the thermocouple located at 1 cm is 2.07 °C and at 6 cm it is 2.76 °C, and at 10 cm it is 2.72 °C, these deviations are relatively small considering the dimensions and uncertainties involved; it can therefore be concluded that this model is validated.

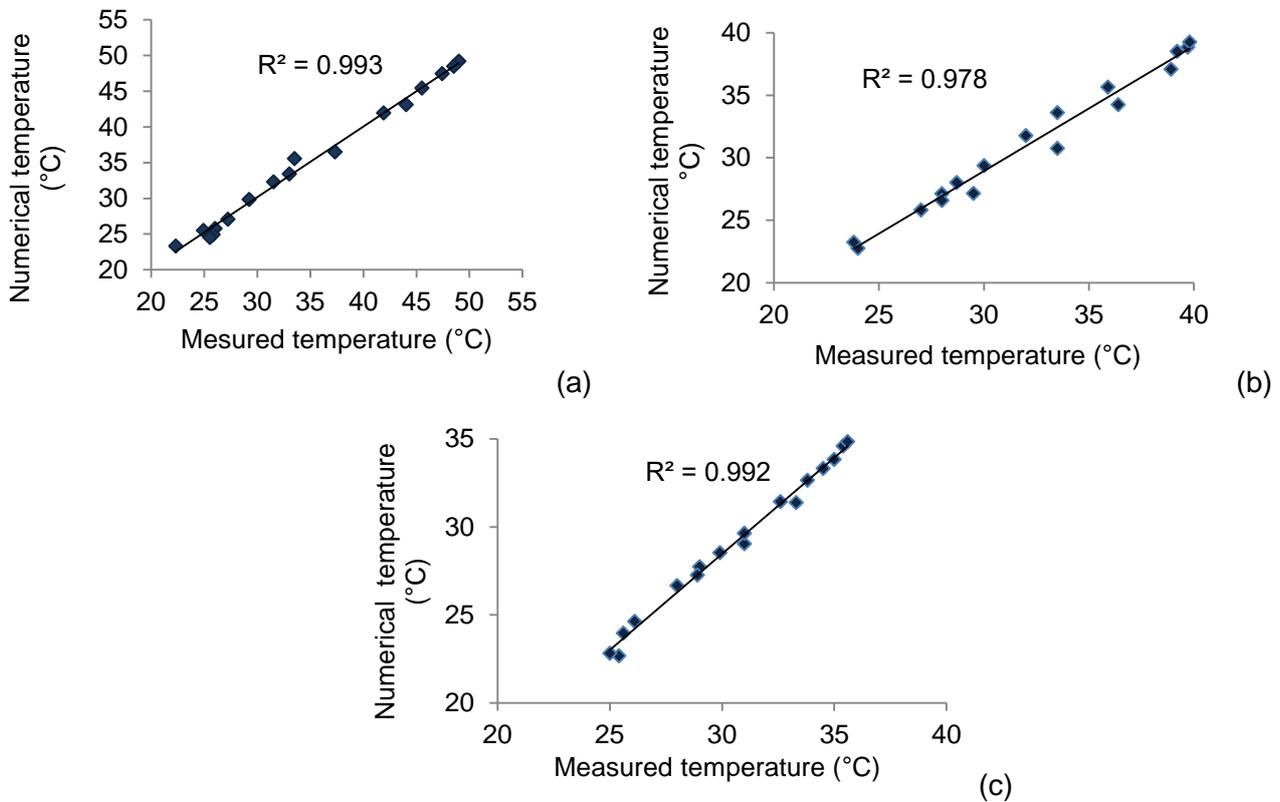


Fig. 5 - Correlation of experimental and numerical temperatures: (a) At TH 1 cm. (b) At TH 6 cm. (c) At TH 10 cm

Simulation of the raw asphaltic concrete facing (without protection)

Figures 6 and 7 illustrate the temperature evolution within the unprotected structure, at time 12.15 pm the temperature reaches a maximum value of 49.21 °C at the asphaltic concrete facing surface, then it decreases slowly and becomes stable beyond 0.80 m depth, knowing that the air temperature at this time is about 30.6 °C, we also observe that the minimum temperature recorded is from 23.04 °C at 6 am.

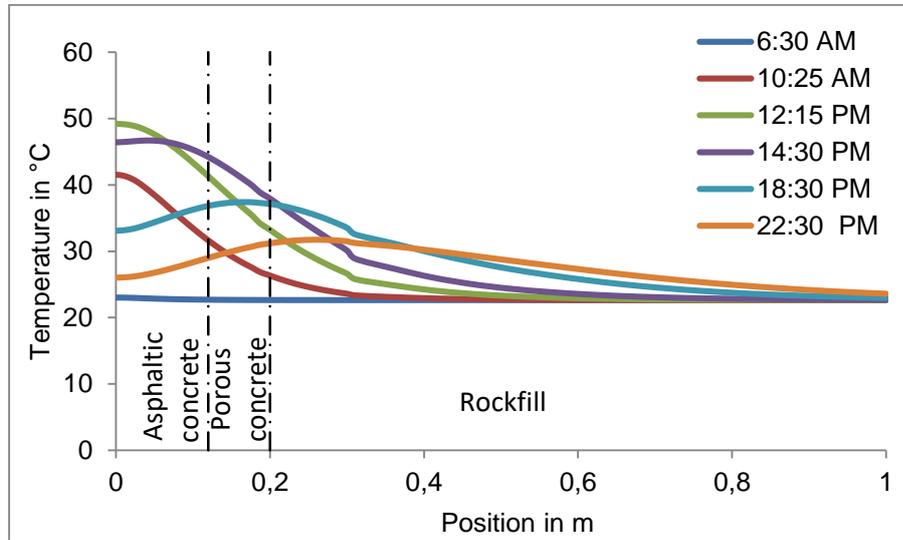


Fig. 6 - Temperature evolution within the raw asphaltic concrete facing

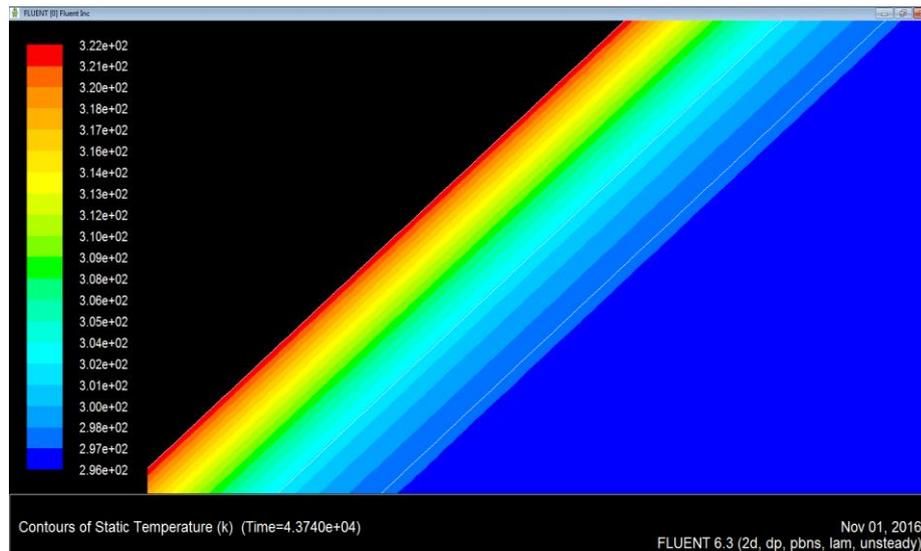


Fig. 7 - Simulation of the temperature variation within the asphaltic concrete facing at 12:15 pm

Simulation of the asphaltic concrete facing protected by a reflective surface

The following model attempts to cool the layers of the asphalt concrete with a reflective surface, where heat exchanges take place in conduction, free convection and also in radiation.

Temporal variation

The maximum simulated temperature at 1 cm from the protected asphaltic concrete facing surface is 37.53 °C at 12.15 pm, 31.42 at 14.3 pm for TH 6 cm, and at 10 cm it reaches its maximum value at 15.3 pm with 28.25 °C (Figure 8).

The minimum temperatures recorded at 6 am for the three thermocouples, respectively 19.84 °C to TH 1cm, 19.55 °C to TH 6cm and 19.5 to TH 10cm.

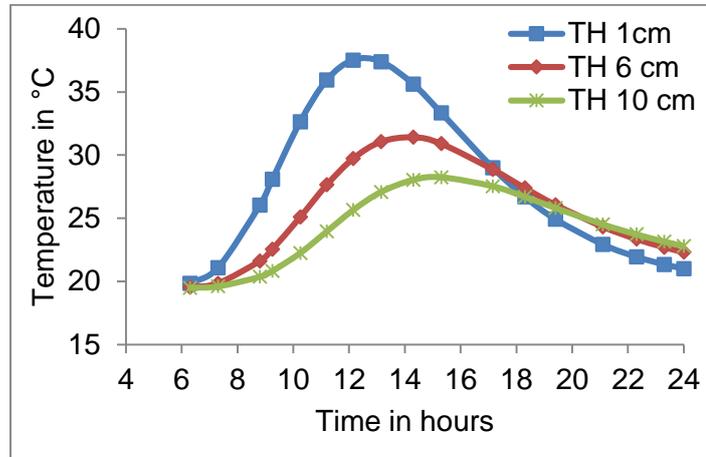


Fig. 8 - Temperature variation for the 3 thermocouples (TH), case of the protected asphaltic concrete facing

Spatial variation

The temperature at TH 1cm, reaches its maximum at 12.15 pm with a value of 38.47 °C and a minimum of 19.73 °C at 6.3 am (Figure 9 and 10).

It should be noted that the location of the maximum temperature varies with time:

- It is maximum at TH 1cm from 6.3 am to 12.15 pm, with a maximum value of 38.47°C at 12.15 pm;
- At 14.3 p.m., the maximum temperature at 4 cm is around 36.84 °C.
- At 6.3 pm, the maximum temperature increases to 17 cm, located in the porous concrete layer with a value of 30.15°C.
- At 22.3 pm, the maximum temperature is about 26.04 °C, at a depth of 26 cm, located at the body of the dam (rockfill);

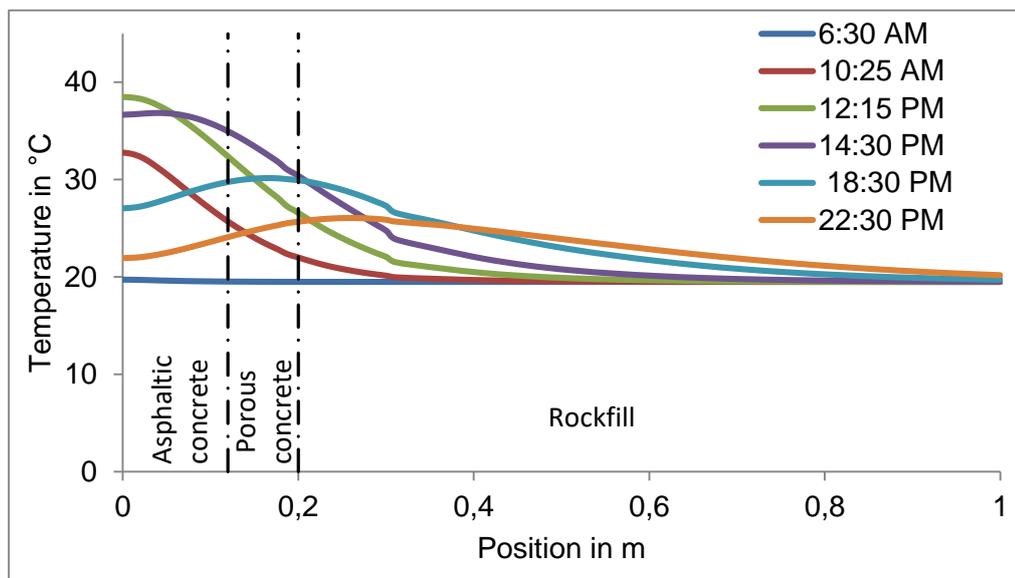


Fig. 9 - Temperature evolution within the protected asphaltic concrete facing



Fig. 10 - Simulation of the temperature variation within the protected asphaltic concrete facing at 12.15 pm

Effect of the reflective surface on asphaltic concrete facing temperatures

The analysis of the difference between the temperatures measured in the raw asphaltic concrete facing and the temperatures simulated on the asphaltic concrete facing protected by the reflective surface, at the level of the three thermocouples located at 1 cm, 6 cm and 10 cm, by the relationship:

Temperature difference = $T_{\text{measured (raw asphaltic concrete facing)}} - T_{\text{simulated (protected asphaltic concrete facing)}}$.

The results are shown in the graph in Figure 11, where a cooling is observed that occupies the entire thickness of the asphalt concrete facing:

A maximum cooling time of 12.15 pm is recorded for the three thermocouples with 11.47°C for TH 1cm, 9.16°C for TH 6cm and 7.64°C for TRH 10cm.

The minimum cooling times are 6.3 am for the three thermocouples, 2.46 °C for TH 1 cm, 4.45 °C for TH 6 cm and 5.9 °C for TH 10 cm.

The presence of the reflective surface positively influences the heating of the asphaltic concrete facing or observes a significant cooling over the entire thickness of the asphaltic concrete facing and especially in the period of maximum temperature (period of high heat).

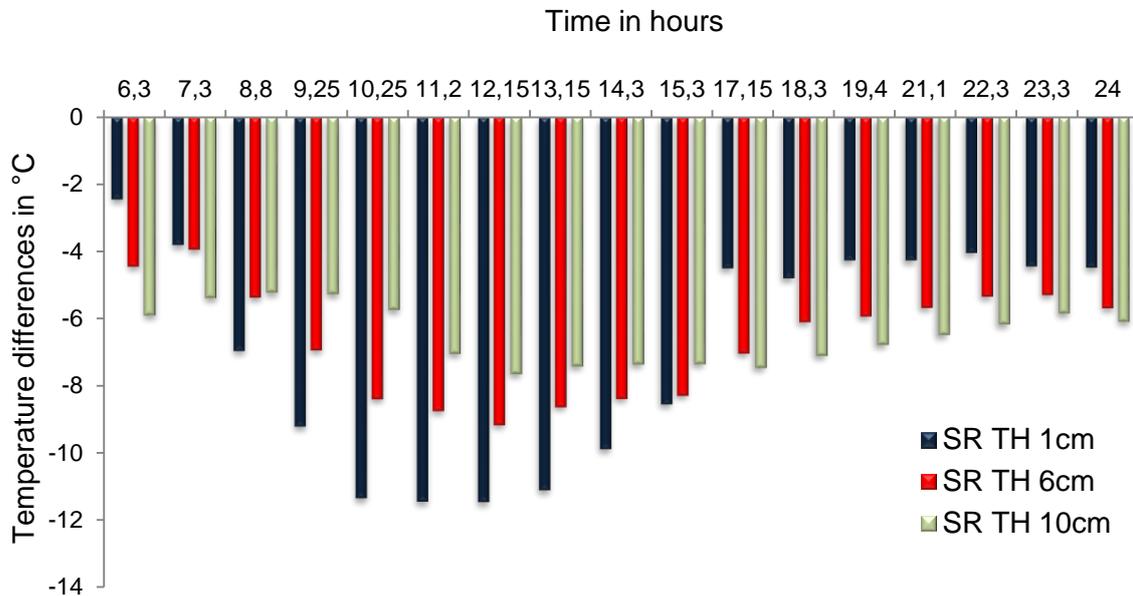


Fig. 11 - Difference between the temperatures measured in the raw asphaltic concrete facing and simulated on the protected asphaltic concrete facing of Ghrib dam (SR: reflective surface)

CONCLUSION

Fluent analysis has proven to be an interesting tool for simulating the transient temperature behaviour of the asphaltic concrete facing of Ghrib dam. The model simulates the temperature of asphaltic concrete facing at different levels in different layers and has been successfully validated by experimental data.

The use of a reflective surface on the asphalt concrete facing, aimed at reducing the absorbency of the asphaltic concrete facing, and thus lowering the temperatures at the surface and within the asphaltic concrete facing to avoid degradation of the asphalt concrete layers.

The protection of the asphalt concrete facing by the reflective surface provides cooling throughout the test period and occupies the entire thickness, with maximum values of 11.47°C, 9.16°C and 7.64°C for the three thermocouples respectively TH 1cm, TH 6cm and TH 10cm at 12.15 pm, i.e. during the period of high heat or when solar radiation reaches its maximum values.

Reflective surfaces are most effective when the surface is as clear as possible and when the surface covers the entire surface of the asphaltic concrete facing.

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