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NUMERICAL SIMULATION OF THE EFFECTS OF TEMPERATURE AND WIND ON CONCRETE AT EARLY AGE

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ABSTRACT

The early age behavior of concrete is a complex phenomenon because of the chemical, physical and mechanical characteristics that evolve in time, with climate being one of the essential conditions influencing this evolution. The objective of our present work is based on the study by numerical simulation, in 3- dimensions, of concrete behavior at an early age during the first 24 h of hydration under severe conditions of temperature and wind speed using a COMSOL Multi-physics.

The temperature was maintained at 55°C for the first 7 h, then from the 8th hour to 24th hour decreasing down to 25°C, with a 12km/h wind speed. The model describes two divided domains air and the concrete slab. The obtained results allow us to better understand the temperature variation phenomena in the slab by heat transfer taking into account the release of heat due to the exothermic reactions of cement hydration as well as the influence of a high wind speed, while varying the thickness of the slab studied and the w/c ratio.

Keywords: Concrete; early age; hydration; heat transfer; temperature; wind.

1. INTRODUCTION

The prevalent climate in the city of Bechar and southern Algeria region is characterized by a dry, desert climate with a hot and dry summer. According to the ACI Committee 305, a hot climate is defined by a high ambient temperature, a high concrete temperature, a low relative humidity, a variable wind velocity and solar radiations [1].

Measures can be taken to eliminate or minimize undesirable effects of these environmental factors. including increased water demand, increased rate of cement hydration ,and the increased rate of evaporation. Al-Amoudi, Maslehuddin, Shameem, and Ibrahim (2007) have reported that in the case of plain cement concrete, there is always some

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bleeding water which would evaporate when hot weather conditions prevail [2]. Bella (2011) showed that the most efficient way to minimize plastic shrinkage and decrease evaporation is to use a curing compound following [3]. The water evaporation induces shrinkage cracking. Once cracks appear on the surface of the concrete, they accelerate the penetration of aggressive agents, resulting in durability reduction in the longer term.

There have been many investigations to avoid hot climate concreting problems by experimental methods [3,4,5].

The first objective of this work is to establish a numerical simulation in three dimensions based on experimental work cited above, to describes the effects of high ambient temperatures and high wind speeds on concrete at an early age. Taking in consideration the effect of hydration reactions by introducing a maturity function using the equivalent time concept in the form of Domain Ordinary Differential Equations. The second objective is to develop a model for predicting temperature development in the concrete slab and incorporate it into COMSOL Multi-physics.

2. EFFECT OF TEMPERATURE

A high ambient temperature causes a higher water demand of the concrete and increases the temperature of the fresh concrete. This results in an increased rate of loss of slump and in a more rapid hydration, which leads to accelerated setting and to a lower long-term strength of concrete [6,7,8,9].

2.1 Energy conservation

The evolution of the temperature inside the concrete slab can be determined by solving the Energy conservation equation including the heat generation Q, which corresponds to the exothermic reactions in the slab. It was derived as a function of the degree of hydration with respect to time multiplied by the final heat of hydration. Using Fourier's law [7,8,10].

$$\rho C_p \frac{\partial T}{\partial t} = \nabla.(K\nabla T) + Q \tag{1}$$

K: thermal conductivity of concrete (W/m·K)
ρ: density of concrete (kg/m^3)
T: temperature (K)
C_P: heat capacity of concrete (J/(kg·K))
Q: heat generation rate (W/m^3)

3. EFFECT OF WIND

Wind can be one of the most important factors in hot weather concreting. The wind speed is introduced by application of coefficient corresponding to a speed of 12km/h for the convective heat transfer coefficient (h) [9,11]].

COMSOL Multi- physics is a suitable tool for solving this kind of problem because it allows the simulation of 3D geometries with a high degree of flexibility with regard to the coupling with the fluid field. Using the Navier -Stokes equation [12]:

$$\rho\frac{\partial u}{\partial t} + \rho(u.\nabla)u = \nabla.[-pI + \mu(\nabla u + (u)^T] \tag{2}$$

ρ: Air density(kg/m^3)
u: velocity of atmospheric air (m/s)
p: pressure of atmospheric air (Pa)
T: Air temperature(K)

3. HYDRATION

3.1 Heat of hydration

The Portland cement in concrete liberates heat when it hydrates and the internal temperature of the concrete rises during this period [2]. The hydration of cement in concrete is an exothermic reaction which liberates up to 500 J of heat per gram of cement [8,10]. This heat source must be included in any early age model of heat transfer [13].

The generation of heat during the hydration process is influenced by various parameters; some of the most important parameters are cement composition and cement fineness [6]. Our modeling uses the equations of maturity, that define the effect of temperature versus time on the formation of products of hydration with respect to a reference temperature (T_r =20°C) [7,9,11]:

$$\frac{dt_e}{dt} = exp\left[\frac{E}{R}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \tag{3}$$

with:
E: activation energy (J/mol)
R: ideal gas constant (J/mol·K)
T_r: reference temperature (K)
T: Concrete temperature (K)

3.2 Degree of hydration

The term "degree of hydration" is intended to constitute a measure of how far the reactions between cement and water have developed: α=0 means that no reactions have occurred and α=1 means that complete hydration has been achieved [11,14].

$$\frac{d\alpha}{dt} = \exp\left[\frac{E}{R}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right].\frac{\alpha_u\beta}{t_e}.\left(\frac{\tau}{t_e}\right)^{\beta}.\exp\left[-\left(\frac{\tau}{t_e}\right)^{\beta}\right] \tag{4}$$

with:

τ , β: maturity parameter (Table 1)
α_u:ultimate degree of hydration. Using the following equation (Mills 1966):

$$\alpha_u = \frac{1.031.\, w/c}{0.194 + w/c} \tag{5}$$

The heat was obtained by multiplying the degree of hydration by the final expected heat of hydration (P. Acker & al. 2004;P.I. Anderson and ME Anderson. 1992; E. Hernandez-Bautista & al. 2015):

$$Q(t) = H_u.\, C.\frac{\alpha_u \beta}{t_e}.\left(\frac{\tau}{t_e}\right)^{\beta}.\exp\left[-\left(\frac{\tau}{t_e}\right)^{\beta}\right].\exp\left[\frac{E}{R}\left(\frac{1}{T_r}-\frac{1}{T}\right)\right] \tag{6}$$

with
H_u:ultimate heat of hydration (J/kg)
C:total amount of cement (kg/m^3)

Table 1: Maturity parameters of model

Parameter	R(J/mol.k)	E(J/mol)	$\mathbf{H_u}$(J/kg)	τ(h)	B
Value	8.341	T≥293K 33.50	3.135	15.20	0.95

4. PROPERTY DEVELOPMENT IN FRESH CONCRETE

Because the hydration of Portland cement significantly alters the volume fraction and spatial arrangement of solids, liquids and gases, it would be expected that the thermo- physical properties of cement paste such as heat capacity , thermal conductivity and density would vary with hydration [7,8,10,13].

4.1 Density of fresh concrete
The mass of fresh concrete m is equal to the sum of the mass of concrete solids "m_c" (Fine aggregates, Coarse aggregates ,Cement) and mass of water "m_w":

$$m = m_w + m_c \tag{7}$$

So, we can calculate the density of fresh concrete by:

$$\rho = \rho_w.\frac{v_w}{v} + \rho_c.\frac{v_c}{v} = \rho_w.\theta_w + \rho_c.\theta_c \tag{8}$$

with: $\theta_c + \theta_w = 1$

θ_c; θ_w: volume fraction of concrete and water
ρ_c: density of concrete (kg/m^3)
ρ_w: density of water (1000 kg/m^3)
Used mixture composition is shown in following table:

Table 2: Mixture composition

Compound	**Composition(kg/m^3)**
Cement	350.00
Water	236.04
limestone sand	786.86
Aggregate (3/8)	888.71
Total: **ρ_c(kg/m^3)**	2261.61

4.2 Heat capacity of a fresh concrete
The formula giving the heat capacity of a fresh concrete is [9]:

$$C_p = \sum_i m_i c_{p_i} \tag{9}$$

with:
C_p: heat capacity of fresh concrete (J/(kg·K))
m_i: amount of ' i ' component in the concrete (kg)
c_{p_i} : heat capacity of 'i' component in the concrete (J/(kg· K))
In the present study, the equivalent volumetric heat capacity of the fresh concrete is calculated by [12]

$$(\rho . C_p)_{eq} = \theta_c . \rho_c . C_{pc} + \theta_W . \rho_w . C_{pw} \tag{10}$$

with
C_{pc} , C_{pw} heat capacity of concrete and water

4.3 Thermal conductivity of fresh concrete
The thermal conductivity of fresh concrete is positively related to its aggregate content and moisture content, and negatively related to its porosity. The equivalent thermal conductivity of fresh concrete K_{eq} is related to the conductivity of concrete K_c (solid phase) and to the conductivity of the water K_w (liquid phase) by [12]:

$$K_{eq} = K_c . \theta_c + K_w . \theta_w \tag{11}$$

Table 3: Parameters of model

Parameter	$\mathbf{C_{pc}}$[J/(kg.K)]	$\mathbf{C_{pw}}$[J/(kg.K)]	$\mathbf{K_c}$[W/(m.K)]	$\mathbf{K_w}$[W/(m.K)]
Value	880	4400	1.8	0.6

5. GEOMETRY

The geometry of the model used is implemented in COMSOL Multi-physics 4.2, with a 3D geometry shown in Fig. 1.The main domain is framed in Cartesians coordinates. The geometry consists of two domains, an air domain represents the geometry of a lab equipment hot climate exposure "climatic chamber" $(0.8x1.8x1.00)m^3$ and a second domain represents a concrete slab of size $(0.7x0.7x0.04)m^{3.}$

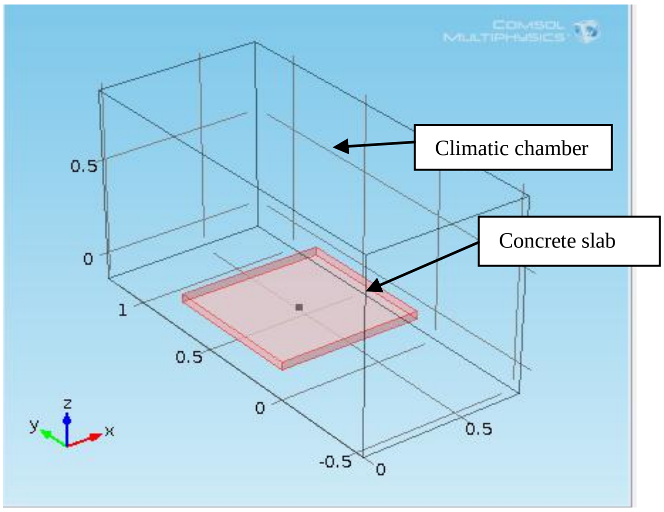


Figure 1. Three-dimensional geometry in meters

5.1 Boundary and initial conditions

The boundary conditions considered for the temperature and wind analysis include the heat transfer due to forced convection and conduction (Comsol guide. 2012;E. Hernandez-Bautista & al. 2015)[12,14].

1/At the upper surface of the slab, we have a convection described by the following formula:

$$n.[(k\nabla T)] = h.(T_{ext} - T) \tag{12}$$

where h is a convection transfer coefficient determined according to the wind speed [15,16].

$$\mathrm{h} = 5.7 + 3.8{\cdot}\mathrm{V} \qquad \mathrm{V} \leq 5\mathrm{m/s} \tag{13}$$

V: wind speed expressed in (m/s)

2/the thermal insulation: this boundary condition means that there is no heat flux across the boundary.

This condition is specified for the lateral and lower surfaces of concrete slab:

$$n.[(k\nabla T)] = 0 \tag{14}$$

6. RESULTS

This section presents the results obtained from the numerical simulation of the model in COMSOL Multi-physics. The solution domain has been discretized using coarser meshes in the air domain and another finer mesh for the concrete domain (slab). The mesh is automatically generated by the corresponding menu, as shown in the following figure.

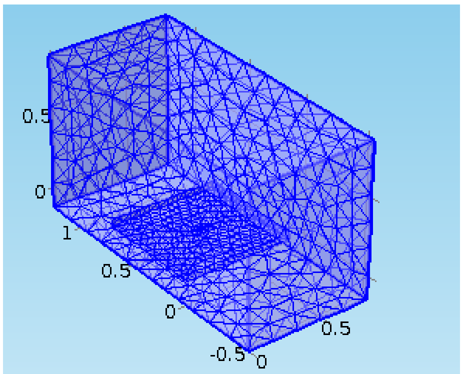


Figure 2. Discretization of model

The model is able to predict the evolution of the degree of hydration over time at the slab for the three different values of w/c ratios 0.5, 0.55 and 0.6 respectively (Fig. 3) using the maturity function.

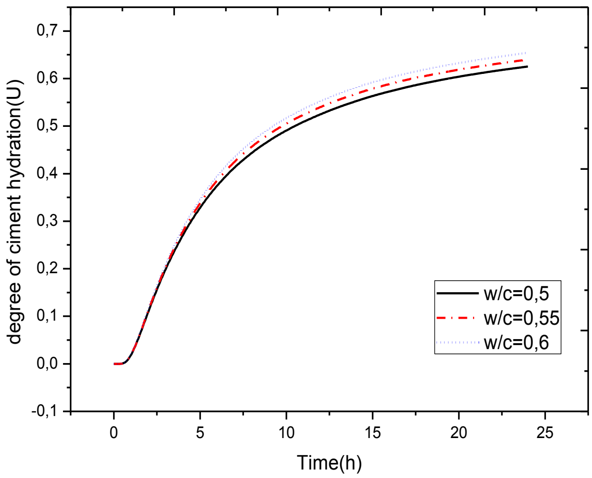


Figure 3. Evolution of hydration rate as a function of time for different values of w/c

The analysis of the curve shows marked increase in the hydration rate for various w/c values. The cement hydration rate is proportional to the amount of water present in concrete, particularly at ages beyond 6h.

6.1 Distribution of wind velocity

The distribution of the wind velocity in the air domain is shown in 3D view in Fig. 4.

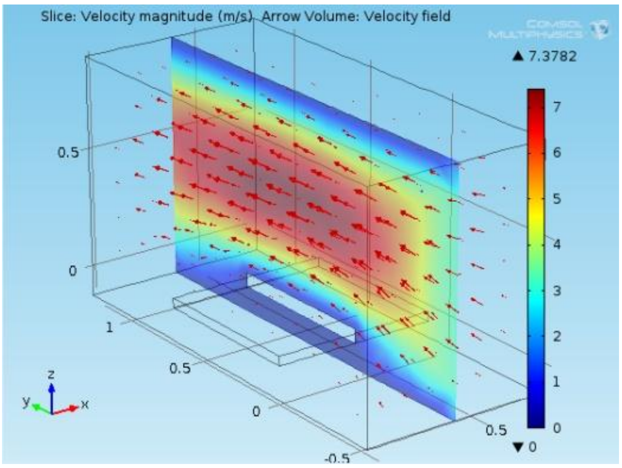
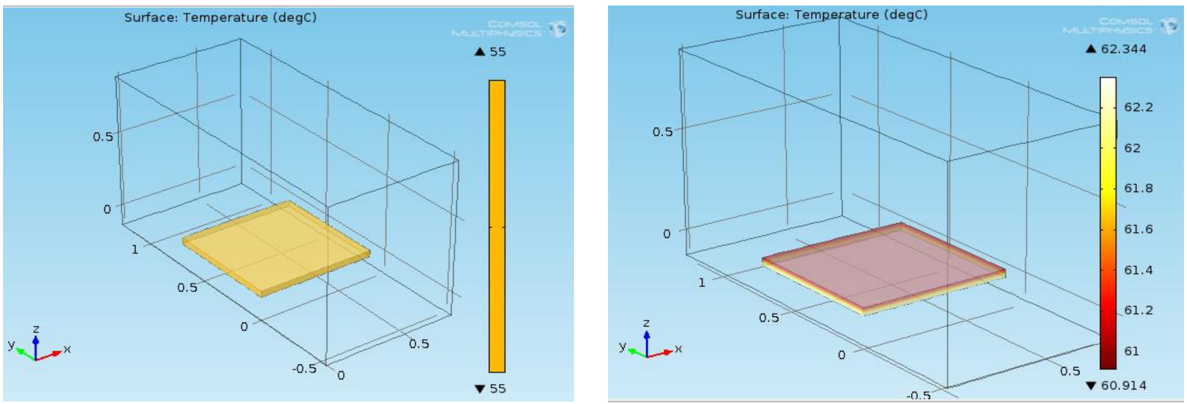


Figure 4. COMSOLS's 3D velocity magnitude in the climatic chamber’s air domain (m/s)

The above figure illustrates a clear air distribution. Air speed is maximal at the center and undergoes a notable decrease with distance from the domain center. In contrast, wind speed decreases closer to the surface of the slab. The results of wind speed simulation show that air flow is asymmetrical along the slab with increased magnitude at the domain center. This result presents a good agreement with that published previously [17].

6.2 Temperature distribution

Evolution of temperature in the slab concrete is shown in 3D view in Fig. 5.



(a): t=0 (b): t=4.25h

Figure 5. COMSOLS's 3D temperature distribution in the slab at the time a) t=0 and b) t=4.25h

The Fig. 5 represents temperature distributions at the initial state and following setting after 4 hours, respectively. These results are obtained under maximum ambient temperature of 55°C and highest wind speed of 12km/h conditions.

This evolution is due to heat transfer via conduction and convection, as well as the dissipation of cement hydration heat. The maximum temperature after the first four hours is predicted to be equal to 62°C.

6.3 Temperature effect

This model allows us to also study the impact/effect of ambient temperature on the concrete slab temperature evolution.

The figure represents the slab's temperature evolution over time for different ambient temperature values. Maximum temperatures reported are 30°C, 40°C, and 55°C, respectively.

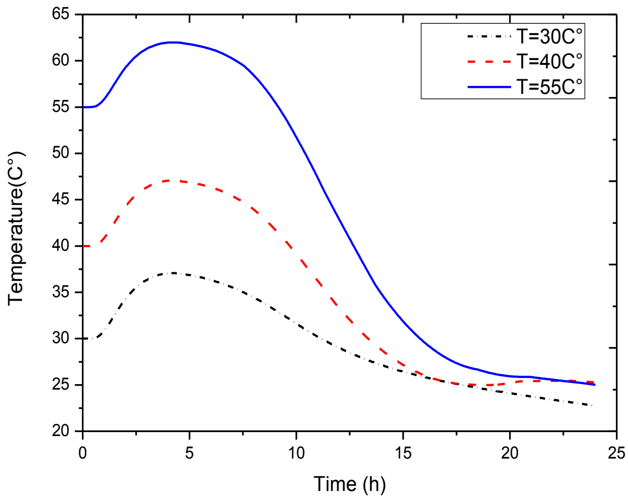


Figure 6. Effect of ambient temperature on the slab temperature evolution

These results are obtained under the same previous conditions - wind speed of 12km/h and w/c=0.55. Fig. 6 shows that the shape of the curve comprises three parts:

A stationary part which corresponds to the slow exothermic reactions of cement during the "dormant" period.

A marked increase in slab temperature due to thermal transfer that follows a temperature gradient caused by the acceleration of exothermic reactions during this phase. We note that after a few hours this increase reaches a ceiling and corresponds to a spike in the heat that is given off.

The temperature decreased rapidly due to the cooling of concrete and final setting of cement.

Table 4: effect of ambient temperature on the slab

Ambient Temperature(°C)	Maximum temperature of the slab (°C)	Time (h)
30	37.42	4.3
40	47.07	4.2
55	62.04	3.9

Table 4 summarizes the effect of ambient temperature on the slab's maximum temperature . According to these results, we note an elevation in ambient temperature induces a significant increase in the slab’s maximum temperature and, as a result, a reduction in reaction time.

For example, for an ambient temperature of 30°C, the maximum temperature of concrete is 37.42°C and the reaction time is 4.3 h whereas for T_a=55°C, the temperature of concrete reaches 62.04°C and reaction time duration is below 4 h (3.9h).

According to the results described in Table 4, it was found that the rate of chemical reaction increases with an increase in temperature for exothermic processes. Therefore, cement hydrates more rapidly when the temperature is elevated.

6.4 Wind effect

Results of the numerical simulation of the wind speed effect on the evolution of temperature in the slab are given in following curve.

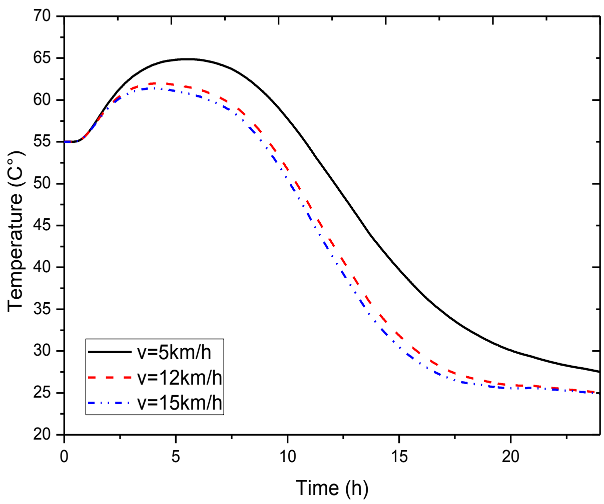


Figure 7. Effect of wind speed on the slab temperature evolution

In order to analyze the effect of the two climatic conditions (wind and temperature), we studied the variation of temperature as a function of time for different wind speed values.

Fig. 7 shows the evolution of concrete temperature as a function of time for wind speed values of 5, 12 and 15 km/h. We note here that the maximum ambient temperature is 55°C.

We see that the elevation in wind speed brings about a minimization in the slab's temperature, which leads in turn to a dissipation in excess heat absorbed/produced by the concrete. We note significantly in our calculations that, an increase of 7 km/h in wind speed results in a 3°C decrease in temperature. The data are summarized in Table 5.

Table 5: effect of wind speed on the slab

wind speed (km/h)	Maximum temperature of the slab (°C)	Time (h)
5	64.88	5.527
12	61.98	4.25
15	61.38	4.00

6.5 Slab thickness effect

The following figure shows the prediction of temperature as a function of time within a concrete slab with thicknesses (h_e) of 0.02 m, 0.03 m and 0.04 m. These results are obtained for an ambient temperature of 55°C and with a wind speed of 12km/h.

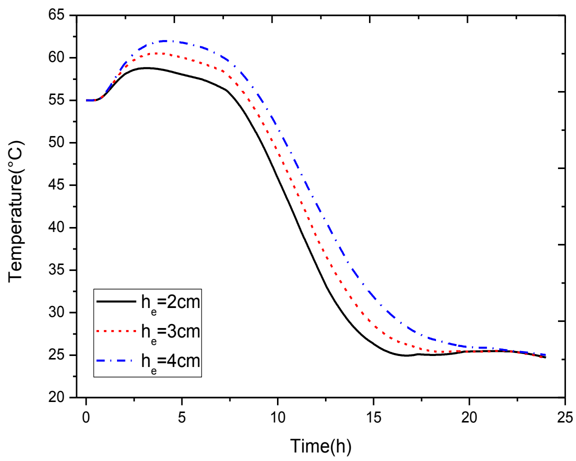


Figure 8. effect of thickness on the slab temperature evolution

From these curves, we note that the maximum temperature of concrete is certainly a function of the slab thickness, with a proportional relationship.

We note a direct correlation between temperature and the thickness of the slab, with temperature increasing by 1.5 °C with each 1 cm increase in slab thickness.

7. CONCLUSION

This analysis investigates the heat transfer processes that occur in concrete slabs subjected to severes conditions of air temperature and wind speed from the first 24 hours using COMSOL Multiphysics.

The developed COMSOL model could simulate the heat transfer problem and apply the different boundary thermal loads simultaneously. The modeled thermal loads included ,the surface convection and volume conduction.

The model describes the evolution of the rate of hydration over time, when applying the concept of equivalent time and the maturity equations in order to describe hydration reactions, taking into account the heat given off during these reactions.

The model allows us to determine:

The evolution of temperature in the slab studied during the first 24 h.

The distribution of wind speed in the atmosphere.

We conclude that the temperature of concrete is inversely proportional to the wind speed at early age.

The elevation in ambient temperature influences the temperature of the slab and an increased slab thickness increases its temperature.

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REFERENCES

1. ACI Committee 305, Hot weather concreting. American Concrete Institute, USA Committee Report ACI 305 R-99, 1999.
2. Al-Amoudi OSB, Maslehuddin M, Shameem M, Ibrahim M. Shrinkage of plain and silica fume cement concrete under hot weather, *Cement and Concrete Composites*, **29**(2007) 690-9.
3. Bella N, Asroun A, Efficacité des solutions de bétonnage par temps chaud approche par la méthode des plans d'expériences, *International Seminar INVACO2*, University of Rabat – Maroc, 2001, 1P-365.
4. Ahmadi BH. Initial and final setting time of concrete in hot weather, *Materials and Structures*, **33**(2000) 511-4.
5. Elsafty A, Matthew KG, Georges E, Mohti A. Analysis prediction and case studies of early age cracking in bridge decks. International, *Journal Advanced Structure Engineering*, **8**(2016) 193-212.
6. ACI Committee 207, Mass concrete. American Concrete Institute, USA Committee Report ACI 207.1R-96, 1996.
7. Byfors J. Plain concrete at early age, forshning F0 research 3-80, 1980.
8. Neville AM. Propriétés des béton. Paris, Eyrolles, 2000.
9. Lamond JF, Pielert JH. Significance of tests and properties of concrete and concrete-making materials, ASTM stock N, STP 169 D, 2006.
10. Acker P, Torrenti JM, Ulm FJ. Comportement du béton au jeune âge, Lavoisier Paris, 2004.
11. Andersen PJ, Andersen ME, Whiting D. A guide to evaluating thermal effects in

concrete pavements, SHRP, 1992.
12. Heat transfer module user's guide, COMSOL 4.3, Protected by U.S. Patents, May 2012.
13. Bentz DP. A review of early - age properties of cement- based materials, *Cement and Concrete Research*, **38**(2008) 196-204.
14. Hernandez-Bautista E, Bentz DP, Sandoval-Torres S, Cano-Barrita J. modeling heat and moisture transport during hydration of cement - based materials in semi - adiabatic conditions, *Cement and Concrete Composites*, **69**(2014) 38-48.
15. Bentz DP. A Computer model to predict the surface temperature and time of wetness of concrete pavements and bridge decks, National Institute of Standards and Technology, NISTIR 6551, 2000.
16. Rabadiya AV, Kirar R. Comparative analysis of wind loss coefficient (wind heat transfer coefficient) for solar flat plate collector, *International Journal of Emerging Technology and Advanced Engineering*, No. 2, **2**(2012) 463-8.
17. George V, Vigneau JP. *Elements de Climatologie*, 2eme edition, Nathan, 2001.