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Modeling of a pumped hydropower storage wall in 3d printing using the software Diana Fea

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Abstract. Pumped Hydropower Storage (PHS) reservoirs are mass concrete structures; therefore, the effects of cementitious materials in early ages, such as heat generation and autogenous retraction, must be assessed to avoid thermal cracking. Construction in layers is one of the solution used to reduce the heat generated from the hydration of the cementitious material and decrease concrete pouring heights and volume of cement. In this paper, 3D printing that uses the deposition of thin layers is studied for a PHS reservoir wall. A 3D numerical model of a 0.40x2.0x3.0 m structure was developed in DIANA FEA software considering concrete mechanical properties defined by Wolf [1] and thermic properties of a 400 kg/m^3 concrete from the Japan Society of Civil Engineers [2]. The software was evaluated as a good modeling tool to simulate the layered construction technique and hydration reactions through Finite Element Analysis. The thermal effects on concrete for 3D printing were discussed, and the impacts of 3D construction on mass concrete were evaluated. It was concluded that the rising temperatures of mass concrete do not damage the structure during the 3D printing; on the contrary, it accelerates the strength gain of the cementitious composite for this construction method.

Keywords: Massive structures, Pumped Hydropower Storage, 3D printing, Finite Element Analysis.

1 Introduction

Brazil presents itself as a country with enormous potential both in the hydroelectric sector, as well as in the wind and solar sectors. These energy sources are clean and renewable, but each one presents its environmental impacts and differentiated costs of implementation and production. In Brazil, the hydroelectric potential of rivers is greatly explored, which has generated positive results in terms of self-sufficiency in energy production [3].

Taking into account low environmental impact, lower cost, and considering that the plants of the Pumped Hydropower Storage (PHS) start to be built with smaller and smaller reservoirs, and have generation of renewable energy and not intermittent, its implementation is the best solution for expanding energy capacity. In this context, PHS's are based on the storage of gravitational energy from water through a difference in elevation, and are based on the same principles of energy conversion as conventional hydroelectric plants.

Large concrete structures, such as the PHS's reservoirs, are considered mass concrete structures. Fairbairn and Azenha [4] defines massive structures as those for which the effects of cementitious materials in early ages, such as heat generation and autogenous retraction, can lead to cracking, induced by the cement hydration reaction.

Several measures can be adopted to prevent cracking of the concrete mass, such as thinner concrete layers, low strength concrete with low cement content or low hydration heat cement, and pozzolanic material to replace part of the Portland cement, for example.

That said, we can use the 3D printing technology that is characterized by the construction in thin layers and still reduces the construction time, the labor employed, has greater precision in the consumption of materials, and reducing waste. The popularization of the use of 3D printers foreshadowed another form and mode of production. The use of these machines in civil engineering presents itself as an option to reduce costs, deadlines and environmental impacts.

In this sense, it is necessary to model a structure, in order to verify the possibility of the construction of massive structures with 3D printer, using the simulation of a wall applicable to a reservoir of a pumped hydropower storage, for this.

2 Theoretical Background

2.1 Modelling parameters for mass concrete

During the hydration of the cementitious matrix, that is, in the addition of water (H), the clinker grains are hydrated and thus form the Calcium Silicates Hydrate (CSH) and Portlandites (Calcium Hydroxide), in addition to generating heat. . Therefore, cement hydration is highly exothermic and is still thermoactivated, which means that the evolution of temperature influences the hydration kinetics. This hydration process can be simplified in eq. (1) below:

$$cement + \; H \rightarrow C - S - H + CH + heat \tag{1}$$

The evolution of the chemical reaction between water and cement can be evaluated through the degree of hydration (represented in the bibliography with ξ or α), which constitutes the objective parameter to characterize the maturity of the concrete. It is defined as the ratio between the amount of hydrates, m(t), and the initial amount, mi, of the cementitious material [5, 6, 7]. The concept is defined by Silva [8] as the advancement of hydration reactions and ranges from 0 to 1.

The experimental determination of this parameter can be done by adiabatic tests. In these tests there is no external heat source, and the exothermic nature of the hydration reaction is solely responsible for the increase in temperature in the system. This phenomenon can be described by the formulation of the Ulm and Coussy thermochemical coupling [9, 10] presented in Eq. (2):

$$C_p\dot{T} = \dot{Q} + L\dot{\xi} + k\Delta^2 T \tag{2}$$

where Cp represents the thermal capacity; T is temperature; Q is the heat flux originating from some heat source; L is a material constant, which is always positive due to the exothermic nature of the hydration reaction; ξ, the degree of hydration and k the thermal conductivity.

The evolution of the hydration reaction is represented by Arrhenius law, given by eq. (3), which considers the exotherm and thermoactivation of the hydration reaction.

$$\frac{d\xi}{dt} = \tilde{A}(\xi)exp\left(\frac{E_a}{RT}\right) \tag{3}$$

where Ea is the apparent activation energy of the reaction, considered constant with respect to the degree of hydration; R is the universal gas constant and T is the absolute temperature. The term of the equation, exp ($-Ea/RT$), considering that the terms Ea and R are constant, varies as a function of temperature and represents the effect of thermoactivation, that is, the reaction intensifies at higher temperatures. The term $\tilde{A}(\xi)$ which is the normalized chemical affinity and is an intrinsic function of the material that describes the evolution of the hydration reaction. The normalized affinity curve that characterizes the material can be obtained through adiabatic temperature rise tests.

2.2 Modelling parameters for 3D printed concrete

The physical model of a 3D printing that uses a cement matrix can be seen in Fig. 1. The model represents a 3D printing process through the deposition of successive layers and illustrates the parameters relevant to the printing process. Q represents the flow rate injected into the system, V represents the speed of the extruder nozzle and L represents the length to be expired. The total height is called Hm while the height of each layer is called h. Finally, W represents the thickness of the layer [11].

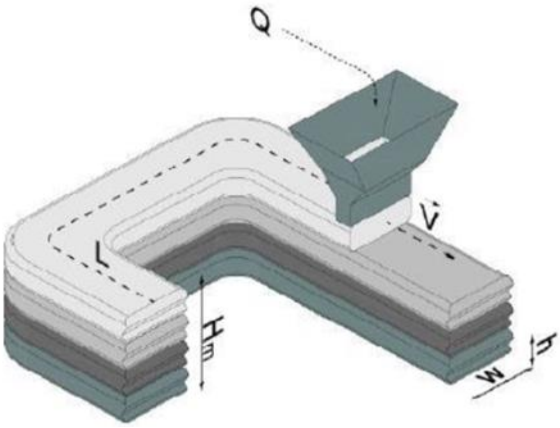

Figure 1. Physical model of 3D printing. [11]

Research carried out over time resulted in a series of equations that describe the behavior of fresh concrete. It is known that the rheological behavior of this material is close to a Binghamian fluid, requiring two parameters for its characterization: the yield stress and the plastic viscosity.

Printable materials, like any other cementitious materials, behave roughly like Bingham's visco-plastic material. They flow only when subjected to stresses greater than a critical threshold value called yield stress.

When material is deposited, it exhibits an initial yield stress (τ_0). Below this yield stress, the material exhibits an elastic behavior. Due to thixotropic phenomena and cement hydration, the flow limit of the cementitious matrix increases with time. The initial flow limit, that is, the one measured as soon as the matrix was mixed, will determine the maximum height ($h_{m,max}$) that each layer can have through the following eq. (4) [11]:

$$h_{m,max} = \frac{\tau_{0,0}\sqrt{3}}{\rho g} \tag{4}$$

where ρ is the density of the cement matrix and g is the acceleration due to gravity.

The thixotropy of these types of materials and their ability to build an internal structure at rest is key to most printing applications [12]. Therefore, an important rheological property is the thixotropic gain (A_{thix}). It corresponds to the rate of increase in the yield limit over time, that is, the greater the thixotropic gain, the faster the cement will gain yield strength.

When depositing layers successively, the stresses induced by gravity progressively increase. Therefore, it is essential that the lower layer has sufficient flow limit to support its own weight in addition to the weight of the upper layer. In order to avoid collapsing, the object's structural kinetics must obey its size and its time window. The relationship between the minimum waiting time required between layers ($t_{h,min}$) and the thixotropic gain is given by eq. (5) [11].

$$t_{h,mín} = \frac{\rho g h}{A_{thix}\sqrt{3}} \tag{5}$$

The maximum print speed (V_{max}) can be obtained by dividing the print length (L), which is the path to be covered, by the minimum waiting time and can be obtained from eq. (6). Printing at speeds greater than the maximum will cause the structure to collapse.

$$V_{máx} = \frac{A_{thix}\sqrt{3} \times L}{\rho g h} \tag{6}$$

It is also possible to obtain, from eq. (4), considering the maximum height of the structure (H_m) and the final yield stress of the concrete, the maximum number of layers that can be printed. At the end of the printing process, the final yield stress of the lower layer ($\tau_{0,f}$), eq. (7), must be sufficient to support the entire height of the structure.

$$\tau_{0,f} = \frac{\rho g \mathrm{H_m}}{\sqrt{3}} \tag{7}$$

3 Numerical Model

The numerical modeling of concrete in the early ages, comprising the phenomenon of hydration, implies considering the exothermic and thermoactivated nature of the chemical reactions involved. Thus, a numerical model that is able to estimate the thermal field in concrete during the hydration and subsequent cooling process should be used [13].

The numerical model is developed using the Finite Element Method based on the Diana package, [14]. The FEM formulation of the heat conductivity eq. (2) yields:

$$k.T + C.\dot{T} = Q \tag{8}$$

where: K – the thermal conductivity matrix, C – the capacity matrix, Q – the nodal discharge. Since a nonlinear thermal problem is considered (properties and/or the boundary conditions depend on time), the incremental-iterative method is used for solving eq. (8).

To enable the modeling of chemical hydration reactions in cement, the DIANA program simulates heat generation based on the degree of reaction or age of the element. In the analysis of heat flux due to hydration, as seen in eq. (8), it is necessary to specify the thermal conductivity and capacitance of the material.

To predict the evolution of the mechanical properties of concrete, the *Diana Fea* program offers the option of calculating the equivalent age of the material by three methods, and in this work the Arrhenius equation was used. The calculation of the equivalent age in this program is a calculation of the maturity index based on the Arrhenius equation:

$$t_{eq} = \int_0^t exp\left(c_A\left(\frac{1}{T_{ref}} - \frac{1}{T(\tau)}\right)\right)\mathrm{d}\tau \tag{9}$$

where c_A is Arrhenius constant e T_{ref}, reference temperature.

In *Diana*, the concept of equivalent age and maturity are equivalent and are indices that represent the progression of concrete curing, based on a certain relationship that considers the history of hydration temperature, age and concrete strength development.

3D concrete printing generally requires a low- to zero-slump material to maintain shape and position after deposition. In this research, a custom designed printable concrete mix was applied as analysed by Wolf [1], containing Portland cement (CEM I 52.5 R), siliceous aggregate with a maximum particle size of 1 mm, limestone filler, additives, rheology modifiers and a small amount of polypropylene (PP) fibers.

The 3D model applied to Diana was a dam wall 3.00 meters high, and length and width of 2.00 m and 0.40 m. The dam is built in 20 cm high layers, simulating the 3D print of the wall applied 1 hour after each deposition, defined from equations 4, 5 and 6. The initial conditions were defined by the throwing temperature of the concrete, observed by Wolf [1], and the environment temperature considering constant. The boundary conditions considered the continuous wall in the direction of the longest length, heat flux between the layers, and concrete as an elastic material.

4 Results

The model developed in the Diana program is shown in Fig. 2. The results were observed from the casting of the concrete up to 5 days, in order to obtain the highest degree of hydration possible, considering the concreting temperature of 24°C, layer height of 20 cm and an interval of 1 hour between layers. The usual thermal properties of concrete estimated by Fairnhain [15] were considered.

The stresses are primarily influenced by the temperature field, and to a less degree by the dead load, while the effect of other loads may be neglected. Figure 3 shows the temperature variation during the construction process, considering the exact moment when layers 1, 5, 10 and 15 are released.

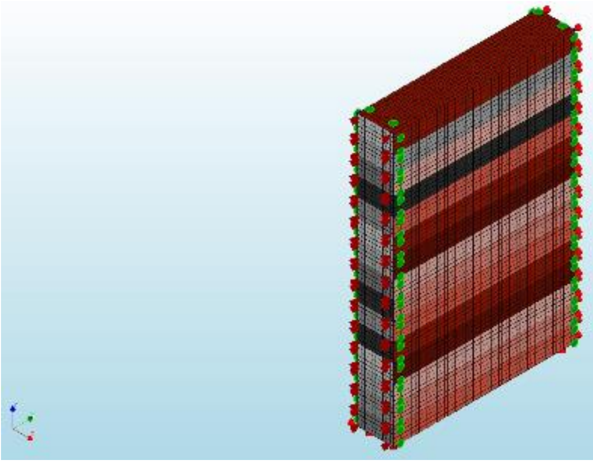

Figure 2. *Diana* numerical model.

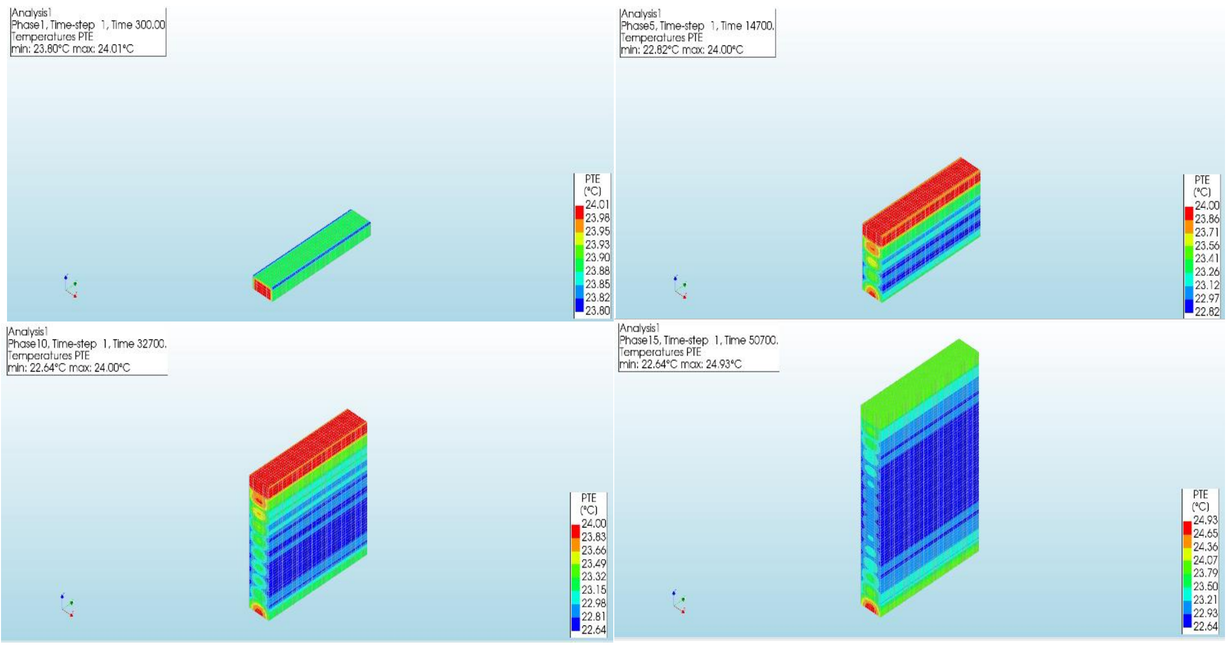

Figure 3. Temperature variation after releases from layers 1, 5, 10 and 15.

The temporal evolution of the thermal field of the wall is shown in Fig. 4 e Fig.5, considering the lower layer of the structure. During the initial phase of construction, until the completion of the superposition of the layers, after just over 50000 sec., there are no large variations in temperature. This temperature-raising core gradually cools, propagating the “hot core” to subsequent layers in smaller proportions.

The rise in the temperature of the concrete is associated with the degree of reaction of the hydration of the cement, where the material's modulus of elasticity grows faster until it reaches its maximum of 30MPa, close to 250000 sec.

As a mechanical result, from the material studied by Wolf [1], the maximum shear stress was approximately 14 MPa, shown in Fig. 6, with a high growth in the temperature rise phase, being the same observed in the main stress, shown in Fig. 7 e 8.

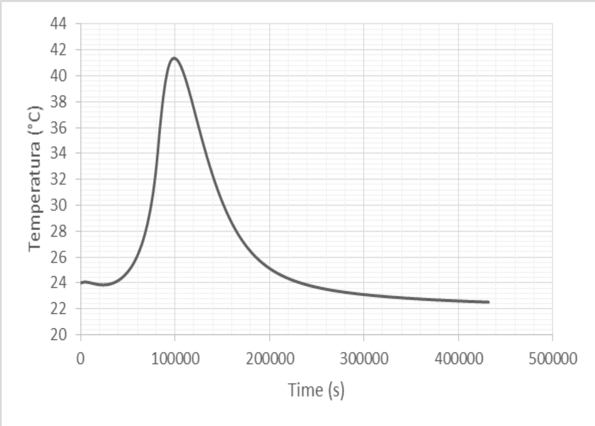

Figure 4. Temperature variation of the lowest layer of the structure over time.

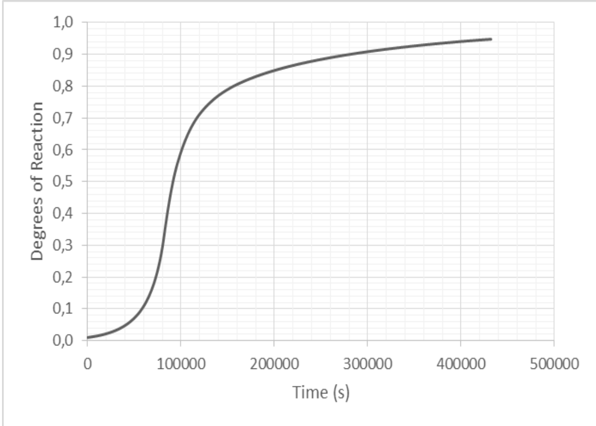

Figure 5. Variation of the degree of reaction of the lower layer of the structure over time.

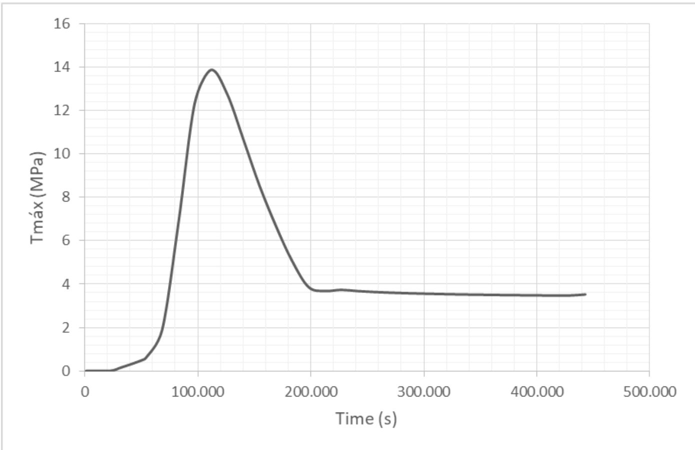

Figure 6. Variation of the maximum shear stress of the lower layer of the structure over time.

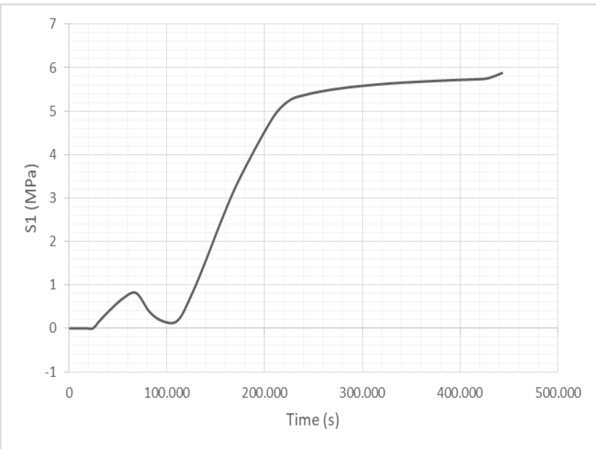

Figure 7. Variation of the main tensile stress of the lower layer of the structure over time.

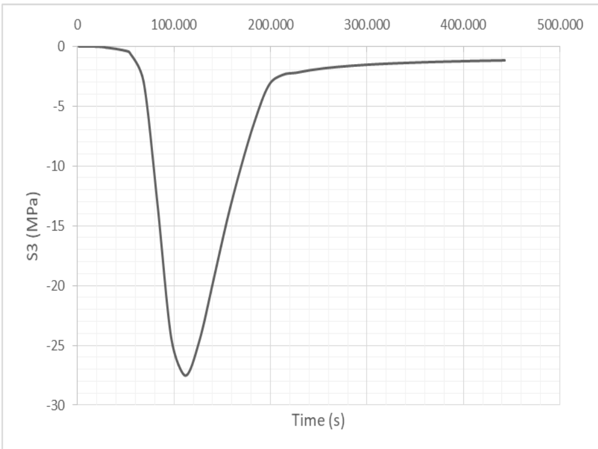

Figure 8. Variation of the main compression stress of the lower layer of the structure over time.

5 Conclusions

Taking into account the objective of this work, to computationally model the construction of a dam by the 3D printing method, using Diana Fea software, the modeling proved to be successful.

Considering that the printing process uses concrete with high cement contents, and due to the exotherm and thermoactivation of this type of material, a considerable temperature rise was observed in the material's hydration process, as expected for massive concrete. Although this is a problem with regard to dam construction, as the printing process is started and concluded with the concrete still in a relatively fluid state, this issue does not affect the construction method.

The thermal and mechanical results of the structure present the expected effects, so regarding the applicability of 3D printing methods for massive structures, this one demonstrates the possibility.

Considering that the concrete used was not designed and studied for such a feat, and also that the modeling was carried out without mechanical data of the material, it is not possible to conclude the effectiveness of the stability of the structure, nor the gain in the same aspect as the use of the 3D printing.

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