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Aplicação do método da maturidade em lajes de cobertura

Application of the maturity method to reinforced concrete roof slabs

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RESUMO

O método da maturidade é um procedimento que associa a evolução da temperatura do concreto e o avanço de suas propriedades no estado endurecido, como a resistência à compressão, geralmente em idades iniciais. Sua aplicação é justificada quando se requer segurança e agilidade para tarefas de construção, como a protensão, a remoção do escoramento, o desmolde e a cura de concreto em baixas temperaturas. As regiões de clima temperado são conhecidas por apresentar temperaturas mais baixas durante o inverno, o que pode retardar o ganho de resistência do concreto. Este estudo aplicou o método de maturidade em uma estrutura de concreto armado localizada no Sul do Brasil, em uma construção industrial. Se observou que o concreto, do qual se esperava o alcance de 30 MPa aos 28 dias, chegou a alcançar 70% da resistência com 8,5 dias para a laje 1 e em 4,4 dias para a laje 2, sendo possível mensurar tal propriedade utilizando o método da maturidade.

Palavras-chave: concreto, durabilidade, análise estatística, especificação técnica.

ABSTRACT

The maturity method is a procedure that associates the evolution of the temperature of concrete cast to the structure and the evolution of its hardened state properties like compressive strength, usually at early ages. Its use is justified when safety and agility are required for activities like prestressing, shoring removal, demolding and low temperature concrete curing analysis. Temperate regions are known for having lower temperatures during the winter, which can delay concrete strength gains. The aim of this study was to apply the maturity method to a reinforced concrete structure located in Southern Brazil in industrial construction. It was noted that the concrete, despite being expected to reach 30 MPa at 28 days, managed to reach 70% of the strength at 8.5 days for slab 1. Slab 2, whose function was to support garners 4, 5 and 6, presented the data at 4.4 days, it being possible to measure such property using the maturity method.

Keywords: maturity method, concrete, compressive strength.

1. INTRODUCTION

Compressive strength is the most relevant property that regards load-bearing capacity and structural behavior of concretes [1]. Checking if a certain strength or its evolution have been met is commonly done through destructive methods, as technical standards suggest [2]. This analysis measures strength gains of concretes at varying ages to assess if the parameters specified in design have been reached, or even to support the performance of tasks such as demolding, shoring removal, prestressing, and others.

The compressive strength of concrete is influenced by several factors, such as: concrete dosage, cement particle-size distribution, type of cement, minerals or chemical substances added to the mixture, molding of

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elements, curing, water/cement ratio and curing temperature [3]. Among these factors, the only one that can't be controlled under real structure casting situations is the temperature of exposure and curing of the elements.

Many authors debate how temperature impacts strength gains and concrete hydration [4-6]. Studies show that compressive strength tends to be higher when the concrete is exposed to higher curing temperatures [7]. Fig. 1 depicts a study developed with the same composition, varying water/cement ration and curing temperatures.

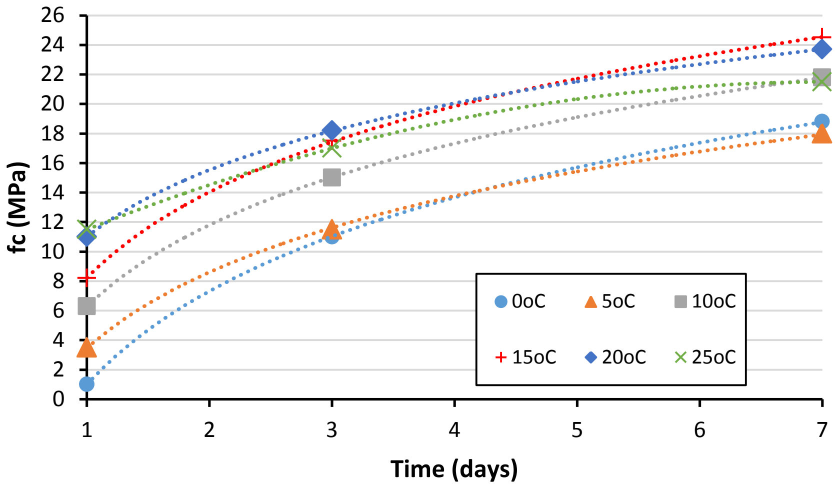


Figure 1: Effects of curing temperature on compressive strength

Figure 1 denotes positive influence of high temperatures on the development of initial strength of concrete, although this influence turns negative at advanced ages. BURG [4] and LAGUNA and IKEMATSU [8] found values that agree with the presented.

It is possible for controllable factors to forecast the behavior of structures concerning their compressive strength and durability based on parameters of mixing and dosage, as technical standards state [9-11]. Temperature must be a relevant parameter in this estimation though, as strength gains of concrete are affected by both the number of reagents and heat intensity [12]. These authors also affirm that increasing the temperature makes molecules move faster and with more energy, increasing chemical reaction rates.

Given its relevance, the influence of temperature on compressive strength of concretes started being studied around 1950 in England, with the intent of developing accelerate curing processes for the precast concrete industry [13-16].

Such study resulted in the maturity method, which is based on the transformation of real-time measurements of temperature when determining the strength of concrete pieces [17]. This method has been used as a non-destructive test that grants safety and agility for building processes [18]. Some of the main motivations for this test are assessing the compressive strength needed for demolding and shoring removal, prestressing concrete pieces and to analyze temperature and time necessary for specific curing processes of the precast concrete industry [19, 20].

Its effectiveness is due to considering temperature as the most relevant parameter for concrete strength at early ages [21]. LI *et al.* [22] evaluated the formation of cracks on concretes for dams by the maturity method, considering summer and winter situations. As per these authors, temperature exerts significant influence not only on concrete hydration, but on the existence and magnitude of cracks as well. The maturity method can be applied following two models, being Nurse-Saul's and one based on the Arrhenius Law. In the United States, the Norse-Saul model is the used most often due mostly to its simplicity, although the model based on the Arrhenius law is more precise scientifically [23].

The law of Arrhenius is used for describing the effect of temperature on the reaction rate of a certain chemical reaction [12]. The application of the maturity method based on the law of Arrhenius was proposed by HANSEN and PETERSON [24] in the first place. These authors presented an equation that could determine the equivalent age of concrete as a function of the temperature to which it was subjected.

Using this equation requires the determination of the activation energy of concrete, though. The activation energy was proposed by Syante Arrhenius in 1888 to explain why chemical reactions do not occur instantly when two reagents make physical contact [12]. This energy, for Arrhenius, comes from the minimum kinetic energy the reagents need to react with each other upon collision [16].

The procedure for determining activation energy of concrete is described by ASTM 1074-98 [25]. According to Carino [26], the materials and the mixture used make activation energy vary, whereas its values usually stand between 41 kJ/mol and 67 kJ/mol. Due to this variation, PERES *et al.* [27] conducted a research to determine the activation energy of cements used in Brazil, whose results are presented in Table 1. It should be noted that these values are specific to those compositions and components.

Table 1: Activation energy (Ea) for Brazilian cements

CEMENT TYPE	Ea (kJ/mol)	CEMENT TYPE	Ea (kJ/mol)
CP-I-S	35.4	CP-III	57.0
CP-II-F-32	31.4	CP-IV	50.4
CP-II-Z-32	31.3	CP-V	43.9

Some software programs currently specialize in applying the maturity method, which can estimate activation energy from the temperature to which the concrete is exposed and its composition, as is the case of Con-Cure®.

As per National Ready Mixed Concrete [23], the maturity method should be applied considering the following steps:

- Determination of the strength-maturity relation for the concrete used in the structure. Check the temperature of specimens through sensors and keep track of the advances of compressive strength to plot the maturity curves (by Nurse-saul or Arnheius);
- Measurement and recording of the hystory of temperature of the structure’s concrete elements by installing sensors on strategic spots (less favorable regarding solar energy or the last volumes to be added to the elements);
- Calculation of the maturity index from the samples’ recordings of temperature and age;
- Awareness or experimental obtention of the activation energy, which varies with respect to the type of cement used;
- “In loco” estimation of the concrete compressive strength based on temperature, maturity index and the prestated relation between strength and concrete maturity.

The method has some limitations that should be considered during application. Galobardes et al. [18] stress that the maturity method should be set for each concrete composition, evaluating the relation between mechanical properties and strength gains for materials in comparison with the mixtures kept under the standard condition.

KIM and RENS [28] point out that the test procedure is dictated by ASTM C1073 [29] with the following limitations: (a) Concrete must be kept under conditions that allow its hydration; (b) The method does not contemplate the effects of the initial temperature on final strength; (c) This method must be complemented by other concrete analyses; (d) The concrete used in the structure is not representative of the one used in laboratory for calibration due to the alterations of concrete, its heterogeneity, amount of air and dosage precision; (e) High temperatures at early ages shall result in an incorrect forecast of the strength at final ages; (f) The use of wrongful data recordings of temperature or activation energy, i.e. inconsistent with the concrete evaluated, may lead to an incorrect compressive strength forecast.

Considering the Southern region of Brazil, which is known for its well-defined seasons and mountain region with lower temperatures, this study monitored concreting processes that occurred under these conditions in the city of Bento Gonçalves, seeking construction safety and the concreting of reinforced concrete slabs, assuring quality on the conduction of tasks from the construction process to meet design specifications.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

This study revolved around the analysis of strength with regards to temperature of concrete with compressive strength of 30 MPa and slump class of 100 mm. The demolding procedure specified a minimum strength of 21 MPa, so the maturity method was used to determine the time needed to obtain this compressive strength and thus release the demolding process. Table 2 presents the characteristics of the concrete.

Table 2: Characteristics of concrete from structural elements

MATERIAL	TYPE	SPECIFIC GRAVITY (kg/dm³)	QUANTITY (kg/m³)
Cement	CP-II-F-40	3.11	282
Pozzolan	Fly ash	2.3	94
Crushed sand	Medium	2.69	709
Gravel	Maximum size of 9.5mm	2.69	100
	Maximum size of 19mm		551
	Maximum size of 25mm		351
Chemical admixture	Multifunctional plasticizer	1.2	3.01

The elements were cast in two stages, being two slabs that supported 3 garners each (slab 1 supported garners 1, 2 and 3, while slab 2 supported garners 4, 5 and 6). The slabs measured 10 x 30 x 1.10m, constituting 330m³ of concrete each. The coarse aggregate used had three maximum aggregate sizes to increase the mixture's packing. Fig. 2 depicts the study site.

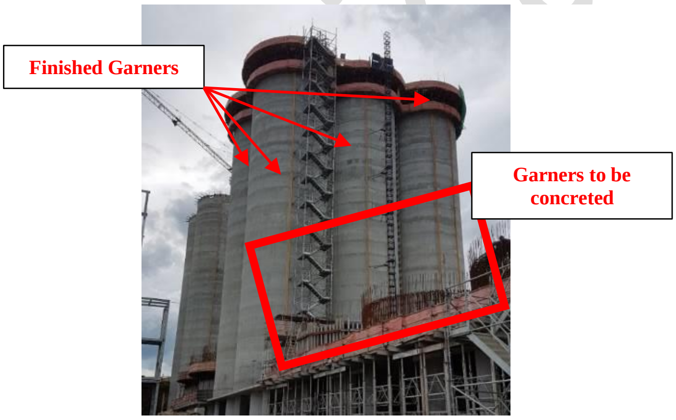


Figure 2: Indication of the concrete place

2.2 Place of Application

The city where the study was developed presents humid subtropical climate, with well-defined seasons, cold winters and hot summers, in which the month of July displays the lowest average temperature of the year, 13°C, which is when the concreting took place. Humidity is high, with yearly mean of 70%. The methods were applied following these steps:

a) Analysis of compressive strength evolution under the condition of temperature controlled in laboratory;

b) Instrumentation and observation of temperatures along the concreting process of both slabs that were analyzed, as Fig. 3 shows;

c) Estimation of compressive strength in real time through the software program named Con-Cure®.

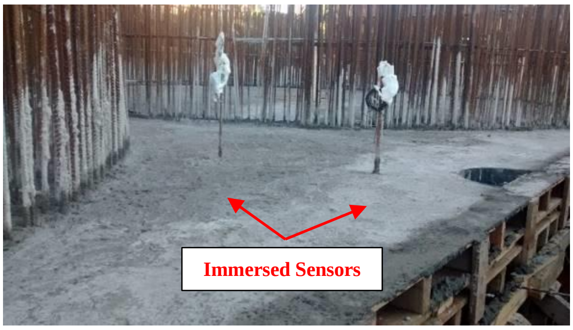


Figure 3: Concreting site (monitoring slab).

For the first stage, 24 specimens were molded to be tested for compressive strength at 1, 2, 3, 5, 7, 14, 28 and 63 days, considering three samples for each age. These samples were stored in a climatic test room under controlled temperature and humidity conditions of 23 ± 2°C and 65 ± 5%.

Being aware of the evolution of this strength, the concreting procedures were performed on the real structure, counting with instrumentation by temperature sensors. These sensors could be removed with plastic hoses and were installed at the depths of 0.20m, 0.35m and 0.55m, being these the positions at garner 1, garner 2 and garner 3 on slab 1 and garners 4, 5 and 6 on slab 2. Data loggers were attached to these sensors and the configuration adopted considered that temperature should be recorded every minute or every time concrete temperature varied 1°C.

The activation energy was determined by the software and the composition of the concrete used. Results pointed out equivalent curing periods, as YIKICI and CHAN [30] had achieved, translating the relation between real curing and gain or delay from exposure temperatures of the structural element.

3. RESULTS

3.1 Initial Evaluation of Concrete and System Calibration

Prior to the application of the method, the concrete composition maturity curve was checked. Fig. 4 plots these data for better visualization. At 28 days, the mixture had not reached its characteristic strength, assessed only at the 63 days. It should be noted, though, that this evolution considers an isothermal curing condition, hence eliminating the influence of temperature.

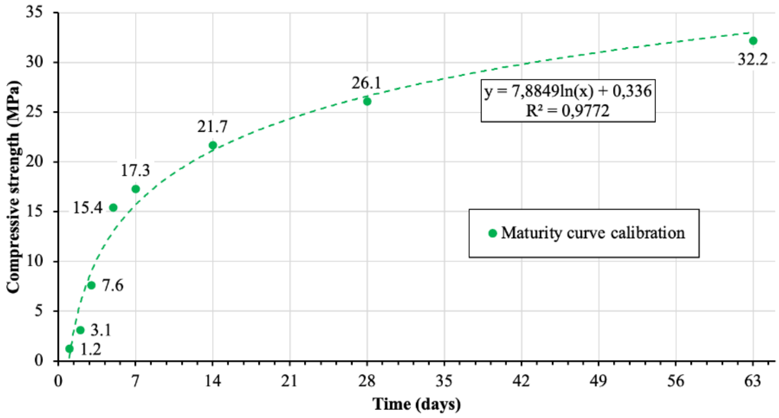


Figure 4: Evolution of concrete strength under isothermal condition

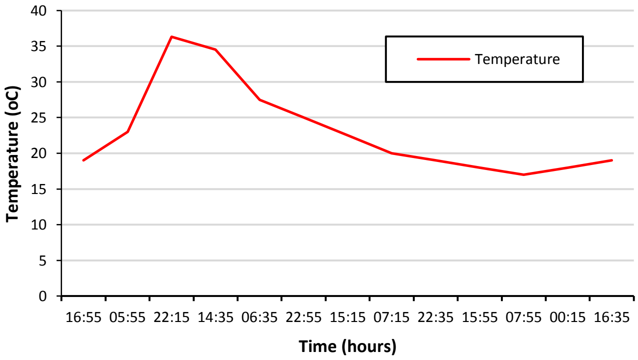
3.2 Monitoring the Concreting Processes

The first concreting embraced slab 1 (support of garners 1, 2 and 3). Its data are presented in Table *3*, and it yielded the compressive strength growth results depicted in Fig. 5-7. The concreting processes were performed during winter, with temperatures between -3 and 17.5°C. The activation energy was 39.1 kJ/mol.

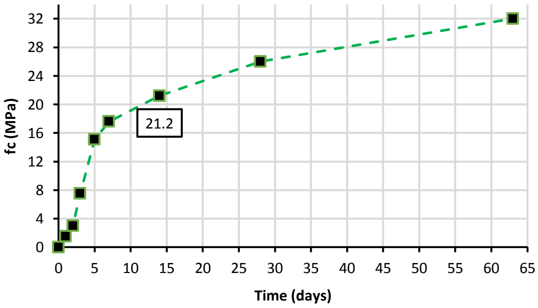
Table 3: Concrete monitoring

SENSOR	GARNER	INITIAL READING	CURING TIME (days)	EQUIVALENT AGE (days)	ESTIMATED STRENGHT (MPa)
1	01	16h55	8.5	13.9	21.2
2	02	15h16	6.5	14.1	21.3
3	03	09h14	4	14.2	21.4

As observed in Fig. 5a, the temperature of the concrete element throughout the period of 8.5 real curing days remained between 17.3°C and 36.3°C. Fig. 5b showed that sensor 1, placed at a depth of 0.20m, presented compressive strength of 21.2 MPa after 8.5 days of curing, which is equivalent to the strength of the specimen cured for 13.9 days in laboratory.



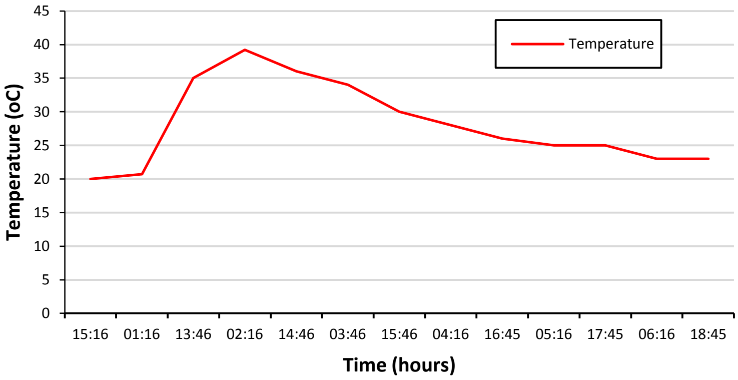
(a) temperature for 8.5 days / Max: 36.3°C / Min: 17.3°C



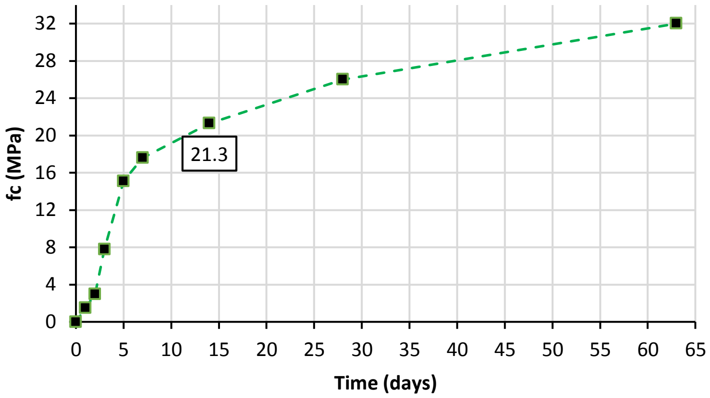
(b) strength and equivalent age (at 13.9 days)

Figure 5: Temperatures and concrete strength for sensor 1 – 0.25m

Fig. 6 shows the data for slab 1, on the position above garner 2. The second sensor was installed 0.35m deep onto garner 2 and indicated a strength of 21.3 MPa at 6.5 days of curing, value that was expected to have been reached after 14.1 days of curing, as the specimen had been cured in laboratory. It was noted that compressive strength was higher for this sensor fixed more deeply.



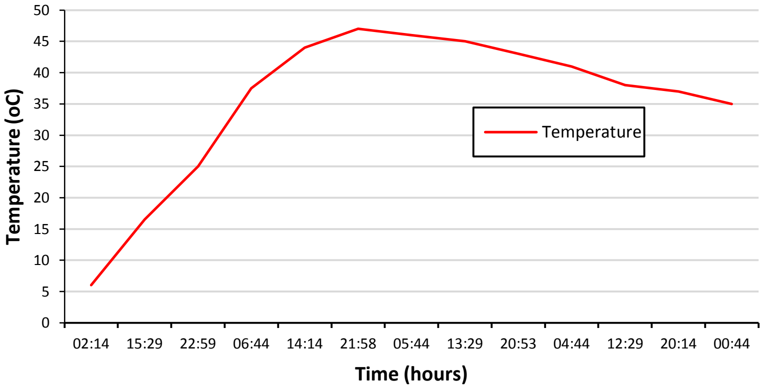
(a) temperature for 6.5 days / Max: 39.2°C / Min: 19.3°C



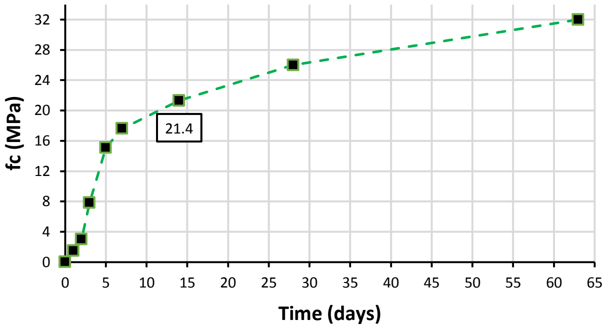
(b) strength and equivalent age (at 14.1 days)

Figure 6: Temperatures and concrete strength for sensor 2 – 0.35m

The third sensor was at a depth of 0.55m on garner 3 and its data are presented in Fig. 7. This sensor spotted a strength of 21.4 MPa after mere 4 days of curing, strength that was expected for 14.1 days in laboratory. Once more, higher mechanical strength was reached as the depth increased.



(a) temperature for 4.0 days / Max: 47.0°C / Min: 6.1°C



(b) strength and equivalent age (at 14.2 days)

Figure 7: Temperatures and concrete strength for sensor 3 – 0.55m

The results coincide with the literature, as concreting processes of greater volumes accumulate heat released by cement hydration reactions that increase concrete temperature [5]. So, despite being less influenced by room temperature or solar incidence, the heat from volume hydration turns out to be more relevant.

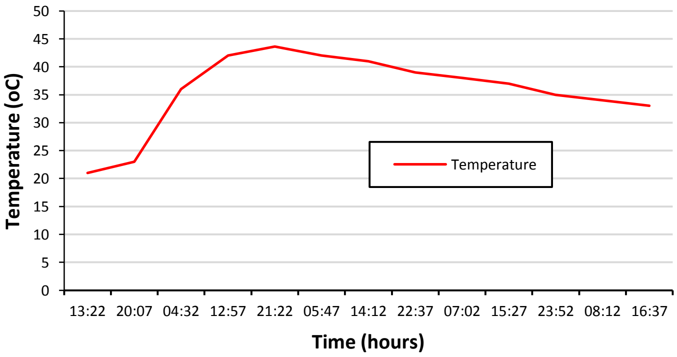
It was generally observed that, even with lower room temperatures (-1°C up to 17.5°C), compressive strength evolved faster than the expected in laboratory, as depths of 0.25m, 0.35m and 0.55m displayed equivalent curing periods of 14.9, 14.1 and 14.2 days, which are lower than the real values of 8.5, 6.5 and 4 days, respectively.

The results for the second concreting are presented in Fig. 8-10, considering the respective bases of garners 4, 5, and 6. The temperatures remained between 7 and 24 °C during the concreting.

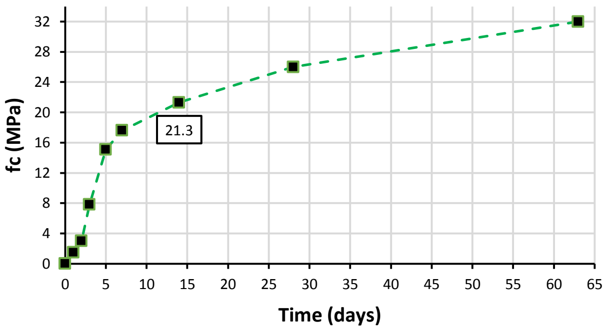
Table 4: Compressive strength results- Monitoring the Concreting Processes

SENSOR	GARNER	INITIAL REAADING	CURING TIME (days)	EQUIVALENT AGE (days)	ESTIMATED STRENGHT (MPa)
1	04	13h22	4.4	14.0	21.3
2	05	11h17	3.0	13.6	21.1
3	06	11h12	2.5	14.3	21.4

Table 4 shows that the volume of concrete used for the second concreting presented faster strength development, as its strength reached 70% of its characteristic value within reduced real curing time. This occurred due to the room temperature now of this concreting, which varied between 7 and 24°C. Fig. 8 refers to the depth of 0.25m and points that, with only 4.4 days of real curing for the structure, the resulting strength was already of 70% of the value estimated for this concrete. Moreover, the temperature measurements of the pieces had minimum value of approximately 17.1°C, while room temperature was 7°C.



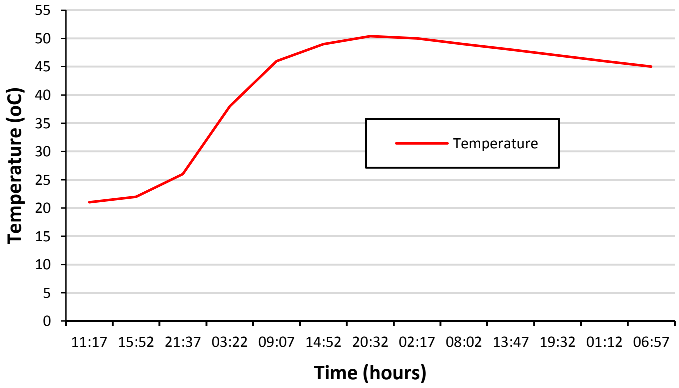
(a) temperature for 4.4 days / Max: 43.6°C / Min: 18.9°C



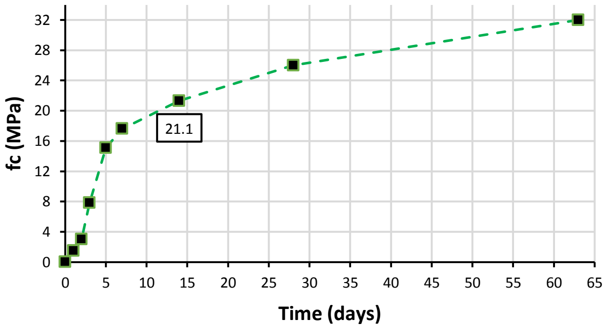
(b) strength and equivalent age (at 14.0 days)

Figure 8: Temperatures and concrete strength for sensor 4 – 0.25m

Continuing the exposition of results, Fig. 9 depicts the data from the sensor fixed at the depth of 0.35m on garner 5. As observed in Fig. 9, regardless the reduced analysis age, it was forecast that 70% of the concrete strength would be reached at 3 days, being equivalent to the isothermal curing of 13.6 days. Fig. 10 finishes the presentation of results by pointing the measurement performed at 2.5 days for the sensor fixed 0.55m from the surface of garner 6.

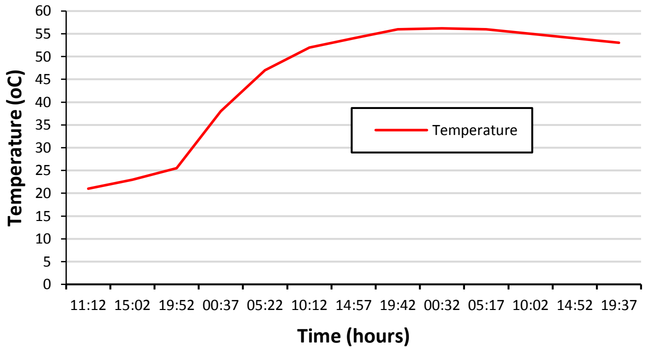


(a) temperature for 3.0 days / Max: 50.4°C / Min: 17.0°C

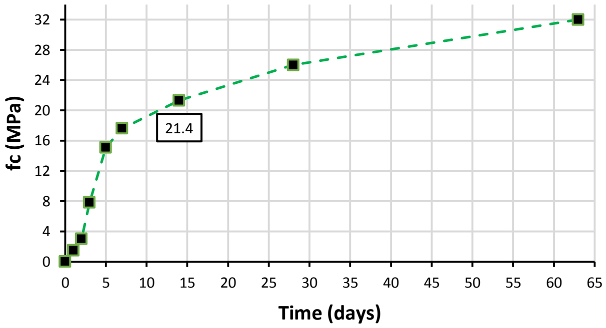


(b) strength and equivalent age (at 13.6 days)

Figure 9: Temperatures and concrete strength for sensor 5 – 0.35m



(a) temperature for 2.5 days / Max: 56.2°C / Min: 17.1°C



(b) strength and equivalent age (at 14.3 days)

Figure 10: Temperatures and concrete strength for sensor 6 – 0.55m

These results are in accordance with those from the first concreting, indicating that higher depths are less influenced by room temperature and solar incidence, despite the gain being compensated by the high volume of concrete. The resulting strength of 70% of the total value took place at 2.5 days for the analysis of the area of the slab pertaining garner 6.

Through a comparative analysis of both concreting processes that were monitored, it can be noted that the curing periods for the second were smaller, what may be related to higher room temperatures.

BENAICHA *et al.* [17] performed similar measurements on high-strength and self-consolidating concretes and found reduced equivalent curing periods with 5h and 7.5h required for these concretes to reach 10 MPa respectively. Upon applying the maturity method to sprayed concrete, GALOBARDES *et al.* [18] found that the depth of the analysis, the materials and their volumes influenced their results, coinciding with the results pointed in this study.

Regarding the types of results achieved, SOUTSOS *et al.* [31] affirm that the analysis can be continued by relating curing temperature ranges and curing periods necessary to reach the strength defined in design.

4. CONCLUSION

The experimental procedure results point out the positive influence of the temperature, which acted as a catalyzer for strength gains. The exposure of concrete to high temperatures accelerates the cement hydration process and, consequently, gains in strength. in this study, a difference of 11.8 days was reached when comparing the actual cure (maturity method) with the equivalent age calculated by the method (laboratory cure). It was possible to indicate the relevant difference between the procedures adopted in the conventional technological control of concrete in specimens and the actual strength of the concrete cast in the element. Also, is worth notice that, besides external temperature, there was influence from cement hydration heat in this study, due to the high volume of concrete, which contributed to its maturity.

Moreover, it is evident that the breaking results for the specimens kept under isothermal condition are lower than the real strength development, confirming the positive contribution of temperature, even though it remained mild in the initial period of curing. It is considered that the results of this study are restricted to the type of cement used and, consequently, its activation energy, as well as the specific mix of concrete and the volume of the structural element. Minding only this method of control for buildings, it would act in favor of safety, may leading to a decrease of costs with equipment rental, hence benefited the logistics of construction and reducing the deadline for performing tasks.

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