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Abstract. The compressive strength of concrete mixtures with accelerator additives designed for structural elements with strength of 5000 psi was correlated with the maturity index of concrete at an early age. The design of the mixture was made by adding the quantity of additives according to the specifications of the supplier. The maturity index was calculated using the thermal profile of the concrete dependent of the setting time, which was obtained through an automated adiabatic system. The number of thermal sensors required for temperature measurement dependent of setting time (1, 3, 7, 14 and 28 days) was determined by a factorial experimental design of two factors. The correlation coefficient was 0.96, so the logarithmic model adequately explains the variability of the compressive strength. The equation obtained was validated by means of the values of resistance to compression measured by the standard method for each age of the concrete; all values are within the calibration range of the resistances estimated by the maturity method.

1. Introduction

Nowadays, in the Colombian building trade, the work execution times are shorter and more demanding, which generates serious inconveniences in the performance of each activity [1]. An important factor in job execution times are the methods used to determine the compressive strength of concrete (CSC). The traditional method of measurement in the universal machine is governed in Colombia under the NTC 673-2010 standard [2] and corresponds to the ASTM C39-2005 standard [3], which establishes the procedure to determine the mechanical behavior of the concrete by means of destructive tests at different ages of curing, and that can last up to 28 days to obtain an estimate of the maximum resistance to compression, time during which the civil work will not be able to continue [4], causing a considerable delay in the progress of a work.

The alternatives to this procedure are the so-called non-destructive mechanical tests. The term "non-destructive" applies to all tests that do not damage or affect the structural behavior of the elements and leave the structure in an acceptable condition [5], as is the case with the ultrasonic pulse velocity (UPV) [6], the nuclear magnetic resonance technique (NMR) [7], and the correlation with maturity [8], among others.

The maturity method is described in ASTM C1074 [9]. This standard permits to express the maturity index in terms of the temperature–time factor (TTF) using the Nurse-Saul Equation (1). This is a non-destructive method that provides a relatively simple approach to assess the CSC at early ages during construction [10], and is based on an indirect measure from the maturity index. The maturity is calculated with the temperature history of the sample during the curing time [8], and it is required to obtain the calibration curve between the CSC and the maturity index. This information can be used for decision making (for example, time for removing forms, post-tensioning time or pavement opening to traffic), which saves time and reduces the cost of construction.

$$M = \sum_{0}^{t}(T - To)\Delta t \quad (1)$$

Where: M: Maturity index, in °C-hour or °C-day, T: Average temperature of the concrete, in °C, during the time interval Δt, To: Reference temperature, in °C, To = 0°C [9], t: elapsed time, Δt: time interval (days or hours).

Although this method is commonly used by the construction industry worldwide, it has not been implemented locally, thus failing to achieve the economic and time benefits that this implies. This work, therefore, seeks to implement this technique and for this purpose, a study of the behavior of compressive strength in concrete mixtures for a resistance of 5000 psi with accelerator additive was carried out, using the method of correlation with maturity under NTC 673-2010 [2].

In the present investigation the following hypothesis was raised, which is the degree of correlation between the maturity index and the CSC. The results of this research may be useful for concrete and construction companies in the city, will allow them to determine the appropriate time for the demolding and reduce costs of quality testing, since the method of maturity requires fewer cylinders than other methods.

2. Materials and methods

Table 1 shows the design of the concrete mix according to the water-cement (a/c) ratio of 0.42 and the aggregates required to achieve a resistance of 5000 psi. The accelerator additive used is Sika L, in the proportions recommended by the supplier.

For the CSC test, 15 cylinders were manufactured in accordance with ASTM C192 [11]. An automatic mixer was used to homogenize the mixture, and NTC 396 [12] was used to determine the settlement of the mixture. Likewise, the samples were dismantled in accordance with ASTM C192 [11] and those cured in water in accordance with ASTM C511 [13]. The CSC test was performed in triplicate for each age of curing (1, 3, 7, 14, 28 days), for which NTC 673-2010 [2] was applied.

Table 1. Design of 5000 psi compressive strength concrete mix, (settlement 2”).

Material	Origin	Quantity	% w/w
Cement (Kg)	Holcim	471.00	20.80
Sand (Kg)	Rock Crusher	692.00	30.56
Coarse aggregate (Kg)	Rock Crusher	894.00	39.00
Water (l)	Cúcuta’s Aqueduct	200.00	8.83
Accelerator additive	Sika L (1.5%)	7.07	0.33
Total		2,264.07	100.00

(a) (b)

Figure 1. Experimental design of the system used to determine the thermal profile of the samples. (a) schematic diagram, (b) adiabatic chamber.

The thermal profile was determined according to ASTM C1074 [9]. The experimental setup is presented in Figure 1(a) and Figure 1(b). The design consists of a double-walled adiabatic chamber of 60x70x80 cm made with expanded polystyrene where the samples are deposited, a data acquisition system and a computer for the analysis of the recorded and measured temperature profiles. Three DS18B20 digital temperature sensors were used, located inside the sample, connected to an Arduino MEGA 2560R3 card (Atmega2560-16AU); a real time clock (RTC) module DS1302 and a micro SD memory. Programming using Lab View software was used to record temperatures and times. The samples are introduced into the adiabatic chamber during 28 days of curing, and the thermal profile is obtained in real time at intervals of 15 minutes.

In order to calculate the concrete maturity index, it is first necessary to know the temperature profile to the age that you want to determine the maturity. Then the time ranges in which the temperature readings and the time temperature factors (FTT) will be determined, and with them know the evolution of the concrete maturity for such moments [9]. The value in each time interval is the cumulative sum of the FTT up to that time interval, that value being the maturity index of the concrete at that age, as shown in Equation (1).

To determine the CSC, Equation (2) [9] is used, where M corresponds to the maturity index for each age obtained using Equation (1), and coefficients A and B are obtained from the best fit to the experimental data between the CSC found by NTC 763-10 [2] and the values of M, using Equation (2).

$$CSC = A + B\ln(M) \tag{2}$$

The hypothesis test was performed using T-student to determine the degree of significance of the constants A and B in Equation (2) and by means of the analysis of anova variance and the determination coefficient R^2 the percentage of variability explained by Equation (2) was found.

The comparison of CSC values found by NTC673-10 [2] with the values of the estimated CSC with Equation (2), allowed verifying that the CSC averages for each test age were within ±10% of the resistance obtained by the maturity method, as suggested by the standard to consider the model valid [9].

3. Analysis and discussion of results

Table 2 shows the average values of the maturity index for the ages of 1, 3, 7, 14, 28 days obtained by means of Equation (1). The results show a linear behavior of the concrete maturity values, due to the relation of the variables on which the equation depends, given that each point is an accumulation of time temperature factors (FTT) [11]. Also, the results of the average of CSC for each age obtained by NTC 673-10 [2] and by the maturity method are shown.

Table 2. Average maturity index (M) values, CSC by NTC 673-10 and CSC by maturity index.

Age (days)	M (°C-h)	CSC (NTC) (Mpa)	CSC (maturity index) (Mpa)	Error (%)
1	709 ± 1	10.50 ± 0.50	13 ± 0.02	-23.80
3	2,157 ± 18	26.50 ± 0.30	23 ± 0.04	13.20
7	5,033 ± 12	32.93 ± 0.30	31 ± 0.02	5.86
14	9,702 ± 9	35.87 ± 0.07	37 ± 0.01	-3.15
28	18,107 ± 22	41.26 ± 0.26	43 ± 0.05	-4.21

The estimation of CSC by the maturity method offers a high percentage error in early ages, this error tends to decrease when the curing temperature stabilizes, reaching errors of less than 10%, these results agree with other investigations [14,15].

Figure 2 shows the behavior of the average temperature as a function of the age recorded by the sensors during the 28 days; the mixture reaches the maximum temperature of 34.24°C in the first 7.25 hours of exothermic reaction due to the accelerator used. This maximum temperature is similar to the results obtained by Mouchine et al [16], and at that time the demolding can be initiated since the concrete reaches in the first day an average of CSC of 10.5 MPa, a value that is above the suggested range, 2 to 8 Mpa [17]. After that time, and until 48 hours, the temperature drops to 28°C; between 48 to 96 hours the temperature rises to 29°C to begin to drop to room temperature (approximately 25°C) for the remainder of the test.

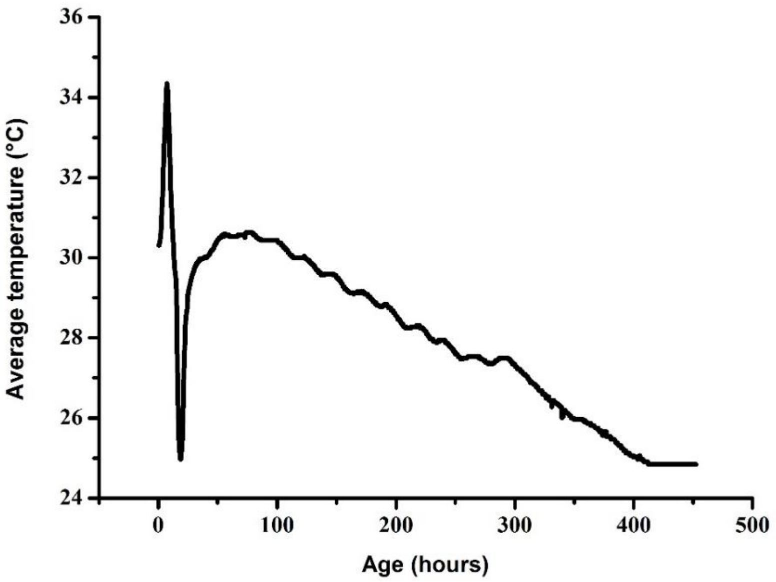

Figure 2. Concrete Mixing Behavior: Average Temperature vs. Age.

Figure 3 shows the adjustment of the experimental data of the CSC using Equation (2) measured by NTC 673-10 standard [2] versus the values of the maturity index for each age. The values of the coefficients are: A=-46.56 and B=9.099, which characterize the designed concrete mix, have a determination coefficient R^2=0.957. So the specific equation for the mix is:

$$CSC = 9.099\, ln\,(M) - 46.56 \tag{3}$$

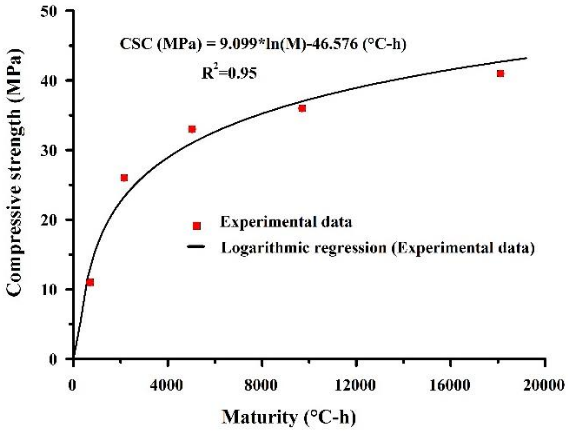

Figure 3. Experimental adjustment of CSC versus maturity index for the designed mixture.

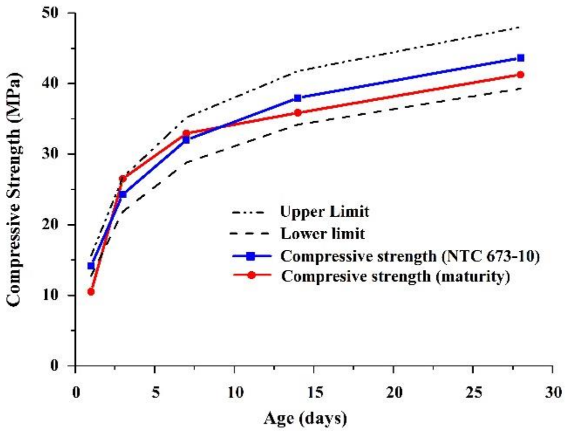

Figure 4. Calibration band (±10), CSC limits estimated by the maturity method.

Figure 4 shows the graph of the CSC as a function of the age (days) obtained by the standard and compared with the validation calibration band of the model, ± 10% of CSC. Bearing in mind that all measured points are within this band, the values of A and B, and therefore the model, are considered to be reliable.

4. Conclusions

The thermal profile of the designed mixture shows that at 7.25 hours the maximum average temperature is reached in the exothermic reaction, therefore, at that time the demolding process can be initiated, which implies a gain in the work time.

It was determined that there is a good correlation (95.7%) between mechanical resistance to compression and maturity index, and that the model expressed in Equation (3) is valid, since the data measured by the standard is within the calibration band.

The results obtained show the possibility of implementing the method of determination of the RMC by its correlation with the index of maturity, the good operation of the method allows to save time and money in the processes of construction.

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