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Experimental and comparative study of the compressive strength of hydraulic concrete samples subjected to various curing techniques

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Abstract

One of the challenges of construction is to guarantee the quality of the properties of the construction materials used, with emphasis on concrete through the curing process, since this is the one that provides significant resistance to the material, so in this project, an experimental study of the compressive strength performance of hydraulic concrete was carried out, using four different curing techniques frequently used in the construction sector (polyethylene plastic sheets, manual curing, standard curing and no curing). These techniques were used in order to highlight the importance of concrete hydration processes and to determine which of the applied curing techniques is the most effective when implemented in civil works. For it, a total of 180 cylindrical specimens of a specific design strength of 21 MPa, were manufactured, cured and tested at 7, 28 and 56 days (15 specimens cured under each of the techniques). According to the results obtained, a higher compressive strength was evidenced in the samples that were cured with polyethylene plastic sheets and the need for the curing process in concrete in the construction of civil works was confirmed.

Keywords: hydraulic concrete, curing techniques, construction sector.

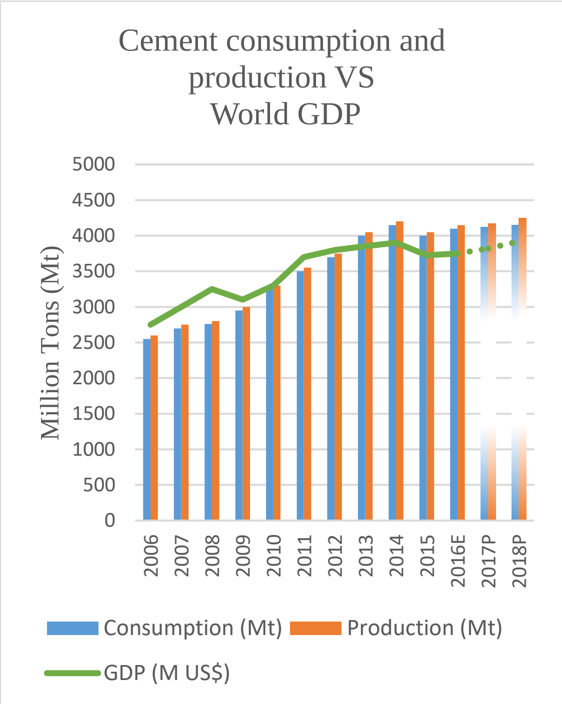
1. INTRODUCTION

In recent years, the execution of civil works has intensified worldwide and nationally, which has directly increased the production of cement and therefore the use of cement in concrete. In Colombia, during the second quarter of 2021, there is evidence of a 27.4% increase in the production of civil works, including construction of highways, streets, railways, runways, bridges and tunnels [1], so it is possible to affirm that, given the increase in the use of concrete, it is of utmost importance the detailed study of the properties of the material in question and its desired strength in order to improve the quality of the structures.

As a considerable compressive strength is required, the quality of a concrete is a determining factor in the safety of a structure, not only with the mix design, as this combination provides mechanical strength to the concrete in the hardened state and controls the volumetric changes that normally take place during setting [2]; but an adequate and complete setting of the concrete mix must be achieved in order to obtain the correct conditions and properties of strength and durability.

The significant increase in cement consumption and production observed in graph 1 shows that cement is the most widely used binder in the world. The main component of concrete is cement, in addition to water, aggregates, chemical and mineral admixtures, and the proportion can vary within a flexible range. Concrete is known for its low tensile strength and potential multiple cracking behavior [3] [4] [5] [6] [7] [8]. It is known as a fundamental material in the construction of civil works, mainly because of its excellent performance. Moreover, concrete is malleable enough in its fresh state to adapt to any type of project in the construction area, regardless of the size of the project [9] [10] [11] [12] [13].

Graph 1 *Ratio of world cement consumption and production to world GDP*



Source: International Cement Review, World Bank and IMF

Elaboration: [14]

A good curing condition favors the development of the strength and durability of concrete, as well as can effectively improve its microstructure and its ability to resist erosion from the external environment. Curing methods are directly favorable to the mechanical performance of concrete, i.e., the longer the curing cycle, the higher the value of the compressive strength, as well as its resistance to environmental agents [2]. The curing process can be carried out through different methods or techniques used, being chosen according to the specific conditions of the environment, economy, ease of application and other project factors. [15].

The manufacture of concrete under extreme climatic conditions, whether high or low temperatures, directly influences its characteristics at any stage of the process: mixing, transport, placement, curing, as well as its physical and mechanical properties [16] [17], therefore, it is of utmost importance to study and research the curing processes in order to guarantee the necessary humidity for an adequate development of its properties.

Some of the methods to guarantee a satisfactory moisture content and temperature are: immersion, use of sprinklers, use of fique fabrics or other absorbent materials, with sand, soil, sawdust, sealing materials such as plastics or impermeable paper or by curing compounds[18] [19] [20], generating the necessary conditions for the hydration of the paste to evolve without interruption until all the cement is hydrated and the concrete reaches its potential properties [21].

Concrete, like many other materials, possesses porosity qualities[22]. Porosity affects the strength of concrete structures during their performance, in addition to allowing fluid infiltration into the material, which can contribute to future cracking of the composite. In this sense, it is possible to state that cracks in concrete are inevitable, difficult to detect and almost impossible to repair. Cracking is a latent threat to concrete structures, since in the long term they can suffer dangerous failures [23], such as vertical failures due to minor settlement or normal shrinkage, and on the other hand there are the horizontal ones that can be caused by poor foundation settlement, moisture damage or clogged pipes [24] [25].

The objective of this research is to evaluate the compressive strength of a concrete with a specific design strength of 21 MPa treated under 4 different curing techniques, frequently used in the construction processes of civil works: manual curing, polyethylene plastic sheeting, standard curing and no curing). The most effective method will be determined from the elaboration of a compressive strength curve performed at 7, 28 and 56 days from the 180 specimens cured in the same period of time.

2. Experimental Program

By means of compressive strength tests, the results and influence of each of the curing techniques on the 180 cylindrical concrete specimens of the same 21 MPa mix design were obtained and compared. Each technique (polyethylene plastic sheet curing, standard curing, manual curing and uncured) had a total of 45 specimens (15 to be tested at 7 days, 15 at 28 days and 15 at 56 days) under ASTM [26] [27] [28] [29] [30] [31].

2.1 Material

In the experimental program of this research, 180 concrete samples were manufactured in the form of standardized cylinders according to ASTM C31[26], which are composed of the following materials: cement type 3, coarse sand (50%), fine sand (50%), gravel 3/4", water, a plasticizing additive (Plastol) and a retarding additive (Eucon).

It is worth noting that the combination of fine sand (from the municipality of Santo Tomás) with coarse sand (from the municipality of Ciénaga) was used in order to reduce costs in the production of the mix (adequate filler for the mix, thus reducing the cement paste content per cubic meter), help control volumetric changes (volume changes resulting from the setting, curing and drying processes of the concrete mix) and contribute to the final strength of the material [28].

2.2.1. Characterization testing

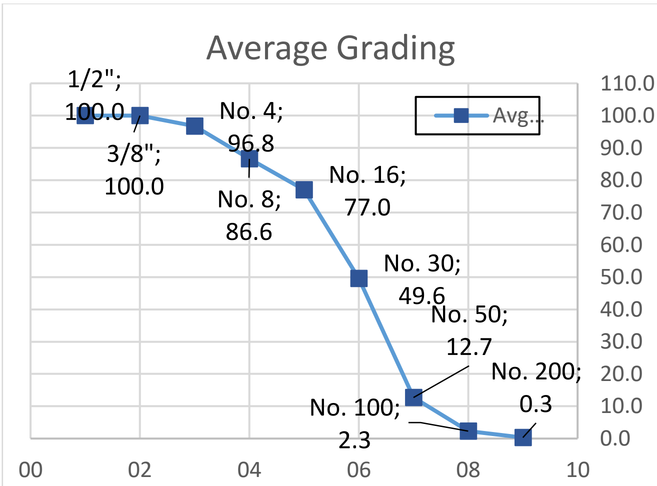
The materials used for the development of this study were supplied by the cement-concrete company Ultracem S.A. according to local market availability. The physicochemical characterization tests of the materials were carried out in compliance with ASTM C33[18], and with environmental conditions of 32 °C.

For their characterization, tests were carried out on granulometry, density, specific weight, humidity, and others, the results of which are summarized below:

Table 1 *Characterization of the fine aggregate to be used for the manufacture of concrete*

Parameter	Fine aggregate	Coarse aggregate
Absorption (%)	1,1	1,4
Fineness modulus	2,7	-
Bulk density (kg/m3)	2613,5	2530
Equivalente de arena Sand equivalent (%)	64	-
Temperature (°C)	23,4	23,4
Humidity (%)	56,2	56,2
Percentage of clay lumps and friable particles (%)	0,23	0,01
Loss of soundness (%)	8,3	4
Crushing index (%)	-	14
Elongation index (%)	-	12

Graph 2 *Physical particle size characteristics of fine aggregate (average grade)*



Graph 3 *Physical particle size characteristics of coarse aggregate (average qualification)*

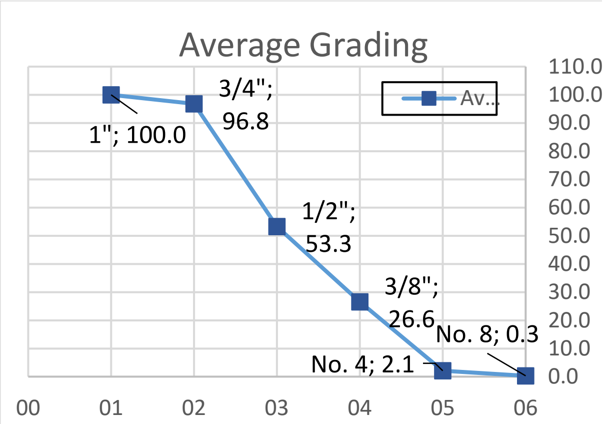


Table 2 y 3 show the properties and quantities of the components of the mixture used for the fabrication of all specimens, respectively.

Table 2 *Mixing design component specifications.*

Materials	Dry mass/m³ (kg)	Density (kg/l)	Volume (l/m³)	Dry mass (kg)
ART Cement	299	3,10	96	28,1
Water	165	1	165	15,5
Coarse aggregate	951	2,53	375	89,5
Fine aggregate	914	2,54	361	86
Air	1%		10	
Eucon	1,43	1,17	1,23	0,13
Plastol	1,79	1,08	1,66	0,17

Materials	Humidity	Absorption	Corrected water	Corrected mass (kg)
ART Cement				28,12
Water				9,84
Coarse aggregate	1,6%	1,4%	-0,18	90,89
Fine aggregate	7,4%	1%	-239,14	92,31
Air				0
Eucon				0,135
Plastol				0,169

Plastol was used as a plasticizing additive to reduce the water content of the cylinders, thus increasing the slump without modifying the water content. In addition, Eucon was added as a retarding agent to optimize the properties of the concrete and adapt it to the needs of this project. The above is based on the temperature conditions that normally occur in the Municipality of Galapa (T ≥ 37°C).

Table 3. *Mixing design used.*

Components per m3	
Cementitious kg/m3	299
Water kg/m³	165
Air (%)	1
Plastol (%)	0,48
Eucon (%)	0,60
A/C	0,552
Mixing volume L	95

2.2 Metodology

The present study employed the same methodological process used in the previously published article by the authors [32].

2.2.2. Tests of concrete in fresh state.

The materials were taken to the mixer at an interval of 15 to 20 minutes to achieve a homogeneous mixture as shown in Figure 3. Subsequently, temperature, slump and air content tests were performed as shown in Figures 4, 5 and 6, respectively, complying with ASTM C143-90 [29] and ASTM C231-09 [30] in the same order, in order to ensure the quality of the mixture.

Figure 1 *Illustration of material mixing process.*

Figure 2 *Temperature test*.

Figure 3 *Settlement test.*

Figure 4 *Air content test.*

2.2.3. Manufacture of concrete cylinders.

The cylindrical samples were made in plastic molds previously greased with mineral oil (Figure 7), with dimensions of 15 cm in diameter and 20 cm in height according to ASTM C31 [26], in sets of 15 samples for the 4 techniques chosen to be tested in the 3 different days within the curing cycle, thus obtaining a total of 180 concrete samples, complying with the number of blows with the rubber mallet and the tamping with the rod to avoid voids in the specimens (Figure 8).

After 24 hours, these samples were stripped to initiate the curing phase and were tested at 7, 28 and 56 days, according to the methodology outlined (Figure 9).

Figure 5. *Greasing of the molds.*

Figure 6. *Forming of concrete samples.*

Figure 7 *Stripped concrete samples.*

2.2.4. Curing techniques application.

Four curing techniques were chosen for this project: polyethylene plastic sheet curing, standard curing, manual curing and uncured. The above techniques were selected because they are the most commonly used in the field, as well as being easily accessible in a small-scale project. Each of the procedures was applied to 45 samples, 15 cylinders per test days (7, 28 and 56 days). In addition, 5 specimens were set aside from each hydration process for each batch, i.e., 5 cylinders were left to cure after 7 days of the 28-day batch, and 5 cylinders after 28 days of the 56-day batch for each technique. The purpose of this was to analyze if there were differences in the strength of the concrete at the time of the compression test at the following age versus those cylinders that were cured for the entire time. This was done in order to make the experiment a little more complex and perform a deeper analysis.

The nomenclature used to identify the cylinders was as follows:

Table 4. *Nomenclature used for sample identification.*

Technique	Items	
	Code by technique	Day to test
T1 - Polyethylene plastic sheets	2630	7, 28 o 56
T2 - Standard	2631	
T3 – Without curing	2632	
T4 - Manual	2633	

Figure 8. *Example of nomenclature used.*

Table 5 illustrates the batch curing process of specimens according to the techniques selected and described previously for this study.

Table 5. *Ilustración de técnicas de curado seleccionadas y empleadas.*

i.

ii.

iii.

T1	T2

iv.

v.

T3	T4

2.2.5. Compressive strength tests.

The measurements corresponding to the diameter and height of each of the cylinders (Figure 11) were taken according to ASTM C31 [26], a in addition to the revision and leveling of the surface of the cylinders in order to achieve homogeneity in the samples. The compressive strength tests were performed in a specialized calibrated machine (Figure 12) and with the normative parameters and the data were automatically taken to a console which worked together under the ASTM C39 standard [31]. Each batch of 15 samples was failed at ages 7, 28 and 56 days.

Figure 9. *Check prior to the compressive strength tests of the compression test used.*

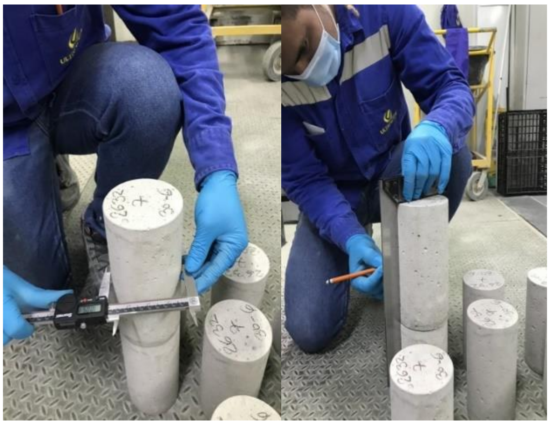


Figure 10. *Machine*

3. Results analysis

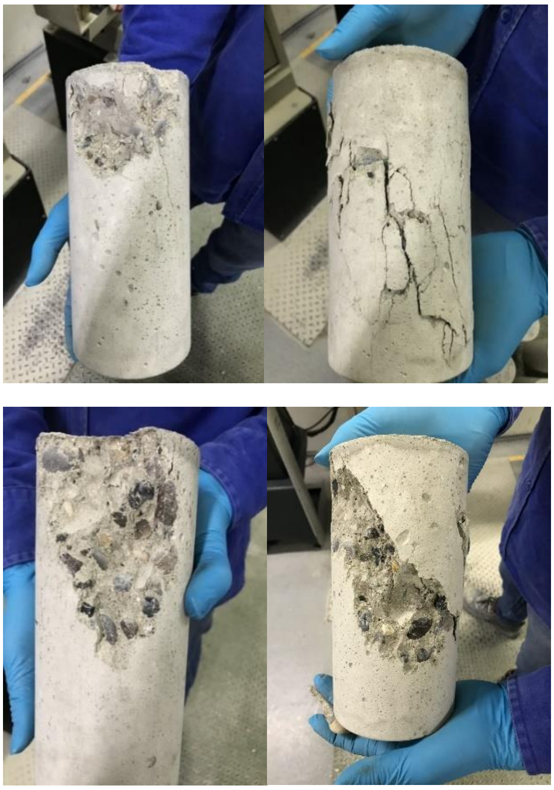
The samples used as reference standard to compare the values of the compressive strengths of the concrete cylinders for the three ages studied were the average of the uncured samples (T3).

3.1 Compressive strength (f'c) at 7 days.

Based on the results of the compressive strength tests of the first 15 samples for each technique, tested 7 days after the curing process, a higher strength value was evidenced by the manual technique (T4) with an average of 24, 5 MPa (4.3% higher than the standard), followed by the standard curing technique (T2) with an average of 24.3 MPa (3.4% higher than the standard) and the technique with plastic film coating (T1) with an average of 24.2 MPa (2.9% higher than the standard). All of them yielded values slightly higher than the strength value of the uncured specimens (standard - T3) with an average of 23.5 MPa.

The following figure shows evidence of the most common failures among the 4 techniques that were observed in the concrete specimens tested 7 days after the curing process.

Figure 11. *Typical failures in cylinders tested after 7 days.*



3.2 Compressive strength (f'c) at 28 days.

The strength data presented after the compression tests of the second batches of 10 samples, tested at 28 days with complete curing (i.e., without interruption), showed that the plastic sheeting technique (T1) had an average of 29.7 MPa (18.3% higher than the standard); standard technique (T2) averaged 27.4 MPa (9.2% higher than the standard); manual technique (T4) averaged 26.0 MPa (3.6% higher than the standard) and finally, uncured (standard - T3) averaged 25.1 MPa.

With respect to the 5 samples of cylinders that, according to the experimental design, were left to cure after 7 days (at day number 8) from the batches of each curing technique, the cylinders of curing technique T1 with a strength of 32.1 MPa, followed by T2 with a strength of 31.8 MPa and T4 with a strength of 26.4 MPa, reached on average the highest strength value.

Figure 12 below illustrates the most common failures observed in the concrete specimens tested at 28 days of the curing process in this investigation.

Figure 12. *Typical failures in cylinders tested after 28 days.*

3.3 Compressive strength (f'c) at 56 days.

According to the results obtained in the compression tests of the third batch of 10 samples per technique associated with a complete curing process, tested at 56 days, a higher strength value was evidenced by the plastic sheet coating technique (T1) with an average of 32, 6 MPa (33.6% higher than the standard), followed by the standard curing technique (T2) with an average of 30.5 MPa (25% higher than the standard) and the manual curing technique (T4) with an average of 29.9 MPa (22.5% higher than the standard). Likewise, all the samples (for all these techniques) yielded higher compressive strength values than the uncured specimens (standard - T3), which obtained an average of 24.4 MPa.

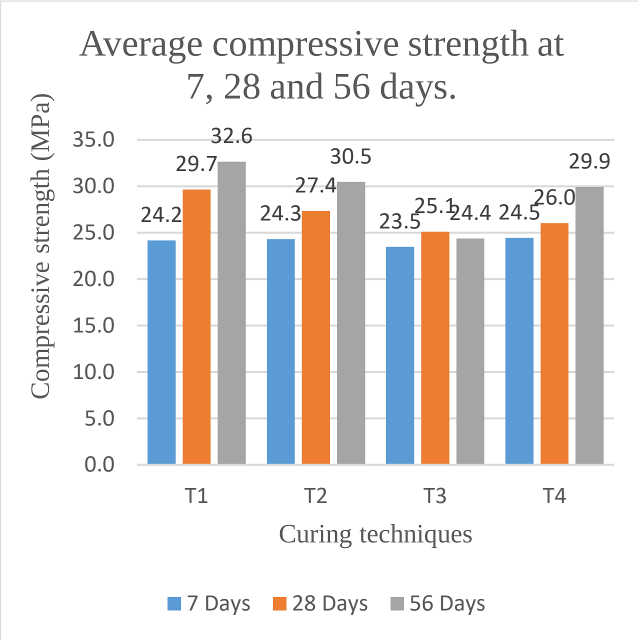
With respect to the 5-cylinder specimens left to cure after 28 days of the batches of each curing technique, the cylinders of technique T2 (standard curing) reached on average a higher strength value with an average of 35.5 MPa, followed by T1 (plastic sheets) with an average of 34.3 MPa and T4 (manual curing) with an average of 30.1 MPa. Figure 13 shows the most common failures observed in the concrete specimens tested 56 days after the curing process.

Figure 13. *Typical failures in cylinders tested after 56 days.*

It can be added that the T3 technique (without curing) has counterproductive effects on the concrete in the long term, since in the previous test (at 28 days) it presented a higher result than that of 56 days. The explanation for this tendency can be attributed to the fact that the chemical reaction of water and cement is affected by the lack of the necessary water, so that the concrete does not acquire the properties that its composition would allow; favoring the formation of cracks. As the water evaporates, it develops forces that generate, in the hardening cement, a shrinkage whose value can exceed the tensile strength of the hardening concrete [33].

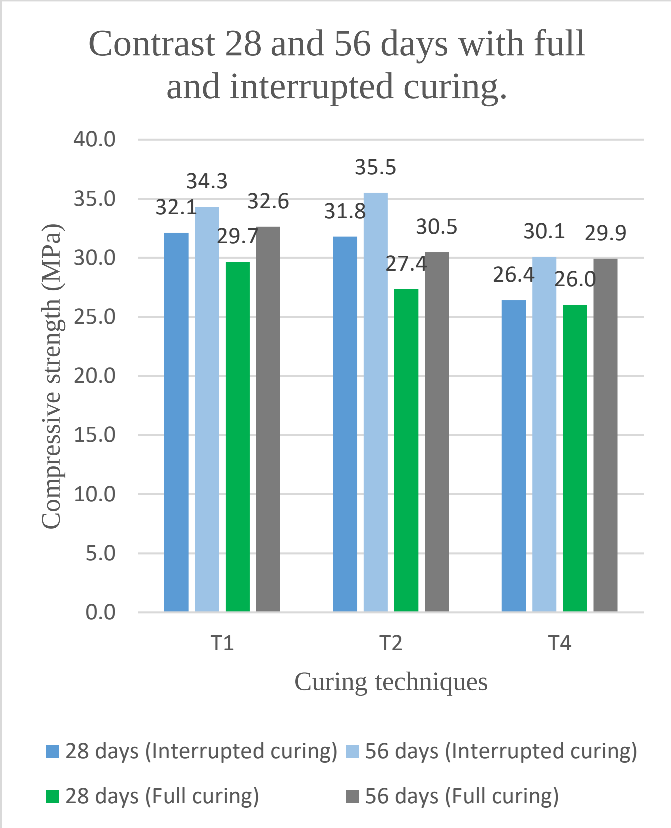
Graph 4 shows the average values of compressive strength in the samples tested, in which it can be seen that, as the curing process is completed in the specimens, the strength increases significantly for techniques T1, T2 and T4 (plastic sheets, standard curing and manual curing), except for samples T3 (uncured), since there is a decrease in the value of the strength, not very relevant, between the ages of 28 and 56 days.

Graph 4 *Average compressive strength values of the batches of samples analyzed.*



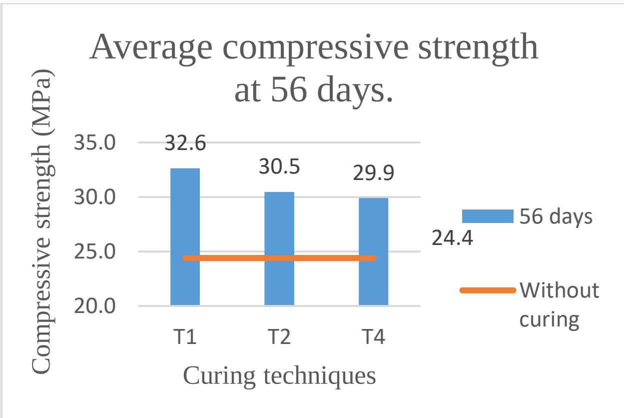
Graph 5 shows the contrast between the compressive strength of the specimens with a complete curing cycle versus the cylinders that were left uncured at 8 and 29 days and at 28 and 56 days, respectively. It can be observed that in the 3 techniques the specimens present a higher strength value when the curing process is interrupted. The early interruption of the curing process adversely affects its strength, and also its modulus of elasticity, since most of the factors that affect the strength affect the modulus in the same way, but, an exception to this is the moisture content of the concrete at the time of the test. Generally, strength increases with decreasing moisture content and modulus decreases. Thus, the initial absorption rate, which is a measure of the amount of water required to fill the larger pores, is likely to be similar to the final absorption rate which represents the amount of water to fill the finer pores [34].

Graph 5 *Contrast of average strength values with complete versus interrupted cure cycle.*



Graph 6 represents the effectiveness of the curing techniques used for the analysis of this study and their respective contrast with the uncured samples. It is worth noting that the resistance values of the three techniques were above the resistance value of the uncured one. With the above, it is confirmed, once again, thanks to the development of this project, how fundamental the curing process is in the contribution of strength to concrete.

Graph 6 *Average compressive strength at 56 days compared with uncured cylinders.*



4. Discussions

On the 56th day of curing in which the batch corresponding to the samples that were treated under the standard curing techniques (T2) and uncured (T3) was tested, a significant difference was found between the concrete strengths of these two processes with a value of 25%; results completely contrary to the research conducted by Rómel Solís Carcaño and Eric Moreno in which the difference between the two techniques (curing by immersion and ambient curing) presents a value of 0.36% [35].

In the exposure of the concrete cylinders under three curing conditions of the present study (T1, T2, T4), there were close values in the compressive strengths at the age of 56 days as shown in Figure 14, which is the maximum period of the research in question, so that based on the article by Rómel Solís Carcaño, Eric Moreno and Carlos Serrano (2005), it is possible to assume that the permanently wet concrete would continue to increase its compressive strength due to the effect of wet curing time, Eric Moreno and Carlos Serrano (2005), since no gain in compressive strength due to the effect of wet curing time was found, it is possible to assume that permanently wet concrete would continue to increase its strength in the long term [35], because of this, it is recommended to study in depth the time in which concrete curing could be extended.

In the case of the cylinders studied in the research in Merida, Mexico [35], the effect of the combination of temperature and wind conditions seems to have been attenuated by the action of the ambient humidity. Hence, it is likely that, in their project, the high humidity of the environment favored a natural curing of the cylinders exposed to the elements. In the curing process carried out in the municipality of Galapa (Atlántico-Colombia), the humidity (average 80%) between the months of May and July could be considered as a possible cause of the increase in the resistance results obtained in the uncured cylinders exposed to the elements.

On the other hand, it is known that the water-cement ratio influences the consistency of the mix, since the greater the amount of water, the greater the fluidity of the mix, the greater the plasticity and workability. In the article by Genesis Guevar et al. (2012), who investigated the effect of the water-cement variation in concrete, concluded that in the tests of the first groups tested in their project, good resistance is observed, because as the mixture is dense, it does not allow the formation of pores and thus there is greater resistance [36]. In the present study, values between 29.9 and 32.6 MPa were evidenced with a complete age curing cycle of 56 days; therefore, it is possible to consider that the mixture lacked porosity, thus favoring our strength results.

Navarrete in 2018 [39] mentions that the variation between the strength of concretes depends directly on the curing method. Contrasted with our research, we agree since differences between techniques were evidenced; they go on to add that, for that reason, given the strength results in their study, it is possible for them to state that not all curing methods satisfy the design strength, but are subject to variables such as climate, time and season in which they are elaborated, etc. Continuing with this idea, and although the present work does not consider the environmental factor, the strength of the specimens could have been affected by the humidity and temperature in the department of Atlántico.

In a study carried out throughout Latin America, Junior Luna [40] determined that the method most used by Latin countries was immersion curing; due to the fact that in all tests better compression results were obtained compared to curing with admixture, steam curing, jute curing, adiabatic curing, sack curing and environmental curing. The strength of the concrete in this project, by means of the most widely used technique in the country, were slightly lower than the polyethylene plastic sheeting technique, with a difference of 0.4% at the age of 7 days. He adds that concrete curing methods affect its compressive strength, setting time and permeability of the concrete, being fundamental the performance of curing, since the omission of its application has a negative influence on the strength, increasing the possibility of cracks and fractures in the concrete. In the present study, the effects of the interruption of curing were evidenced in the compressive strength values of the cylinders at the 3 ages tested with the T3 technique (without curing); since it was carried out in a coastal area, it is more rigorous to take into account the parameters mentioned above, given the temperature to which the concrete elements are subjected, which require continuous curing to avoid cracks or cracking due to water loss.

5. Conclusions and Recommendations

The objective of this study was to evaluate the compressive strength of concrete of the same mix design treated under 4 different curing techniques (polyethylene plastic sheets T1, standard curing T2, no curing T3 and manual curing T4). Compressive strength tests were carried out on specimens at 7, 28 and 56 days cured at the same time. In addition, 5 samples per batch of techniques were separated by interrupting the curing process at 8 and 29 days in order to compare the strength values obtained. Based on the results obtained, the following conclusions were reached:

- At 56 days, the three techniques analyzed (T1, T2 and T4) are effective against the uncured samples, since these samples show an average strength of 36.2, 30.5 and 29.9 MPa, respectively, with the samples treated under T1 (polyethylene plastic sheeting) showing the highest compressive strength.

- The cylinders of techniques T1, T2 and T4 presented higher compressive strength on day 56 with complete curing process. In other words, an increase in strength is evidenced as the curing process progresses. On the other hand, the samples whose curing process was interrupted showed mixed results: the cylinders in which curing was stopped at 8 days and tested at 28 days presented higher resistance than the specimens that were interrupted at 29 days and tested at 56 days, i.e., the resistance values decreased in the last two ages.

- Based on the theory, the contributions in concrete strength show their vitality in the first days following the design and casting of the specimens, i.e., the most critical days in curing are the interval after stripping and the first test age of the samples (the first 7 days in our project), therefore it can be attributed that the results obtained in this study for the batches interrupted from the 8th and 29th day had an adequate strength, given the compliance with the theory described above.

Thanks to this research, it is once again proven that the curing process in concrete is indispensable, regardless of the technique used, to achieve higher compressive strength. In general terms, results of great interest were found in this study. However, it is recommended to analyze other parameters, such as the microstructural approach, in order to deepen the justification of these results. In addition, it is suggested to add other types of techniques such as hot water immersion or to increase the age of curing of the samples (from 56 to 77 days, for example) in order to observe the behavior of the strength of the specimens at an even longer age.

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