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Comparative analysis of the compressive strength of concrete under different curing methods

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Abstract. Concrete is the most widely used material in construction, which possesses different characteristics and possible manufacturing methods. Concrete is, also, characterized by its high resistance to compression and durability, factors that could have been directly influenced by the curing method in early ages. The objective of this research is to demonstrate the importance of the concrete curing process, as well as to analyze the influence of the chosen curing method on the compression resistance. 48 concrete test samples were manufactured, by the standard requirements. Subsequently, the samples were divided into eight batches, subjected to different types of curing: immersion curing, twice a day; outdoor curing; total immersion curing in different waters, application of commercial curing agent; with polyethylene foil coating and without curing. Performing compression testing at 7 and 28 days. Among the results obtained, the batch that underwent the method of curing with polyethylene coating presented a more efficient effect in terms of resistance to compression; followed by the techniques of immersion in water.

1. Introduction

Concrete is the most widely used agglomerate worldwide. It is known as a basic material and construction tool in civil works, mainly for its excellent performance and low cost. Besides, concrete is ductile enough to adapt to any type of project in the construction area, regardless of the size of the project [1]. In particular, the binder itself consists of mixing the cement with an exact dose of water, to keep the concrete in a saturated state. So that the spaces originally filled with water are filled with moisturizing products. If water is not present, the hydration stops, leaving excessive porosity that reduces the mechanical properties and durability of the concrete [2-3], and a variable proportion of mineral additives such as aggregates (sand and gravel) [4]. The hydration provides the compound to be applied easily and resistance to extreme conditions [5]. Globally, the ready-mixed concrete industry is projected to exceed \$600 billion in revenues by 2025 [6].

On the other hand, it is essential to know that fly ash (FA) is a subproduct of coal-fired power plants whose use is important to reduce the environmental impact of the cement industry. Therefore, FA has been widely used in the construction sector as a mineral additive for the manufacturing of concrete, mineral filling for asphalt concrete, sub-base for pavement layers, among others. It should be noted that, in the field of construction, this material is known as a useful supplementary cementing material [7].



Considering how valuable the load-bearing of any material is, it is crucial to think about the strength conditions. Whose ownership is responsible for the quality control of the material and the concern of designers [8]. Concrete has a great success in its level of compressive load capacity. However, like many other materials, concrete has porosity qualities [9]. Porosity affects the strength of concrete structures during their performance, As well as allowing fluid infiltration into the material, this infiltration can contribute to the future cracking of the compound. In this sense, it is then known that cracks in concrete are inevitable, difficult to detect, and almost impossible to repair. Cracking results in a latent threat to concrete structures since in the long term they can suffer from dangerous faults [10].

Curing is a process in which hydraulic cement concrete develops hardening properties through the hydration of cement in the presence of water and heat [11]. Without effective curing, significant defects related to the long-term durability of the concrete can occur. These defects usually manifest in the form of visible cracks, micro-cracks, and a weak surface. A good state of curing favors the development of the strength and durability of the concrete, as well as can effectively improve the microstructure of the concrete and its ability to resist erosion from external environment. The curing, inherent to the concrete curing process, is directly proportional to the mechanical performance, in addition to its resistance to environmental agents [8].

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 factors of the project [12]. Several studies have now been conducted to demonstrate the viability of several curing agents under different conditions. According to studies conducted by engineers at Landmark University in Nigeria [5], curing depends on the type of agent used in the sample. The samples, in this case, are cylindrical and with conventional properties previously dosed, curing time, and environmental conditions. Other studies have also provided evidence of the variety and permutability of benefits in different properties of the compound [5]. This means that different methods provide different benefits separately, but at the same time show ineffectiveness in other factors. According to the researched literature, two steam curing methods were found [13-16]; burning ash method [17]; microwave curing [18] which consist of techniques commonly used in the practice of curing concrete with heating and atmospheric vapor pressure which according to research has a great advantage in a higher compressive strength at an early age and a lower compressive strength at a later age.

This current research aims to evaluate the strength of treated concrete under eight different curing methods: standard projection, which consists of hydrating the surface of the sample set [19-20]; outdoor curing, involving the non-intervention of external agents [5, 21]; spraying of two types of liquid compounds forming curing membranes; immersion in seawater and immersion in freshwater [22-23], two separate methods in which only the source of the water where the samples are intended to be immersed varies; plastic or vinyl wrappers [14, 24-25]; and immersion in freshwater with lime [1, 26]. The practice of these methods will be further developed in the subparagraphs that require the development of these techniques. The most effective method will be determined by compressive strength test performed on each cylindrical sample, as explained in the methodology.

2. Experimental program

The compressive strength, at 7 and 28 days of hydraulic concrete cylinders that were induced to different curing methods, was evaluated according to the requirements and procedure guidelines established by the ASTM standard [27]. In addition to estimating the results in a laboratory, these results were compared to check if there is an influence between the chosen curing method on the compression resistance values of the concrete. Each curing method had three cylinders for its application, so forty-eight samples were produced (24 to be tested at 7 days and 24 at 28 days).

2.1 Materials

For the experimental program of this research, samples of concrete were made in cylindrical form (20 cm in height and 10 cm in diameter), dosed with two cementitious materials (Portland and FA cement). The samples are composed of the following materials: structural cement type grey, fly ash (from Mount Libano), coarse sand, fine sand, gravel TM 3-8", water, a plasticizing additive, and a retardant additive.

The physical and chemical characterization tests of the materials were performed before design under ambient conditions of 24.2 °C and 62.1% humidity. The physical characterization procedures were carried out by ASTM C33 [28] and ASTM C131-03 [29], and the procedures related to chemical characterization were carried out under ASTM 1218 [30]. Table 1 shows the properties of the aggregates used for this concrete mixture.

Table 1. Physico-chemical characterization of the concrete component aggregates.

Chemical Properties	Fine Aggregate	Coarse Aggregate
Sulphate-SO ₄ [%]	0,088	0,712
Chlorides-Cl [%]	0,0002	0,00117
Physical Properties		
Equivalent percentage of baked sand [%]	68	-
Wear Resistance [%]	-	22,9
Light Particles [%]	0	0
Density [kg/m ³]	2.616	2.539

The fly ash was taken as a supplementary cementing of the mixture to mitigate the environmental impact, aiming at LED certification and to improve the durability factor of said concrete. The characterization of the ashes used in this research is presented in Table 2.

Table 2. Physico-chemical properties of fly ash used.

Chemical Properties	(%)	Chemical Properties	(%)
Silicon Oxide – SiO ₂	44,5	Sulfur Oxide – SO ₃	3,2
Aluminum Oxide – Al ₂ O ₃	19,3	Sodium Oxide – Na ₂ O	1,1
Ferric Oxide – Fe ₂ O ₃	14,5	Potassium Oxide – K ₂ O	1,3
%SiO ₂ + %Al ₂ O ₃ + %Fe ₂ O ₃	78,2	Equivalent Bases – Na ₂ O _{eq}	2
Calcium Oxide – CaO	6,7	Fire Losses	4,6
Magnesium Oxide – MgO	3,1	Humidity	1
Physical Properties			
Sieve fineness N°325 (45 µm)	24		
Density (g/ml)	2,5		

The dosing of the raw materials for the designed concrete mixture was performed for a net capacity of 100L according to the ACI method [31] and is presented in Table 3.

Table 3. Designed mixing dosage.

Raw Materials	Dry weights	
	Quantity (kg)	Tolerance (%)
Portland Cement	246	±4
Fly Ashes	43	±4
Coarse Sand	468	±3
Fine Sand	468	±3
Gravel TM 3-8"	950	±3
Water	165	±1

Additive 1 (Plasticizer)	1,44	±3
Additive 2 (Super Plasticizer)	2,17	±3

The plasticizing and super plasticizing additives were added as aqueous solutions that allowed to regulate, balance, and maintain the design of the mixture. Note that the calculation did not alter the water-cement conditions. Thus, the first additive (plasticizer) achieved the mixture to obtain greater malleability, reduced segregation, and maintained its viscosity; and the second additive (superplasticizer) acted as reducer and retardant of setting water. The mixture was considered considering the characteristic temperature conditions of the coast zone (Barranquilla-Atlántico).

2.2 Methodology

2.2.1. Mixing. The previously dosed materials were placed in a concrete mixer for a period of 15 minutes, ensuring a uniform mixing process.

2.2.2. Trials in a fresh state. The tests were carried out to verify the quality and efficiency of the mixture, to guarantee the correct mixing process of the concrete. The settlement test according to ASTM C143-90 [32] and the density and air content tests according to ASTM C231-09 [33] were performed. The procedure of these trials is illustrated in Figures 1 and 2. The results showed a settlement of 6 ± 1 in, a density of 2.116 kg/m³ and air content of 2%.



Figure 1. Settlement test illustration.



Figure 2. Air content test illustration.

2.2.3. Manufacture of concrete cylinders. We proceeded to manufacture and form concrete cylinders in plastic molds that had dimensions of 10 cm in diameter and 20 cm in length (Figure 3). After 24 hours, the cylinders were uncoupled and prepared for the application of the different curing techniques already mentioned as an objective of this investigation (Figure 4).



Figure 3. Concrete sample formwork.





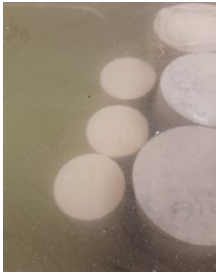





Figure 4. Uncoated concrete cylinders.

2.2.4. Application of curing methods. The curing methods that were applied in this study correspond to conventional on-site and unconventional methods. Eight curing methods were chosen: immersion in drinking water, immersion in seawater, immersion in drinking water + lime + temperature control,

application of brand name curing agent #1. Application of brand name curing agent #2, coating with polyethylene plastic foil, standard manual spraying of fresh water and non-application of curing (6 specimens for each of the curing techniques). Each of these procedures was performed on each trio of samples during the 7 and 28 days after they were unwrapped.

Table 4 specifies the nomenclature and description of the eight curing techniques chosen for the investigation.

Table 4. Nomenclature for selected and applied curing techniques.

			
T1 - Immersion in tap water	T2 - Immersion in sea water	T3 - Immersion in tap water + lime + temperature control	T4 - Curing agent 1
			
T5 - Curing agent 2	T6 - Polyethylene plastic sheets	T7 - Manual water sprinkling	T8 - Without curing

2.2.5 Hardened State Tests. The compressive strength tests were implemented on each of the samples. Two machines were used to carry out these tests. The first one is a cylinder compression frame, with a capacity of 1500 kN, of the reference CT-1500 of the Dirimpex brand. The second machine is a super-automatic console Automax reference 50-C10F04 also of the brand Dirimpex. These machines worked together to carry out the compression tests, which were carried out according to the ASTM C39 standard. Three specimens (of the six specimens of concrete cured under each curing method) failed within 7 days of stripping, and the other three specimens corresponding to each method failed within 21 days (28 days after stripping).

3. Analysis of Results

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

Based on the results obtained from the compressive strength tests of the concrete samples subjected to the curing process during the first 7 days, showed that the batch of samples submitted under the curing technique corresponding to polyethylene plastic sheets (T6) presented a higher resistance value, reaching an average value of 26.7 MPa, followed by the curing agent of brand #1 (T4), which had to undergo an average compression of 26.1 MPa to fail. Moreover, the method of flooding with drinking water with lime + temperature control (T3), presented the weakest yield, with a value of f'_c of 22,8 MPa. These resistance values are slightly lower than those achieved by the samples without receiving any curing method (25,5 MPa).

3.2 Compressive strength (f'_c) at 28 days

According to the values given by the compressive strength tests carried out on the sample groups at 28 days, the samples cured with polyethylene foil (T6) repeat as the most resistant. This time with a value of 32.7 MPa. Followed by the T6, are the drinking water and seawater flooding techniques (T1-T2), with values of 32.2 and 32 MPa, respectively. These two techniques did not present the same efficiency in the seven-day tests. It is pertinent to note that all the samples increased their performance considerably concerning the previous test, so it is easy to deduce that these methods must incorporate into the concrete through a longer rest time.

This was the case for the samples to which the drinking waterflood technique with a solution and temperature control (T3) was applied, which showed the most unfavorable results in the first test, while in the latter they delivered a more resistant product than the samples to which the method related to the spraying with drinking water (T7) and the technique with curing agent #1 (T4) were applied, which provided a final compressive strength of only 27.4 MPa, being further outweighed by the uncured samples. In other words, it could be said that the method with the curing agent of the trademark #1 has counterproductive effects on the concrete in the long term, since in the previous trial (at 7 days) presented an immediate efficiency, which, with the passage of days, was diminished.

Figure 5 shows an illustration of the characteristic failures of the cylinders tested at both 7 and 28 days, their appearance being very similar for each of the groups of samples subjected to the different curing techniques studied.



Figure 5. Typical cylinder failures tested at 7 and 28 days.

Figure 6 summarises the average compressive strength values of groups of samples by curing technique used at 7 and 28 days, respectively:

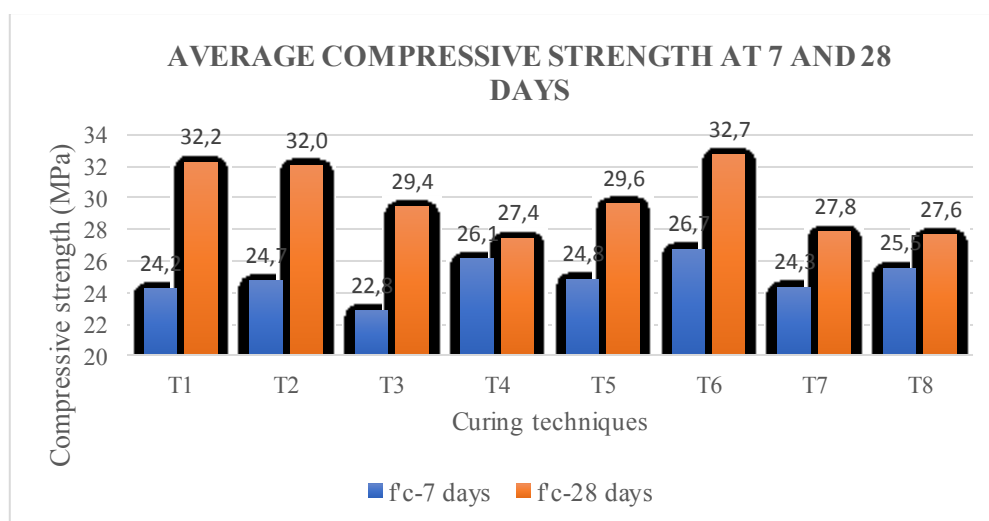


Figure 6. Average compressive strength values of the batches of the samples tested.

Figure 7 illustrates the efficiency of each of the curing techniques selected for the analysis, contrasted with the samples that were not subjected to any curing process (T8). It is worth highlighting the similarity of the technique corresponding to the manual spraying of water (T7), which is a method commonly used in works, with the samples uncured. That fact could be supported as it is a manual process with a lot of care to consider, it is difficult to guarantee its correct and constant procedure.

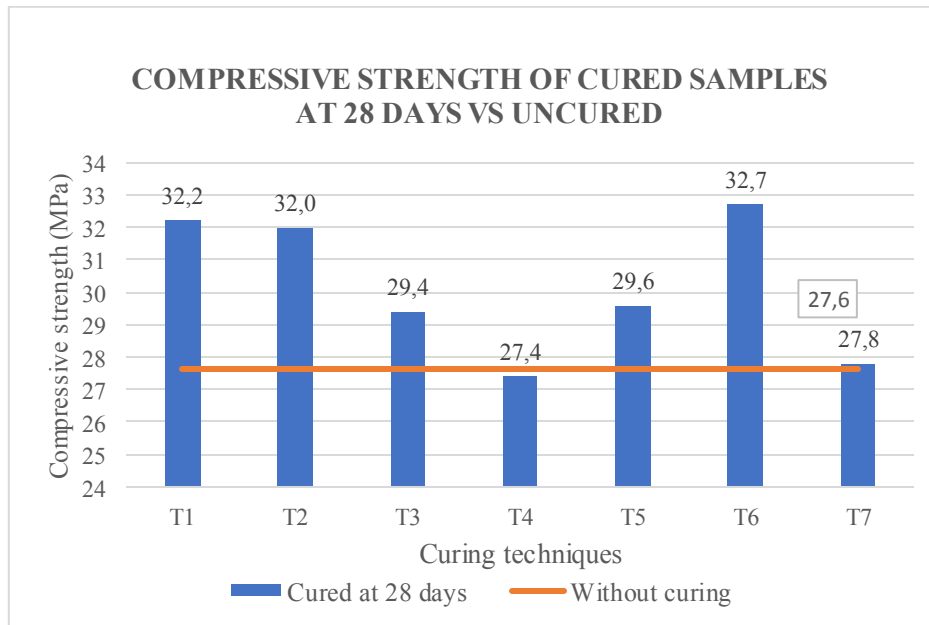


Figure 7. Comparison of the results of curing versus curing techniques.

Table 5 presents a simple statistical analysis of the results obtained, given from the value of the standard deviation, rating these results according to the criterion of ACI 214 [34], as: excellent, very good, good and, only in a poor case (T7), indicating for the latter a considerable dispersion in the values released. It should be noted that resistance was worked with at 28 days, as the results of the ACI 214 report are valid only for this age.

Table 5. Statistical analysis of the results obtained.

Technique	$f'c$ av. (MPa)	Standard Deviation σ (MPa)	ACI 214 Classification
T1	32,2	0,428	Excellent
T2	32	1,112	Excellent
T3	29,4	1,483	Very Good
T4	27,4	1,926	Good
T5	29,6	1,687	Very Good
T6	32,7	0,877	Excellent
T7	27,8	2,672	Poor
T8	27,6	1,69	Very Good

Based on the results of the investigation, the peak of efficacy was evident in the technique using polyethylene plastic sheets (T6), which showed favorable results from its compression trial applied at 7 days (26.7 MPa) ratifying with an average resistance of 32.7 MPa after 28 days.

At the same time, when evaluating the experimental results, it was possible to observe the negative influence on the compression resistance of the commercial curing agent #1 (T4), which was evidenced at 28 days with an average resistance of 27,7 MPa, differing from samples that were not cured (T8) by only 0.5 MPa (26.7 MPa), with the latter being the least effective curing technique of all those studied here. For this reason, perhaps a better control or greater application of the product is suggested.

About the manual spraying technique for drinking water (T7), it can be concluded that although it is the most frequently used standard technique in the local construction industry and from which better results were expected, yielded an average compressive strength at 28 days also very similar to not applying any type of curing (27.8 MPa versus 26.7 MPa). With the result, the recommendation to change the curing methods in the usual constructions is generated, putting in alert the quality of the concrete in a matter of resistance to the compression.

Finally, the technique of immersion in seawater (T2) was found to increase the resistance to 28 days of the samples by a value of 32 MPa, demonstrating the benefits of compression resistance in concrete. However, it is worth noting that these analyses were carried out to a specific standard without reinforcement, so that the response of reinforced concrete to the application of the technique of curing by immersion in seawater is opened to other investigations, which is presumed to have corrosion and carbonation consequences due to the concentration of salts, lowering the pH of the concrete. It is necessary to emphasize that the application of this technique would be appropriate to the demand for environmental awareness and the inevitable use of water in construction.

4. Conclusions and Recommendations

- From the results of the present investigation, it is concluded that the techniques where immersion in water (T1, T2 and T3) and the technique of coating with polyethylene plastic around specimens (T6) are the most effective methods to perform curing on site.
- The cylinders with curing agent 1 (T4), presented an adequate behavior to the resistance to the compression at 7 days, but its lack of efficacy is evident in more advanced days and to be able to maintain the humidity in the concrete because resistance to compression was obtained very similar to the resistance that was obtained without carrying out the curing process.
- The compression resistance of the cylinders with the seawater curing technique yielded positive results. However, the seawater is not recommended for use with concrete as the reinforcing steel is usually in conjunction with the concrete and could end up with problems of accelerated corrosion and carbonation.
- Positive results according to ACI 214 on the standard deviation of the compressive strength of concrete cylinders are evident, which supports an adequate experimental procedure. However, the T7 technique gave "poor" confidence because when simulating spraying conditions on-site, it probably was not performed uniformly, as it happens in construction sites.
- The need for the curing process in the concrete is evident independently of the technique used to achieve greater resistance to compression.
- Finally, despite the results found in the research, it is recommended to continue analyzing the influence of concrete curing methods on other parameters such as durability, water absorption, carbonate penetration, among others; and it is also recommended to carry out a microstructural analysis of the samples tested to further deepen the interpretation of the results obtained, as well as taking a greater number of samples per batch.

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