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Influence of Multiple Methods and Curing Temperatures on the Concrete Compressive Strength

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Abstract: The present study aimed to analyze the interference of different curing conditions on the development of the concrete compressive strength under the perspective of construction management. It is known that the conditions of humidity and temperature are the main factors related to the behavior of the concrete strength, so that modifying these parameters directly affects the material's behavior and, consequently, construction management. Forty-two specimens of concrete were molded and each 6 specimens were submitted to different temperature and humidity conditions. The first group was oven-cured at a temperature of 100°C. The second and third groups were kept at ambient temperature of 23 ± 2°C being that the latter was submerged in water and the former was exposed to the air humidity. The specimens of groups 4 and 5 were placed in a freezer at 5°C. Group 4 was submerged in water and group 5 was not. The curing of group 6 occurred under submerged condition with water at about 100°C. Group 7, on the other hand, was cured in water vapor. The group submitted to curing at room temperature and submerged condition was the one with the highest compressive strength value, while the ones with the lowest compressive strength were the groups of samples cured in the oven and those submerged at 100°C. The results were compared and tested using statistic methods, which proved that the curing conditions directly affected concrete properties.

Keywords: Concrete strength, curing temperatures, statistic.

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1. Introduction

With the advent of technology, allied to the needs of modern society, concrete has become one of the materials that is most consumed in the world. Due to its properties of strength and workability, it became a protagonist in the civil construction scenario, being one of the main responsible for the economic movement not only in Brazil but also throughout the world (Mehta and Monteiro, 2005). It is possible to present some main reasons why concrete has acquired so much importance in the civil construction. The first of these is due to the fact that, unlike wood and steel, it exhibits resistance to water, fire and corrosion, making it possible to be used in structures such as bridges, dams, canals and containment structures. Secondly, it can be molded in various sizes and shapes, thus being able to meet the most varied needs of use. In addition, after acquiring strength, the molds can be removed and reused. Another reason that favors the use of concrete is the ease of obtaining the material (Mehta and Monteiro, 2005).

During its application, concrete undergoes constant temperature and humidity variations due to climatic alteration. Factors such as precipitation, relative humidity, temperature and wind speed affect the characteristics of the material (Mehta and Monteiro, 2005; Neville and Brooks, 2010).

In view of all the advantages mentioned above, it is possible to understand the importance of the use of concrete in constructions. However, for this material to be of maximum benefit, it is essential that the first days after its application are constantly monitored, especially the humidity and temperature conditions. This process is known as concrete cure. The main function of curing at normal temperature is to keep the concrete as saturated as possible, so that the spaces that were originally occupied by water in the fresh cement are filled by the products of cement hydration. (Neville and Brooks, 2010).

The main compounds present in the Portland cement are the Tricalcium Silicate, the Dicalcium Silicate, the Tricalcium Aluminate and the Tetracalcium Ferroaluminate. In the presence of water, these compounds give rise to hydration products which give a firm and resistant mass. The aluminates, when in the presence of the gypsum, are responsible for the formation of ettringites, which are responsible for the setting of the concrete. This reaction occurs early in the hydration. The silicates, on the other hand, are related to resistance characteristics (Neville and Brooks, 2010).

In fact, according to Mehta and Monteiro (2005), the compounds do not hydrate at the same rate. Aluminates are known to hydrate faster than silicates. In fact, the stiffening and hardening characteristics of a Portland cement paste are largely determined by the hydration reactions involving the aluminates. The silicates, which make up about 75% of the common Portland cement, play a dominant role in determining the resistance characteristics.

Since concrete reactions only occur in the presence of water, the importance of controlling temperature and humidity in concrete works is comprehensible. In the application, there are several ways of performing concrete curing such as the application of blankets that keep the surface constantly wet or even the application of water on the surface within certain periods of time are common use (Mehta and Monteiro, 2005).

In Brazil, some of the standards governing the conditions for curing the concrete are ABNT NBR 14931: 2004 and ABNT NBR 12655, the first of which defines that surface structural elements must be cured until they reach a compressive strength equal to or greater than 15 MPa. (ABNT NBR 14931, 2004). Studies suggest that the higher concrete resistance rate occurs in the first three days, so that humidity should be controlled with greater caution in this period (Neville and Brooks, 2010).

When it comes to curing temperature, it is important to take into account the fact that very high temperatures lead to a high rate of water evaporation present in the concrete, leading to possible cracks. On the other hand, concreting at too low temperatures has the problem of freezing the water that is present in the concrete capillaries, which generates an increase in void volume and a consequent increase in porosity, which directly affects the material. Thus, both temperatures require caution in the curing process (Neville and Brooks, 2010).

Powers (1947) stated that hydration reactions decelerate when indoor humidity is low, and almost stop when humidity is below 80%. In other words, due to the loss of water and the corresponding reduction of internal relative humidity in the pores of a cementitious material, the development of concrete properties can be hampered, even though the system still has a considerable amount of water.

Mi et al. (2018) developed four curing chambers, capable of automatically controlling temperature and relative humidity. The study stated that the development of various properties of the concrete structure depends on the available water and if the structure is exposed to very low humidity, surface hydration will be interrupted and this phenomenon will cause surface cracks and will not provide the desired protection. Gradually, the hydration of internal parts will also be affected, since the water present in the pores is also lost through the draining surface of the system.

Saengsoy et al. (2008) analyzed the behavior of cured concrete in five different environmental conditions. The curing conditions were: submerged cure, sealed cure and curing at 60%, 80% and 95% relative humidity. Their studies showed that the compressive strength of water-cured concrete with 95% moisture increased rapidly and became virtually constant after 28 days. However, when exposed to a humidity of 80%, the strength of the concrete developed slowly. Particularly at 60% moisture, the resistance practically did not increase after 7 days, causing a loss of approximately 41% in resistance, when compared to the material cured in water, that is, at 100% humidity.

The studies of Shoukry et al. (2010) point out that the increase in concrete temperature at 80°C results in a loss of compressive strength and tensile strength at 38% and 26%, respectively. In that study, 137 specimens were molded, and cured in adapted chambers that produced hot and cold air. Subsequently, the specimens were tested for compression and horizontal tensile forces. The horizontal and vertical loads were recorded, as well as the magnitude of the load applied. This way, it was possible to verify the behavior of the modulus of elasticity and the Poisson coefficient. It was concluded that the modulus of elasticity decreases as the curing temperature increases; in their studies a temperature rise from 20°C to 50°C resulted in a reduction in modulus of elasticity ranging from 62% to 23%. Regarding moisture, studies showed that the modulus of elasticity decreased as the degree of saturation increased. In fact, there was a decrease of almost 20% in the modulus of elasticity as humidity increased from 0% to 100%. In relation to the Poisson coefficient, it was concluded that the different temperature and humidity conditions can not affect their characteristics after curing the material, and the variation of the values is negligible.

Nassif and Petrou (2013) studied the influence of cold weather during casting and curing on the stiffness and strength of concrete. The experimental program involved casting and curing 25 concrete slabs of 750 x 750 x 300 mm which were kept in a room with monitored temperatures of 20°C, 10°C, 3°C, 0°C and -5°C. They concluded that the curing at near freezing temperature caused the formation of micro cracks up to 10 mm wide and 10 mm long. Besides that, the 28-day compressive strength was reduced by approximately 25% when the concrete slab was cured at 0°C instead of 20°C. The reduction increased to 50% when the cured temperature dropped to -5°C.

The concrete management is a process that requires attention during all its stages, since production up to post application, once concrete performance strongly depends on the curing management. According to Mehta and Monteiro (2005), construction engineers should have a general understanding of the possible effects of both lower and higher-than-normal temperatures on concrete properties, and the methods of evaluating and controlling them.

Still according to Mehta and Monteiro (2005), the problem usually arises when the construction scheduling decisions are based on laboratory cured cylinders whereas the actual curing history of the in-place field concrete happens to be very different. For that matter, the importance of this paper lies on the fact that temperature is a crucial characteristic to be controlled during the concrete production, and it is essential to point out that Brazil is a country with continental dimensions, so that the temperature may vary considerably from region to region on the same day. Furthermore, in some regions, there is also a great variation of humidity and temperature throughout the year, depending on the season. Due to this variation, it is fundamental to pay special attention to the particularities that each region presents on the day of application, as well as on the subsequent days.

2. Methodology

For the accomplishment of this experiment, 42 cylindrical concrete specimens were cast. The sand used had a characteristic maximum dimension of 2.36 mm and fineness modulus of 1.94. The crushed stone used was number 0 with characteristic maximum dimension of 9.5 mm. The cement was Portland type II, with the addition of Filler (CP II-F 32), with chemical composition similar to ASTM Type I. According to Brazilian standard ABNT NBR 5738 (2008), each specimen had a cylindrical shape, with 10 cm diameter and 20 cm in length and they were cast in metallic molds.

The concrete dosing in mass was 1: 1.49: 2.06: 0.48 (cement : sand : gravel : water). Due to the large amount of material required for the molding of the specimens, it was necessary to perform two batches. The first one with 14.5 cm slump and the second with 15.5 cm, resulting in an average of 15 cm of slump.

After 24 hours, the 42 specimens were demolded and subjected to curing under different temperature and humidity conditions. The first group was cured in a laboratory oven at a temperature of 100°C (Fig 1). The second group was also in the laboratory, but submerged in water and kept at room temperature, which varied around 21-25°C (Fig 2). The third group was also maintained in the laboratory at room temperature of 23+/-2°C and average humidity of 91%. The fourth group was placed in a freezer, inside a container with water with temperature monitored around 5+/-1°C (Fig 3). The fifth group was also at 5+/-1°C, since it was in the same freezer, but this group was not submerged, maintaining its lower humidity (Fig 4). The sixth group was submerged in a vessel that allowed temperature control, which was maintained around 100°C and the seventh group was cured in the steam generated by the water present in the vessel where the group 6 had been submerged. Table 1 presents the curing conditions of each group.

After 28 days, the specimens were submitted to compression tests in a hydraulic press with a capacity of up to 2000 kN, according to ABNT NBR 5739 (2007) (Fig 5).

Fig. 1. Laboratory oven for curing of group 1

Fig. 2. Specimens submerged in water

Fig. 3. Specimens submerged in water and kept in a freezer.

Fig. 4. Specimens cured in a freezer

Fig. 5. Hydraulic press in which specimens were tested

Table 1. Curing conditions of the specimens

Curing condition	Quantity of specimens	Description
1	6	Oven at 100°C
2	6	Submerged at room temperature
3	6	Not submerged, at room temperature,
4	6	Submerged at 5°C
5	6	Not submerged, at 5°C
6	6	Submerged at 100°C
7	6	Steam cured, at 100°C

3. Results and Discussion

According to the data presented in Table 2, the groups that presented the highest values were groups 2 and 3, which were (i) submerged at room temperature and (ii) not submerged, also at room temperature, respectively. The groups that presented less strength were groups 1,5 and 6, i.e. the group that was cured in an oven, the one that was cured in the freezer (not submerged) and the one that was submerged in water at 100°C.

One-way analysis of variance, also known as ANOVA, was performed, in order to identify whether the differences in the results were significant or not. The null hypothesis for ANOVA states that the values of compressive strength do not differ from one another in a significant way. On the other hand, the alternative hypothesis states that the values are not the same; therefore, there is a significant difference among the values of compressive strength. The results are presented in Table 3. The significance level threshold was α=0.05, which means that, if the p–value is higher than 0.05, the null hypothesis must be accepted and if it is lower than 0.05, the null hypothesis must be rejected. Once the p-value is 0.000, i.e, lower than the α value, it´s possible to conclude that the null hypothesis was rejected and that the variation in the compressive strength values was significant.

Once it was established that the difference in values was significant, the Tukey´s test was also performed in order to analyze which were the groups that presented the most considerable discrepancy.

Table 2. Values of compressive strength and standard deviation

Group	Specimen	Compressive Strength (MPA)	Compressive Strength Average (MPa)	Standard Deviation	Variation Coefficient %
1	1	37.98	34.56	2.93	8.47
	2	38.25			
	3	33.96			
	4	32.59			
	5	31.06			
	6	33.52			
2	1	45.82			

Table 2. Values of compressive strength and standard deviation (continued)

Group	Specimen	Compressive Strength (MPA)	Compressive Strength Average (MPa)	Standard Deviation	Variation Coefficient %
2	2	46.92	46.08	2.15	4.67
	3	49.89			
	4	45.65			
	5	44.19			
	6	44.04			
3	1	41.8	41.69	4.18	10.53
	2	34.26			
	3	44.18			
	4	41.82			
	5	41.58			
	6	34.67			
4	1	38.75	37.75	2.48	6.57
	2	33.83			
	3	36.81			
	4	39.08			
	5	41.08			
	6	36.97			
5	1	35.96	34.83	2.00	5.75
	2	33.53			
	3	33.42			
	4	38.44			
	5	33.77			
	6	33.84			
6	1	30.85	33.52	2.14	6.40
	2	34.42			
	3	36.59			
	4	34.05			
	5	33.96			
	6	31.24			
7	1	32.05	37.00	3.20	8.65
	2	41.28			
	3	35.9			
	4	35.57			
	5	38.49			
	6	38.72			

Table 3. ANOVA results

Source	Degrees of freedom	Sum of Squares	Mean Square	F- ratio	p - value
Regression	6	662.683	110.447		
Error	35	278.592	7.959	13.875	0.000
Total	41	941.275			

Table 4. Tukey´s test results

Comparison	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
Group 1		11.52	7.13	3.19	0.27	1.04	2.44
Group 2	11.52		4.39	8.33	11.25	12.56	9.08
Group 3	7.13	4.39		3.94	6.86	8.17	4.69
Group 4	3.19	8.33	3.94		2.92	4.23	0.75
Group 5	0.27	11.25	6.86	2.92		1.31	2.17
Group 6	1.04	12.56	8.17	4.23	1.31		3.48
Group 7	2.44	9.08	4.69	0.75	2.17	3.48	

The Tukey´s test established an Honestly Significance Difference (HSD) value of 5.1. It means that the groups that presented a variation of more than 5.1, have a significant level of variation in the compressive strength. The results of Tukey´s test are presented in Table 4. The hatched values are higher than the HSD. From the Tukey´s test, it was possible to conclude that every group presented a significant difference with at least one other group.

It can be observed that in the groups with higher values of compressive strength, the temperature varied around 20°C, whereas in groups 1, 5 and 6, which presented some of the lowest resistance values, the curing temperature was maintained in very hot (100°C) or very cold (5°C) situations. From these data, it can be seen that the curing temperature had a significant influence on the concrete compression strength value.

In fact, higher temperature causes loss of water with greater speed, leaving the material with low humidity. In addition, the rapid evaporation of water results in loss of workability and reduction of hydration reactions, which generates an inappropriate strength development during cement hydration. Another effect that occurs quite frequently due to the rapid loss of water in the concrete is the plastic retraction fissure. Although it does not have a great influence in the resistance of the concrete, the fissures influence negatively in the aesthetic question besides being a problem in the matter of the infiltration (Neville and Brooks, 2010).

Another characteristic of high temperature cured concrete is that it exhibits higher values of initial compressive strength, but after 28 days, it presents a lower development of strength if compared to concrete cured at relatively lower temperatures (Mehta and Monteiro, 2005).

In the case of group 1, which presented an average value of 34.56 MPa, the conditions were of high temperature, which resulted in rapid evaporation and probably caused the mentioned problems. In the case of group 6, it is possible that, due to the high temperature, even if submerged, evaporation of water from the capillaries inside the specimen has occurred, causing a reduction in resistance values.

The specimens of groups 4 and 5 presented average compressive strength values of 37.75 MPa and 34.83 MPa, respectively. These specimens were subjected to a rather low temperature. It is important to notice that, at very low temperatures, water may freeze the mixture, which causes an increase in the volume of free-surface concrete masses, and a delay in reactions due to the lack of available water. Once the thaw occurs, the concrete will harden in its expanded form, thus having a greater amount of voids, affecting its resistance. If the freezing occurs before the setting, it is possible to revert the concrete back to its natural pore volume, however this practice is not very recommended since it is difficult to specify the moment the setting starts. If the freezing occurs after the setting has started, however, before the material has acquired considerable strength, the expansion causes an irreparable strength loss. Generally, the more advanced the hydration stage, the greater the concrete resistance against water freezing effects (Neville and Brooks, 2010).

The groups with the highest average strength value were presented by groups 2 and 3, with 46.08 MPa and 39.72 MPa, respectively. It is noticed that the temperature played a fundamental role in the strength development, since in these cases, the specimens were not submitted neither to very high nor very low temperatures. At room temperature, the concrete does not suffer loss of water in an accelerated manner, nor does it suffer from an increase in volume of voids due to the capillary water freezing, so that there is no interruption in the cement hydration process. Compared to group 3, group 2 had greater strength development; this result is due to the fact that in group 2, the humidity of the test specimen was always 1, whereas in group 3, this was slightly smaller, causing a relative decrease in the hydration processes.

When compared, the submerged groups, 2, 4 and 6, respectively, presented values of 46.09 MPa, 37.75 MPa and 33.52 MPa, respectively. It is observed that there was a great discrepancy in the values. That is, in these three cases, the only factor responsible for the difference in results was the temperature, since all were being cured with humidity 1. Figure 6 also presents the results obtained in the experiment.

Comparing to literature data, Shoukry et al. (2010) observed a reduction in concrete compressive strength in the order of 38% when the curing temperature was 80°C, whereas Nassif and Petrou (2013) observed a reduction of resistance in the order of 25% at curing temperatures of 0°C. In this study, the results obtained corroborate both studies; after all, when comparing the resistance to compression of group 2 with groups 5 and 6, it is possible to observe that the resistance variation was 24.41% and 27.25%, respectively.

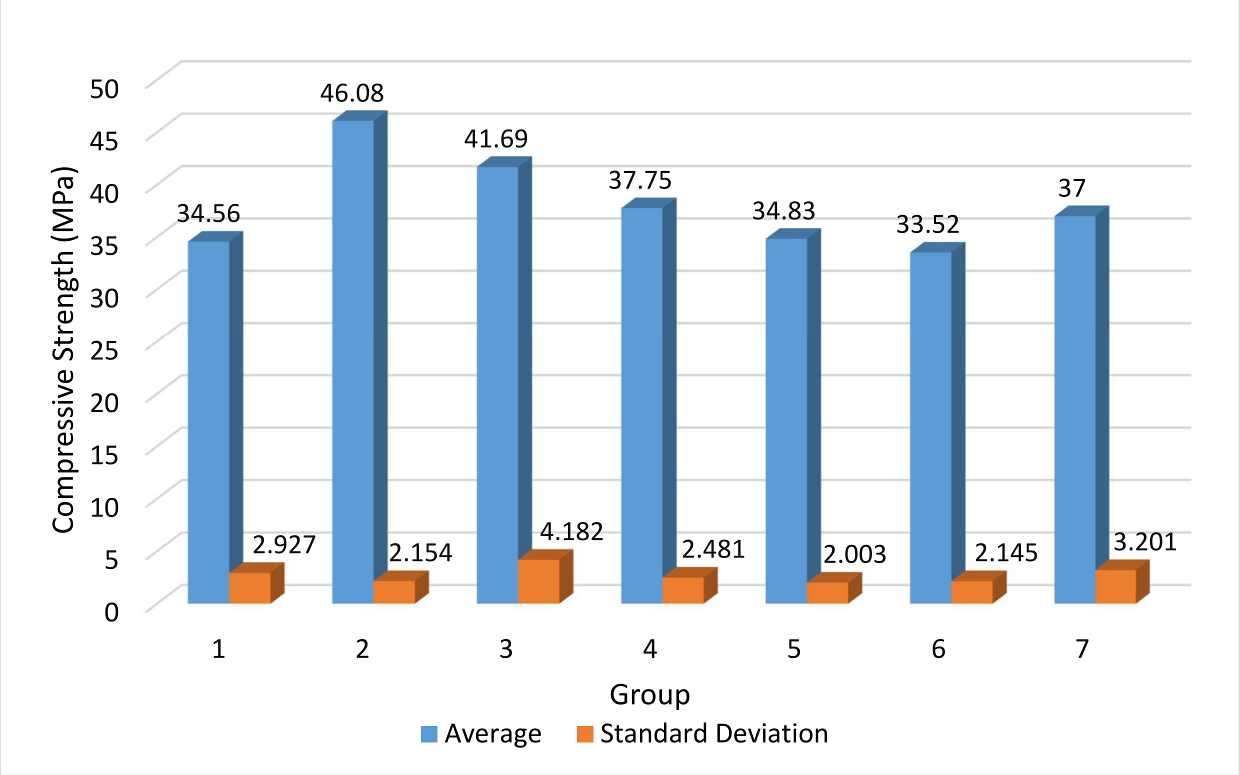

Fig. 6. Values of compressive strength and standard deviation

When it comes to relative humidity, Saengsoy et al. (2008) observed a reduction of 41% when the relative humidity was 60%. In this study, a reduction in resistance was observed, however, with values ranging from 9.52 to 24.41%, comparing the resistance of groups 3 and 5.

4. Conclusion

The temperature and humidity curing conditions are directly related to each other, both of which directly affect the characteristics of the material after its application.

In everyday life, it is important to take into account the fact that the temperature and other climatic conditions of the place where the concrete will be applied can cause undesirable effects on the structures, especially those with large flat exposed surfaces.

The loss of moisture due to high temperature is one of the main phenomena that should be avoided, because it causes plastic retraction and consequently, cracks. The best solution to such adversity is to keep the structure always moist.

The main conclusions that can be draw by this work are:

- The best curing methodology was obtained by group 2, using submerged curing at 23+/- 2ºC.
- The worst compressive strength performance was obtained from concrete cured submerged at 100ºC, due to loss of water present in the capillary spaces for cement hydration.
- The concrete curing methodology below temperatures of 5ºC (groups 4 and 5) or over 100ºC (groups 1, 6 and 7) can lead to a reduction of almost 20% in the concrete strength independently of the relative humidity condition.

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