Journal of Engineering, Project, and Production Management
2018, 8(2), 56-64

Influence of Distinct Curing Environments on the Compressive Strength of Concrete

Ronaldo A. Medeiros-Junior[1], Maryangela Geimba de Lima[2], and Carlos Eduardo Tino Balestra[3]
[1]Professor Ph.D, Department of Civil Construction, Federal University of Parana (UFPR), Centro Politecnico, Curitiba, Parana, Brazil. E-mail: medeirosjunior.ufpr@gmail.com.
[2]Professor Ph.D, Department of Civil Engineering, Aeronautics Institute of Technology (ITA), Marechal Eduardo Gomes, 50, Sao Jose dos Campos, Sao Paulo, Brazil. E-mail: magdlima@gmail.com
[3]Professor Ph.D, Department of Civil Engineering, Federal University of Technology – Paraná, Cristo Rei street 19, Toledo, Paraná, Brazil. E-mail: carlosbalestra@utfpr.edu.br (corresponding author).

Engineering Management
Received June 29, 2018; received revision July 16, 2018; accepted July 16, 2018
Available online July 21, 2018

Abstract: This paper discusses the influence of different curing conditions on the compressive strength of concrete test specimens monitored for 365 days. Five cures were analyzed. Statistical tests were applied (variance analysis and Fisher's) in order to evaluate the data. According to results, different curing conditions influence the compressive strength of concrete. The main novelty of this article is that the curing conditions affect the concrete compressive strength significantly only for ages over 28 days. Furthermore, this study shows that concrete specimens saturated with water have superior strength to concrete cured in a standard environment (moist chamber). The compressive strength of concrete decreases, respectively, with the following types of curing investigated: water tank, moist chamber, tank with water and lime, laboratory internal environment and external environment. The compressive strength gain over time also varies for each condition. The lower values found for the external environment confirm the greater difficulty of controlling the water loss on this environment, resulting in decrease of compressive strength.

Keywords: Concrete structures, compressive strength, cure, statistical, building.

1. Introduction

The construction industry plays a key role in the economy of several nations in the world, being cement Portland concrete the main material for execution of structures (Algorafi et al., 2011; Lam and Gale, 2015; Mehta and Monteiro, 2008). In this way, the adequate binding of the cement in concrete is associated with the hydration reaction products of cement and water. Premature water loss of the fresh concrete due to high temperatures, low relative humidity and high wind speed may harm the hydration and, consequently, the compressive strength (Zhao et al., 2012; Bingöl and Tohumcu, 2013). Thus, curing is a treatment that avoids an excessive drying and provides enough water content to the concrete mass in order to hydrate especially, its external layers (Gayarre et al., 2014; Medeiros-Junior et al., 2014). Curing of cement composites plays an essential role for both the strength and durability properties of the hardened concrete. According to Ibrahim et al. (2013), some problems of concrete cracking have been reported from the field due to inadequate curing.

The curing process is even more important in hot weather conditions. Reduced durability is one of the major problems in concrete produced under hot weather conditions and this may cause several problems for both the fresh and the hardened concrete (Medeiros-Junior and Lima, 2016). Under these extreme conditions, an extended curing period of time may usually be necessary for the concrete structure (Ibrahim et al., 2013). Proper curing conditions are also important to improve corrosion resistance (Maslehuddina et al., 2013) and the surface electrical resistivity of concrete (Presuel-Moreno et al., 2013).

Several methods of curing may be employed in concrete. Some examples are: pounding and immersion, impervious paper, wet coverings, fogging and sprinkling, plastic sheets, steam curing, infrared curing and microwave (Bingöl and Tohumcu, 2013; Prommas and Rungsakthaweekul, 2014). The most effective method for curing concrete depends on the materials used, the method of construction, and the intended use of the hardened concrete (Prommas and Rungsakthaweekul, 2014). In laboratory, for concrete quality control, immersion or moist chamber are generally used to concrete curing. In the field, wet covering is widely used. Recently, steam curing has been studied and better understood to be used in concrete. According to Ramezanianpour et al. (2014), initial heat or steam curing at atmospheric pressure is highly recommended to improve the initial compressive strength of concrete.

Gayarre et al. (2013) verified the effect of curing conditions on the compressive strength of recycled aggregate concrete. The strength of concretes with recycled aggregate that are cured outdoors decreases significantly. This behavior is clearer when the percentage of replacement is greater. They also found that the decreases of resistance in samples of concrete with recycled aggregate cured outdoors are more significant after 28 days than at 7 days. In this way, it should be pointed out that a significant increase of cement hydration occurs during first 28 days (Mehta and Monteiro, 2008; Neville and Brooks, 2013); Consequently, this is the reference age for concrete quality control.

Bingöl and Tohumcu (2014) observed the effect of air curing, water curing and steam curing on the compressive strength of Self Compacting Concrete (SCC) incorporating fly ash and silica fume until 28 days. The highest compressive strength was observed in the concrete specimens in water curing (28 days). The lower strength was obtained from concrete specimens in air curing under laboratory conditions, also for 28 days.

Jiang et al. (2014) studied the effect of curing temperatures on high performance concrete and found that curing temperature is also very important to autogenous shrinkage properties. The rate and the magnitude of autogenous shrinkage increases with the increase of the curing temperature; extents of this influence varies with the water/binder ratio, age and composition of cementitious materials. The hybrid curing technique that combines internal curing with shrinkage reducing admixture may be a potential approach for reducing the total shrinkage and cracking mainly on high performance concrete (Zhutovsky et al., 2013).

Besides the influence on durability and strength, according to Prommas and Rungsakthaweekul (2014), concrete curing interferes on the water tightness, abrasion resistance, volume stability, and resistance to freezing and thawing, and deicers.

Within this context, the compressive strength test is widely used in engineering for construction control and verification of concrete dimensioning. This is one of the most popular assays in specimens in civil construction and generally used as a parameter for the final control of concrete poured on the structure.

Thus, the curing process of concrete tries to oppose the undesired effects of some environmental actions - relative humidity, high temperatures, wind and sun radiation (Gayarre et al., 2014; Medeiros-Junior et al., 2015), so the effect of standard and non-standard curing environments on the compressive strength of concrete is studied in this paper. The objective of this paper is to compare five methods of concrete curing, verifying the differences on the results obtained, once this methods can be applied in the manufacture of pre-cast concrete structures imparing the concrete strength. The greater virtue of this study is that concrete resistance was monitored until 1 year, unlike many of the studies that follow compressive strength only until 28 days. As will be verified in this paper, the influence of the types of curing on the compressive strength of the concrete may vary between the early ages and the more advanced ages.

2. Material and Methods

Cylindrical test specimens of ϕ 10 cm x 20 cm of length were cast. The moldings were made according to Brazilian standard ABNT (2008). The molds used were metallic ones, prepared according procedure specified by the mentioned standard.

The concrete used was dosed at plant. Table 1 presents the characteristics of the concrete. A concrete without additives was requested, that met the specifications of conventional concretes of current constructions in the city of Sao Jose dos Campos – SP (Brazil), where this study was performed.

The CPIIIRS Portland cement with blast furnace slag and sulfate resistant (ABNT, 1991) was used as binder. Natural and artificial sand (basaltic origin) as well as the crushed stone were used. Table 2 shows data regarding the physical characterization of aggregates.

Water used for concrete dosage was also analyzed (Table 3), and results show that the sample is within the general and specific requirements for water to be used in mortar and cement concretes (ABNT, 2009).

Table 1. Specification of concrete mix

Cement (kg/m^3)	Natural sand (kg/m^3)	Artificial sand (kg/m^3)	Crushed stone (kg/m^3)	Water (l/m^3)
351	529	277	1003	191

Table 2. Aggregates specifications

Aggregate	Specific mass (kg/dm^3)	Unit Mass (kg/dm^3)	Characteristic maximum dimension (mm)	Fineness modulus
Natural sand	2.62	1.40	2.4	2.45
Artificial sand	2.70	1.55	4.8	2.65
Crushed stone	2.70	1.49	25	7.19

Table 3. Water specification

Parameters	Result in 100 ml of specimen diluted at 10%	Result in 100 ml of specimen 10% filtered	MAV
Iron (mg/l)	0.03	0.03	1
Silica (mg/l)	6.1	6.0	NE
Manganese (mg/l)	0.08	0.10	NE
Nitrite (mg/l)	0.10	0.07	NE
Nitrate (mg/l)	1.00	1.00	NE
Sulfate (mg/l)	19	17	300
pH	7.1	7.1	6.0-9.5

As determined by ABNT (1998a), the slump test was performed for receiving the concrete, according to ABNT (1998b). A slump of 60mm was identified for the used concrete, meeting the initial specification.

The samples were manually densified, according to the following procedure prescribed by standard ABNT (2008): the manual densification was performed using metallic and cylindrical steel rods.

Those rods have a smooth surface and dimensions of ϕ 1.6 cm and 65 cm of length, with one of the extremities of hemispherical shape, with diameter equal to the one of the rod. The filling of molds was performed in two layers of approximately equal volumes, densified with 12 hits each one. Then, the razing of surface was performed in each sample, a metallic rule being used for that.

After molding, the specimens were immediately covered with non reactive and non absorbing material, aiming to avoid the water loss of concrete and to protect it from bad weather. After this procedure, 24 hours were given to allow the initial hardening condition of concrete, in order to finally, perform the demolding.

Five types of curing (exposure environments) were selected for investigation in this paper, namely:

(1) Curing in moist chamber: this procedure follows conditions established by Brazilian standard (ABNT, 2007) and will generate the reference values (Fig. 1).

(2) Curing in tank with potable water: the curing of test specimens were performed with them totally submerged in water; the finality is to avoid water evaporation, keeping the concrete saturated (Fig. 2).

(3) Curing in tank with water saturated with lime: this curing had the objective of avoiding the exit of calcium ions of concrete for the water, in order to establish a comparative with the condition mentioned in (2) (Fig. 3).

(4) Curing in environment internal to the laboratory: this condition was added in order to have a comparative with the external environment, totally exposed (Fig. 4).

(5) Curing in environment external to the laboratory: this condition aimed to simulate the curing identified on constructions. However, it is important to highlight that many times on the constructions those concretes are submitted to processes of wetting or protective films (Fig. 5).

Fig. 1. Concrete curing in moist chamber

Fig. 2. Concrete curing in tank with potable water

Fig. 3. Concrete curing in tank with lime saturated water

Fig. 4. Concrete curing in environment internal to the laboratory

Fig. 5. Concrete curing in external environment

In this paper, the test of compressive strength was planned for the following ages: 7, 28, 63, 91, 180 and 365 days; thus, until the specimens completed one year.

Compressive strength was determined according to standard ABNT (2007); test specimens were broken in universal press for tests (model HD-200T), under constant loading speed.

3. Results and Discussion

Table 4 shows the values of compressive strength of specimens according to different curing methods at 28 days. Fig. 6 shows the mean values of compressive strength for each condition of curing and age. Estimated standard deviation inside the test was 1.03, 2.10, 0.25, 0.64 and 0.81 MPa, for curing conditions: moist chamber, water tank, water and lime tank, internal environment and external environment, respectively.

According to Fig. 6, resistance is higher for the curing saturated in water tank and smaller for the curing under exposition to external environment. The decrease of compressive strength of the concrete exposed to the external environment is caused by uncontrolled conditions of temperature and relative humidity. Those conditions are more extreme in the external environment and cause a greater water loss of the concrete mass needed for the adequate hydration of cement. Fig. 7 shows the maximum, mean and minimal monthly temperatures and the mean relative humidity, during the study period (1 year) of this paper, recorded by the nearest weather station from the place where the concrete test specimens were molded. Between the months of May and August are observed the lower temperatures and relative humidity of this period. The higher temperatures are identified between the months of November and February.

Table 4. Concrete strength values at 28 days

Specimen	Curing condition				
	Moist chamber	Water tank	Water and lime tank	Internal enviroment	External environment
1	27.8	32.7	26.7	23.5	21.7
2	28.5	29.5	26.6	24.2	20.5
3	28.3	33.5	27.2	25.0	21.0
4	28.6	34.9	27.2	23.9	21.6
5	27.0	29.7	26.7	23.0	20.3
6	30.4	29.9	27.1	23.4	27.7
Mean value	**28.4**	**31.7**	**26.9**	**23.8**	**21.3**
Standard Deviation	1.03	2.10	0.25	0.64	0.81

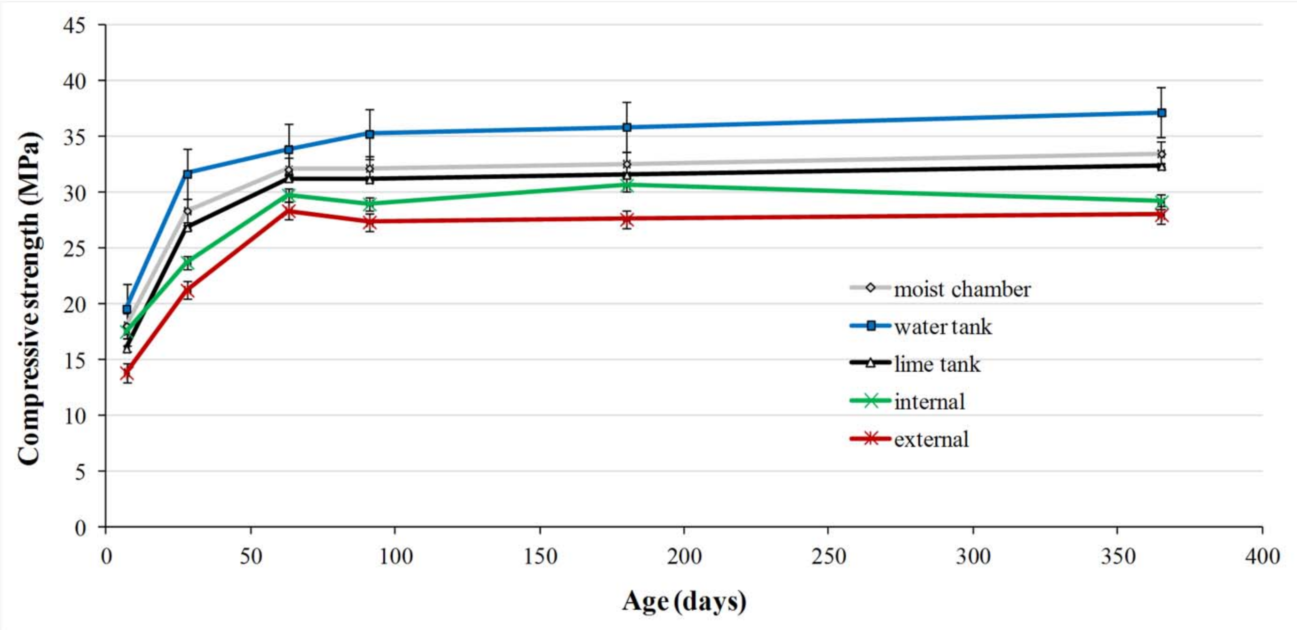


Fig. 6. Evolution of compressive strength (MPa) as a function of age for the different curing conditions

Results from Fig. 6 justify the need of controlling environmental parameters during the curing of concrete, also according to what Gayarre et al (2014) verified for concretes with recycled aggregates, at risk of reducing the compressive strength.

According to Fig. 6, the compressive strength of the concrete decreases, respectively with the following investigated types of curing: water tank, moist chamber, tank with water and lime, internal environment of the laboratory, and external environment. Fig. 8 shows the behavior of the relative compressive strength of concrete after 28 and 365 days depending on the curing conditions and compared with the reference concrete (moist chamber = 100%).

Fig. 8 reveals that the compressive strength of concrete cured in water tank is about 11% greater than the reference condition (moist chamber), both in 28 as well as in 365 days. However, all other conditions of curing/exposition that were investigated had inferior strength than curing in moist chamber. Curing in tank with water and lime had results near the reference condition (approximately 5% lower, for both analyzed ages).

Fig. 8 also allows to note that the percentage difference between the compressive strength of the reference condition and the condition of external exposure is greater on the first ages (=25% for 28 days) than in more advanced ages (=16.5% for 365 days).

One-way analysis of variance, also known as ANOVA, was performed in order to verify if the differences of compressive strength between the curing types are significant or not. One-way ANOVA produces an analysis for a quantitative dependent variable affected by a single factor (independent variable). This analysis is commonly used to verify the significance of differences between two or more means.

In the present study, the null hypothesis for ANOVA test states that data of compressive strength of the compared curing conditions show the same behavior and are not different from each other. In contrast, the alternative hypothesis states that these measures are different and thus did not have the same kind of behavior. The significance level threshold was $\alpha=0.05$. Thus, if α is less than 0.05, the null hypothesis should be rejected. The results of ANOVA test for combinations of curing conditions are displayed in Table 5.

Table 5. ANOVA results

Combination	Moist chamber, water tank, lime tank, internal and external	Moist chamber, water tank, lime tank, internal and external
Age (days)	Data from 7 to 365	Data from 28 to 365
α	0.236	0.000
Null hypothesis	Accepted	Rejected

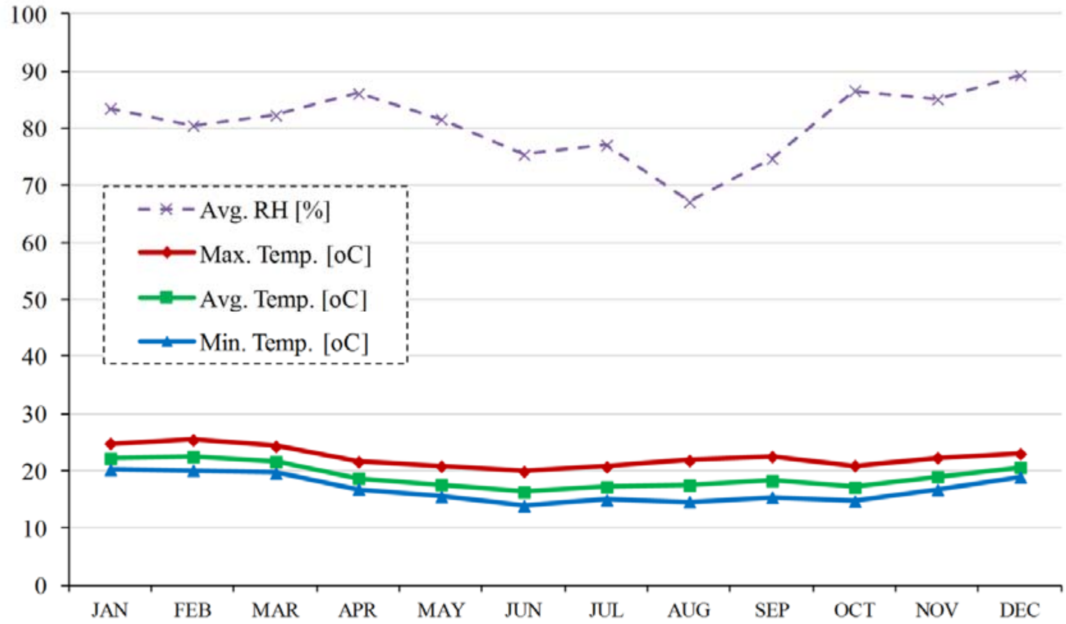


Fig. 7. Data of temperature and relative humidity

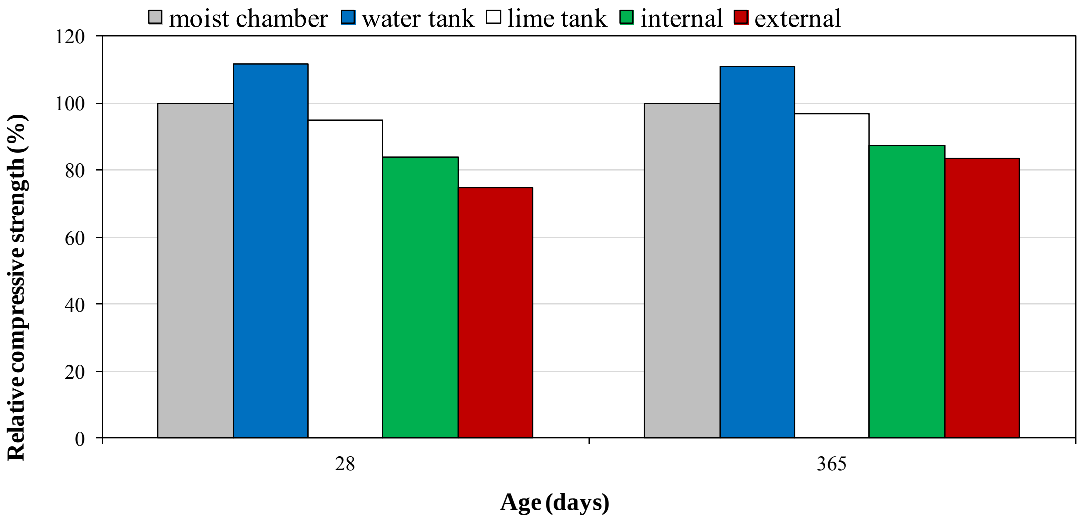


Fig. 8. Percentage comparison of concrete compressive strength

According to Table 5, when the whole testing period is analyzed together, in other words, results of compressive strength test between 7 days until 1 year, the significance level for ANOVA is greater than 0.05. This indicates that the null hypothesis cannot be rejected, meaning that there is no statistically significant difference between measurements. When the analyzed age is between 28 days until 1 year, significance level falls for 0.000, and ANOVA's result does not confirm the null hypothesis. This means that those measurements are different and do not have the same behavior.

Therefore, the variance analysis allows to conclude that from 28 days, the types of curing investigated in the paper produce significant differences on compressive strength of concrete. This is according with Gayarre et al (2014), which discovered that the fall of compressive strength is more significant after 28 days than in the first week for concretes with recycled aggregates.

Fig. 9 shows the interaction between the different parameters that were taken into account in the present study (age, curing conditions and compressive strength).

Fig. 9 helps to visualize what was confirmed in ANOVA. The slope of the line indicating the resistance of the different types of curing at 7 days is smaller than the slope of the lines at 28 and 365 days. This shows a trend of greater variation between resistances for ages over 28 days, as was confirmed during the variance analysis. Another point clearly observed in Fig. 9 is that the compressive strength gain between 7 and 28 days is greater for curies moist chamber, water tank and lime tank, than the compressive strength gain between 7 and 28 days for cures internal and external. For the latter two conditions, the resistance gain seems to be equally distributed along the whole first year, while on the three first curing conditions, the gain is very expressive on the first ages (from 7 to 28 days). This confirms that the climatic parameters interfere on the compressive strength gain of concrete mainly during the period from 7 until 28 days.

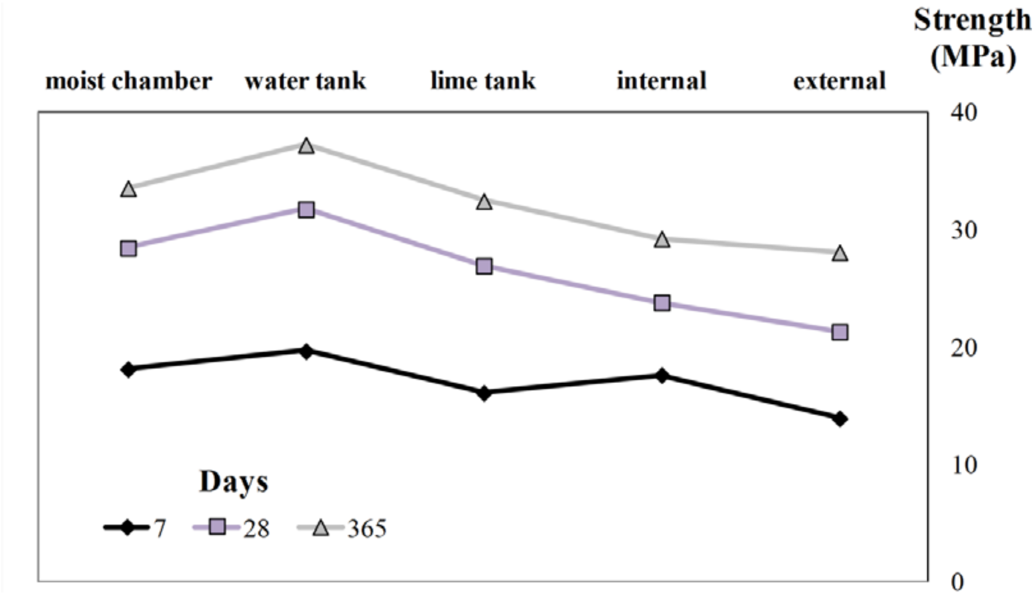


Fig. 9. Interaction between the different analyzed parameters

Finally, Fisher's method was applied with the combination of all curing conditions. This method was used to identify which groups are formed with curing conditions that have the same behavioral tendency. Fisher's method results are shown in Table 6.

According to Table 6, it was observed that for the conditions investigated in this paper, four different groups of curing combinations were formed, according to the data of compressive strength. Group A is restricted to moist chamber and water tank curing. Therefore, the compressive strength data of the water tank curing have a behavior trend compatible only with the reference curing (moist chamber). As can be noted in group B, the reference condition may also be combined with lime tank condition. Group C contains the lime tank and internal curing conditions. The external environment curing condition may be combined only with the internal to laboratory curing condition (group D). Those are precisely the two curing conditions with less control over the environmental parameters.

Those results show that no group was formed with all of the curing conditions. Thus, once again, it has been proved the need to control and specify the type of curing adopted for developing the compressive strength of concrete, at risk of having distinct values, mainly for ages over 28 days, as demonstrated in this paper.

Table 6. Fisher's method results– compressive strength from 28 to 365 days

Group	Curing conditions
A	moist chamber and water tank
B	moist chamber and lime tank
C	lime tank and internal

4. Conclusions

According to this paper, different curing conditions influence the compressive strength of concrete. This influence is significant for ages over 28 days. The compressive strength of concrete decreases, respectively, with the following types of curing investigated: water tank, moist chamber, tank with water and lime, laboratory internal environment and external environment.

The compressive strength gain between 7 and 28 days is lower for internal and external cures; for those two conditions, the strength gain seems to be equally distributed along the whole first year, while under the other studied conditions, the strength gain is more expressive on the first ages (from 7 to 28 days).

The lower values found for the external environment confirm the greater difficulty of controlling the water loss on this environment, resulting in decrease of compressive strength. Extrapolating those results for the construction reality, remains the recording of caring about the curing method of the test specimens as well as about the technological control of the concrete used on the construction. According to this paper, ensuring the water saturation during the curing period may result in higher compressive strength values.

This paper makes clear that the curing conditions are really important for the compressive strength of concrete through a controlled study of the concrete during one year. It must be considered that in usual works the environmental conditions are not easy to be controlled, so the curing conditions must be carefully controlled in order to obtain satisfactory results. Concrete must be protected from climate effects by means of an adequate curing process. This paper demonstrated that concrete has better compressive strength under standard conditions, mainly under curing fully saturated in water.

Acknowledgments

The authors want to record thanks to the Aeronautics Institute of Technology, Federal University of Parana, CAPES and Cortesia Concretos for providing the concrete used on the study.

References

ABNT (1991). NBR 5735 Portland cement of blast furnace. Brazilian Association of Technical Standards.

ABNT (1998a). NBR NM 67 Concrete - slump testing. Brazilian Association of Technical Standards.

ABNT (1998b). NBR NM 33 Concrete - fresh concrete sampling. Brazilian Association of Technical Standards.

ABNT (2007). NBR 5739 Concrete - compressive test of cylindrical specimens - test method. Brazilian Association of Technical Standards.

ABNT (2009). NBR 15900 Water to concrete mix. Brazilian Association of Technical Standards.

ABNT (2008). NBR 5738 Molding and curing cylindrical or prismatic specimens of concrete. Brazilian Association of Technical Standards.

Algorafi, M. A., Ali, A. A. A., Othman, I., Jaafar, M. S., and Almansob, R. A. (2011). Evaluation of Structural Behavior of Externally Prestressed Segmented Bridge with Shear Key under Torsion. *Journal of Engineering, Project, and Production Management*, 1(1), 28-35.

Bingöl, A. F. and Tohumcu, I. (2013). Effects of different curing regimes on the compressive strength properties of self compacting concrete incorporating fly ash and silica fume. *Materials & Design*, 51, 12-18. doi: 10.1016/j.matdes.2013.03.106.

Gayarre, F. L., Pérez, C. L. C., López, M. A. S., and Cabo, A. D. (2014). The effect of curing conditions on the compressive strength of recycled aggregate concrete. *Construction and Building Materials*, 53, 260-266. doi: 10.1016/j.conbuildmat.2013.11.112.

Ibrahima, M., Shameem, M., Al-Mehthel, M., and Maslehuddin, M. (2013). Effect of curing methods on strength and durability of concrete under hot weather conditions. *Cement and Concrete Composites*, 41, 60-69. doi: 10.1016/j.cemconcomp.2013.04.008.

Jiang, C., Yang, Y., Wang, Y., Zhou, Y., and Ma, C. (2014). Autogenous shrinkage of high performance concrete containing mineral admixtures under different curing temperatures. *Construction and Building Materials*, 61, 260-269. doi: 10.1016/j.conbuildmat.2014.03.023.

Lam, T. Y. M., Gale, K. S. (2015). A Procurement Performance Model for Construction Frameworks. *Journal of Engineering, Project and Production Management*, 5(2), 60-70.

Maslehuddina, M., Ibrahim, M., Shameem, M., Ali, M. R., and Al-Mehthel, M. H. (2013). Effect of curing methods on shrinkage and corrosion resistance of concrete. *Construction and Building Materials*, 41, 634-641. doi: 10.1016/j.conbuildmat.2012.12.064.

Mehta, P. K. and Monteiro, P. J. M. (2008). *Concrete - Microstructure, Properties and Materials*. New York: McGraw-Hill, Third Edition, 684p.

Medeiros-Junior, R. A. and Lima, M. G. (2016). Electrical resistivity of unsaturated concrete using different types of cement. *Construction and Building Materials*, 107, 11-16. doi: 10.1016/j.conbuildmat.2015.12.168.

Medeiros-Junior, R. A., Lima, M. G., Brito, P. C., and Medeiros, M. H. F. (2015). Chloride penetration into concrete in an offshore platform - analysis of exposure conditions. *Ocean Engineering*, 103, 78-87. doi: 10.1016/j.oceaneng.2015.04.079.

Medeiros-Junior, R. A., Lima, M. G., and Medeiros, M. H. F. (2014). Discussion about models for estimation of relative humidity - case study of the brazilian coast versus influence in concrete durability. *Revista Ingeniería de Construcción*, 29(3), 270-282. doi: 10.4067/S0718-50732014000300004.

Neville, A. M. and Brooks, J. J. (2013). *Concrete - Technology*. London: Pearson, Second Edition, 344.

Presuel-Moreno, F., Wu, Y. Y., and Liu, Y. (2013). Effect of curing regime on concrete resistivity and aging factor over time. *Construction and Building Materials*, 48, 874-882. doi: 10.1016/j.conbuildmat.2013.07.094.

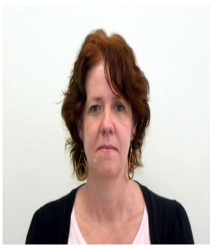
Prommas, R. and Rungsakthaweekul, T. (2014). Effect of microwave curing conditions on high strength concrete properties. *Energy Procedia*, 56, 26-34. doi: 10.1016/j.egypro.2014.07.128.

Ramezanianpour, A. M., Esmaeili, K., Ghahari, S. A., and Ramezanianpour, A. A. (2014). Influence of initial steam curing and different types of mineral additives on mechanical and durability properties of self-compacting concrete. *Construction and Building Materials*, 73, 187-194. doi: 10.1016/j.conbuildmat.2014.09.072.

Zhao, H., Sun, W., Wu, X., and Gao, B. (2012). Effect of initial water-curing period and curing condition on the properties of self-compacting concrete. *Materials & Design*, 35, 194-200. doi: 10.1016/j.matdes.2011.09.053.

Zhutovsky, S., Kovler, K., and Bentur, A. (2013). Effect of hybrid curing on cracking potential of high-performance concrete. *Cement and Concrete Research*, 54, 36-42. doi: 10.1016/j.cemconres.2013.08.001.

Ronaldo A. Medeiros-Junior is a Researcher Engineer and Professor at Federal University of Paraná, Curitiba (Brazil). He received his BS from University of Pernambuco and his MS and PhD from Technological Institute of Aeronautics (ITA). Author of several articles and chapter of books, he is supervisor of MS and PhD students. His research interest includes durability, non-destructive testing and service life prediction of concrete structures.



Maryangela Geimba de Lima is a Researcher Engineer and Professor at Technological Institute of Aeronautics (ITA), São José dos Campos (Brazil). She received his BS from Federal University of Santa Maria and her MS from Federal University of Rio Grande do Sul and PhD from University of São Paulo. Author of several articles and chapter of books, she is supervisor of MS and PhD students. Her research interest includes durability, non-destructive testing and service life prediction of concrete structures.

Carlos Eduardo Tino Balestra is a Researcher Engineer and Professor at Federal University of Technology - Paraná, Toledo (Brazil). He received his BS from University of Taubaté and his MS and PhD from Technological Institute of Aeronautics (ITA). Author of several articles and chapter of books. His research interest includes durability, non-destructive testing and service life prediction of concrete structures.