ORIGINAL ARTICLE
DOI: 10.5433/1679-0375.2021v42n1p103

Tensile strength of corroded steel bars

Resistência à tração de barras de aço corroídas

Flavia de Fatima Emi Murakami[1]; Elizamary Otto Ferreira[2];
Carlos Eduardo Tino Balestra[3]; Gustavo Savaris[4]

Abstract

Among the pathological manifestations associated with reinforced concrete, corrosion of the reinforcement is one of the most serious issues since it is related to the durability of the structures and the safety of the users. Although the reinforcement in the structural components is protected by a covering layer, carbonation or the presence of chlorides in the concrete generates necessary conditions for corrosion of the reinforcement. This causes a reduction in the cross section and the generation of products that, due to their volumetric expansion, cause cracks in the interior of the concrete. This work evaluates the effects of corrosion on mechanical properties of corroded reinforcements through accelerated conditions in the laboratory. Steel bars installed inside cylindrical concrete specimens are subjected to accelerated corrosion, immersed in a saline solution with the application of an electric current for periods of 1, 3, 5 and 7 d. After corrosion, the steel bars are removed and their weight loss, degree of corrosion and tensile strength are evaluated. The results demonstrate an increased degree of corrosion with exposure time to the saline solution and the non-uniform reduction of the tensile strength of the bars due to the formation of corrosion pits with varying depth along the bar.

Keywords: Corrosion. Concrete. Steel reinforcement. Mechanical properties. Structures.

Resumo

Dentre as manifestações patológicas relacionadas ao concreto armado, pode-se considerar a corrosão das armaduras, como um dos problemas mais graves, relacionado à durabilidade das estruturas e segurança dos usuários. Apesar das armaduras nos componentes estruturais estarem protegidas pela camada de cobrimento, a carbonatação ou a presença de cloretos no concreto geram condições necessárias para corrosão das armaduras, ocasionando perda da seção transversal e gerando produtos que, devido a sua expansão volumétrica, causam fissuras no interior do concreto. Este trabalho avalia os efeitos da corrosão nas propriedades mecânicas de armaduras corroídas através de condições aceleradas em laboratório. Barras de aço instaladas dentro de corpos de prova cilíndricos de concreto foram submetidas à aceleração da corrosão, imersas em uma solução salina com aplicação de corrente elétrica, durante os períodos de 1, 3, 5 e 7 dias. Após a corrosão as barras foram removidas e avaliadas quanto à perda de massa, grau de corrosão e resistência à tração. Os resultados demostram o aumento no grau de corrosão com o tempo de exposição à solução salina e a redução da resistência à tração das barras de forma não uniforme, devido à formação de pites de corrosão com profundidade variada ao longo da barra.

Palavras-chave: Corrosão. Concreto. Armadura. Propriedades mecânicas. Estruturas.

[1] Master's Student, PPGEC, UTFPR, Curitiba, Paraná, Brazil, E-mail: flaviaemi21@yahoo.com.br
[2] Master's Student, PPGEC, UTFPR, Curitiba, Paraná, Brazil, E-mail: elizamaryotto@gmail.com
[3] Prof. Dr., PPGQB, UTFPR, Toledo, Paraná, Brazil, E-mail: carlosbalestra@utfpr.edu.br
[4] Prof. Dr., PPGEC, UTFPR, Curitiba, Paraná, Brazil, E-mail: gsavaris@utfpr.edu.br

Introduction

Due to the availability of its raw materials and easy usage, concrete has become the most material used for structural purposes in buildings (ISAIA, 2010; MEHTA; MONTEIRO, 2014). The term pathology in civil engineering is used when studying the events that cause a loss or reduction in the performance of a product or structural component. Starting in the 20th century, the pathological manifestations that involve reinforced concrete began to occur with high intensity and frequency, with significant costs required for their restoration (CAIRNS *et al.*, 2005; HELENE, 1993; ROCHA, 2015).

Reinforcement corrosion can be considered as one of the most serious issues associated with structural degradation, since it is related to durability and the safety of the users (APOSTOLOPOULOS *et al.*, 2013; BALESTRA, 2013; HELENE, 1986; ROCHA, 2015). Corrosion is understood as the gradual wear of a structure, which undergoes some changes, and can be chemical or physical, resulting from the interaction of this structure with the environment. The susceptibility of the reinforcement to corrosion can compromise the integrity of the structure and consequently its useful life (MEHTA; MONTEIRO, 2014).

According to Gentil (2011), corrosion in reinforced concrete structures is an electrochemical process that can occur via the following mechanisms: uniform, throughout the length of the reinforcement; punctiform: localized in the reinforcement in the form of pits or alveoli; intergranular: between the grains of the crystalline network of the metallic material, when the reinforcement suffers mechanical stress and is subjected to a brittle rupture; transgranular: occurs within the grains and may lead to rupture when subjected to mechanical stresses; hydrogen embrittlement: caused by atomic hydrogen, which diffuses into the interior of the reinforcement, allowing embrittlement and a consequently loss of ductility, leading to possible fracture.

The reinforcements in structural elements are protected against corrosion by the concrete cover layer which, due to the alkalinity of concrete (pH aprox. 12), forms a passive layer against external agents. The passivating layer is basically composed of iron oxides that adhere to the steel bars. These oxides come from the dissolution of hydroxides, which come from the cement paste and saturate in the pores of the concrete (ROCHA, 2015). In the presence of water and oxygen, chloride ions do not attack the concrete, but start the corrosion process that destroys the passive layer (MOTA *et al.*, 2012).

Furthermore, causing successive damage in terms of a loss of cross section, reinforcement corrosion generates other effects due to its volumetric expansion and because it is an evolutive and irreversible process, it can lead a structure to collapse (CASCUDO, 2005). This expansibility is related to the transformation of metallic iron into corrosion products (rust), also accompanied by an increase in volume, which, depending on the oxidation state, can reach more than 600% related to the original material. The increase in volume can be considered the main cause of the expansion and cracking of concrete (MEHTA; MONTEIRO, 2014).

Several studies have been carried out with the aim of understanding the corrosion mechanisms that degrade the bars, but there are few that relate the change of mechanical properties under the influence of corrosion (APOSTOLOPOULOS; PAPADAKIS, 2007). According to Balestra (2013), both the degree of corrosion of the steel bar and the decrease in the resistance of the reinforcement and the structural element require an evaluation of its mechanisms as a method to investigate the structural degradation by corrosion and stipulate a safety level for such.

In the literature, recent studies have evaluated the corrosion of reinforced concrete structures naturally exposed to aggressive environments (ZHU *et al.*, 2013) or by accelerating corrosion in the laboratory using sodium chloride solutions and applying an electric current to the reinforcement (APOSTOLOPOULOS *et al.*, 2013; IMPERATORE *et al.*, 2017; KASHANI *et al.*, 2013; ORTEGA; ROBLES, 2016).

In general, corroded reinforcements result in reductions in strength and ductility, due to the formation of corrosion pits (APOSTOLOPOULOS *et al.*, 2013; ZHU *et al.*, 2013). According to Kashani *et al.* (2013), for a bar mass loss of 10% a reduction of aprox. 50% of the total plastic deformation of tensioned bars and 20% of the buckling resistance of compressed bars occurs.

Furthermore, Apostolopoulos *et al.* (2013) verified that bars immersed in concrete present a less accelerated corrosion process than bars exposed to the environment, but the formation of more extensive and deeper pits occurs, due to the formation of active zones of metal dissolution. The changes in the mechanical properties of steel are related to the differentiated degradation between the constituent materials of the bars, reducing their yield stress and ultimate tensile stress, as well as the specific deformation of the bars, as observed by Imperatore *et al.* (2017).

According to Rocha (2015), if the significant resources used in the recovery of structures under corrosion attacks were used with preventive measures, there would be a dramatic reduction in expenses during the lifetime of a structure. Concrete structures are subject not only to human failure during the design and execution phases, but also due to natural causes, such as the aggressiveness of the exposure environment and the intrinsic characteristics of concrete. NBR 6118 (ABNT, 2014) presents four classes of environmental aggressiveness, ranging from weak to very strong, which determine the class of resistance and reinforcement cover that must be used according to the environment where the structure will be implemented.

Studies on the effects of corrosion on the mechanical properties of corroded reinforcements are justified to contribute to structural safety, to evaluate the bearing capacity of degraded structures and to help the academic community to develop techniques that can minimize the impact through preventive measures.

On this basis, this study investigates the effects of corrosion on the mechanical properties of a corroded reinforcement through accelerated conditions in the laboratory, thereby contributing to the understanding of the durability of reinforced concrete structures.

Experimental programme

To evaluate the effects of corrosion on the mechanical properties of reinforcements installed in concrete structures, an experimental program was developed using cylindrical concrete specimens containing steel bars, which were immersed in salt water to induce corrosion using an electric current.

The experiment considered four different periods of exposure to corrosion using six specimens per period, therefore giving a total of 24 specimens.

After the induction of corrosion, the steel bars were extracted from the specimens, evaluated for mass loss and subjected to axial tensile testing for strength determination, similar to the process performed by Apostolopoulos *et al.* (2013).

Materials and concrete production

The concrete used was produced with a mix ratio of 1:1.53:2.12 (cement:sand:coarse aggregate), with a w/c ratio of 0.48, adapted from the mix presented by Segalin *et al.* (2020). Portland cement CP V 32-RS was used as a binder and natural river sand and crushed basaltic rock were used as aggregates, with specific masses of 2.64 and 2.98 g/cm^3, respectively, determined according to NBR NM 52 (ABNT, 2009) and NBR NM 53 (ABNT, 2003), respectively.

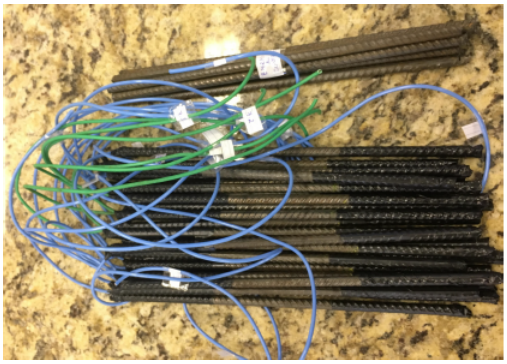
The concrete resulted in a fresh state slump equal to 17 cm and an average compressive strength at 28 d of 49.6 MPa, as determined from tests according to NBR NM 67 (ABNT, 1998) and NBR 5739 (ABNT, 2007), respectively.

From a steel bar of class CA-50 with a commercial diameter of 8 mm, 30 segments with a length of 30 cm were cut, with 24 segments used in the specimens with accelerated corrosion and six segments tested intact for control.

The steel bars were initially weighed on a precision balance (0.01 g) and identified with the letter "C" and a number ranging from 1, 3, 5 or 7, corresponding to the period of exposure to corrosion, in days. The reference specimens were identified only with the letter "R".

At one end of the bars, a copper wire was fixed, as shown in Figure 1, responsible for transmitting the current from the source to the bar, and at both ends of the bars, 10 cm were insulated using insulating tape, to ensure a length without corrosion where the claws of the universal machine for the axial tensile test were subsequently fixed.

Figure 1 – Steel bar segments prepared to insertion in concrete specimens



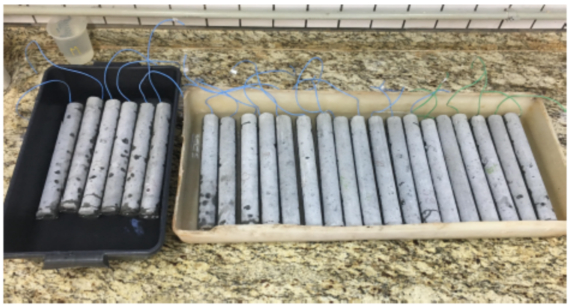
Source: The authors.

In order to ensure a minimum reinforcement cover of 2 cm, corresponding to the smallest value of cover specified by the NBR 6118 standard (ABNT, 2014), the concrete specimens were molded in PVC tubes with a diameter of 50 mm. One end of the tube was capped and filled with concrete to a height of 30 mm and the steel bar was then manually inserted and centered inside the tube, with the rest filled with concrete.

After 24 h, the specimens were demolded and subjected to curing in a humid chamber for 28 d.

After curing, the specimens were placed in an oven to dry at 60 °C for a period of 24 h to reduce the amount of water in the concrete pores and to allow the entry of saline water. They were then immersed in a 3.5% sodium chloride solution for a period of 7 d, Figure 2, to saturate the specimens before the start of the corrosion stage.

Figure 2 – Concrete specimens immersed in saline water to saturate

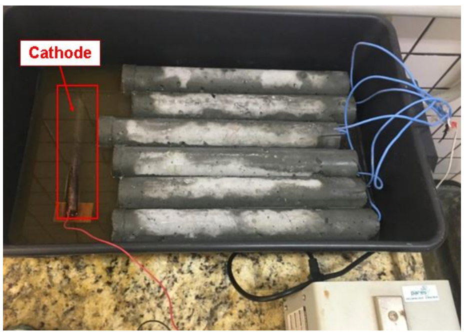


Source: The authors.

Corrosion acceleration procedure

The specimens were separated into four groups, with six specimens per group, corresponding to corrosion acceleration times of 1, 3, 5 and 7 d. The corrosion acceleration was performed using a circuit similar to that presented by Apostolopoulos *et al.* (2013) and Zhu *et al.* (2013). The circuit was assembled with a Minipa MPL-1303M source, a copper bar used as cathode in the negative terminal, the steel bars embedded in the concrete specimens and a 35 g/L water saline solution, corresponding to the concentration of sodium chloride present in seawater. This solution was responsible for the current circulation in the circuit, with a voltage of 30 V and a current of aprox. 0.4 A, Figure 3.

Figure 3 – Concrete specimens in corrosion acceleration process



Source: The authors.

Corrosion degree and tensile strength

After the corrosion acceleration period, the steel bars were removed, with the rupture of the concrete by diametrical compression in a hydraulic press, and washed in running water, using a steel brush to remove the concrete adhered to the bars.

The bars were then weighed to determine their final mass and the degree of corrosion (DC) was calculated using equation 1. The bars were subjected to axial tensile testing, following the recommendations of the standard NBR ISO 6892-1 (ABNT, 2013), using a universal testing machine with a maximum load capacity of 1000 KN. Axial tensile tests were performed until the bar ruptured, with an increasing load speed of 1 N/s.

$$G_c = \frac{m_i - m_f}{m_i}, \quad (1)$$

where:

m_i = steel bar mass before corrosion;

m_f = steel bar mass after corrosion.

Statistical analysis of results

The results obtained were submitted to an analysis of variance (ANOVA) using the R statistical software by evaluating the dispersion of the sample means and comparing these means using the Tukey–Kramer method.

Results and discussion

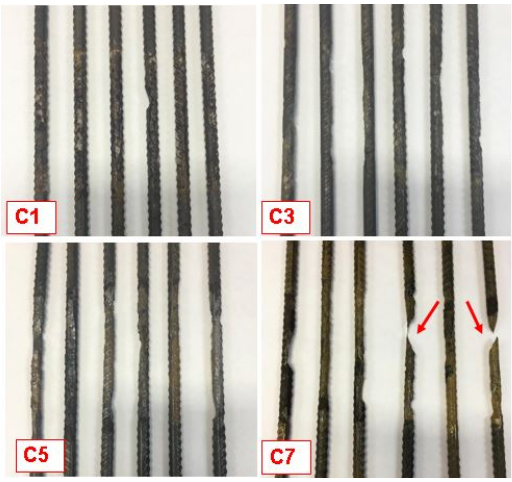
The tested steel bars were evaluated regarding their mass loss, degree of corrosion and ultimate tensile strength.

Loss of mass and degree of corrosion

Figure 4 presents the bars submitted to corrosion after extraction from the concrete and cleaning. The loss of cross section of the bars was evident with increasing exposure time to the corrosive process. Among the bars of group C7, two samples presented rupture of the cross section during the removal of the specimen, due to the longer exposure time and consequently higher degree of corrosion.

Table 1 shows the mass of the bars before and after corrosion and the calculated corrosion degree. Large variations in the reduction of the mass of the bars, between 0.41 and 19.67 g, and in the corrosion degree, between 0.35% and 17.78%, are observed, with an increase in the degree of conversion with increasing time in which the specimen was submitted to the corrosion acceleration test.

Figure 4 – Steel bars after corrosion process

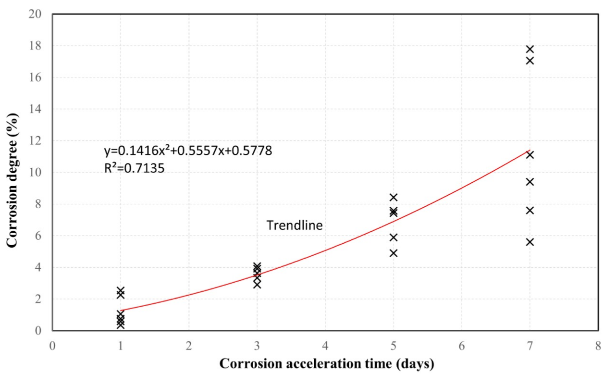


Source: The authors.

Evaluating the confidence intervals for the different treatments, using Student's t distribution (NAVIDI, 2010), values of 5.35 and 13.30 for treatments C3 and C5, respectively, were disregarded in the calculation of the means and standard deviations because they exceeded the limits of the intervals.

Figure 5 shows the evolution of the corrosion degree with the corrosion acceleration time. A greater dispersion and nonlinear increase in the corrosion degree can be observed, indicating the acceleration of the corrosion process over time.

Figure 5 – Corrosion degree vs. corrosion acceleration time



Source: The authors.

The analysis of variance was performed using the values of the corrosion degree of the four treatments, with the significance level α of 5%, and the results are presented in Table 2.

It can be observed that the $F_{calculated}$ value is greater than the critical F value (F_{critic}), indicating that the means of the corrosion degrees of the treatments cannot be considered equal. Thus, the Tukey–Kramer test was applied to compare the means two by two. In Table 1, equal letters identify treatments with statistically equal means. Thus, two groups of corrosion degrees are observed, the first formed by treatments 1 and 3 and the second formed by treatments 5 and 7.

Tensile strength

Table 3 shows the breaking loads of the bars obtained in the direct tensile test for the control treatments C1, C3, C5 and C7, as well as the means, standard deviation and coefficient of variation for each treatment. In the control group, there was a failure during the test of bar number 2 and its value was therefore discarded in the analyses.

Using the average rupture force values for each treatment and considering the cross-section area of the 8 mm diameter bar equal to 50.26 mm^2, the ultimate stresses of the control bars and the apparent stresses for the corroded bars of the other groups were calculated and are presented in Table 4.

Due to the formation of pits that reduce the cross section at certain points, resulting in the sudden variation of stress at these points, as presented in Figure 6, it is observed that the degree of corrosion does not represent the geometric imperfections of the corrosion on the bars. Works by Zhu *et al.* (2013), Imperatore *et al.* (2017), Apostolopoulos *et al.* (2013) and Kashani *et al.* (2013) present experimental results similar to those obtained in this work, with an increased loss of cross section for the bars over the time of exposure to the corrosive agent, even presenting an alteration in the ductility of the bar due to non-uniform pitting formation.

Figure 7 shows the points referring to the ultimate strength and the degree of corrosion where a linear behavior for the data is verified. Highlighted in red, it can be observed that point B has a higher degree of corrosion than point A. However, the ultimate strength is higher, even with a higher degree of corrosion, this fact is justified because the corrosion degree does not adequately represent the behavior of the bar after the corrosion, because it does not show the variation of section along the bar.

Table 1 – Initial and final mass, mass loss and corrosion degree

Treatment	Sample	Initial mass (g)	Final mass (g)	Mass loss (g)	CD (%)	Mean CD (%)	Standard deviation (%)
C1	1	115.79	114.91	0.88	0.76	1.26[a]	0.92
	2	117.8	115.14	2.66	2.26		
	3	116.09	114.86	1.23	1.06		
	4	115.15	112.23	2.92	2.54		
	5	116.19	115.51	0.68	0.59		
	6	117.07	116.66	0.41	0.35		
C3	1	114.62	110.79	3.83	3.34	3.57[a]	0.47
	2	115.5	109.32	6.18	5.35*		
	3	115.55	110.85	4.7	4.07		
	4	115.99	112.61	3.38	2.91		
	5	116.08	111.87	4.21	3.63		
	6	115.17	110.65	4.52	3.92		
C5	1	115.89	100.48	15.41	13.30*	6.85[b]	1.42
	2	116.6	107.94	8.66	7.43		
	3	116.06	109.22	6.84	5.89		
	4	116.04	106.27	9.77	8.42		
	5	116.28	110.58	5.7	4.90		
	6	116	107.22	8.78	7.57		
C7	1	116.21	107.38	8.83	7.60	11.42[b]	4.99
	2	115.31	102.51	12.8	11.10		
	3	115.9	105.01	10.89	9.40		
	4	116.45	95.75	20.7	17.78		
	5	116.37	109.85	6.52	5.60		
	6	115.38	95.71	19.67	17.05		

*Values that exceeded the limits of the intervals Equal letters identify treatments with statistically equal means.
Equal letters identify treatments with statistically equal means.

Source: The authors.

Table 2 – ANOVA result for corrosion degree

Source	SS	df	MS	F	*p*-value	Fcritic
Between groups	349.52	3	116.51	16.89	1.5E-05	3.098
Within groups	137.91	20	6.89			

Source: The authors.

Table 3 – Tensile strength test results

Treatment	Sample	Ultimate force (kN)	Mean ultimate force (kN)	Standard deviation (kN)	CV (%)
R	1	47.40	44.92	5.72	12.75
	2	33.25			
	3	47.15			
	4	47.30			
	5	47.70			
	6	46.70			
C1	1	45.20	44.43	4.21	9.48
	2	46.80			
	3	44.40			
	4	36.15			
	5	46.50			
	6	47.55			
C3	1	40.16	39.32	1.57	3.99
	2	36.50			
	3	41.05			
	4	40.05			
	5	39.05			
	6	39.10			
C5	1	28.20	35.08	4.39	12.51
	2	34.55			
	3	39.90			
	4	33.60			
	5	39.85			
	6	34.40			
C7	1	26.05	32.26	5.25	16.27
	2	31.15			
	3	33.10			
	4	-			
	5	38.75			
	6	-			

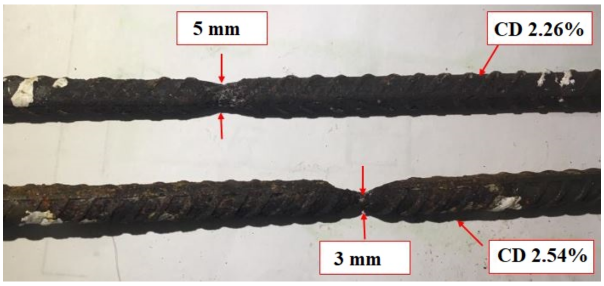
Source: The authors.

Table 4 – Treatments corrosion degree and ultimate strength

Treatment	R	C1	C3	C5	C7
CD (%)	0	1.26	3.57	6.85	11.42
σ_u (MPa)	893.75	884.00	782.33	697.97	641.86

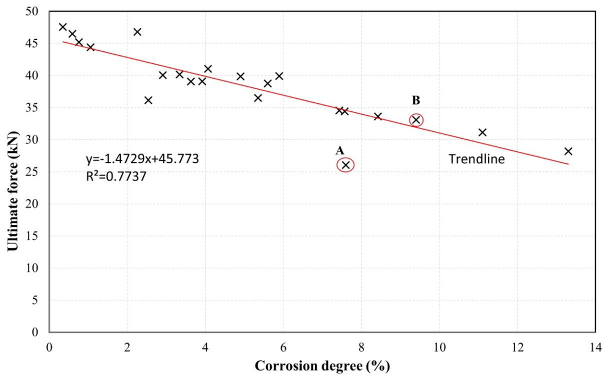
Source: The authors.

Figure 6 – Steel bar segments 1.2 and 1.4 after accelerated corrosion



Source: The authors.

Figure 7 – Ultimate force vs. corrosion degree



Source: The authors.

Conclusions

This study analyzed the effects of reinforcement corrosion in reinforced concrete structures by means of an experimental program with the acceleration of steel bar corrosion. From the results obtained, the following conclusions can be formulated.

- The acceleration of corrosion in reinforcements installed inside concrete specimens immersed in a saline solution was possible with the use of an electric current, showing an average corrosion degree above 11% at 7 d of testing.
- Specimens submitted to the same conditions of corrosion acceleration presented dispersion in the results, demonstrating the randomness of the corrosion process, related to the characteristics of the concrete and the environment that surrounds it.
- The corrosion degree of reinforcement presented a non-linear behavior over time, with acceleration of the process and greater dispersion during the tests.
- Corrosion degree is a factor that cannot represent certain points with loss of cross section along the bar, i.e., bars with similar corrosion degrees can have divergent yield and ultimate stresses due to a deeper pitting in one bar and a more extended corrosion in another.
- The strength of the steel bars presented a linear decay in relation to the corrosion degree, evidencing that the exposure time to the aggressive agent should be taken into consideration when estimating the service life of the structures.

Acknowledgments

The authors would like to thank the Federal University of Technology - Parana and the Materials and Structures Research Group (GPMAES) for supporting this project.

References

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *NBR NM 52*: agregado miúdo: determinação da massa específica e massa específica aparente. Rio de Janeiro: ABNT, 2009. 6 p.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *NBR NM 53*: agregado graúdo: determinação de massa específica, massa específica aparente e absorção de água. Rio de Janeiro: ABNT, 2003. 8 p.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *NBR NM 67*: concreto: determinação da consistência pelo abatimento do tronco de cone. Rio de Janeiro: ABNT, 1998. 8 p.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *NBR 5739*: concreto: ensaio de compressão de corpos de prova cilíndricos. Rio de Janeiro: ABNT, 2007. 9 p.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *NBR 6118*: projeto de estruturas de concreto - Procedimento. Rio de Janeiro: ABNT, 2014. 238 p.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *NBR ISO 6892-1*: materiais metálicos: ensaio de tração parte 1: método de ensaio à temperatura ambiente. Rio de Janeiro: ABNT, 2013. 70 p.

APOSTOLOPOULOS, C.; PAPADAKIS, V. G. Consequences of steel corrosion on the ductility properties of reinforcement bar. *Construction and Building Materials*, Guildford, v. 22, p. 2316–2324, nov. 2007. DOI: https://doi.org/10.1016/j.conbuildmat.2007.10.006.

APOSTOLOPOULOS, C. A.; DEMIS, S.; PAPADAKIS, V. G. Chloride-induced corrosion of steel reinforcement – mechanical performance and pit depth analysis. *Construction and Building Materials*, Guildford, v. 38, p. 139–146, jan. 2013. DOI: https://doi.org/10.1016/j.conbuildmat.2012.07.087.

BALESTRA, C. E. T. *Influência do grau de corrosão na resistência à tração de armaduras*: estudo de caso das fundações da Nova Ala Zero do ITA. 2013. Dissertação (Mestrado em Engenharia de Infraestrutura Aeroportuária) - Instituto Tecnológico de Aeronáutica, São Paulo, 2013.

CAIRNS, J.; PLIZZARI, G. A.; DU, Y.; LAW, D. W.; FRANZONI, C. Mechanical properties of corrosion-damaged reinforcement. *ACI Materials Journal*, Detroit, v. 102, n. 04, p. 256–264, jul./ago. 2005.

CASCUDO, O. Inspeção e diagnóstico de estrutura de concreto com problemas de corrosão da armadura. *In*: ISAIA, G. C. (Org.). *Concreto*: ensino, pesquisa e realizações. 1a ed. São Paulo: Instituto Brasileiro do Concreto, 2005, v. 2, p. 1071-1108.

GENTIL, V. *Corrosão*. Rio de Janeiro: LTC, 2011.

HELENE, P. R. L. *Corrosão em armaduras para concreto armado*. São Paulo: PINI, 1986.

HELENE, P. R. L. *Contribuição ao estudo da corrosão em armaduras de concreto armado*. 1993. Tese (Doutorado) — Escola Politécnica da Universidade de São Paulo, São Paulo, 1993.

IMPERATORE, S.; RINALDI, Z.; DRAGO, C. Degradation relationships for the mechanical properties of corroded steel rebars. *Construction and Building Materials*, Guildford, v. 148, p. 219–230, set 2017. DOI: https://doi.org/10.1016/j.conbuildmat.2017.04.209.

ISAIA, G. C. *Concreto*: ensino, pesquisa e realizações: o concreto da era clássica a contemporânea. São Paulo: IBRACON, 2010. 1581 p.

KASHANI, M. M.; CREWE, A. J.; ALEXANDER, N. A. Nonlinear stress–strain behaviour of corrosion-damaged reinforcing bars including inelastic buckling. *Engineering Structures*, Oxford, v. 48, p. 417–429, 2013. DOI: https://doi.org/10.1016/j.engstruct.2012.09.034.

MEHTA, R.; MONTEIRO, P. J. M. *Concreto*: microestrutura, propriedades e materiais. São Paulo: Instituto brasileiro de concreto: IBRACON, 2014. 782 p.

MOTA, J. M. F.; BARBOSA, F. R.; SILVA, A. J. C.; FRANCO, A. P. G.; CARVALHO, J. R. Corrosão de armadura em estruturas de concreto armado devido ao ataque de íons cloreto. CONGRESSO BRASILEIRO DO CONCRETO, 54., 2012. Maceió. *Anais* [...]. Maceió: [*s. n.*], 2012. p. 17.

NAVIDI, W. *Principles of statistics for engineers and scientists*. New York: McGraw-Hill, 2010.

ORTEGA, N. F.; ROBLES, S. I. Assessment of residual life of concrete structures affected by reinforcement corrosion. *HBRC Journal*, [London], v. 12, n. 2, p. 114–122, ago. 2016. DOI: https://doi.org/10.1016/j.hbrcj.2014.11.003.

ROCHA, I. Corrosão em estruturas de concreto armado. *Revista Especialize IPOG*, Goiania, v. 1, p. 1–26, dez. 2015.

SEGALIN, L. P.; BALESTRA, C. E. T.; SAVARIS, G.; BRESSIANI, L. Effect of cooling method on concrete compressive strength after exposure to high temperatures. *Semina*: Ciências Exatas e Tecnológicas, Londrina, v. 41, n. 1, p. 13-20, jan./jun. 2020. DOI: http://dx.doi.org/10.5433/1679-0375.2020v41n1p13.

ZHU, W.; FRANÇOIS, R.; CORONELLI, D.; CLELAND, D. Effect of corrosion of reinforcement on the mechanical behaviour of highly corroded RC beams. *Engineering Structures*, Oxford, v. 56, p. 544–554, nov. 2013. DOI: https://doi.org/10.1016/j.engstruct.2013.04.017.

Received: Dec. 29, 2020
Accepted: June 28, 2021
Published: June 30, 2021