ENGLISH VERSION

Flexural mechanical properties of steel fiber reinforced concrete under corrosive environments

Propiedades mecánicas a flexión del concreto reforzado con fibras de acero bajo ambientes corrosivos

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Fecha de Recepción: 01/08/2016
Fecha de Aceptación: 22/02/2017
PAG 59-72

Abstract

The influence of two corrosive environments at a short term and the fiber dosage on the flexural performance of steel fiber reinforced concrete, SFRC, is assessed in this paper. The experimental program comprised the tests of 54 SFRC specimens having steel fibers characterized by a length/diameter ratio of 65 and fiber dosages of 30 and 60 kg/m^3. Regarding the corrosive environments, cylinders and beams were subjected to the action of a watery environment and to an environment of 3.5% NaCl solution (chloride ion) during a period of 60 days. The results were compared with those of cylinders and beams kept in unaltered conditions. For this exposure time that is equivalent to the corrosion initiation phase, it was observed that chloride ions of 3.5% NaCl solution cause degradation in mechanical performance of SFRC; for instance, loss of flexural strength of roughly 10% and reduction of flexural toughness equal to 11%. However, saline exposure caused an increase of the deflection capacity of SFRC for the initiation phase of corrosion, which can improve its ductility and bond capacity between the matrix and embedded steel fibers. Finally, equations have been proposed to describe the effect of watery and saline environments in the initiation phase of corrosion on CRFA subjected to bending stresses.

Keywords: *SRFC, chloride ion, corrosion initiation, flexural tests, deflection, toughness*

Resumen

En este artículo se evalúa la influencia de dos ambientes corrosivos a corto plazo, y de la dosificación de fibras sobre el desempeño a flexión del concreto reforzado con fibras de acero, CRFA. El programa experimental comprendió el ensayo de 54 especímenes de concreto reforzado con fibras de acero que tienen relación longitud/diámetro de 65 y dosificaciones de fibras de 30 kg/m^3 y 60 kg/m^3. En cuanto a los ambientes corrosivos, cilindros y vigas fueron sometidos a la acción de un medio acuoso y un medio de solución NaCl al 3.5%, por un periodo de 60 días. Los resultados fueron comparados con aquellos cilindros y vigas que permanecieron en condiciones inalteradas. Para dicho tiempo de exposición que corresponde a la fase de iniciación de la corrosión, se observó que los iones cloruro presentes en el medio salino (NaCl al 3.5%) ocasionan degradación en el desempeño mecánico del concreto con fibras de acero, por ejemplo, pérdida aproximada del 10% en la resistencia a flexión y disminución del 11% de la tenacidad en flexión. No obstante para la fase de iniciación de la corrosión, la exposición al medio salino provocó un incremento de la capacidad de deflexión del CRFA que puede mejorar su ductilidad y la capacidad de adherencia entre la matriz y las fibras de acero embebidas. Finalmente, se han propuesto ecuaciones que permiten describir el efecto de ambientes acuosos y salinos en la fase de iniciación de la corrosión sobre el CRFA sometido a esfuerzos de flexión.

Palabras clave: CRFA, ion cloruro, iniciación de corrosión, ensayos a flexión, deflexión, tenacidad

1. Introduction

Corrosion is the process by whichwhere oxidation reactions and reduction of steel cross-sectional reactions occurs in the steel, due to their interaction with the environment. Under normal conditions, the reinforcement embedded in the concrete is protected by high alkalinity (pH~13) and the thickness of the coatingconcrete cover between the exposed surface and the metal contact. However, environmental agents such as chloride ions, sulfates and contaminant gases react with the chemical products of the matrix and are able to destroy this protection, which reduces the pH value, deteriorates the steel and, later on, reduces the mechanical properties of the concrete. As an example thereof, structures built in coastal areas are generally subjected to seawater waves splashing and/or moisture-temperature gradients, which cause concrete cracking and subsequent degradation due to the formation of expansive products. According to Tuutti (1982), the service life of a concrete structure in terms of corrosion can be generally divided in two phases: initiation and propagation. The initiation phase is considered the time required for external agents, mainly chloride ions, sulfates and carbonation, to penetrate inside the concrete and cause steel depassivation. The propagation phase is characterized by active corrosion, which is characterized by comprises a loss of the cross-sectional area of the reinforcement and the gradual accumulation of rust that causes cracking and spalling of the concrete matrix, which reduces the structural safety. The same causes of corrosion causes related to conventional reinforced concrete are applicable to Steel Fiber Reinforced Concrete (SFRC) and conventional reinforced concrete, mainly the corrosion induced by chlorides and the corrosion caused by a pH reduction of the concrete matrix due to carbonation (ACI 544.5R, -2010).

The This present paper presents shows the results of an experimental study that evaluates the effect of chloride ions on the flexural mechanical properties of the SFRC during the initiation phase of corrosion (short term). According to the durability report of the fiber-reinforced concrete (ACI

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544.5R, -2010), the flexural mechanical properties, and particularly the flexural toughness, provide adequate tests to evaluate corrosion in the SFRC. Thus, the experimental program of this study includes flexural tests on concrete specimens reinforced with two different dosages of steel fibers, which were subjected to the action of corrosive environments.

1.1 Corrosion in SFRC

It has been widely reported that the corrosion of steel fibers is much less severe than the corrosion of conventional reinforcing steel bars in concrete structures (Berrocal et al., 2015a; Sadegui-Pouya et al.; 2013). Steel fibers can reduce the entrance of aggressive agents and the degradation of concrete by controlling cracking at early ages through of shrinkage or temperature gradients and cracking by external loads (Berrocal et al., 2015b). According to Lambrechts (2003), if steel fibers are rustedcorroded, the relatively low volume of fibers is not enough to create rupture stresses associated to the corrosion of reinforcing bars of having larger diameter and, therefore, for a well compacted concrete, fiber corrosion is exclusively limited to the surface of the SFRC. In the case of the corrosion induced by chlorides, the local depassivation of steel occurs when they chlorides exceed a certain limit known as chloride critical content or chloride threshold, which generates a localized breaking of the passive layer of the reinforcement, a phenomenon called pitting corrosion (Angst et al., 2011; Stansbury and Buchanan, 2000). However, the chloride threshold, which is generally accepted in the range of 0.4-1.0% for conventional reinforced concrete structures, has revealed itself asvalues significantly higher for the SFRC, in orders up to 4.5% by weight of cementitious material (Raupach et al., 2004). According to studies of Angst et al. (2011), this improved corrosion strength of steel fibers embedded in concrete is due to the combination of (i) short steel fibers, which prevent large electric potential differences along the fiber and limits the formation of different anode and cathode regions, and (ii) manufacturing conditions (flotation of the fibers in the concrete matrix), which allow the formation of a very thin and well defined interfacial layer rich in $Ca(OH)_2$, between concrete and steel, without voids in the interface as in the ordinary bar reinforcement.

Although Steel Fiber Reinforced Concrete (SFRC) is less vulnerable to the effects of corrosion, compared with the traditional reinforced concrete, its properties are inevitably modified during the exposure to aggressive environments. According to Granju and Balouch (2005), corrosive environments can affect the flexural performance of the SFRC if steel fibers are rusted corroded (fibers in the conductive state), since they cause reductions in the maximum loading peak, together with a fragile and brittle post-peak behavior. Nevertheless, if there is self-curing of SFRC during the marine saline exposure is observed, the maximum loading peak should increase given the restoration of cracks and discontinuities inside the matrix. Therefore, the knowledge regarding concrete degradation mechanisms caused by the corrosion of steel fibers is insufficient, which restricts the SFRC application to a conservative design approach in structural elements (Solgaard et al., 2010).

There are not enough research works studies to date (2017) dealing with the characterization of the SFRC performance under the influence of corrosion. The behavior of the fibers has not been fully understood, and the design with steel fibers is more influenced by experience than by scientific knowledge (Frazão et al., 2015). In tThe chapter 9.6.3.1 of , the ACI 318-14 Regulation Code specify specifies the use of steel fibers as a shear reinforcement in concrete beams. Additionally, in the chapter 19.3 of, the ACI 318-14 specifies the durability requirements of concrete based on exposure categories and classes of exposure to which it will be exposed toof concrete. However, as mentioned in the observation commentary R9.6.3.1 of these this codeRregulations, there are no data concerning the use of steel fibers as a shear reinforcement in concrete members nor design equations for flexural elements exposed to chlorides from deicing salts, salt, salted water, seawater or splashing from these sources. Consequently, the use of steel fibers as shear reinforcement in corrosive environments should consider protection against corrosion according to current codes. In the absence of formulations for the SFRC subjected to corrosive environments, the experimental results obtained in the present research study were used to formulate prediction equations describing, in the initiation phase of corrosion, the flexural performance of SFRC for this kind types of environments in the initiation phase of corrosion. Thus, the knowledge about the behavior of steel fibers and the documentation of parameters used in the manuals and regulations, will be a valuable contribution to engineers and technical staff in general concerning tools aimed at informing about the employment of SFRC in the design of constructions concrete structures under the action of corrosive environments.

2. Experimental program

The purpose of the experimental program was to analyzestudy, during the initiation phase of corrosion, the flexural performance of SFRC under the action of corrosive environments during the initiation phase of corrosion. The program involved testing of 54 steel fiber reinforced concrete specimens, in the form of cylinders and beams, with fiber having a length/diameter ratio of 65 and fiber dosage of 30 kg/m^3 and 60 kg/m^3.

2.1 Concrete Mix

The nominal compressive strength of concrete at 28 days was 25 MPa. The materials dosage by cubic meter of concrete mix used in this study was 321 kg of conventional Portland cement Type I, 35 kg of flying ash corresponding to a 10% replacement of the main cementitious material, and 185 kg of water, which gives a water/cement (w/c) ratio of 0.58 y. As stony materialcoarse aggregate, 870 kg of fine aggregates gravel like river sand and rock sand were used, with fineness modulus of 3.02 and 1.49, and absorption of 0.77% and 0.79%, respectively. As coarse aggregate, 870 kg of fine gravel of gray tonesgray-colored fine gravel and with nominal maximum size (NMS) of 10 mm, were used. A superplasticizer (Sika, 2012a) was used to ensure the handling of the mix, with dosage by weight of 0.25% of the main cementitious material, as well as a water reducer admixture (Sika, 2013) with dosage by weight of 0.45% of the main cementitious material.

2.2 Types of steel fibers

The This study used straight steel fibers with low carbon content, length of 35 mm, diameter of 0.55 mm, *aspect ratio of approximately 65, and hooked ends. The experimental program envisaged comprised only one type of mix with different fiber dosages: plain concrete (PC) without fiber addition, and concrete reinforced with steel fibers in dosages of 30 kg/m^3 and 60 kg/m^3, corresponding to volume fractions of 0.38% and 0.76% in relation to the concrete's total volume of concrete. In this study, the fiber dosage selection was based on the guidelines of chapter 26.4.2.2 of the ACI 318-14 Code, which contemplates the use of the a minimum fiber dosage of 60 kg/m^3, when used as a shear reinforcement in concrete membersbeams. In addition to the minimum dosage allowed, the this present study used a dosage corresponding to half of the minimum dosage (30 kg/m^3), with the aim of better characterizing the effect of different fiber dosages on the flexural performance of the SFRC and its degradation by corrosion. Additionally, the volume fractions of 0.38% and 0.76% used in this study are within the typical range used for manufacturing SFRC members on site, that is, fractions of 0.25% to 1.5% by volume of concrete (ACI 544.1R-96). The fiber addition rate to the concrete mix was 1.7 kg/min and the mixing time in the fresh state was 5 minutes for the two dosages employed. The mixing rate and time comply with the mixing recommendations for steel fibers; that is, maximum rate of fiber addition of 60 kg/min and minimum mixing time of 5 minutes (Bekaert, 2005).*

2.3 Specimen types and curing process

During tThe study involves, 54 specimens that were manufactured and distributed as follows: 27 cylinders with standard dimensions of 150 mm diameter and 300 mm high, and 27 specimens in the form of beams with square cross section of 150 mm per side and length of 600 mm long. The formwork of Aall specimens were was demolded removed 24 hours after their manufacture, and they specimens were immediately cured by applying a curing membrane on their surfaces (Sika, 2012b). This membrane consists of a watery emulsion of paraffin, which guarantees the strength development of concrete.

2.4 Environment types

The study simulated two types of corrosive environments. Thus, 9 cylindrical specimens and 9 beams were subjected to the action of a watery environment and 9 cylinders and 9 beams, to the action of a saline environment. The notation of the environments is indicated in Table 1. Results were compared with those of 9 cylindrical specimens and 9 beams under normal ambient conditions (unaltered).

Once the specimens were stabilized at their maximum strength development of specimens was stabilized (at age close to 90 days), they were subjected to the environment A1 or A2. The specimens remained immersed in those environments for a period of 60 days, corresponding to the initiation phase of corrosion where external agents (chlorides, sulfates, carbonation) start penetrating inside the concrete and causing the depassivation of steel (Tuutti, 1982). In order to confirm the initial state or initiation phase of corrosion, where SFRC specimens were tested, the present study reported herein refers to the results of the work research undertaken by Aperador et al. (2017), who evaluated corrosion potentials at the same time on the same SFRC specimens after 60 days of exposure to the watery and saline environments, for dosages of 30 kg/m^3 and 60 kg/m^3. The results of Aperador et al. (2017) allowed evidencing that the SFRC specimens analyzed in the this present study, with fiber dosages of 30 kg/m^3 and 60 kg/m^3, remain in the passive state at the end of their exposure. Thus, in this study, the SFRC specimens tested in this study undergo the initiation phase of corrosion after their 60-days that were exposure exposed to the studied corrosive environments, according to the passivation criterion established by Tuutti (1982). Finally, the specimens were removed from their immersion and stored under conditions of room ambient temperature and humidity in order to test them mechanically later on.

2.5 Test methods

During the study, c Standard tests for haracterization characterizing tests of the mechanical properties of plain concrete (PC) and steel fiber reinforced concrete (SFRC) were carried out in this study. The purpose of tThese tests was were aimed to at evaluate evaluating the effect of corrosive environments on the flexural performance of the SFRC. Table 2 describes the mechanical tests performed in this study.

Table 1. *Description of the exposure environments*

Nomenclature		Meaning
A0		Ambient conditions (T=22°C)
A1		Watery environment = Tap Water (T=20.6°C)
A2		Saline environment = Sodium chloride solution - NaCl at 3.5% (T=10.5°C)

Tabla 2. *Description and number of mechanical tests*

Type of Test	Specimen Type	Environment A0			Environment A1			Environment A2		
		D_f, kg/m^3			D_f, kg/m^3			D_f, kg/m^3		
		0	30	60	0	30	60	0	30	60
Compressive Strength, f_c	Cylinder	3	3	3	3	3	3	3	3	3
Flexural Performance, f_r	Beam	3	3	3	3	3	3	3	3	3

2.5.1 Fiber content

The real content or real dosage of steel fibers in each concrete mix, Df, was measured according to the recommendations of the UNE-EN 14488-7-07 standard (2007) standard. The calculation of the real dosage and the corresponding volume fraction of fibers per cubic meter of mix was obtained from the weight resulting from the fibers and the volume of the mold used.

2.5.2 Flexural strength

The beam specimens were subjected to flexural tests, following the guidelines of ASTM C- 78 (2015) standard for plain concrete (PC) (equivalent Colombian standard: NTC 2871-99) and the guidelines of ASTM C- 1609 (2012) standard for SFRC. Based on the specifications of ASTM C- 78 (2015), the loading speed rate was 130 N/s for PC, and it remained constant during the entire test. As for the SFRC, tThe average value of the testing speed rate for the SFRC was established in terms of displacement and it was equal to 0.05 mm/min, which complies with the speed ranges of loading rates proposed by ASTM C- 1609 (2012); that is, 0.035 mm/min to 0.10 mm/min for midspan deflections lower than 1/900 of the span; and 0.05 mm/min to 0.30 for greater deflections. The test consisted in two- one-point, continuous and, smooth no-impact loads applications, through a head assembly with two rollers located on the middle third of the specimen, as shown in Figure 1. Two displacement transducers were coupled on each side of the beam specimen. The average of the two measurements allowed calculating the deflection generated by the load applications and, subsequently, the stress-deflection curve for each specimen.

The results' analysis was based on statistical parameters such as the arithmetic mean (X) and the coefficient of variation (CV), which represent the average and the dispersion of the measured values, respectively. Likewise, the correlation coefficient (r) was used to quantify the correspondence degree between the analyzed variables.

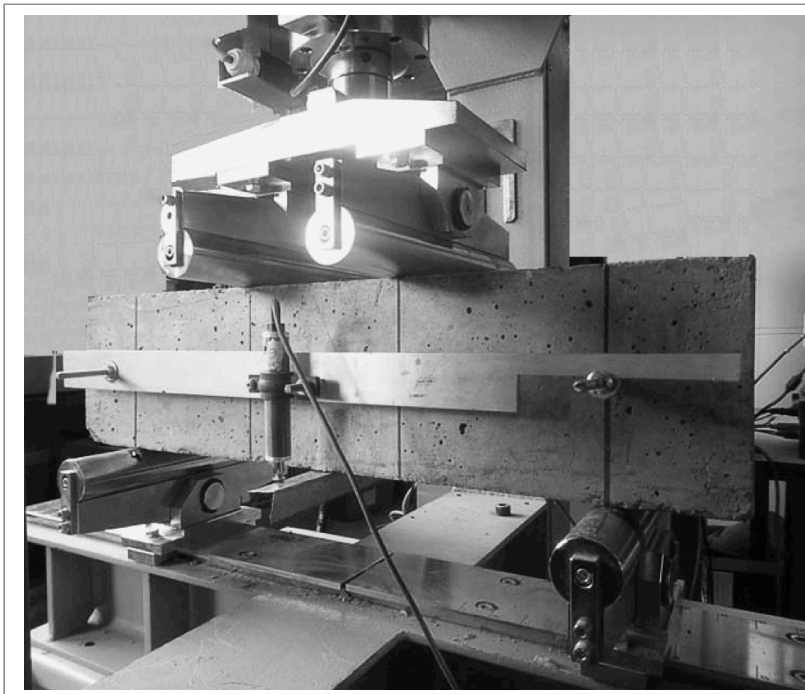

Figure 1. *Configuration of the flexural test*

3. Results and discussion

Based on results measured in the flexural test, the stress-deflection curves for the SFRC specimens were calculated and the short-term effect (initiation phase) of corrosive environments was evaluated on in terms of the parameters of flexural toughness, peak strengths and deflections associated to these strengths. According to the guidelines of ASTM C- 1609 (2012) standard, this study estimated the equivalent flexural strength ratio (RTD.150), defined as the average residual strength level after the first crack and that strength until the a deflection value of ℓ/150; that is, a value of 100% values indicates a perfectly plastic behavior, and lower values indicate lower performance.

Likewise, based on the criteria of ASTM C- 1399 (2010), this study also calculated the average residual strength (ARS) of the SFRC, after the first crack. According to Johnston and Gray (1986), residual factors reflect the hardening effect provided by fibers and the strengthening effect that can be achieved in the concrete;. For for example, the strength increase after the first crack. These factors depend mainly on the fiber type, and dosage, and the aspect ratio of the fibers, regardless of whether the matrix is a mortar or concrete.

Table 3 indicates the nomenclature of the parameters evaluated in this study, and a diagram thereof is shown in Figure 2. Table 4 presents shows the results for each one of the real fiber dosages. HenceforthHereinafter, and for the purpose of the analysis, real dosage values will be used for the fiber dosages. Table 4 also shows the specimens' test results for of unit massweight, M, and compressive strength, f_c, of specimens reported by Carrillo et al. (2015).

Table 3. *Nomenclature of the studied mechanical properties*

Abbreviation		Meaning
D_f		Real fiber dosage (measured)
V_f		Real fiber volume fraction of fibers (measured)
ℓ		Span distance between supports
M		Unit mass weigth
f_c		Compressive strength
f_r		Modulus of rupture
f_{max}		Maximum flexural strength
$f_{\ell/600}$		Flexural strength corresponding to deflection ℓ /600
$f_{\ell/150}$		Flexural strength corresponding to deflection ℓ /150
T_{flex}		Flexural toughness
δ_r		Deflection associated to Modulus modulus of Rupture
δ_{max}		Deflection associated to maximum flexural strength
$R^T_{D.150}$		Equivalent flexural strength ratio
ARS		Average of residual strength

Table 4. Flexural values for each type of mix

Parameter		A0			A1			A2		
D_f, kg/m^3		0	27.5	58.1	0	27.5	58.1	0	27.5	58.1
V_f, %		0	0.35	0.74	0	0.35	0.74	0	0.35	0.74
M, kg/m^3	X	2277	2285	2298	2277	2285	2298	2277	2285	2298
	CV, %	0.2	0.2	0.11	0.2	0.2	0.11	0.2	0.2	0.11
f_c, MPa	X	38.1	36.7	38.7	42.0	43.1	41.0	40.3	42.1	40.9
	CV, %	2.0	1.7	1.7	4.8	1.4	1.6	5.0	0.7	1.4
f_r, MPa	X	4.03	-	-	4.12	-	-	4.19	-	-
	CV, %	1.2	-	-	6.1	-	-	8.7	-	-
δ_r, mm	X	0.0529	-	-	0.0655	-	-	0.0762	-	-
	CV, %	1.3	-	-	10.8	-	-	3.6	-	-
f_{max}, MPa	X	-	4.50	4.96	-	4.49	4.78	-	4.30	4.49
	CV, %	-	1.3	1.4	-	8.6	13.6	-	6.8	7.9
δ_{max}, mm	X	-	0.0728	0.0746	-	0.0751	0.0768	-	0.0767	0.0801
	CV, %	-	3.0	4.7	-	15.0	0. 3	-	7. 4	8.9
$f_{\ell/600}$, MPa	X	-	3.58	4.44	-	3.78	4.28	-	3.57	3.92
	CV, %	-	1.1	1.1	-	5.6	15.0	-	7.5	6.9
$f_{\ell/150}$, MPa	X	-	1.91	3.16	-	2.09	2.86	-	1.87	2.48
	CV, %	-	0.5	0.3	-	1.1	3.4	-	2.1	1.3
T_{flex}, J	X	0.81	60.54	90.78	1.48	57.99	87.52	1.88	54.96	80.48
	CV, %	4.4	2.0	1.5	12.3	7.9	11.9	12.9	5.4	3.9
$f_r/\sqrt{f_c}$	X	0.66	-	-	0.63	-	-	0.66	-	-
	CV, %	1.8	-	-	4.5	-	-	9.7	-	-
$f_{max}/\sqrt{f_c}$	X	-	0.74	0.80	-	0.68	0.74	-	0.66	0.70
	CV, %	-	2.2	1.9	-	8.5	13.0	-	6.5	7.5
$f_{\ell/600}/\sqrt{f_c}$	X	-	0.59	0.72	-	0.58	0.67	-	0.55	0.61
	CV, %	-	1.5	1.1	-	6.0	14.5	-	7.2	6.3
$f_{\ell/150}/\sqrt{f_c}$	X	-	0.31	0.51	-	0.32	0.45	-	0.29	0.39
	CV, %	-	10.0	0.6	-	17.5	11.5	-	2.8	2.4
$T_{flex}/\sqrt{f_c}$	X	0.1	10.0	14.6	0.2	8.8	13.7	0.3	8.5	12.6
	CV, %	4.5	1.2	2.1	11.7	8.4	11.7	14.3	5.1	4.6
$R^T_{D.150}$, %	X	-	59.8	81.3	-	57.4	81.4	-	56.8	79.7
	CV, %	-	4.5	3.0	-	1.9	5.0	-	10.2	11.1
ARS, MPa	X	-	3.50	4.34	-	3.40	3.97	-	3.30	3.75
	CV, %	-	5.1	8.0	-	4.2	6.5	-	4.0	15.0

Based on the stress-deflection curves measured during the study, Figures 2a1 to 2c3 show the effect of the steel fiber addition and the exposure environments on the flexural mechanical properties of the SFRC. The curves calculated with the average of the three curves of each environment and dosage are shown in Figures 2d1 to 2d3. Based on the trends of the measured results, Figure 3 shows the relationship between the flexural performance parameters and the product between the volume fraction and the aspect ratio of the fibers, $[V_f(l_f/d_f)]$.

In order to establish the relevance of the fiber dosage and the type of environment in the flexural results, the one-way and multifactorial ANOVA analysis of variance was carried out for each evaluated parameter. Table 5 shows the results of the ANOVA analysis.

Table 5. *Flexural values for each type of mix*

Parameter		One-way ANOVA	Multifactorial ANOVA		
		D_f=0 kg/m^3	Environment	Fiber Dosage	Environment-Fiber Dosage
f_c , MPa	Coefficient of variance	-	25.49	1.69	2.65
	Associated P Value		0.0000	0.2118	0.0669
f_r , MPa	Coefficient of variance	30.80	-		
	Associated P Value	0.0007			
	Bartlett Test	0.693			
δ_r , mm	Coefficient of variance	13.96	-		
	Associated P Value	0.0055			
	Bartlett Test	0.047			
f_{max} , MPa	Coefficient of variance	-	2.13	2.90	0.73
	Associated P Value		0.1610	0.1145	0.5040
δ_{max} , mm	Coefficient of variance	-	1.24	0.04	0.13
	Associated P Value		0.3238	0.8404	0.8803
$f_{\ell/600}$, MPa	Coefficient of variance	-	0.49	12.53	1.92
	Associated P Value		0.6215	0.0041	0.1887
$f_{\ell/150}$, MPa	Coefficient of variance	-	0.06	34.72	0.89
	Associated P Value		0.9462	0.0001	0.4365
T_{flex} , J	Coefficient of variance	-	0.20	68.17	7.20
	Associated P Value		0.8212	0.0000	0.0012
$f_r /\sqrt{f_c}$	Coefficient of variance	1.32	-		
	Associated P Value	0.3359			
	Bartlett Test	0.318			
$f_{max} /\sqrt{f_c}$	Coefficient of variance	-	4.43	2.61	0.12
	Associated P Value		0.0363	0.1321	0.8907
$f_{\ell/600} /\sqrt{f_c}$	Coefficient of variance	-	2.15	8.77	0.11
	Associated P Value		0.1595	0.0119	0.8992
$f_{\ell/150} /\sqrt{f_c}$	Coefficient of variance	-	4.55	67.64	0.59
	Associated P Value		0.0339	0.0000	0.5709
$T_{flex} /\sqrt{f_c}$	Coefficient of variance	-	0.89	46.41	1.98
	Associated P Value		0.4276	0.0000	0.1411

Regarding the effect of the fiber dosage and type of environment, in Table 5 the variability of the maximum flexural strength, f_{max}, does not show a significant difference, just as the behavior of and the trend of maximum SFRC deflection, δ_{max}, do not show a significant difference in Table 5. Based on the analyses of variance for flexural strength corresponding to deflection values $\ell/600$ and $\ell/150$, $f_{\ell/600}$ - $f_{\ell/150}$, Table 5 also shows that the fiber dosage has quite a different influence when adding steel fibers to concrete specimens, in opposition contrast to the effect produced by the type of environment. LikewiseSimilarly, Table 5 shows that flexural toughness values, T_{flex}, vary significantly when increasing the steel fiber content, which is associated to the fact that the interaction between the fiber dosage and the change of environment of the product is equally significant in each association. In this case, This this demonstrates that, in this case, the environment effect depends on the fiber dosage effect. As forIn terms of the flexural strength values associated to a deflection of $\ell/600$, $f_{\ell/600}$ and $\ell/150$, $f_{\ell/150}$, the fiber dosage does influences the variability of these strengths.

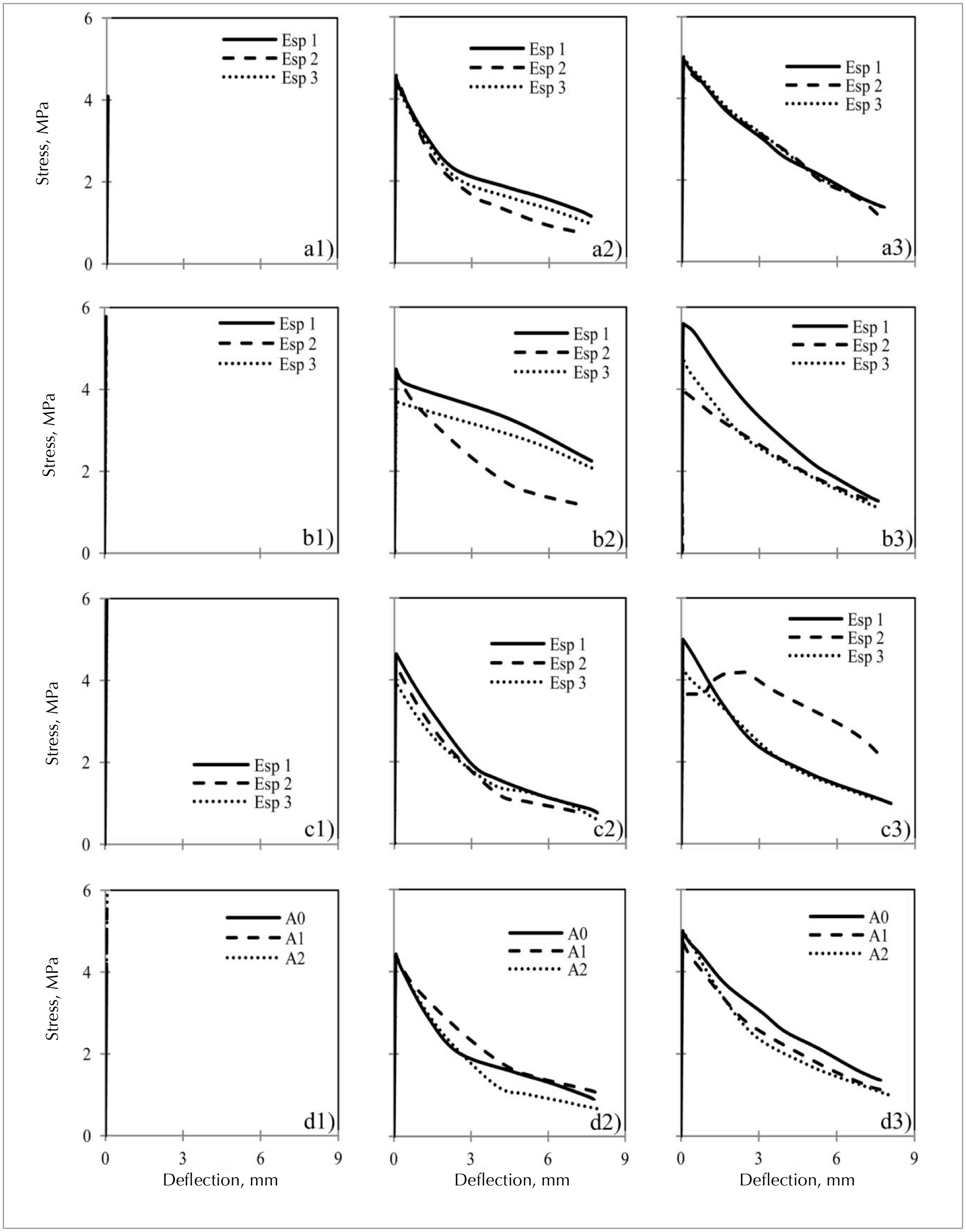

Figure 2. *Flexural stress-deflection curves for each type of mix: a1) A0-0, a2) A0-27.5, a3) A0-58.1, b1) A1-27.5, b2) A1-58.1, b3) A1-27.5, c1) A2-58.1, c2) A2-27.5, c3) A2-58.1, d1) D_f = 0 kg/m^3, d2) D_f = 27.5 kg/m^3, d3) D_f = 58.1 kg/m^3*

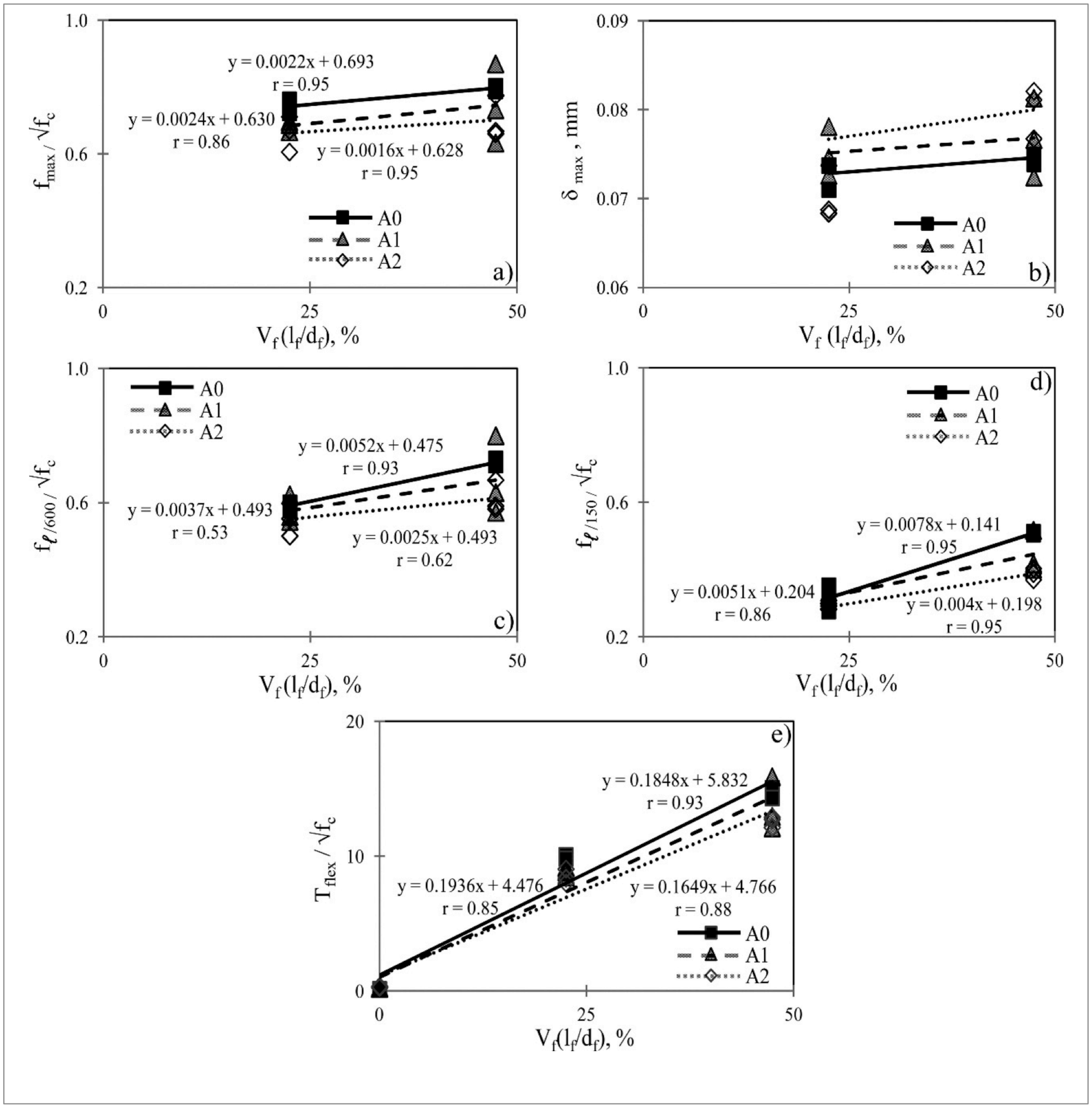

Figure 3. *Trends of flexural tests: a) f_{max}, b) δ_{max}, c) $f_{\ell/600}$, d) $f_{\ell/150}$, e) T_{flex}.*

In relation terms to of the fiber dosage effect, Figure 3a shows that the maximum flexural strength, f_{max}, increasedaugmented when increasing the fiber dosage of the specimens in the normal environment A0. In this environment A0, the f_{max} values increased up to 19% compared with the concrete without fiber addition. The fmax increase evidenced in this study is consistent with the results obtained by Yazici et al. (2007), who evaluated the influence of the fiber volume fraction, Vf, on the flexural strength of concrete. They found that the use of steel fibers increased the maximum flexural strength of concrete in a range varying from 3% to 81% in when relation compared to with plain concrete. Thus, when adding a larger volume of fibers to the concrete, an modification alteration was observed in the failure mode under flexural stress of the SFRC, from a sudden and fragile mode to a ductile mode in the failure mode under flexural stress of the SFRC was observed when adding a larger volume of fibers to the concrete.

Figure 3b presents shows the behavior of the SFRC maximum deflection, δ_{max}, For the normal environment A0, Figure 3b shows a deflection increase when the $[V_f(l_f/d_f)]$, product increases, which reflects the strengthening effect provided by steel fibers in the concrete matrix.

Regarding the normal environment A0, Figures 3c and 3d show that, when increasing the fiber dosage of the specimens, the flexural residual strength for deflection values ℓ/600 y ℓ/150, $f_{\ell/600}$ - $f_{\ell/150}$ increase when increasing the fiber dosage of the specimens. LikewiseSimilarly, Figure 3e shows that the flexural toughness values, Tflex, increase when increasing the $[V_f(l_f/d_f)]$ values in the normal environment A0. These trends demonstrate an increase in the strength and energy absorption capability of the SFRC when incorporating higher contents of steel fibers.

In relation toterms of the effect of corrosive environments during the initiation phase of corrosion, Figure 3a shows a decrease of 2% and 4% of the f_{max} values of the SFRC in the watery environment A1 for dosages of 27.5 kg/m^3 and 58.1 kg/m^3, respectively. The results of reduced flexural strength of the SFRC in the watery environment are consistent with the results reported by Anandan et al. (2004), who found that the exposure to alternate cycles of moisture in normal water and drying do not entail a considerable reduction in the flexural strength of concrete with steel fibers, but they do show a reduced flexural strength compared with the reference specimens not exposed to aggressive agents. Figure 3a, fFor the saline environment A2, Figure 3a shows reductions of 5% and 10% for the SFRC with dosages of 27.5 kg/m^3 and 58.1 kg/m^3, respectively. This indicates that, regarding the normal environment A0, the decrease of the maximum flexural strength is higher for the saline environment A2 than for the watery environment A1. Thius, it istrends evidenced that the severity of the chloride ion attack on the SFRC, particularly on steel fibers, is higher than in the saline environment A2.

Figure 3b shows that, Ffor the saline environment A2, Figure 3b shows that the deflection associated to the maximum flexural strength, δ_{max}, is higher than the oneat registered by the specimens of environments A0 and A1. For example, compared with the deflection capability of plain concrete, increases of 3% and 5% were evidenced for the dosage of 27.5 kg/m^3 in environments A1 and A2, and 3% and 7% for the dosage of 58.1 kg/m3 in environments A1 and A2, respectively, when compared with the deflection capability of plain concrete. The greater deformation capability provided by the dosage of Df = 58.1 kg/m^3 is partly because steel fibers can further restrict the crack dissemination propagation caused by the watery and saline environments on the SFRC. On the other hand, as shown in Figures 2 and 3, the saline environment presents entails the highest increase in the deformation capability caused by chloride ions, due to the formation of salt crystals that increase the friction between the matrix and the fibers (Sadeghi-Pouya et al., 2013; Hashimoto et al., 2014; Kwan et al., 2014; Alizade et al., 2016). According to Frazão et al. (2015), the saline environment increases the surface roughness of the fibers eimbedded in the SFRC, due to the corrosion products rust that improve the interfacial bond between fibers and the cementitious matrix, and their pullout resistance. LikewiseSimilarly, Bathia and Foy (1989) state that this effect is due to a smaller accumulation of corrosion productsrust on the surface of the steel fibers, which generates confining stresses between the matrix and the fibers. This strengthening effect of the matrix under the exposure of saline environments has been reported by Ramli et al. (2013), who ascribe this fact not only to the cohesion effect between the matrix and the fibers, but also to effects associated to the salt crystallization inside the porosities. These effects can contribute to seal the microcracks in the cementitious matrix; this self-curing effect was also reported in the study of Nordström (2005). Additionally, Carrillo et al. (2015) ascribe this strengthening effect to the formation of non-expansive salts that increase the compactness of the cementitious matrix and make it less perviousporous.

Kosa and Naaman (1990) evaluated the effect of corrosion on the flexural properties of concrete with steel fibers. In the such a study, SFRC specimens were saturated in a solution of NaCl at 3.5% for different exposure periods. During the first 60 days of exposure in the saline environment, the specimens showed increases in the peak stress and flexural toughness when, compared with the control specimens cured in an air chamber at room temperature. Kosa and Naaman (1990) indicate that these increases were generated by the early effect of corrosion that might have improved the bond strength of the interface between the matrix and the fibers, in the short term. On the other hand, Alizade et al. (2016) affirm that the mechanical properties of the SFRC are generally improved at early ages, which derives from the expansion of steel fibers providing their best anchor to the cementitious matrix due to the corrosion processes. Other researches (Anandan et al., 2014) reported an effective bonding development, at 180 days of saline exposure, in the interface between cementitious matrix and fibers, which provides an improved resistance to fiber pullout and, consequently, an increased flexural loading capabilitycapacity. The present study reported herein only evaluates the effect of watery and saline environments on the SFRC flexural properties in the short term, (60 days), which corresponds to the initiation phase of corrosion where cracks generated by corrosion processes in the concrete have not been formed yet; but mechanical increases were evidenced during this period, particularly on the deflection capability of the SFRC. On the other hand, Kosa and Naaman (1990) observed that, after 300 days of exposure to the saline environment, there were reductions of 8% and 27% reductions in the peak flexural stress and the flexural toughness index, respectively, due to a progressing corrosion degree in the SFRC and consequent reduction of the steel fibers' diameter. Thus, Kosa and Naaman conclude that the reduction in the flexural strength and the toughness index during the propagation phase of corrosion are controlled by the reduction of the fibers' diameter and not by a reduced bonding capacity between the matrix and the fibers. Although the present study did not evaluate the flexural properties of the SFRC in the long term, that is, it only analyzed the flexural mechanical properties of the SFRC at the beginning of the corrosion processes, a generalized degradation is expected in later ages (propagation phase of corrosion) concerning the performance of the SFRC. This trend is, not only due related to the reduction of the fibers' diameter, but also to the constant increase of the rust volume, which induce internal tensile stresses to the cementitious matrix and the generation of thicker wider cracks. LikewiseSimilarly, Alizade et al. (2016) argue that when the SFRC reaches a high degree of corrosion, its mechanical properties are reduced by the loss of steel volume in the fibers. According to previous studies (Serna and Arango, 2008; Berrocal et al., 2015; Alizade et al., 2016), a gradual change is expected during the propagation phase in the type of failure of steel fibers, from the typical extraction mode to the breaking of fibers.

For the watery and saline environments A1 and A2, Figure 3d shows that, for the watery and saline environments A1 and A2, the reduction of flexural strength values associated to a deflection ℓ/150, $f_{\ell/150}$, is more evident for the fiber dosage of 27.5 kg/m^3 than for the dosage of 58.1 kg/m^3. This trend indicates that, although a reinforcement effect is perceived noticed in the concrete by the steel fiber dosage increase, corrosive environments induce reductions in the residual strengths of the SFRC, which entails causing a lower post-crack performance. The reduction of the values of $f_{\ell/150}$ is higher for the saline environment A2 than for the watery *environment A1, due to the aggressiveness of the environment exposure in the presence of chloride ions.*

In the initiation phase of corrosion, Figure 3e shows that, in the initiation phase of corrosion, there are reductions in the toughness values influenced by the corrosive environments, mainly by the saline environment A2, due to its aggressiveness. The toughness reduction is more evident for the fiber dosage of 58.1 kg/m^3 than for the dosage of 27.5 kg/m^3, mainly due to the higher content of steel fibers.

As shown in Table 4, for the 60-days exposure corresponding to the initiation phase of corrosion, the equivalent flexural strength ratio, $R^T_{D.150}$, increases when increasing the steel fiber dosage in the concrete, and slightly decreases with the exposure to corrosive environments, which in turn reduces the flexural performance of the SFRC and the transfer bridging capacity of the fibers after the first crack. On the other hand, Table 4 and Figure 4 show increases in the ARS values when increasing the fiber dosage. However, a reduction of the ARS values up to 14% was observed, corresponding to the dosage of D_f = 58.1 kg/m^3 and the saline environment A2. This trend reflects a loss in the energy absorption capability when the SFRC is exposed to the action of saline environments.

Based on the trends of measured results, Table 6 shows proposes prediction equations for predicting main SFRC parameters of flexural mechanical performance of SFRC., and Table 7 indicates the constants used for this determinationestimation. The dispersion of the parameters was analyzed with the correlation coefficient, r, defined as an indicator of the intensity of the linear relationship between estimated values and experimental data. Based on r values of the equations, it is possible to affirm that the proposed equations are appropriate and reliable, since they are associated to a strong correlation among the measured variables (r values close to one).

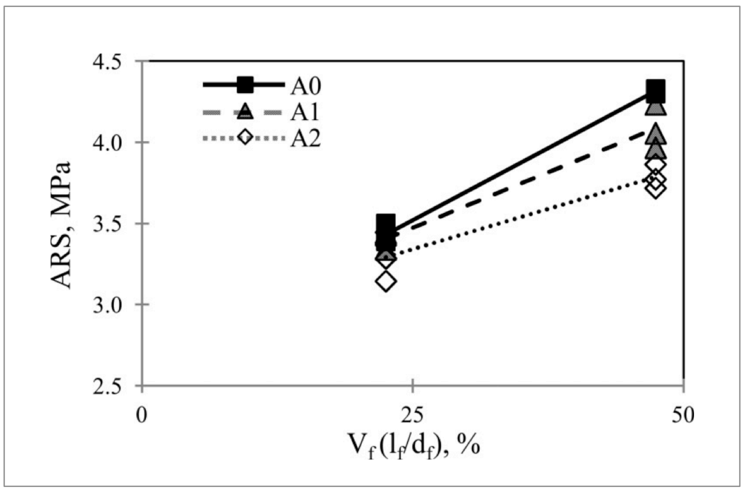

Figure 4. *Trends of the Average Residual Strength, ARS*

Table 6. *Equations proposed for the determination of the SFRC flexural properties*

Proposed Equation	Unit
$f_{max} = \left[A\left(V_f \times (l_f/d_f)\right) + B\right]\sqrt{f_c}$	MPa
$f_{\ell/600} = \left[A\left(V_f \times (l_f/d_f)\right) + B\right]\sqrt{f_c}$	MPa
$f_{\ell/150} = \left[A\left(V_f \times (l_f/d_f)\right) + B\right]\sqrt{f_c}$	MPa
$T_{flex} = \left[A\left(V_f \times (l_f/d_f)\right) + B\right]\sqrt{f_c}$	Joule

Table 7. *Constants of the equations Proposed for the Flexural Determination of the SFRC*

Parameter	Exposure Environment	Constant		Correlation Coefficient
		A	B	
f_{max}	A0	0.0022	0.693	r=0.95
	A1	0.0024	0.630	r=0.86
	A2	0.0016	0.628	r=0.95
$f_{\ell/600}$	A0	0.0052	0.475	r=0.93
	A1	0.0037	0.493	r=0.53
	A2	0.0025	0.493	r=0.62
$f_{\ell/150}$	A0	0.0078	0.141	r=0.95
	A1	0.0051	0.204	r=0.86
	A2	0.0040	0.198	r=0.95
T_{flex}	A0	0.1848	5.832	r=0.93
	A1	0.1936	4.476	r=0.85
	A2	0.1649	4.766	r=0.88

4. Conclusions

This paper evaluated the flexural behavior of the SFRC under the short-term action of corrosive environments, which corresponds to the initiation phase of corrosion. The paper proposes equations that allow describing this behavior, and the results of the study allow concluding the following:

- *Regarding the initiation phase of the corrosion process, where cracks generated in the concrete by corrosion processes have not yet been formed, results showed that the saline environment (NaCl at 3.5%) caused an approximate loss of approximately 10% and 11% in the values for flexural strength and flexural toughness in the SFRC, respectively, with fiber dosage of Df = 58.1 kg/m^3, respectively. Therefore, in the presence of saline environments, the SFRC with higher fiber dosage evidences larger reductions in its energy absorption capability when, compared with the watery or moist environments without no presence of chlorides.*
- *For the exposure time of 60 days, corresponding to the initiation phase of corrosion, no significant effects of corrosion on steel fibers were observed; however, there was a slight improvement in the deflection and bonding. It seems that this favorable effect improves the ductility and energy absorption capability of the specimens, due to the formation of salt crystals in the microstructure that improve the friction between the matrix and the fibers. Nevertheless, based on previous studies by other authors mentioned throughout this paper, it is expected that with longer exposure times periods there might be a reduction of the mechanical properties of the SFRC, due to the reduction of the fibers' diameter and the formation of thicker wider cracks due to the propagation of corrosion.*
- *In generalOverally, during the initiation phase of the corrosion process, the mechanical properties of concrete with steel fibers was mostly affected in the saline environment A2, rather than in the watery environment A1, due to the effect of the chloride ions (Cl), which are capable of reacting with the oxygen and reduce the pH of the matrix. This does not only provoke a gradual reduction of the fibers' diameter, but also the generation of new ferric products such as magnetite and goethite. These products foster cause tensile stresses in the matrix, which induce cracks and later degradation of the structural members. However, due to the short exposure time used in this study, these effects were not clearly appreciated; only slight reduction effects of up to 11% were observed in the flexural strength and mechanical performance parameters, corresponding to the initiation phase of the corrosion process.*

- *Based on the trends of experimental results, this study proposes equations that allow describing the effect of the initiation phase of corrosion (analyzed in a short term of 60 days) of watery and saline environments on the SFRC under flexural stresses. The proposed equations can be applied used forto concretes with normal weight, unit mass weight between 2250 kg/m^3 and 2350 kg/m^3, compressive strength between 35 MPa and 45 MPa, with hooked-end steel fibers with tensile strength of 1345 MPa, and product values of [$V_f(l_f/d_f)$] ranging from 24.8% to 49.7%.*

5. Acknowledgements

The authors wish to thank the Research Vicerectory Office of the UMNG (Vicerrectoría de Investigaciones) for their financial support aimed at developing the IMP-ING-2130 project. Additionally, the authors express their gratitude to the companies Argos and Proalco (representative of Bekaert in Colombia), especially to the engineers Diego Velandia and Liliana Cardona, respectively. LikewiseIn addition, to the engineers Sebastián Varela, Miguel Ospina and Felipe Riveros, and the technicians William Castaño and Oliverio Pinzón, who supported the execution of the tests in the Aggregate and Concrete Laboratory, and Thermal Engineering Laboratories Laboratory of the Universidad Militar Nueva Granada.

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