Eco-Friendly Concrete Made with System CPC-SCBA-SF As a Protector Against Sulfate Corrosion of Reinforcing Steel AISI 1018

Brenda Paola Baltazar-García, Daniel Francisco Baltazar-Zamora, Laura Landa-Ruiz, Ce Tochtli Méndez, Rodolfo Solorzano, Francisco Humberto Estupiñan López, René Croche, Griselda Santiago-Hurtado, Victor Moreno-Landeros, Citlalli Gaona-Tiburcio, Facundo Almeraya-Calderón, and Miguel Angel Baltazar-Zamora

***Abstract* — In the present investigation, the protector against sulfate corrosion of reinforcing steel AISI 1018, which provides the Eco-friendly Concrete system CPC-SCBA-SF, was evaluated. This system was made with CPC-SCBA-SF cementitious materials, in percentages of 90-5-5 and 80-10-10 respectively, with exposure of the concrete specimens to a 3.5% $MgSO_4$ solution, an experimental arrangement that simulates the foundations of Civil Works such as bridges, buildings, pavements, etc.; in soils contaminated with sulfates. The design of the concrete mixtures was in accordance with the ACI 211.1 method. The behavior of the corrosion potential E_{corr} and the corrosion rate (i_{corr}) of the AISI 1018 steel embedded in Conventional Concrete (CC) and in the EC were evaluated during a period of 180 days of exposure to an aggressive environment. The E_{corr} values indicate between a 10% risk of corrosion and uncertainty, according to the ASTM C-876-15 standard, but the i_{corr} indicates a negligible level of corrosion but with a tendency towards the activation of the system, with the eco-friendly concrete EC-20 having the best performance.**

***Keywords* — Eco-Friendly Concrete, Corrosion, AISI 1018, System CPC-SCBA-SF, Magnesium Sulfate.**

I. Introduction

The corrosion of reinforcing steel is the most destroying pathology that reinforced concrete structures (RCS) present, considered by the experts the main causative factor of the operation, durability and useful life decrease of the RCS [1]-[4], what means a big problem of premature economic costs or medium period in addition to a negative impact to our society due to the uncertainty of possible significant structural failures in civil works [5]-[12].

The corrosion problem of the RCS depends on many factors but the environment in which these structures are exposed is determining, therefore in environments in which aggressive ions are presented such as sulfates and chlorides, the corrosion of reinforcing steel will develop more easily [13]-[22].

The sulfates are usually present in polluted soils, underground water, and in seawater [23]-[28]. There have been developed a global level a big amount of studies to try to control, decrease, or delay the corrosion problem of reinforcing steel concrete, a numberless of proposals or experiment arrangements that always try to simulate the diverse conditions that RCS (ECR) experiment, it has been done from work in situ and the most used, which are the essays in laboratory controlled conditions, elaborating concrete specimens and exposing them in aggressive environments simulating the contact environments, variating the method of concrete construction, additive types, pozzolanic materials like fly ash, slag of high oven, rice ash, sugar cane bagasse ash [29]-[34].

Also, there has been proposed the use of alternating Steels to Steel AISI 1018, such as galvanized steels and stainless steels like reinforcement in conventional concretes as well as in sustainable concretes [35]-[41].

The objective of the present investigation was evaluating through electrochemical techniques, the Eco-friendly Concrete based on the system CPC-SCBA-SF as a protector against sulfate corrosion of reinforcing steel AISI 1018, as a sustainable response due to evaluating the Eco-friendly concretes, promoting the use of Agro-industrial wastes and industries in order to substitute Portland concrete in the fabrication of concretes, which is going to allow a decrease in the use of cement and will be reflected on less emitions of CO_2 by the cement industry, responsible of the 6 to 8% of the total CO_2 emitions at global level [42]-[45].

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B. P. Baltazar-García, Universidad Veracruzana, Mexico.
(e-mail: pao.baltazar.08@gmail.com)
D. F. Baltazar-Zamora, Universidad Veracruzana, México.
(e-mail: danielfbz8917@gmail.com)
L. Landa-Ruiz, Universidad Veracruzana, México.
(e-mail: lalanda@uv.mx)
C. T. Méndez, Universidad Veracruzana, México.
(e-mail: cmendez@uv.mx)
R. Solorzano, Universidad Veracruzana, México.
(e-mail: rsolorzano@uv.mx)
F. H. Estupiñan López, Universidad Autónoma de Nuevo León, Mexico.
(e-mail: francisco.estupinanlp@uanl.edu.mx)
R. Croche, Universidad Veracruzana, México.
(e-mail: rcroche@uv.mx)
G. Santiago-Hurtado, Universidad Autónoma de Coahuila, Mexico.
(e-mail: grey.shg@gmail.com)
V. Moreno-Landeros, Universidad Autónoma de Coahuila, Mexico.
(e-mail: vmmorlan@gmail.com)
C. Gaona-Tiburcio, Universidad Autónoma de Nuevo León, Mexico.
(e-mail: citlalli.gaonatbr@uanl.edu.mx)
F. Almeraya-Calderón, Universidad Autónoma de Nuevo León, Mexico.
(e-mail: facundo.almerayacld@uanl.edu.mx)
M. A. Baltazar-Zamora, Universidad Veracruzana, Mexico.
(e-mail: mbaltazar@uv.mx)

II. Materials and Methods

A. Materials

1) Dosage and proportioning of concrete mixtures

The dosage and proportioning of concrete mixtures were done in accordance with ACI 211.1 [46]. This method is based on the physical characteristics of the fine and coarse aggregates to be used in the preparation of the concrete mixtures, which allow the dosing of the materials in kg according to the quality of the concrete required.

The tests to determine the physical properties of the aggregates were carried out under the ASTM standards [47]-[50], and the results are shown in Table I.

In the present investigation, the concrete mixtures were designed for a water/cement ratio (w/c) = 0.65 and according to the physical properties of the aggregates (Table I), the dosage of the conventional concrete (CC) and Eco-friendly concrete (EC) was obtained, the dosages of the three mixtures are shown in Table II.

TABLE I: Summary of Aggregate Characterization Results

Physical properties of materials	Coarse aggregate	Fine aggregate
Specific Mass (MES) g/cm³	2.60	2.20
Bulk Volumetric Mass (BVM) Kg /m³	1443	-
Absorption (%)	1.7	1.8
Module of Fineness	-	2.94
Maximum Size Nominal (TMN)	¾ "	-

TABLE II: Dosage of Concrete Mixtures in KG for 1 m^3

Materials	CC	EC10	EC20
Water	205.00	205.00	205.00
CPC 30R	315.00	283.5	252.00
SCBA	0.00	15.75	31.50
SF	0.00	15.75	31.50
Fine aggregate	746	746	746
Coarse aggregate	881	881	881

B. Method

1) Characterization of fresh and hardened conventional concrete and eco-friendly concrete

According to the tests of the ONNCCE and ASTM standards [51]-[54], the characteristics of the CC and EC concretes in the fresh and hardened state were determined; the results are shown in Table III.

TABLE III: Properties of Eco-Friendly Concrete (Fresh and Hardened state)

TEST	CC	EC10	EC20
Slump, cm	8	7	6.5
Temperature, °C	25	24.5	24.0
Density, kg/m³	2254	2268	2273
F´c, Kg/cm²	337	313	346

2) Characteristics of reinforcing steel

The reinforcing steel used as the working electrode (WE) was AISI 1018. The steel bars were cut to 15 cm in length. Cleaning was performed on each of the bars until a clean surface of any impurity was obtained. The areas where a primary paint and a layer of anticorrosive paint were placed were delimited, (see Fig. 1), an arrangement used by the scientific community in the study of reinforced concrete corrosion [55], in addition, a AISI 316 stainless steel bar of 1/8" as auxiliary electrodes (AE) with a dimension of 15 centimeters in length.

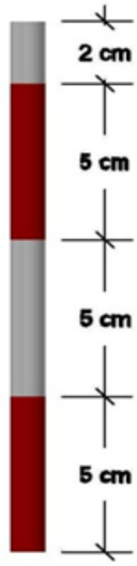

Fig. 1. Characteristics of bars embedded in Eco-friendly Concrete.

3) Nomenclature of the specimens

The nomenclature used for monitoring the corrosion potential E_{corr} and corrosion rate I_{corr} of AISI 1018 steel in CC and EC, exposed in water (Medical Control) and in 3.5% $MgSO_4$ Solution is shown in Table IV.

TABLE IV: Nomenclature Test Specimens of Green Concrete

Specimen
CC-1018
EC10-1018
EC20-1018

- CC= Conventional Concrete – 100% CPC 30R -
- EC10= Eco-friendly concrete based on the system 90% CPC 30R, 5%CBCA and 5%HS
- EC20= Eco-friendly concrete based on the system 80% CPC 30R, 10%CBCA and 10%HS
- 1018 = AISI 1018 Carbon Steel

4) Specimens for corrosion test

For the corrosion electrochemical behaviour of the AISI 1018 as reinforcement in the Eco-friendly Concrete, was used prismatic specimens, (see Fig. 2). The electrochemical cell was in accordance with ASTM G59 [56] standard.

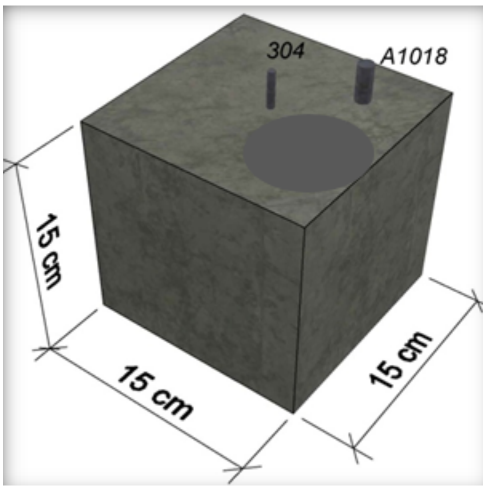

Fig. 2. Characteristics of concrete specimens for corrosion test.

The parameters used to perform the LPR test, the sweeping potential was ±20 mV with respect to the corrosion potential and the sweep rate was 10 mV/minute, the IR drop potential was considered, they were the same as those used by other researchers [57]-[58], electrochemical technique as Electrochemical Impedance Spectroscopy and Potentiodynamic Polarization where the arrangement of three electrodes are used in a similar way [59]-[60]. The monitoring of the corrosion potentials Ecorr and corrosion current intensity I_{corr}, was carried out every week for a period of more than 180 days of exposure to the two media, the control medium (water) and the aggressive medium (3.5% solution of $MgSO_4$).

III. Results and Discussion

A. Corrosion Potential (E_{corr})

Table V shows the values obtained according to the ASTM C876-15 [61], to interpret the results of the corrosion potential of each of the test specimens, adding a rank according to the literature [62].

As indicated in the previous sections, there are 3 studio mixes, one control mix denominated conventional concrete (CC) with 100% CPC 30R, and two mixes of Eco-friendly concrete based on the cementitious system CPC-SCBA-SF, in which was realized a partial substitution of CPC 30R in a 10 and 20% for combinations of Sugarcane bagasse ash (SCBA) and silica fume (SF).

In Fig. 3, we can observe that in the curing stage, all the specimens present values of E_{corr} more negative than -200 mV, so in the passing of time report more positive values, maintaining during all the process of monitoring the specimen CC-1018 and the EC20-1018 the closest values to -100 mV, which according to the ASTM C-876-15 norm indicates 10% of corrosion risk. With regard to the specimen with 10% of substitution of SCBA-SF presents at 150 days with a more negative value than -200 mV, which according to the norm will indicate uncertainty of corrosion risk, to presenting in the last monitoring an E_{corr} of -176 mV, indicating a 10% of corrosion risk.

In Fig. 4, the obtained values of the corrosion potentials of the studio specimens to be exposed for more than 180 days to the solution at 3.5% of Magnesium sulfate in an aggressive environment are presented.

TABLE V: Corrosion Potential in Reinforced Concrete (E_{CORR}).

Corrosion potentials mV vs $Cu/CuSO_4$	
<- 500	Severe corrosion
<-350	90% Probability of Corrosion
-350 to -200	Uncertainty
> -200	10% Probability of Corrosion

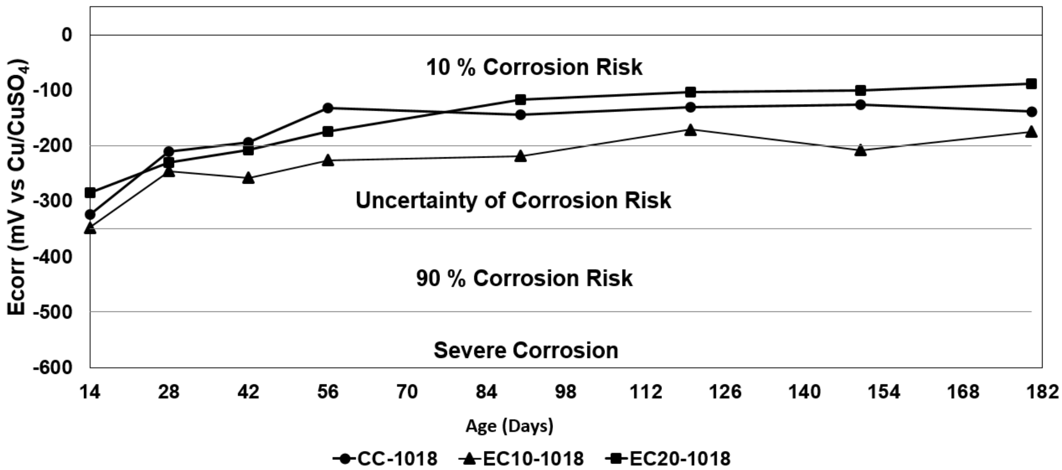

Fig. 3. Ecorr of AISI 1018 steel in concrete exposed to control environment.

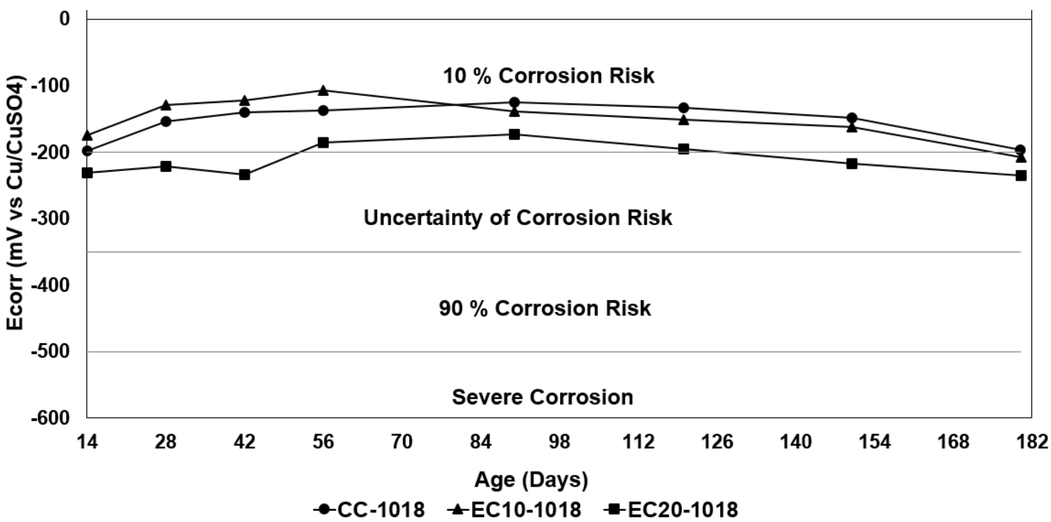

Fig. 4. Ecorr of AISI 1018 steel in concrete exposed to MgSO4 solution.

It has that all specimens present a similar behavior to the observed in the specimens exposed to the control medium, from the curing period to day 90, with a tendency from going to the most negative values to the most positive than -200 mV, which indicates only a 10% of corrosion risk according to the norm ASTM C-876-15, nevertheless after the day 100 of exposition in the aggressive medium, it has that the potentials of corrosion present a light tendency to more negatives values, presenting at the end of the monitoring the specimen CC-1018 an E_{corr} of almost -200 mV, for the case of the specimens EC10-1018 and EC20-1018, present values of E_{corr} more negatives of -200 mV, which indicates according to the norm ASTM C-876-15 uncertainty of corrosion risk.

A. Corrosion Current Density (I_{corr})

The results of the Corrosion Current Density (I_{corr}), were interpreted according to the criteria of the Red Durar Manual [63], see Table VI.

TABLE VI: LEVEL OF CORROSION ACCORDING TO I_{CORR}

Corrosion rate (I_{corr}) µA / cm^2	Level of Corrosion
< 0.1	Despicable
0.1 - 0.5	Moderate
0.5 to 1	High
> 1	Very high

Fig. 5 presents of the results of I_{corr} of all specimens' study in a period of 180 days of exposure in a control medium.

The specimens of reinforcement studios with Steel AISI 1018 present values from 0.65 to 0.31 µA/cm^2, in the curing period day 14 to 28, for decreasing to values between 0.19 to 0.11 µA/cm^{2} ^{on} day 42, concurring the values with diverse reported works in the literature associated to the formation of the passive cape of embedded steel in concrete on its curing period, the tendency to more noble values of Icorr through the pass of time observes in the three specimens, CC-1018, EC10-1018 and EC20-1018. It has that the specimens that present a better development or less value of I_{corr} are the specimens elaborated with 20 of substitution of CPC for CBCA-HS, EC20-1018 and the CC-1018, Concrete Eco-friendly and conventional concrete, in response that since the day 90 presents values below 0.10 µA/cm^2, which indicates a despicable level of corrosion according to the indicated in the manual of the RED DURAR, a tendency that maintains until the end of the monitoring reaching values of 0.051 µA/cm^2 the specimen EC20-1018, 0.065 for the specimen CC-1018 and of 0.098 the EC10-1018, values that indicates a despicable corrosion level.

In Fig. 6, the behavior of the corrosion rate I_{corr} of the specimens exposed to the aggressive medium (solution to 3.5% of $MgSO_4$) is exposed.

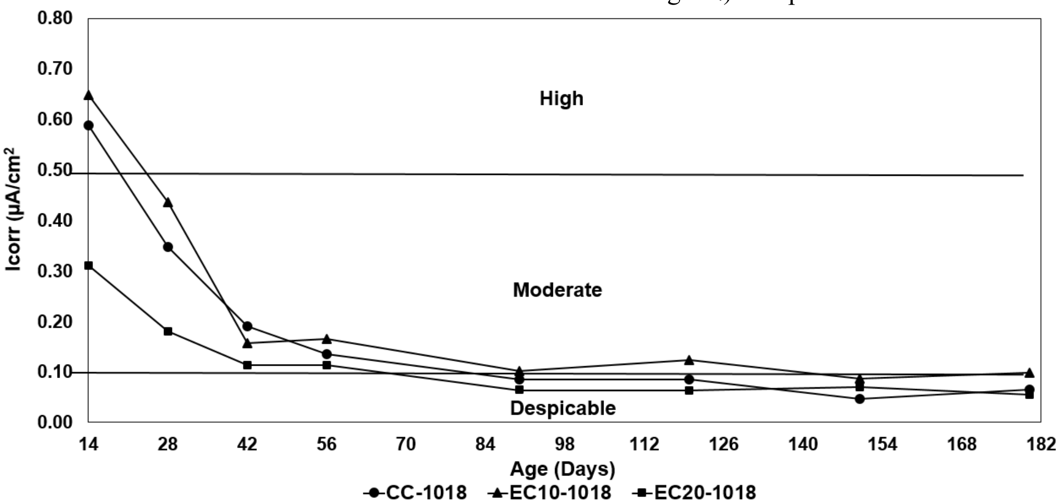

Fig. 5. Icorr of AISI 1018 steel in concrete exposed in control environment.

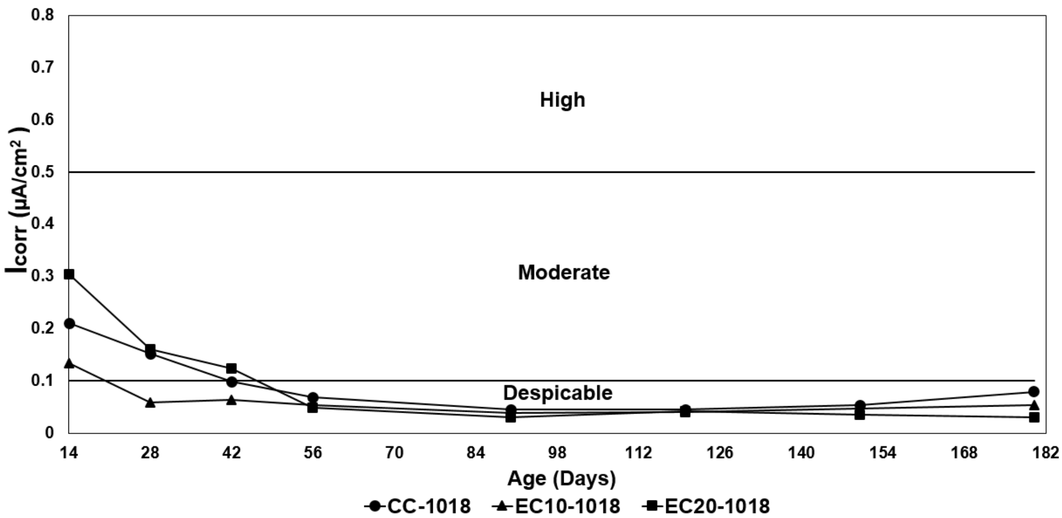

Fig. 6. Icorr of AISI 1018 steel in concrete exposed to MgSO4 solution.

The specimens reinforced with Steel AISI 1018, CC-1018, EC10-1018, and EC20-1018 present in the curing period a very similar behavior to the reported in the reference specimens exposed to the control medium, with values in the day 14 I_{corr} in between 0.34 and 0.13 µA/cm^2, for reaching in the day 28 to values in between 0.18 and 0.06 µA/cm^2, associated to the formation of the passive cape.

When exposed to the aggressive medium, it continues with a trend to lower values of I_{corr}, reaching in the day 90 values in between 0.03 and 006 µA/cm^2, which indicates in that instance a despicable corrosion level, according to the similar results reported in the literature, where indicated an apparently benefice against corrosion in the first months of exposition to sulfates [64]. However, after the day 120 of exposition there is a trend of increases in I_{corr} values for the three specimens CC-1018, EC10-1018 y EC20-1018, which accord with the values of E_{corr} reported in the figure 3, for these specimens, the tendency to more positive values of I_{corr} keeps to the end of the monitoring, reaching almost the activation of the system for the day 180 and the specimen CC-1018, with an I_{corr} nearby to 0.10 µA/cm^2, and keeping the specimens EC10-1018 and the specimen EC20-1018 to the end of the monitoring with values of I_{corr} of 0.05 and 0.03 µA/cm^2, which indicates that in the conditions of the present studio the Eco-friendly concretes with a 10 and 20% of substitution of CPC for the combination of SCBA-HS presented higher protection against the corrosion of the steel AISI 1018 in presence of magnesium sulfate to 3.5% of the concentration in the medium.

IV. Conclusions

The specimens elaborated with Eco-friendly concrete presented a higher protection against corrosion to steel AISI 1018 when being exposed to magnesium sulfate to 3.5% of concentration than conventional concrete.

The Eco-friendly concrete that presented the higher protection to the steel AISI 1018 was the one elaborated with 80% of CPC 30R, 10% of SCBA, and 10% of SF, so it is recommended the cementitious system 80-10-10 (CPC-SCBA-SF) for sulfate environments causatives of corrosion.

Based on the results it is highly recommended the use of supplementary cementitious materials as partial substitutes for Portland cement until 20%, for elaborating Eco-friendly concretes, which would allow the reduction of the same percent of substitution of CO_2 emissions for the fabrication of cement.

The use of Eco-friendly concretes would increase the sustainability of the building industry for the benefice of our society.

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