Corrosion of AISI 316 Stainless Steel Embedded in Green Concrete with Low Volume of Sugar Cane Bagasse Ash and Silica Fume exposed in Seawater

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Abstract — In the present research the corrosion behavior of AISI 316 Stainless Steel was analyzed, as reinforcement in Green Concrete made with Low Volume of Sugar Cane Bagasse Ash (SCBA) and Silica Fume (SF), compared to AISI 1018 steel. Four concrete mixtures were made, all with a ratio $w/c = 0.65$, the percentages of substitution were 0%, 10%, 20% and 30%. The specimens were exposed in seawater as an aggressive medium, corrosion was evaluated by monitoring the corrosion potential E_{corr} (ASTM C-876-15) and corrosion rate i_{corr} (ASTM G59). The results of E_{corr} and i_{corr} after 150 days of exposure show a better performance of AISI 316 steel, with a 10% of probability corrosion and a negligible level of corrosion respectively, the Green Concrete with 30% partial replacement of the CPC by the combination of SCBA-SF presented the best protection against corrosion.

Keywords — AISI 316, Corrosion, Green Concrete, SCBA, SF, Seawater.

I. INTRODUCTION

For a couple of decades, researchers have pointed out that the corrosion process is one of the main deteriorations of reinforced concrete, considering it as an affectation of the performance of structures [1]-[4]. The corrosion in concrete structures is a very important economic, by billions of dollars in the world [5]-[10] concentrating these repair costs mainly on the infrastructure built in marine environments [11]-[21], it is for the above that in recent years, the scientific community has worked to counteract this phenomenon with different perspectives, from innovation in concrete technology, as well as cement, special additions of inhibitors, among others, as well as studies of different media, marine, urban, both real and simulated [22]-[26]. One of the most aggressive means is where the structures are exposed in marine environments, where high concentrations of chlorides are present, and the phenomenon of corrosion is more accelerated [27]-[34] also the sulfate ions are also considered as aggressive agents [35]-[46]. To diminish this phenomenon, there is a history of the use of additions or substitutions of

portland cement for such as rice clay ash [47], fly ash [48], [49], sugar cane bagasse ash [50]-[52] and slag from blast furnace [53]. Likewise, the use of stainless steel 316 to reduce the phenomenon of corrosion and therefore increase the durability of concrete structures exposed in marine environments [54]. In this investigation, reinforced concrete specimens with sustainable concrete and reinforcement steels of 304 stainless steel and AISI 1018 steel were made. The ternary concretes were made with substitutions of sugarcane bagasse ash (SCBA) and silica fume (SF) agroindustry and industrial waste products respectively. Likewise, a conventional concrete was developed to be used as reference and comparison for ternary concrete. Results of E_{corr} and I_{corr} from the steels of a 180-day evaluation period are presented for the sustainable concrete exposed to a marine environment as an aggressive environment and drinking water as a means of control. The main objective of this research is to contribute to the scientific society with information necessary to build sustainable concrete structures that help increase the durability of these exposed in marine environments, and likewise, that present an environmental and economic benefit to our society.

II. MATERIALS AND METHODS

A. Materials

1) Dosage of Concrete Mixtures

The dosage of concrete mixtures was carried out according to the method of ACI 211.1 [55].

TABLE I: SUMMARY OF AGGREGATE CHARACTERIZATION RESULTS

Physical properties of materials	Coarse aggregate	Fine aggregate
Specific Mass (MES) g/cm ³	2.60	2.20
Bulk Volumetric Mass (BVM) Kg / cm ³	1332	1442
Absorption (%)	1.7	1.8
Module of Fineness	-	2.94
Maximum Size Nominal (TMN)	¾ "	-

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This method is based on the quality of the concrete required, taking into account mainly the resistance to strength compression (F'_c), the settlement (workability or consistency), and in addition to the characterization of the physical properties of the aggregates (sand and gravel) to be used, knowing these parameters it is possible to perform the necessary concrete dosage, which determines the quantity of materials (cement, water, gravel and sand). Table I summarizes the physical characteristics of the aggregates, the tests were performed in accordance with the ASTM standards [56]-[59].

Table II summarizes the dosages of the Green Concretes produced. The study mixtures were with relation $w/c = 0.65$. The reference mixture (REF) with 100% composite portland cement (CPC). Subsequent mixtures were made partial portland cement substitutions from 10% to 30%, these percentages were formed by 50% of each addition used, for example, the second mixture with partial replacement of 10% CPC by SCBA and SF it contains is of 5% Sugar Cane Bagasse Ash and 5% of Silica Fume.

TABLE II: DOSAGE OF CONCRETE MIXTURES IN KG FOR 1 M³

Materials	REF	10% (05SCBA05FS)	20% (10SCBA10FS)	30% (15SCBA15FS)
Water	205.00	205.00	205.00	205.00
Cement	315.00	283.5	252.00	220.50
Sugar Cane Bagasse Ash	0.00	15.75	31.50	47.25
Silica Fume	0.00	15.75	31.50	47.25
Fine aggregate	746	746	746	746
Coarse aggregate	881	881	881	881

B. Method

1) Characterization of Fresh and Hardened of Green Concrete

In accordance with the ONNCCE and ASTM standards [60]-[63], the tests were carried out to determine the physical and mechanical characteristics of the fresh and hardened concrete. The tests performed were slump, temperature, volumetric mass, and compressive strength (F'_c), the results are summarized in Table III.

TABLE III: PROPERTIES OF GREEN CONCRETE (FRESH AND HARDENED STATE)

TEST	REF	10% (05SCBA05FS)	20% (10SCBA10FS)	30% (15SCBA15FS)
Slump, cm	8	7	6.5	6
Temperature, °C	25	24.5	24.0	23.5
Density, kg/m ³	2254	2268	2273	2289
F'_c , Kg/cm ²	337	313	346	358

2) Specifications of the test specimens

The following steel bars were embedded in the study specimens: an AISI 1018 steel bar with a 3/8" diameter, the second 316 stainless steel bar with a 3/8" diameter and a third 304 stainless steel bar with a diameter of 1/16". The first two bars were used as working electrodes (WE) for the evaluation of the corrosion behavior (monitoring of E_{corr} and I_{corr}) as

indicated in the literature [64], the two bars delimit an area of exposure as shown in Fig. 1. A 304 stainless steel rod was used as the auxiliary electrode.

Fig. 1. Characteristics of bars embedded in Green Concrete.

3) Nomenclature of the specimens

For the identification of laboratory tests and steels for electrochemical evaluation, the nomenclature presented in Table IV is established. It is mainly based on the Green Concrete mixtures, the exposure medium and the steels embedded in the concrete.

TABLE IV: NOMENCLATURE TEST SPECIMENS OF GREEN CONCRETE

REF (100% CPC)	10% (05SCBA05FS)	20% (10SCBA10FS)	30% (15SCBA15FS)
REF-1-8	05SCBA05FS-1-8	10SCBA10FS-1-8	15SCBA15FS-1-8
REF-1-6	05SCBA05FS-1-6	10SCBA10FS-1-6	15SCBA15FS-1-6
REF-2-8	05SCBA05FS-2-8	10SCBA10FS-2-8	15SCBA15FS-2-8
REF-2-6	05SCBA05FS-2-6	10SCBA10FS-2-6	15SCBA15FS-2-6

- REF = Concrete (100% CPC)
- 05SCBA05FS = Concrete with 10% of SCBA-SF.
- 10SCBA10FS = Concrete with 20% of SCBA-SF.
- 15SCBA15FS = Concrete with 30% of SCBA-SF.
- 1 = Water (Control environment).
- 2 = Seawater (Aggressive environment).
- 6 = AISI 316 Stainless Steel.
- 8 = AISI 1018 Carbon Steel.

4) Specimens exposed to seawater (Electrochemical cell).

For the evaluation of the electrochemical behaviour of the steels embedded in the Green Concrete, concrete cubes were made (15×15×15 cm). The electrochemical cell was manufactured in accordance with what is established in ASTM G59 [65] to be able to use linear polarization resistance electrochemical (LPR), see Fig. 2. Technology and the results were detected by the "Analysis" of version 4 of ACM. The parameters used to perform the LPR test, they were the same as those used by other researchers [66], the sweep potential was ±20 mV with respect to the corrosion potential and the sweep rate was 10 mV/minute, the IR drop potential was considered. The corrosion current density (I_{corr}) was estimated from resistance to charge transference (R_{ct}) using:

$$\text{Corrosion Current Density } (I_{corr}) = B/R_{ct} \text{ (}\mu\text{A/cm}^2\text{)} \quad (1)$$

where B is Stern-Geary constant ($B = 26 \text{ mV}$ for uniform corrosion) [67].

This monitoring was conducted weekly with the concrete cubes immersed in Water as Control environment and Seawater as Aggressive environment.

Fig. 2. Study specimens exposed to seawater.

III. RESULTS AND DISCUSSION

A. Corrosion Potential (E_{corr})

Table V shows the values obtained according to the ASTM C876-15 [68], to interpret the results of the corrosion potential of each of the test specimens, adding a rank according to the literature [69].

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

In Fig. 3, we can observe the behavior of the corrosion potential of AISI 316 embedded in the Green Concretes exposed to a control environment (H_2O), in the stage of curing the stainless steels present E_{corr} values in a range of -40 to -180 mV. Then there is a trend with a decrease in E_{corr} values, which we can observe from day 28 to 63. Subsequently, the E_{corr} values are maintained in an area of 10% probability of corrosion, and we can observe a better performance of the stainless steel embedded in the concrete with 20% and 30% substitution of CPC by the combinations SCBA and SF in low volume.

Fig. 3. E_{corr} of 316 and 1018 steel in concrete exposed to control environment.

The AISI 1018, have a greater variability in the corrosion potentials values (E_{corr}), this showed more negative E_{corr} values in the stage of curing (until 28 day), with E_{corr} values in a range of -190 to -345 mV. The results after 28 days are in a range of -105 mV to -230 mV, the mixture that presents a best behaviour with E_{corr} values located in the zone of 10%

probability of corrosion, is the substitution of 20% of combination of SCBA and SF (10SCBA10FS-1-8).

Nevertheless, the mixtures with 10 and 30% of combination of SCBA and SF in the last days of monitoring, present E_{corr} values that indicate indicating according to the ASTM C-876 standard corrosion uncertainty.

In Fig. 4, the behaviour of stainless steel 316 exposed to a seawater (Aggressive environment) is presented, a similarity of potentials in the reference mixture and with substitutions in the curing stage is observed. During the exposure time we can observe that the mixtures are maintained in an area of 10% probability of corrosion, the ranges are of the order of -160 mV and -20 mV. The stainless steels that present a greater positive tendency are those that are found within the 15SCBA15FS and 10SCBA10FS mixtures.

Fig. 4. E_{corr} of 316 and 1018 steel in concrete exposed to a marine environment.

In the case of AISI 1018, there is a trend of more negative E_{corr} results compared with AISI 316, the AISI 1018 embedded in 05SCBA05FS and REF-2-8 concretes present more negative E_{corr} values, in a range of -240 mV to -430 mV. The opposite case of the 10SCBA10FS and 15SCBA15FS mixtures at the beginning of the evaluation presented more positive E_{corr} results and from day 63 they tended to an area of greater negativity to reach an area of 90% probability of corrosion.

A. Corrosion Current Density (I_{corr})

TABLE VI: LEVEL OF CORROSION ACCORDING TO I_{corr}	
Corrosion rate (I_{corr}) $\mu A / cm^2$	Level of Corrosion
< 0.1	Despicable
0.1 - 0.5	Moderate
0.5 to 1	High
> 1	Very high

The results of the Corrosion Current Density (I_{corr}), were interpreted according to the criteria of the Red Durar Manual (70), see Table VI.

In Fig. 5 present of the results of I_{corr} of all specimens' study in a period of 180 days of exposure in a control medium (H_2O). The 316 stainless steel has an excellent anti-corrosion behavior with values that are in a negligible area below $0.1 \mu A/cm^2$. In the case of AISI 1018 steels embedded in a reference concrete and in a 10% substitution, they show an activation from the beginning of the evaluation period oscillating between a high and moderate level of corrosion.

Fig. 5. I_{corr} of 316 and 1018 steel in concrete exposed to a control environment (H_2O).

The AISI 1018 steels that are found in the mixtures with 20% and 30% substitutions (10SCBA10FS and 15SCBA15FS) present an activation in the first 14 days appearing at the high and moderate level of corrosion level and later reach at the age of 63 days a passivity when positioning in a zone of negligible corrosion level. According to the above we can see a benefit to add SCBA and FS in the concrete conventional.

In Fig. 6, the I_{corr} results of steels embedded in Green Concrete exposed to a seawater (Aggressive environment) are presented. The specimens with AISI 316 show an excellent behavior when kept in an area of negligible corrosion level, the best behavior is contributed to the 15SCBA15FS mixture when obtaining values of 0.11 to 0.01 $\mu A/cm^2$.

Fig. 6. I_{corr} of 316 and 1018 steel in concrete exposed to a marine environment.

The specimens with AISI 1018 presents a greater value of I_{corr} , from the beginning of the evaluation to the end. The specimen made with the reference concrete (100% CPC) is maintained in a zone of high corrosion level all time. However, the I_{corr} results of the specimens of the Green Concretes made with 10 and 20% substitutions of SCBA and FS (5SCBA5FS and 10SCBA10FS) from the day 35 they have a tendency to a zone of moderate corrosion level. The best performance is attributed to the Green Concrete made with a 30% substitution (15SCBA15FS) present the AISI 1018 steel embedded activation in the first 14 days of exposure, later passing to an area of corrosion level moderate until day 49 and subsequently remained in a zone of negligible corrosion level to obtain 0.92 to 0.06 $\mu A/cm^2$.

IV. CONCLUSIONS

The specimens with AISI 316 embedded in Green Concrete made with 30% (15% of Suggar Cane Bagasse Ash and 15% of Silica Fume) showed the better behavior or corrosion resistance after the 180 of exposition in Seawater (Aggressive environment), with values of I_{corr} below 0.10 $\mu A/cm^2$.

The specimens with AISI 1018 steel embedded in the Green Concrete, made with 30% (15% of Suggar Cane Bagasse Ash and 15% of Silica Fume), presents a very acceptable behavior; with a moderate corrosion level until day 49, for to present values of I_{corr} of 0.92 to 0.06 $\mu A/cm^2$ to the end the monitoring due to the denser concrete matrix of Green Concrete.

The best percentage of substitution in Green Concretes was 30% (15% of Suggar Cane Bagasse Ash and 15% of Silica Fume), presenting the best performance against corrosion when using AISI 316 stainless steel when exposed to very aggressive media such as seawater.

The results show that Green Concretes can be used to build Civil Infrastructure in marine environments, presenting great resistance against corrosion by seawater as well as contributing to sustainability due to the use of agro-industrial and industrial waste that the least in Mexico is not used in the proportions and combinations presented in this research.

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