Corrosion of AISI 316 Stainless Steel Embedded in Sustainable Concrete made with Sugar Cane Bagasse Ash (SCBA) Exposed to Marine Environment

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Abstract—This research evaluates the electrochemical behavior of steel bars of the AISI 316 and AISI 1018 embedded in sustainable concrete with partial replacement of CPC 30R by Sugar Cane Bagasse Ash (SCBA) and Silica Fume (SF). The electrochemical techniques used to evaluate the corrosion were half-cell potential or $E_{corr}$ -ASTM C-876-15- and the Linear Polarization Resistance Technique (LPR) - ASTM G59. $E_{corr}$ and $I_{corr}$ results indicate after more than 300 days of exposure to the marine environment (3.5% NaCl solution), a high resistance of AISI 316 steel, with $E_{corr}$ values lower than -200 mV indicating a 10% probability of corrosion, and a level of negligible corrosion, with values less than 0.1 µA/cm² in the three mixtures, with sustainable concrete values slightly lower. The results indicate a resistance of more of almost 100 times greater than AISI 316 steel compared to the results obtained in AISI 1018 steel.

Index Terms—Sustainable Concrete, Corrosion, AISI 316, SCBA, Marine Environment.

I. INTRODUCTION

The corrosion that occurs in steel construction presents a global economic and social problem, due to the damages that this phenomenon causes in the constructions and that many times are not taken care of until a major intervention and investment is required millionaire. Structures collapse causing damages to be human losses, they are structures of relevant importance since they are generally places where active work is maintained most of the time or conglomeration of masses of people; as they are; docks, active work is maintained most of the time or conglomeration of masses of people; as they are; docks, bridges, buildings, etc. [1-2]. Therefore, an effort is made with teams, researchers, infrastructure managers, builders to mitigate the damage caused by this phenomenon; this is done from different perspectives such as the use of additives, procedures in the production of concrete, alternative materials, concrete exposed to contact media that simulate aggressive environments that trigger corrosion, such as seawater, wastewater, industrial environments, etc., [3-5]. In the global context it is very important to create solutions that help reduce CO₂ emissions caused by the cement industry, which is responsible for between 5% and 7% of total CO₂ emissions per year worldwide [6-7], so that an effort is made to implement a sustainable approach to the design of hydraulic concrete mixtures. The present investigation evaluates the behavior of AISI 316 and AISI 1018 steel embedded in sustainable concretes elaborated on a partial substitution basis in 10% of Portland Cement with Sugar Cane Bagasse Ash (SCBA), an agroindustrial waste resulting from the combustion of bagasse in the boilers of sugar mills, which according to the literature presents large amounts of SiO₂ and Al₂O₃, which classifies it as a class N or F pozzolanic material [8], and which has been used mostly in works of concrete durability [9], and to a limited extent in soil improvement for road construction [10]. The other sustainable concrete mix was based on 10% silica fume (SF) as a partial replacement for portland cement, an industrial waste that has been used in other investigations [11]. The results of $E_{corr}$ and $I_{corr}$ of more than 300 days of exposure to the marine environment (3.5% NaCl solution) and control medium (water), show a high corrosion resistance of AISI 316 steel in Sustainable Concrete, information that validates the benefit of the use of SCBA and HS, for can be used in the construction of durable civil works, which contribute to the sustainable development of our society.

II. MATERIALS AND METHODS

A. Materials

1) Materials used in the design of concrete mixes.

| TABLE I: RESULTS OF THE CHARACTERIZATION OF THE AGGREGATES |
|-------------------------------------------------------------|
| Physical properties of materials                           | Coarse aggregate | Fine aggregate |
|-------------------------------------------------------------|
| Specific Mass (MES) g/cm³                                  | 2.38             | 2.60           |
| Bulk Volumetric Mass (BVM) Kg/cm³                         | 1372             | 1            |
| Absorption (%)                                             | 5.1              | 1.56           |
| Module of Fineness                                         | -                | 2.9            |
| Maximum Size Nominal (TMN)                                 | ½ *              | -              |

The method used to calculate the dosage of concrete was that of ACI 211.1 [12], which is based on the physical...
characteristics of the materials (fine and coarse). For the physical characterization of the aggregates the tests are carried out according to ASTM standards [13-17], table I summarizes these characteristics of the materials used.

2) Dosage of Sustainable Concrete mixtures

The table II shows the dosage obtained to develop the three mixtures in study, all the mixtures were from ratio W/C = 0.65. The first mixture is with 100% of CPC 30R RS, the second with partial replacement of 10% of SCBA by portland cement and the third mixture with partial replacement of 10% of SF.

| Materials       | CPC 30R RS | SCBA | SILICA FUME |
|-----------------|------------|------|-------------|
| Water           | 205        | 205  | 205         |
| Cement          | 315        | 283.5| 283.5       |
| Partial replacement | 0        | 31.5 | 31.5        |
| Coarse aggregate| 928        | 928  | 928         |
| Fine aggregate  | 647        | 647  | 647         |

B. Method

1) Test to the Fresh and Hardened Sustainable Concrete

The tests for the characterization of concrete mixtures in a fresh state were performed the Standards ONNCCE and ASTM, the Slamp according to the standard NMX-C-156-ONNCCE-2010 [18], Temperature according to the standard ASTM C 1064/C1064M-08 [19], Density according to the standard NMX-C-162-ONNCCE-2014 [20] and the Compressive Strength according to the standard NMX-C-083-ONNCCE-2014 to 28 days [21]. The results obtained for the two concrete mixtures are shown in table III.

| Parameter       | CPC 30R RS | SCBA | SILICA FUME |
|-----------------|------------|------|-------------|
| Slamp           | 2 cm       | 1.5 cm | 1.0 cm    |
| Temperature     | 22.0 °C    | 22.0 °C | 22.0 °C   |
| Density         | 1896 kg/m³ | 1892 kg/m³ | 1703 kg/m³ |
| Compressive strength (F´c) | 216 kg/cm² | 211 kg/cm² | 257 kg/cm² |

2) Characteristic of test specimens.

In each specimen it would be two bars of 3/8” of diameter, one of AISI 316 stainless steel, the second of AISI 1018, these bars were used as working electrodes (WE), for the evaluation of the corrosion behavior (monitoring of Ecorr and Icorr), to the two bars are delimited an exposure area as shown in Figure 1.

All bars and were cleaned to remove any impurities that might have been present on them [22-23] and the manufacture of the test specimens was performed as indicated in the standard ASTM C 192 [24].

3) Nomenclature of the test specimens

For the test specimens and in accordance with the parameters for monitoring, it is elaborated the nomenclature that is shown in the table IV.

| TABLE IV: NOMENCLATURE TEST SPECIMENS |
|---------------------------------------|
| CPC 30R RS | SCBA | SILICA FUME |
| CP-316     | CC-316 | HS-316    |
| CP-1018    | CC-1018 | HS-1018   |

- CP=Concrete (100% CPC 30R RS)
- CC=Concrete (Replacement of 10% of SCBA)
- HS=Concrete (Replacement of 10% of Silica Fume)
- 316= AISI 316 Stainless steel
- 1018= AISI 1018 Steel

4) Electrochemical cell

With the objective of evaluating the electrochemical behavior of sustainable concrete based on SCBA and SF as partial substitutes for Portland Cement, concrete cubes were made, (15 cm x 15 cm x 15 cm). As mentioned before, in each specimen it would be two bars of 3/8” of diameter, one of AISI 316 stainless steel, the second of AISI 1018, these bars were used as working electrodes (WE) and a bar 1/8” of diameter, of AISI 304, as an auxiliary electrode (AE), this type of arrangement allows to evaluate the corrosion current density (Icorr) by the technique of linear polarization resistance (LPR) as indicated by the ASTM-G59 standard [25].

The equipment Gill AC Galvanostat/Potentiostat/ZRA from ACM Instruments was used for these method (LPR), and with a standard copper-copper sulfate (Cu/CuSO4) as reference electrode. The results were analyzed using Version 4 Analysis specialized software from ACM Instruments, see figure 2.

![Fig. 2. Electrochemical cell for the monitoring of Corrosion Current Density (Icorr)](image)

The parameters used to perform the LPR test, they were the same as those used by other researchers [26-28], 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 (Icorr) were estimated from resistance to charge transference (Rct) using:

\[
\text{Corrosion Current Density (I}_{\text{corr}}) = \frac{B}{R_{\text{ct}}} \text{ (μA/cm}^2\text{)} \tag{1}
\]

where B is Stern-Geary constant (B = 26 mV for uniform corrosion) [29].

This monitoring was conducted weekly with the concrete
cubes immersed in the solution of sodium chloride at 3.5% concentration, simulating a marine environment.

III. RESULTS AND DISCUSSION

A. Corrosion potential (E<sub>corr</sub>)

The standard ASTM C876-15 [30], considering a more interval according to the literature [31], was used to perform the monitoring of the corrosion potential (E<sub>corr</sub>) and interpretation of the probability of corrosion (see table V).

| Corrosion potentials mV vs Cu/CuSO₄ | Severe corrosion | 90% Probability of Corrosion | Uncertainty | 10% Probability of Corrosion |
|-------------------------------------|-----------------|-----------------------------|-------------|-----------------------------|
| < -500                              |                 |                             |             |                             |
| < -350                              |                 |                             |             |                             |
| -350 to -200                        |                 |                             |             |                             |
| > -200                              |                 |                             |             |                             |

1) E<sub>corr</sub> of AISI 316 stainless steel and AISI 1018 steel

In Figure 3, it is observed how the AISI 316 stainless steel presents potential in the curing stage from -120 mV to -240 mV, when exposed to the control environment, water, continuing the trend of the CP-316 specimen at more negative values until reaching -260 mV on day 154, being located in the area of uncertainty, to then present more positive E<sub>corr</sub> values, staying in a range of -200mV to -260mV until the end of the monitoring. In the case of the CC-316 and HS-316 specimens, this showed a similar behavior, with E<sub>corr</sub> corrosion potential, in a range of -225 mV to -200 mV, indicating corrosion uncertainty according to ASTM C-876, after 100 days, present both specimens E<sub>corr</sub> values more positive at -200 mV, until the end of the monitoring, indicating according to ASTM C-876, 10% corrosion probability of AISI 316 stainless steel, having the specimen with 10% silica fume (HS-316), the most positive E<sub>corr</sub> values, followed by the specimen made with 10% SCBA (CC-316).

Specimens reinforced with AISI 1018, CP-1018, CC-1018 and HS-1018, when exposed to the control medium, all three have a very homogeneous behavior in the E<sub>corr</sub> corrosion potential values, with a tendency from the curing stage of more negative to more positive values, going from values of -330 mV, -290 mV and -270 mV, to -220 mV, -235 mV and -170 mV in the curing stage, for these specimens. To continue this passivity trend until the end of the monitoring with values of up to -50 mV for the HS-1018 specimen, from -140 mV for is specimen CC-1018 and -148 mV for the specimen with 100% CPC (CP-1018). This behavior is normal due to the formation of the passive layer in the AISI 1018 steel and the excellent protection of the major concrete matrix in the specimen with 10% Silica Fume (HS-1018), followed by the specimen with 10% SCBA (CC-1018) and finally by the specimen with 100% Cement Portland (CP-1018). This indicates, at least in the corrosion potential test, a better performance of the SCBA and HS base sustainable concrete.

The results of monitoring E<sub>corr</sub> corrosion potentials of specimens exposed to the aggressive environment are shown in Figure 4, according to ASTM C-876, it is observed as being immersed in the NaCl solution at 3.5% concentration, significantly affects corrosion in specimens reinforced with AISI 1018 steel, which in the curing stage presented a passivation behavior, reporting specimens CP-1018, CC-1018 and HS-1018, corrosion potentials (E<sub>corr</sub>) of the order of -450 to -320 mV on day 7 and -270 and -210 mV on day 28. However, when in contact with aggressive media (3.5% NaCl solution), the concrete that provided a better performance, at least until the middle of the monitoring period, it was the sustainable concrete made with 10% of silica fume, specimen HS-1018, which presents E<sub>corr</sub> values between a range of -220 mV to -340 mV until day 147, which indicates a period of uncertainty according to ASTM C-876, to present E<sub>corr</sub> values from day 154 to 210 indicating a 90% corrosion probability, ending with E<sub>corr</sub> values of up to -575 mV, which indicates according to the standard ASTM C-876-15 the presence of severe corrosion. Of the two remaining specimens, it is observed after day 98 of exposure, that the specimen made with CBCA by 10%, specimen CC-1018, it showed a better performance with E<sub>corr</sub> values at the end of the monitoring of -630 mV, lower than those reported by the specimen made with 100% CPC, CP-1018 specimen, which presented E<sub>corr</sub> values of up to -680 mV., indicating a presence of severe corrosion according to ASTM C-876-15.

As regards specimens reinforcing with AISI 316 stainless steel, CP-316, CC-316 and HS-316, they have corrosion potentials that range from -60 mV to -205 mV in the curing stage. The behavior when exposed to the aggressive medium, NaCl at 3.5 concentration (simulated marine environment), is as follows, the specimen made with 100% CPC, CP-316, presents a period of corrosion uncertainty, with E<sub>corr</sub> values from day 35 to day 100, between -280 and -310 mV, according to ASTM C-876-15, after day 112, enter a passivation state, with more positive E<sub>corr</sub> values of -200 mV, until the end of monitoring. For specimens considered sustainable concrete, CC-316 and HS-316 present from day 49 until the end of monitoring, day 301, E<sub>corr</sub> values more positive than -200 mV, which indicates passivation of the AISI 316-Sustainable Concrete steel system, indicating a 10% probability of corrosion according to ASTM C-876-15.
B. Corrosion Current Density (I_corr)

The criteria of the the DURAR Network Manual [22], were used to interpret the results of the Corrosion Current Density (I_corr), see table VI.

### Table VI: Level of Corrosion According to I_corr

| Corrosion rate (I_corr) µA/cm² | Level of Corrosion |
|-------------------------------|-------------------|
| 0.1                           | Despicable        |
| <0.1                          | Despicable        |
| 0.5                           | Moderate          |
| 0.5 to 1                      | High              |
| > 1                           | Very high         |

1) I_corr of specimens exposed to control medium

Table VII shows the corrosion rate presented by study specimens after 300 days of exposure to the Control Medium, as can be seen, all specimens presented I_corr values that indicate a negligible level of corrosion according to what is established in the DURAR NETWORK Manual, the negligible level of corrosion perfectly matches the behavior of the same specimens in the corrosion potential test (E_corr), with values that indicated, according to ASTM C-876-15, a 10% probability of corrosion or passivation of steel. The corrosion rate values E_corr and I_corr are consistent because the study specimens are exposed to a non-aggressive environment, however, the corrosion resistance offered by AISI 316 stainless steel can be distinguished in this non-aggressive medium, with I_corr values up to 5 times lower than those of AISI 1018 steel, having a similar performance against corrosion the sustainable concrete elaborated based on SCBA and SF, as well as the one in the normal CP concrete, in a non-aggressive environment.

### Table VII: I_corr of specimens in control medium (Evaluation time 300 days)

| SPECIMEN | (I_corr) µA/cm² | LEVEL OF CORROSION |
|----------|-----------------|--------------------|
| CP-316   | 0.009           | Despicable         |
| CP-1018  | 0.053           | Despicable         |
| CC-316   | 0.008           | Despicable         |
| CC-1018  | 0.051           | Despicable         |
| HS-316   | 0.007           | Despicable         |
| HS-1018  | 0.049           | Despicable         |

2) I_corr of specimens exposed to marine environment

Table VIII shows the corrosion rate presented by study specimens at 300 days of exposure to a 3.5% NaCl solution (synthetic marine environment), the specimens reinforced with AISI 316 stainless steel, they have a high resistance against corrosion with values of I_corr between 0.0124, 0.0155 and 0.0191 µA/cm², for specimens HS-316, CC-316 and CP-316 respectively, values that indicate a protection of almost 100 times greater against corrosion in sustainable concrete exposed to a marine environment, compared to sustainable and normal concrete reinforced with AISI 1018 steel, presenting the specimen CP-1018 (normal concrete with 100% CPC 30R) an I_corr=1.887 µA/cm², I_corr indicating a very high level of corrosion of the reinforcing steel according to the provisions of table VI, very high level of corrosion that also occurs in specimens CC-1018 with an I_corr = 1.643 µA/cm² and the specimen HS-1018 with an I_corr of 1.298 µA/cm², a positive influence is also identified in these specimens by using Sugar Cane Bagasse Ash and Silica Fume as a partial substitute for Portland Cement by 10%, because these sustainable concrete presented lower values of I_corr than the specimen made with normal concrete, CP-1018.

It is concluded that for a more aggressive environment such as the marine environment, the best option is to reinforce sustainable concrete based on replacement of Portland cement by 10% of SCBA or SF, with AISI 316 stainless steel to optimize the benefit of the use of these agroindustrial and industrial waste, conclusion based on the results obtained in the present investigation and that agree with those reported by other researchers [33-36].

### Table VIII: I_corr of specimens in 3.5% solution of NaCl (Evaluation time 300 days)

| SPECIMEN | (I_corr) µA/cm² | LEVEL OF CORROSION |
|----------|-----------------|--------------------|
| CP-316   | 0.0191          | Despicable         |
| CP-1018  | 1.887           | Very high          |
| CC-316   | 0.0155          | Despicable         |
| CC-1018  | 1.643           | Very high          |
| HS-316   | 0.0124          | Despicable         |
| HS-1018  | 1.298           | Very high          |

IV. Conclusion

The specimens HS-316, CC-316 and CP-316, reinforced with AISI 316 stainless steel, present a high resistance against corrosion with values of I_corr of 0.0124, 0.0155 and 0.0191 µA/cm², respectively, values of I_corr that indicate a protection of almost 100 times greater against corrosion in sustainable concrete exposed to a marine environment, compared to sustainable and normal concrete reinforced with AISI 1018 steel.

It is concluded that for a more aggressive environment such as the marine environment (3.5% of NaCl solution), the best option is to reinforce sustainable concrete based on replacement of portland cement by 10% of SCBA or SF, with AISI 316 stainless steel, for to optimize the benefit of the use of these agroindustrial and industrial waste.

The use of waste such as Sugar Cane Bagasse Ash (SCBA) and Silica Fume (SF) to produce Sustainable Concrete is feasible as well as its use in the construction of civil works, because it has physical, mechanical and durability properties that meet the requirements for such constructions, contributing significantly to sustainable development in the construction industry and in our society.

The CO2 emissions caused by the cement industry are reduced, when Sugar Cane Bagasse Ash (SCBA) and Silica Fume (SF) are used as a partial substitute for Portland cement in the preparation of concrete mixtures, considered as sustainable, ecological or green concretes.

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