European Journal of Engineering and Technology Research
ISSN: 2736-576X

Corrosion Behavior of AISI 1018 Reinforcing Steel in Sustainable Concrete made with Sugar Cane Bagasse Ash and Recycled Aggregates Exposed in Seawater

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***Abstract* — In the present research, the electrochemical behavior of corrosion in Conventional Concrete (CC) and Sustainable Concrete (SC) made with 80% of Portland Cemment, 20% of Sugar Cane Bagasse Ash and Recycled Aggregates with 50% and 100% was evaluated, AISI 1018 steel bars were embedded in all the specimens, which were exposed to seawater for more than 300 days. For corrosion monitoring, the electrochemical techniques of Corrosion Potential (E_{corr}) and Linear Polarization Resistance was used to determine the intensity of the corrosion current (I_{corr}). The results of E_{corr} and I_{corr} indicate that the sustainable concrete of this study can be used in non-aggressive environments, but not in highly aggressive media such as seawater, since according to the results, its protection against corrosion is weak, with the SC having the worst performance with 100% recycled aggregate.**

***Keywords* — AISI 1018, Corrosion, Recycled Aggregates, Seawater, Sugar Cane Bagasse Ash, Sustainable Concrete.**

I. Introduction

Currently and for a long time, the most used construction material in the world is hydraulic concrete, which together with AISI 1018 steel reinforcement bars, form the system known as reinforced concrete[1]-[4]. However, one of the most important problems for the maintenance of the structural integrity of civil works such as bridges, tunnels, highways, docks, etc., of a country, and that is the cause of premature maintenance of several billion dollars quantified only in industrialized countries, is the corrosion of reinforcing steel as indicated in the literature [5]-[12]. Corrosion of steel embedded in concrete is an electrochemical process in which an anode is developed where oxidation occurs and a cathode where reduction occurs. The corrosion process can be caused by various factors, among the most important is due to the entry of aggressive depassivating ions such as chlorides present in marine environments [13]-[22], and the sulfates, which are part of the inorganic salts that are normally present on the ground, in groundwater and surface water, although their degree of concentration can be highly variable [23]-[28]. The problem of corrosion in reinforced concrete has been tried to solve from different perspectives.

Evaluating the effect of the various factors that intervene in this phenomenon, such as simulation of aggressive environments in the laboratory, exposure to chlorides, sulfates, carbonation, and chemicals such as acids, as regards the preparation of concrete, corrosion inhibitors have been used, pozzolanic materials as partial substitutes for portland cement industrial waste, fly ash, blast furnace slag, silica fume or agro-industrial waste such as sugar cane bagasse ash, coconut ash, rice ash [29]-[34], about reinforcement steel, it has been shown that alternative steels to AISI 1018, they are the ones that most increase resistance to corrosion in various very aggressive environments, with galvanized steel and stainless steel AISI 304 and AISI 316 presenting the best performance or resistance to corrosion [35]-[41].

Parameters such as environmental awareness, protection of natural resources, and sustainable development play an important role in modern construction site requirements, therefore, the use of Recycled Concrete Aggregates (RCA) in construction works is an issue of great importance in the construction industry worldwide, data indicate that 10% of the aggregates used in Great Britain are RCA [42], 78,000 tons of RCA were used in the Netherlands in 1994 [43], since the corresponding national organization admitted that the use of 20% coarse RCA did not differentiate properties of concrete in fresh or hardened state.

Therefore, the main objective of this research is to evaluate the electrochemical behavior of corrosion in Conventional Concrete (CC) and Sustainable Concrete (SC) made with 80% of Portland Cement, 20% of Sugar Cane Bagasse Ash and Recycled Aggregates with 50% and 100% and AISI 1018 steel as reinforcement, when exposed to seawater for more than 300 days, in order to determine the feasibility of using these types of sustainable concrete in marine environments. This project aims to contribute to a friendly impact on the

Submitted on November 03, 2022.
Published on December 12, 2022.
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environment, due to the use of SCBA as a substitute for Portland Cement, because the cement industry is responsible for the 6 to 8% of the total CO_2 emissions at global level [44]-[47], and the use of recycled aggregates.

II. Materials and Methods

A. Materials

1) Dosage and Proportioning of Concrete Mixtures

The design and proportioning of concrete mixtures were carried out according to the method ACI 211.1 [48].

The physical characteristics of the aggregates were determined according to the ASTM standards [49]-[52], because they are essential information to be able to use said concrete mixture design method, Table I shows the summary of the results obtained from said characterization.

The concrete mixtures were designed for a water/cement ratio = 0.65, the dosage of conventional concrete (CC), Sustainable Concrete with 20% Sugarcane Bagasse Ash and 50% Recycled Aggregates (SC-50RA), as well as Sustainable Concrete with 20% Sugarcane Bagasse Ash and 100% Recycled Aggregates (SC-100RA) is shown in Table II.

TABLE I: Physical Characteristics of the Aggregates

Physical properties of materials	Coarse Aggregate	Recycled Aggregate	Fine Aggregate
Specific Mass (MES) g/cm³	2.62	2.20	2.24
Bulk Volumetric Mass (BVM) Kg /m³	1443	1367	-
Absorption (%)	1.73	11.72	1.85
Module of Fineness	-		2.94
Maximum Size Nominal (TMN)	¾ "	¾ "	-

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

Materials	CC	SC-50RA	SC-100RA
Water	205	205	205
CPC 30R	315	252	252
SCBA	0.00	63	63
Coarse Aggregate	886	443	0
Recycled Aggregate	0	443	886
Fine Aggregate	770	881	881

B. Method

1) Quality control test of the fresh and hardened of conventional concrete and sustainable concrete

The quality control tests of the mixtures of CC, SC-50RA and SC-100RA were carried out according to the ONNCCE and ASTM standards [53]-[56], the results are shown in Table III.

TABLE III: Properties of Conventional Concrete and Sustainable Concrete (Fresh and Hardened state)

TEST	CC	SC-50RA	SC-100RA
Slump, cm	10	3	2
Temperature, °C	24	23	22
Density, kg/m³	2220	2135	2040
F´c, Kg/cm²	217	164	115

2) Reinforcing steel - specifications

As reinforcing steel, AISI 1018 steel bars of 15 cm length were used, to which an area susceptible to corrosion was delimited, as indicated in the literature so that the electrochemical cell is used as a working electrode (WE) [57], see Fig. 1.

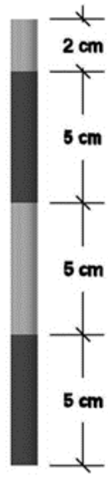

Fig. 1. Reinforcing steel -Specifications-.

3) Nomenclature of the specimens

The nomenclature used for monitoring of E_{corr} and I_{corr} of AISI 1018 steel in CC, SC-50RA and SC-100RA, exposed in water (Medium Control) and in Seawater is shown in Table IV.

- CC= Conventional Concrete – 100% CPC 30R -
- SC-50RA = Sustainable Concrete with 20% SCBA and 50% Recycled Aggregates
- SC-100RA = Sustainable Concrete with 20% SCBA and 100% Recycled Aggregates

TABLE IV: Nomenclature Test Specimens of Green Concrete

SPECIMEN
CC
SC-50RA
SC-100RA

4) Specimens for corrosion test

For the corrosion electrochemical behaviour of the AISI 1018 as reinforcement Conventional Concrete and Sustainable Concrete, was used prismatic specimens, see Fig. 2. The electrochemical cell was in accordance with ASTM G59 [58] standard, with a WE (bars AISI 1018 steel) and auxiliary electrode (AE) with AISI 304 stainless steel bar of 1/8" as auxiliary electrodes 15 centimeters in length.

The Linear Polarization Resistance test was carried out with, 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, according to what was reported in the literature [59]-[60], this type of three-electrode arrangement is also used in other electrochemical techniques, used to a lesser extent in the steel-concrete system and more used in other industrial areas [61]-[62].

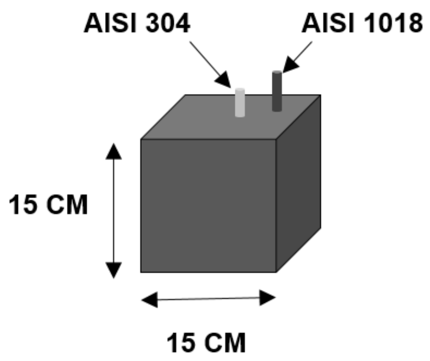

Fig. 2. Characteristics of concrete specimens for corrosion test.

The monitoring of the corrosion potentials E_{corr} and I_{corr}, was carried out for a period of more than 300 days of exposure to the control medium (water) and the Seawater.

III. Results and Discussion

A. Corrosion Potential (E_{corr})

The interpretation of the E_{corr} results was carried out according to what is indicated in the ASTM C-876-15 standard [63] and in the literature [64], table V shows the parameters for the analysis of the corrosion potentials of the present study.

As indicated in the previous sections, there are 3 studio mixes, one control mix denominated conventional concrete (CC) with 100% Natural Coarse Aggregates and 100% CPC, and two mixes of Sustainable Concretes SC-50RA and SC-100RA.

Fig. 3 shows the obtained results about the monitoring of the potential of corrosion E_{corr}, specimens CC (Conventional concrete -100% CPC and 100% Natural aggregates), SC-50RA (Sustainable concrete -80% CPC-20% CBCA and 50% of Recycled aggregate) and SC-100RA (Sustainable concrete -80% CPC-20% CBCA and 100% of Recycled aggregate).

It is observed that the specimen CC presents potential in the curing stage that goes form the -260 mV to -160 mV, passing the day 7 to day 28 of the uncertainty stage to the stage of 10% of corrosion risk according to the norm ASTM-C-876-15, the tendency to more positive values continues during all the period of evaluation, reaching values up to -60mB in the day 196 to finally end up with values in the range of 80 to 90 mV, which indicates a 10% of corrosion risk for said specimen.

For the case of specimen SC-50RA it has a very similar behaviour to the specimen CC, with values of E_{corr} in the curing stage of -250 mV, getting to the day 28 with a value of -95 mV, to keeping stable during all the period of monitoring with values of E_{corr} that indicates a 10% of corrosion risk, values between -80 and -110 mV.

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

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

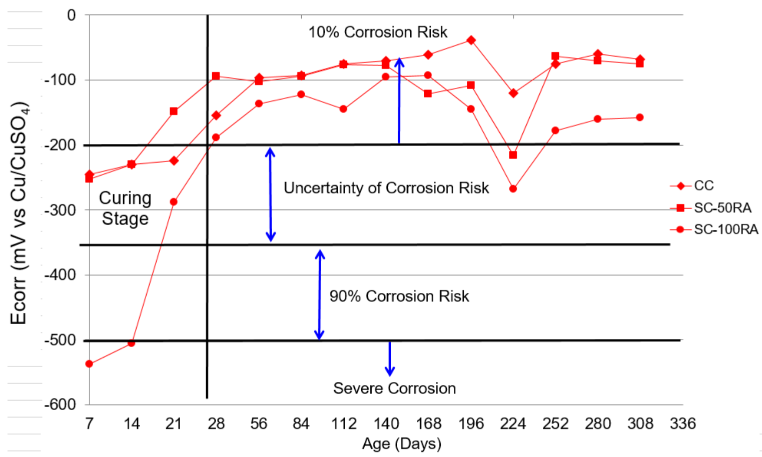

Fig. 3. E_{corr} of AISI 1018 steel in Sustainable Concrete exposed to control environment.

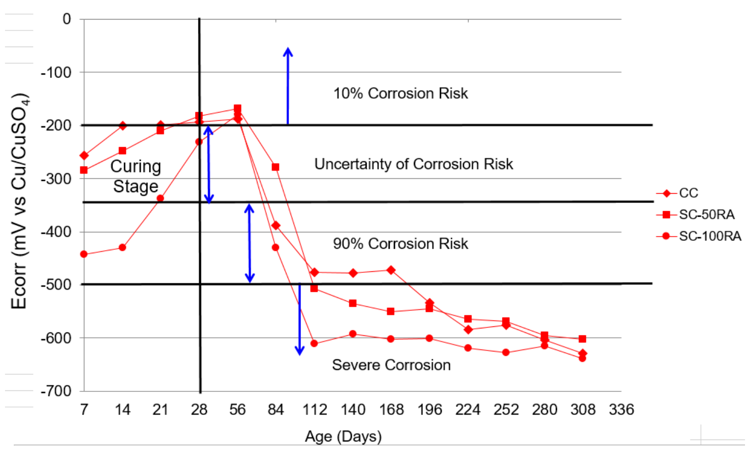

Fig. 4. E_{corr} of AISI 1018 steel in Sustainable Concrete exposed to Seawater.

The specimen SC-100RA presents a behaviour more unfavourable, with values of E_{corr} in the curing stage of -530 mV on day 7 to reach a -190 mV on day 28 and presenting more negative values than those of specimen CC the SC-50RA, but with lower values to -200mV, in a range of -120 mV to -190 mV which indicates a 10% of corrosion risk. The reported values for the three specimens match with the literature [65], due to that the exposing medium is a non-aggressive medium whereby it does not present an increase in the probability of corrosion.

Fig. 4 shows the obtained results of the potentials of corrosion E_{corr}, of specimens CC, SC-50RA, SC-100RA at having been exposed in sea water for more than 300 days. It has that the specimen CC presents in its curing stage potential of corrosion that goes from -260 mV in the day 7 to -185 mV for the day 28, at being in contact with the marine medium presents a potential of -190 mV in day 56, which indicates a 10% of corrosion risk according to the norm ASTM-C-876-15, nevertheless for the period of the day 84 to 168 presents potentials of corrosion that indicate a 90% of corrosion risk with a range of values that goes to -390 mV to -485 mV continuing with this tendency to more negative values getting to the final of the monitoring to higher potentials of -600 mV which indicate, according to the norm, the presence of severe corrosion.

For the case of the specimen with SC-50RA it has that in the curing stage presents potentials that's goes from -290 mV to -190 mV, this associated to the formation of the passive cape, such as the specimen CC even for the day 56 presents a potential of -180 mV, indicating a 10% of corrosion risk, having for the day 84 a potential of corrosion of -285 mV which indicate uncertainty of the presence of corrosion, presenting from day 112 until the end of the monitoring a tendency to values of potential of corrosion higher to -500 mV which indicates a severe corrosion according to the norm ASTM-C-876-15. The specimen SC-100RA presents in the curing stage more negative values that the presented for the specimens CC y SC-50RA, values that goes form -480 mV in the day 7 to -230 mV for the day 28, reporting for the day 56 a potential of -195 mV, however with the passing of time presents a tendency to more negative values of potential of corrosion, presenting since the day 112 to the end of the monitoring lower values to -600 mV, which indicates the presence of severe corrosion, it is observed that the values of E_{corr} of the specimen SC-100RA are bigger than the presented for the specimens CC and SC-50RA, this is associated to the pore network which is higher than the said specimen due to it contains a substitution of the 100% of recycled aggregate by natural aggregate [66].

B. *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 [67], 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

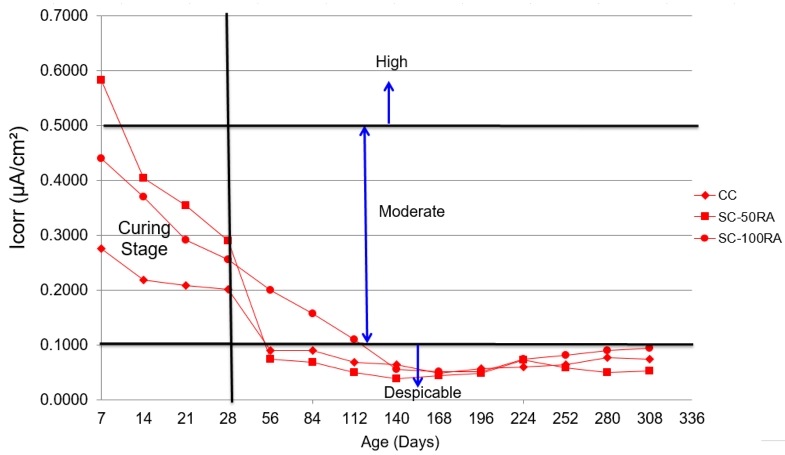

Fig. 5. I_{corr} of AISI 1018 steel in Sustainable Concrete exposed to control environment.

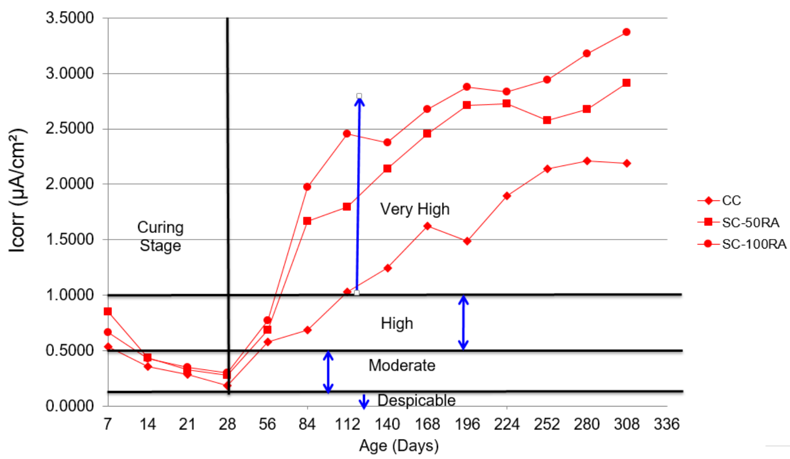

Fig. 6. I_{corr} of AISI 1018 steel in Sustainable Concrete exposed to Seawater.

Fig. 5 presents the behaviour of the corrosion rate I_{corr}, of the specimens CC, SC-50RA, SC-100RA to be exposed to potable water as a medium of control or non-aggressive for more than 300 days. It has that the specimen CC presents in the day 7 in the curing stage an I_{corr} of 0.27 µA/cm^2 decreasing to the day 28 to a value of 0.21 µA/cm^2, continuing with a tendency to the passivation with the passing of time presenting for the day 56 a value of I_{corr} of 0.095 µA/cm^2, maintaining lower values to 0.091 µA/cm^2 until the end of the monitoring in a range of 0.09 a 0.05 µA/cm^2, the obtained values of I_{corr} of the specimen CC indicate passivation of reinforcing steel and based on the Table VI a level of despicable corrosion (absence of corrosion).

For the specimen SC-50RA it has a similar behaviour of passivation that the presented for the specimen CC, however with higher values of I_{corr} since the curing stage, presenting in the day 7 a value of I_{corr} equal to 0.58 µA/cm^2 and having for day 28 an I_{corr} de 0.29 µA/cm^2, to present from day 56 to the end of the monitoring values of I_{corr} under 0.1 µA/cm^2, in a range of 0.07 and 0.04 µA/cm^2, which indicates a of despicable corrosion; for the specimen SC-100RA it has a behaviour that is similar to the other two mentioned specimens with an un I_{corr} in day 7 of 0.44 µA/cm^2 going to 0.26 µA/cm^2 for the day 28, and presenting a value of I_{corr} of 0.11 µA/cm^2 until the day 112 for passing to a stage of passivation from the day 140 until the end of the monitoring with values of I_{corr} in a range of 0.06 µA/cm^2 a 0.095 µA/cm^2, which indicates a level of despicable corrosion equal to the other two specimens, the behaviour of corrosion rate in the three specimens agrees with the reported in numerous investigations on account of that are exposed in a non-aggressive medium so therefore corrosion does not present in the system of steel-concrete [68].

Fig. 6 presents the behaviour of corrosion rate in the study specimens exposed for more than 300 days in seawater. The specimen CC presents in the curing stage values of I_{corr} that goes from 0.55 to 0.15 µA/cm^2, but when entering in contact with the aggressive medium present for day 50 a corrosion rate or I_{corr} of 0.57 µA/cm^2 which indicates, according to table VI a high level of corrosion, for the day 84 present a value of I_{corr} of 0.74 µA/cm^2, value that indicates a high level of corrosion, for presenting to the end of the monitoring a I_{corr} of almost 2.5 µA/cm^2, which indicates a very high level of corrosion. For the specimen SC-50RA presents moderate corrosion in the curing stage and until the da 56 with and I_{corr} of 0.12 µA/cm^2, but for the day 84 the magnitude of corrosion is greater than 1.5 µA/cm^2, continuing until the end of the monitoring with constant increases in the corrosion rate reaching values of 2.92 µA/cm^2, which indicates a very high level of corrosion, and with a similar behaviour to the specimen CC.

The specimen SC-100RA presents the most unfavourable behaviour of the three specimens, presenting for the day 56 a level of I_{corr} of 0.86 µA/cm^2, increasing to 2.05 µA/cm^2 for the day 84 and getting until a maximum value of 3.47 µA/cm^2 at the end of the monitoring, so that the double of the reported for the specimens CC and SC-50RA. It can be observed that the reinforced steel AISI 1018 presents less resistance to corrosion when the concretes either Conventional or Sustainable are exposed a marine medium, being the one with less efficiency the SC-100RA, so that for the use of elaborated concretes with this recycle aggregates and substitution of Portland Cement in a 20% for SCBA, it is recommended their use in non-aggressive environments, or including in their elaboration corrosion inhibitors or alternative reinforcing steels like galvanized, or stainless for aggressive environments such as marine or sulphated that have shown improving significantly the resistance to corrosion for chlorides in marine environments [69].

IV. Conclusions

Sustainable concretes based on recycled aggregates and sugar cane bagasse ash and reinforced with AISI 1018 steel can be used in non-aggressive environments, and for non-structural elements.

The results of E_{corr} and I_{corr} showed that even the Conventional Concrete specimens and more the Sustainable Concretes based on Recycled Aggregate in 50 and 100%, with 20% sugar cane bagasse ash do not offer adequate resistance against corrosion when being exposed in sea water.

The use of additives that reduce the water/cement ratio of sustainable concretes with recycled aggregate is recommended, which would allow a denser concrete matrix with lower permeability.

The use of alternative steels to AISI 1018 steel such as galvanized steel, steel with epoxy coating or stainless steel would allow a significant resistance against corrosion in this type of sustainable concrete with recycled aggregates and sugar cane bagasse ash.

Acknowledgment

MA Baltazar-Zamora, et. al., thank PRODEP for the support granted by the SEP, the Academicians UV-CA-458 "Sustainability and Durability of Materials for Civil Infrastructure" under the Call 2018 for Strengthening Academic Bodies with IDCA 28593. Thanks for the technical support to Abigail Landa Sánchez.

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