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RESEARCH ARTICLE

Anticorrosive Efficiency of the AISI 316 SS in Sustainable Ecological Concrete Manufactured with SCBA-SF Exposed to Magnesium Sulphate

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ABSTRACT

In this research, it was evaluated the anticorrosive efficiency of AISI 316 SS embedded in Sustainable Ecological Concrete (SEC) manufactured with partial substitutions of Portland Cement by combinations of SCBA and SF in 10%, 20%, and 30%. For the electrochemical evaluation, the Sustainable Ecological Concretes (SEC) were exposed to solution at 3.5% of $MgSO_4$, these aggressive ions are found in soils, industrial or marine environments and that interact with the civil works that are built in these places. The dosage or proportioning of the Sustainable Ecological Concrete (SEC) mixtures was carried out as indicated by ACI 211.1. The anticorrosive efficiency of the AISI 316 SS was evaluated through the tests of the potential of corrosion (E_{corr}) and corrosion rate (I_{corr}) during a period of 180 days of exposition to the aggressive medium. The values of E_{corr} indicate in the AISI 316 SS a 10% of corrosion risk and uncertainty at the end of monitoring, according to the norm ASTM C-876-15, in all the mixtures, but the values of I_{corr} in the specimens manufactured with SEC indicate resistance to sulfate corrosion more than 10 times compared to conventional concrete and AISI 1018 steel.

Keywords: AISI 316, magnesium sulphate, SCBA, sustainable ecological concrete.

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1. Introduction

Due to its great versatility, physical and mechanical properties and low cost, hydraulic concrete is the most used material in the world in the construction area, allowing human beings in recent decades, with its technological development that began more than a century ago, build civil infrastructure of large magnitudes essential for the development of our societies [1]–[4].

The corrosion is a phenomenon that damages in a destructive way the structures of reinforced concrete, being one of the principal factors that cause the diminution or the shortening of the useful life, durability and functioning of the same [5]–[14]. This problem obeys the exposition of the structures in mediums where are found aggressive ions or dispassivation such as sulphates and chlorides [15]–[18].

When sulphates are found in different levels of concentration in nature, they are considered practically inoffensive, but as they increase their level of concentration, their presence becomes a condition of risk for concrete structures because they can produce volumetric changes in the elements in such a way that deterioration occurs in the concrete. It is noteworthy to mention that the most unfavourable condition when sulfates exist is when they are soluble in water. The sulphate ion (SO_4^{-2}) can be present in industrial wastewater in the form of a diluted solution of sulfuric acid in the subsoil waters [19]–[29].

In general, the prevention of the corrosion of reinforced steel begins from the phase of design and production of the concrete, selection of materials, preparation, compression and cured. In order to produce concrete of quality, the stipulated norms for its durability in front of aggressive mediums must be followed, which could save millions of dollars in premature maintenance [30]–[34]. The problem of corrosion of reinforcing steel is a problem of great importance worldwide, which is why various research has been carried out from various perspectives, simulating environments, concrete, special steels, the inclusion of pozzolanic materials, etc., in order to contribute to mitigating this phenomenon [35]–[41].

For everything mentioned in the previous paragraphs, the objective of the present investigation was to analized the anticorrosive efficiency of the reinforced steel AISI 316 SS in comparison to the steel AISI 1018 at being embedded in Sustainable Ecological Concrete (SEC) manufactured with partial substitutions of Portland Cement by combinations of SCBA and SF in 10%, 20%, and 30% exposed to the solution at 3.5% of $MgSO_4$, as aggressive environment. This research contributes to the development of durability concretes and the use of agro-industrial and industrial wastes, and in the decrease of use of cement, what is going to impact the reduction of emissions of CO_2 from the cement industry, which is responsible for the 6% to 8% of the emissions of CO_2 at global level [42]–[46]. With the obtained results of corrosion potential (E_{corr}) and corrosion rate (I_{corr}), of the steels of the present research, it can be identified the mixture of concrete SEC that brings a higher protection or durability against corrosion for the presence in magnesium sulphate.

2. Materials and Methods

2.1. Materials

2.1.1. Dosage and Proportion of Conventional Concretes (CC) and Sustainable Ecological Concrete (SEC)

The used method for the design of the mixtures of the Conventional Concretes (CC) and Sustainable Ecological Concrete (SEC) was the ACI 211.1 [47], which has as a base the physical characterization of the fine and thick aggregates that will be used in the elaboration of the mixtures of hydraulic concrete, due to that according to the obtained values it can be realised the dosage of the materials according to the quality of the required concrete. The tests for determining the physical properties of the aggregates were realised under ASTM standards [48]–[51]; the results are shown in Table I.

For the present research were take in consideration the next parameters for the dosage of the mixtures of the concretes CC and SEC:

- Compressive strength, f´c = 250 kg/cm^2
- Slump of 10 cm
- Maximum Aggregate Size of 19 mm
- Concrete without air
- Ratio water/cement (w/c) = 0.65
- Portland Cement (CPC 30R)

According to the mentioned parameters and the physical properties of the aggregates (Table I), it was obtained the dosification of the mixtures is show in Table II.

TABLE I: Physical Characteristics of the Aggregates

Physical properties of materials	Coarse Aggregate	Fine Aggregate
Bulk Density ("Unit Weight") kg/m^3	1433	1695
Absorption (%)	1.70	1.80
Relative Density (Specific Gravity)	2.60	2.20
Module of Fineness	–	2.94
Maximum Size Nominal	¾ "	–

Fig. 1. AISI 316 SS and AISI 1018 of 3/8″ of diameter.

2.2. Methods

2.2.1. Characterization of Concretes CC and SEC on the Fresh and Hard State

According to the test of ONNCCE and ASTM standars [52]–[55], it was determined the characteristics of the concretes CC and SEC in fresh state and in hard state, the tests and the results of them are presented in Table III.

2.2.2. Characteristics of the Reinforced Steel

The reinforced steels used in this investigation, according to American Iron and Steel Institute (AISI) were the AISI 1018 and AISI 316 SS. The steel bars were cut in 15 cm of length. It was realised the corresponding cleaning to each one of the bars until obtaining a surface clean of any impurity, see Fig. 1.

The zones in which the primary paint and a cape of anticorrosive paint would be placed were delimited. These areas were, in the inferior part of the bar, which was painted 4 cm, then it was left uncovered a length of 5 cm in which this area will be in contact with the matrix of hydraulic concrete, after that 4 cm were painted and at the end, it left 2 uncover cm for the connection of the experimental arrangement. At the same time, it was using one bar of AISI 316 stainless steel of 1/8 cm used as an auxiliary electrode with a dimension of 15 cm of length; this arrangement has been used for the scientific community in the study of the corrosion of reinforced concrete [56], [57].

TABLE II: Proportion of Conventional Concrete and Sustainable Ecological Concrete kg for 1 m^3

Mixture	Cement	SCBA	SF	Water	FA	CA
CC	315	–	–	205	746	881
SEC10	283.50	15.75	15.75	205	746	881
SEC20	252	31.50	31.50	205	746	881
SEC30	220.50	47.25	47.25	205	746	881

TABLE III: Physical and Mechanical Properties of the Mixtures of CC and SEC

Mixture	Temperature, °C	Slump cm	Unith weight kg/m^3	Compressive strength (28 days) kg/m^2
CC	24	7	2345.83	318
SEC10	23.5	6	2307.29	292
SEC20	23.5	5.5	2301.24	306
SEC30	22.5	5	2276.04	246

TABLE IV: Specimens of the Mixtures CC and SEC

Nomenclature	Characteristics of the mixture
CC	Conventional concrete – 100% CPC 30R -
SEC10	Sustainable Ecological Concrete (90% of CPC 30R, 5% SCBA and 5% SF)
SEC20	Sustainable Ecological Concrete (80% of CPC 30R, 10% SCBA and 10% SF)
SEC30	Sustainable Ecological Concrete (70% of CPC 30R, 15% SCBA and 15% SF)

TABLE V: Nomenclature for the evaluation of the corrosion in the exposed mediums

Control medium-water		Solution at 3.5% of $MgSO_4$	
AISI 1018	AISI 316	AISI 1018	AISI 316
CC-MC-1018	CC-MC-316	CC-SM-1018	CC-SM-316
SEC10-MC-1018	SEC10-MC-316	SEC10-SM-1018	SEC10-SM-316
SEC20-MC-1018	SEC20-MC-316	SEC20-SM-1018	SEC20-SM-316
SEC30-MC-1018	SEC30-MC-316	SEC30-SM-1018	SEC30-SM-316

Note: CC, SEC10, SEC20, and SEC30 indicate the mixture of concrete according to Table IV. MC – Control Medium (Water), SM – Aggresive Medium (Solution at 3.5% of $MgSO_4$), 1018, 316 – Bars of AISI 1018 and AISI 316 SS.

TABLE VI: 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

2.2.3. Nomenclature of CC and SEC for the Evaluation of the Corrosion

To realize an appropriate management of the results of the present investigation, it was assigned a nomenclature of the four mixtures elaborated according to their characteristics, which is summarized in Table IV.

The nomenclature used for the monitoring of corrosion potential (E_{corr}) and corrosion rate (I_{corr}) of AISI 316 SS and AISI 1018 embedded in the CC and SEC, exposed in water (Control medium) and in solution at 3.5% of $MgSO_4$ (aggressive medium) is shown in Table V.

3. Results and Discussion

3.1. Corrosion Potential (E_{corr})

Table VI shows the range of E_{corr} values for evaluating the risk of corrosion in reinforced concrete according to the standard ASTM C-876-15 [58], in addition, the severe corrosion range is considered according to the literature [59] to carry out an adequate interpretation of the values obtained from E_{corr}.

In Fig. 2, it can be observed the behaviour of the potentials of corrosion E_{corr} of all the specimens of study when they were exposed to the control medium (water), as much as the reinforced with steel AISI 1018, CC-MC-1018, SEC10-MC-1018, SEC20-MC-1018 and SEC30-MC-1018, as well as the reinforced with AISI 316 stainless steel, CC-MC-316, SEC10-MC-316, SEC20-MC-316 and SEC30-MC-316. Like it was indicated in the last paragraphs, there are four mixtures of study, one control mixture of denominate Conventional concrete (CC) with 100% CPC 30R, and three mixtures of Sustainable Ecological Concrete in base to partial substitution of the CPC 30R in a 10%, 20%, and 30% for combinations of Sugar Cane Bagasse Ash (SCBA) and Silica Fume (SF).

What corresponds to the curing stage, the specimens with steel 1018 present values of E_{corr} more negative than -200 mV, for to the passing of time reporting more positive values maintaining during all the period of monitoring of the specimen CC-MC-1018 and the SEC20-MC-1018 the nearby values to -100 mV, which according to the norm ASTM C-876-15 indicates 10% of corrosion risk. What refers to the specimens with 10% and 20% of substitution of SCBA-SF after the 150 days present more negative values to -200 mV, which, according to the norm, would indicate uncertainty of corrosion risk, but in the last monitoring, the specimen with 30% of substitution of CPC for the system SCBA-SF, specimen SEC30-1018 keeps with an E_{corr} of -226 mV. For the specimen with AISI 316 SS, all present from the curing stage until the end of the monitoring had more positive potentials than -200 mV, which indicates a 10% of corrosion risk. It is not observed influence of the type of concrete in which they are embedded, either it is conventional concrete (CC) or Sustainable Ecological Concrete (SEC).

Fig. 3 shows the behavior of the E_{corr}, half-cell potential after 180 days of exposure to sulphates (3.5% $MgSO_4$ solution) of reinforced specimens with steel AISI 1018, CC-SM-1018, SEC10-SM-1018, SEC20-SM-1018 and SEC30-SM-1018, such as the reinforced with AISI 316 SS, CC-SM-316, SEC10-SM-316, SEC20-SM-316 and SEC30-SM-316. The specimens with steel AISI 1018 present a similar behaviour to the observed in the specimens exposed to the control medium from the curing stage until day 114, with a tendency to passivation only for the specimens CC-SM-1018, placing itself in a zone of 10% corrosion risk by the end of monitoring, for the specimens with 20% and 30% of SCBA-SF, SEC20-SM-1018 and SEC30-SM-1018, with values of E_{corr} of -231 mV and -282 mV, respectively, indicating uncertainty of corrosion risk, according ASTM C-876-15 standard.

For the case of the specimens reinforced with AISI 316 SS, CC-SM-316, SEC10-SM-316, SEC20-SM-316 and SEC30-SM-316, the values of E_{corr} present a very similar behaviour to the exposed to the control medium, with values during the curing stage that go from –141 mV to –78 mV, behave that keeps during all the time of exposition to the aggressive medium, with minor values to –100 mV in all the specimens, values of E_{corr} that according to the norm ASTM C-876-15 indicates a 10% of corrosion risk, not identifying an influence of the type of concrete, but it is associated to the high protection that offers the steel AISI 316 against the corrosion for sulphates, the reported values in the present investigation agree with the reported in the literature [60].

3.2. Corrosion Rate (I_{corr})

Monitoring and interpretation of the corrosion rate or I_{corr} was performed based on DURAR Network Specifications [61], see Table VII.

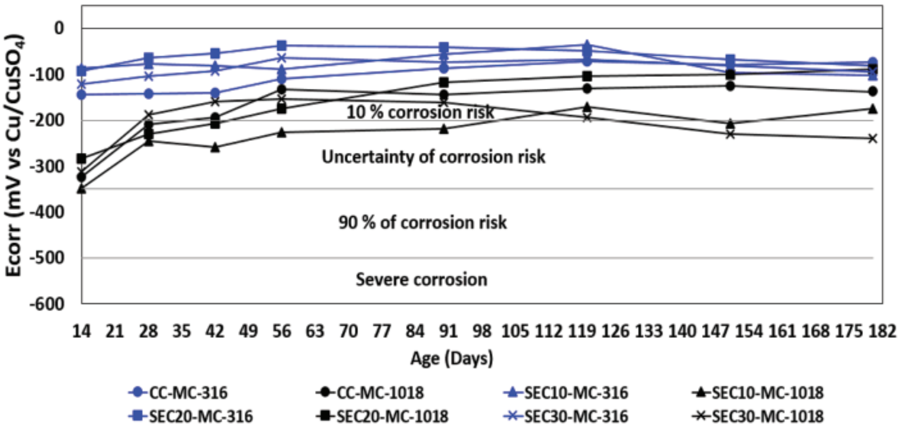

Fig. 2. E_{corr} of specimens exposed in the control medium (water).

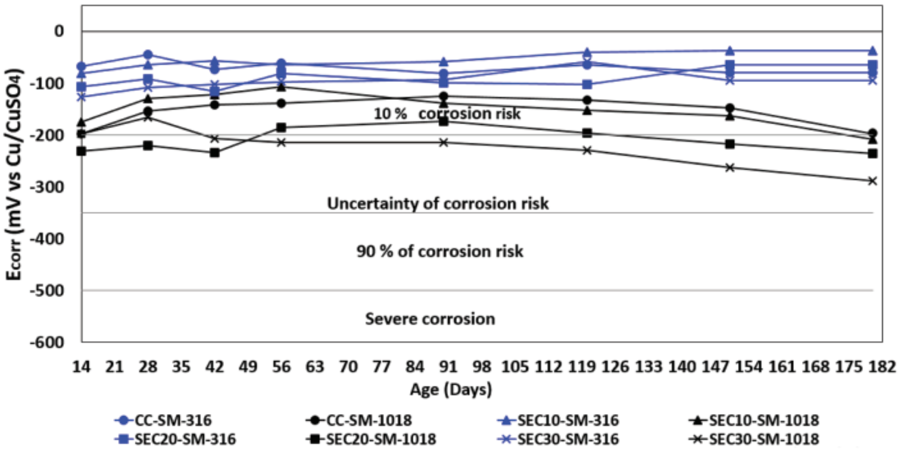

Fig. 3. E_{corr} of specimens exposed to the aggresive medium (solution at 3.5% of $MgSO_4$).

TABLE VII: 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

In Fig. 4, it is observed the behaviour of the corrosion rate or intensity of current, Icorr, for the specimens reinforced with steel AISI 1018, CC-MC-1018, SEC10-MC-1018, SEC-MC-1018 and SEC30-MC-1018, as well as the reinforced with AISI 316 SS, CC-MC-316, SEC10-MC-316, SEC20-MC-316 and SEC30-MC-316, of Conventional Concrete and Sustainable Ecological Concrete immersed in a control medium (water). The specimens with steel AISI 1018 present values among 0.68 to 0.33 $\mu A/cm^2$, in the curing stage, for present values between 0.18 to 0.09 $\mu A/cm^2$ in the day 56, agreeing the values with the some researchs [61]. The decrease in I_{corr} values occurs in all four specimens, CC-MC-1018, SEC10-MC-1018, SEC-MC-1018 and SEC30-MC-1018, due to exposure to a non-aggressive medium (water), presenting all specimens at the end of monitoring, I_{corr} values less than 0.1 $\mu A/cm^2$, which indicates, according to Table VII, a despicable level of corrosion.

For the case of the specimens with AISI 316 SS, CC-MC-316, SEC10-MC-316, SEC20-MC-316 and SEC30-MC-316, the behaviour is very similar with high values of I_{corr} at the beginning of the curing stage, with values at day 14 in between 0.17 and 0.06 $\mu A/cm^2$, but reaching in the day 28 values from 0.05 to 0.03 $\mu A/cm^2$, results that are congruent due to the protection of the cape of protection of the stainless steel and more in the curing stage or non-aggressive medium, all the specimens with steel AISI 316 present smaller values to the specimens with steel AISI 1018, observing also a better development in the specimens with 20% and 30% of SCBA-SF, specimens SEC20-MC-316 and SEC30-MC-316 in comparison with the specimens of CC and SEC with 10% of SCBA-SF, CC-MC-316 and SEC10-MC-316. However, all the specimens present values of I_{corr} that indicate a despicable level of corrosion or no corrosion, which agrees with the reported in other research [62], when the corrosion rate in the medium of control is evaluated.

Fig. 5 shows that for the specimens CC-SM-1018, SEC10-SM-1018, SEC20-SM-1018 and SEC30-SM-1018, reported a corrosion rate, I_{corr} of between 0.54 and 0.13 $\mu A/cm^2$, in the first 28 days (curing stage), behaviour observed in the specimens exposed to the control medium. However, upon coming into contact with the aggressive medium (3.5% $MgSO_4$ solution), the specimens with AISI 1018 report I_{corr} values less than 0.1 $\mu A/cm^2$, which indicates a negligible level of corrosion, an apparent protection effect of the aggressive medium, observed. in other

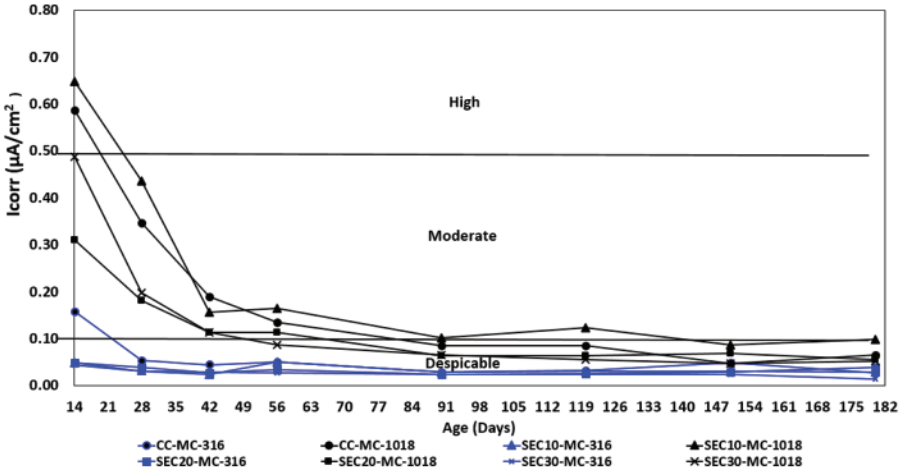

Fig. 4. I_{corr} of specimens exposed in the control medium (water).

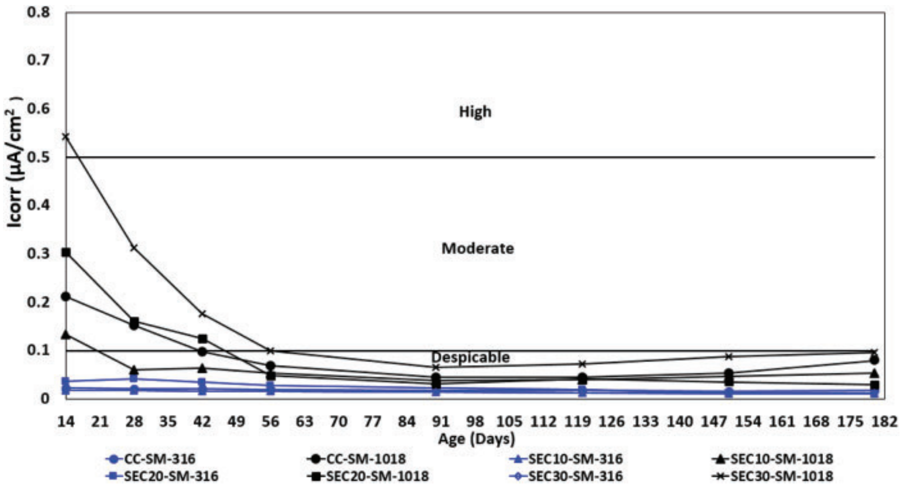

Fig. 5. I_{corr} of specimens exposed to the aggressive medium (solution at 3.5% of $MgSO_4$).

research works [63]. Even though after day 120 of exposition, it presents a tendency of increments in the values of I_{corr} for the four specimens CC-SM-1018, SEC10-SM-1018, SEC20-SM-1018 and SEC30-SM-1018, which agrees with the values of E_{corr} reported in Fig. 3, for mentioned specimens, the tendency to more great values of I_{corr} keeps until the end of the monitoring, reaching almost the activation of the system for the day 180 two specimens, the el CC-SM-1018 and the SEC30-SM-1018, with nearby values to 0.10 $\mu A/cm^2$, and keeping the specimens SEC10-SM-1018, SEC20-SM-1018 at the end of the monitoring with 0.08 and 0.06 $\mu A/cm^2$, respectively, which indicates that in the conditions of the present study Sustainable Ecological Concrete with 10%, 20%, and 30% of substitution of CPC for the combination of SCBA-SF presented a higher protection against corrosion at the steel AISI 1018.

It has that in the specimens with Steel AISI 316, CC-SM-316, SEC10-SM-316, SEC20-SM-316 and SEC30-SM-316, it also presented in the curing stage a very similar behaviour at the analysis in the specimens exposed to the control medium, with values of I_{corr} between 0.036 and 0.017 $\mu A/cm^2$, in the curing stage, with a tendency of diminution of the level of corrosion present in the system, reaching values among 0.019 and 0.011 $\mu A/cm^2$, for the day 90 and remaining in that range until the final of the monitoring reaching values for the day 180 all the specimens with steel AISI 316 up to 0.014 and 0.010 $\mu A/cm^2$, without showing some indication of increment of the corrosion rate, demonstrating the benefit of the steel AISI 316 against corrosion for sulphates, observing that the concretes SEC presented lower values than the conventional concrete, behaviour observed in the reinforced with steel AISI 1018. In summary, the specimens with steel AISI 316 present during the period of exposition at the magnesium sulphate an excellent development, reporting values of I_{corr} till 0.010 $\mu A/cm^2$, corrosion rate or intensity of corrosion ten times lower to 0.1 $\mu A/cm^2$, a boundary that indicates the Manual of the RED DURAR for considerating the presence of corrosion in the system steel-concrete-medium aggressive evaluated.

4. Conclusions

The Sustainable Ecological Concrete elaborated with 10%, 20%, and 30% of substitution of CPC for the combination of SCBA-SF increase the corrosion resistance of AISI 1018 steel due to sulfates compared to conventional concrete.

The protection against sulphate corrosion of Sustainable Ecological Concrete increases significantly using the AISI 316 stainless steel, so it is recommended this combination, Portland Composite Cement, Sugarcane bagasse ash and Silica Fume, until a percentage of substitution of Portland Cement of 30% for the SCBA and the SF, for elaborating structures of concrete that will be exposed for environments with high concentrations of sulphates, which could double the useful life of the structure, from 50 years to 100 years.

The use of Sustainable Ecological Concrete in the construction of civil infrastructure, in addition to increasing the durability and useful life of the structures, would contribute to a great reduction in CO_2 emissions due to the manufacture of Portland Cement, which would significantly benefit reducing the global warming problem.

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Conflict of Interest

Authors declare that they do not have any conflict of interest.

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