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Electrochemical Behaviour of Galvanized Steel Embedded in Concrete Exposed to Sand Contaminated with NaCl

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This research evaluates the corrosion of reinforced concrete, exposed to marine sand, simulating what happens with the elements of laying of foundations of all concrete structures constructed on coasts of Mexico and the world. In such concrete specimens a steel bar AISI 1018 and Galvanized Steel was embedded as reinforcement, the mixed concrete was of ratio w/c=0.45 (f´c = 350 kg / cm^2), according to ACI 211.1, using two type cements CPC 30R and CPC 30R RS. The corrosion rate was evaluated by electrochemical techniques, corrosion potential E_{corr} (ASTM C-876-09) and Linear Polarization Resistance (ASTM-G59). These specimens were exposed in a marine sand contaminated with 0, 1, 2 and 3% NaCl, the exposure time was 260 days where, according to the electrochemical results of E_{corr} and I_{corr}, we could determine that the better performance of the specimens was galvanized steel and concrete made with cement CPC 30R RS, this research demonstrated the importance of developing special to elaborated concrete durability in aggressive environment such as is the ground where uproots all reinforced concrete structures.

Keywords: Foundations, Soil, Reinforced Concrete, Corrosion, Chlorides.

1. INTRODUCTION

Several researches has shown that damage by corrosion of reinforcing steel it is one of the causes of deterioration of concrete structures, regardless of their highly heterogeneous and complex structure [1-2]. In Mexico no figures, however, has more than ten thousand kilometers of coastline and numerous works them are susceptible to corrosion damage. External causes that usually affect the durability of the concrete structure are mainly due to their conditions of service [3-4].

The corrosion of reinforcing steel has several causes of deterioration, one of which is the chloride ions. These ions can be in the concrete mix or come from the environment [5-7]. While there is information on preventive measures to avoid such damage, mostly conducted studies have been conducted to chloride or (concrete-water) sulphate ions relationship; however, few investigations have studied the effect of the concentration of chloride and sulphate in the soil corrosion of reinforced concrete [9-10].

The electrochemical behaviour is importance of galvanized steel and 1018 carbon steel with reinforcements, present in much of the country arises because as mentioned account with about 10,000 kilometers of coastline, where a large number of structures are grounded. That is why in this paper the influence of chlorides present in a soil SP (bad sand graded) will be studied, to reinforced concrete, using two types of cement and two types of steel, to determine which has the best performance this means of contact.

2. EXPERIMENTAL

For this investigation used the mixed concrete was of ratio water/cement = 0.45 (f´c = 350 kg / cm^2), according to ACI 211.1 [11], using two type cements CPC 30R and CPC 30R RS, reinforcing steel embedded in concrete specimens was AISI 1018 steel (WE) and galvanized steel bars (WE), placing a stainless steel bar as auxiliary electrode (AE). For this research the concrete specimens were exposed to sand in presence of 0, 1, 2 and 3% NaCl by weight of the soil, for to do the electrochemical evaluation use the electrochemical techniques Half Cell Potential ,E_{corr}, based on standard ASMT C876-09 [12] and Linear Polarization Resistance (LPR), I_{corr}, based on standard ASMT G59-97 [13]; as is done by the scientific community [14-16].

2.1 Physical characteristics of the aggregates.

Table 1. Physical characteristics of the aggregates

Physical characteristic	Coarse Aggregate	Fine Aggregate
Specific Gravity (gr/cm^3)	2.32	2.66
Volumetric Weight Dry Compacted (kg/cm^3)	1380	- - -
Absorption (%)	4	3.5
Fineness modulus	- - -	2.4
Maximum Aggregate Size (mm)	19	- - -

Concrete mixtures were prepared indicated by the ACI 211.1, as mentioned earlier, this method is based on the characterization of aggregates to utilizer, because the results are used to find the dosage of materials to utilizer wings specifications required for each mixture according to their f'c o ratio w/c among the most important. Table 1 show the physical characteristics of the aggregates that were used in this investigation.

2.2 Design and Proportioning of concrete mixture.

According to the physical characteristics of the aggregates, a concrete mixture design for the ratio w/c=0.45 (f'c = 350 kg/cm^2); the amount of material in kg it observed in the table 2.

Table 2. Proportioning of concrete mixture 1 m3

Materials (kg)	w/c=0.45 ratio (f'c=350kg/cm$^{2)}$
Water	205
Cement	456
Coarse Aggregate	912
Fine Aggregate	772

2.3 Test of concrete in fresh and hardened state.

For quality control of concrete mixtures, the tests are done according to standard of the ASTM [17] and ONNCCE [18-20]. The tests and the results obtained shown in table 3.

Table 3. Physical and mechanical properties of concrete mixture

Test	CPC 30R	CPC 30R-RS
Temperature	24 ºC	23 ºC
Slamp	4 cm	5 cm
Density	2150 kg/m^3	2148 kg/m^3
Compressive Strength	362 kg/cm^2	358 kg/cm^2

2.4 Characterization and specifications of specimens

In the specimens were embedded two type's bars as reinforcement as working electrodes (WE), bars low carbon steel AISI 1018 and bars of Galvanized Steel, was used a stainless steel plate as auxiliary electrode CAE), see figure 1.

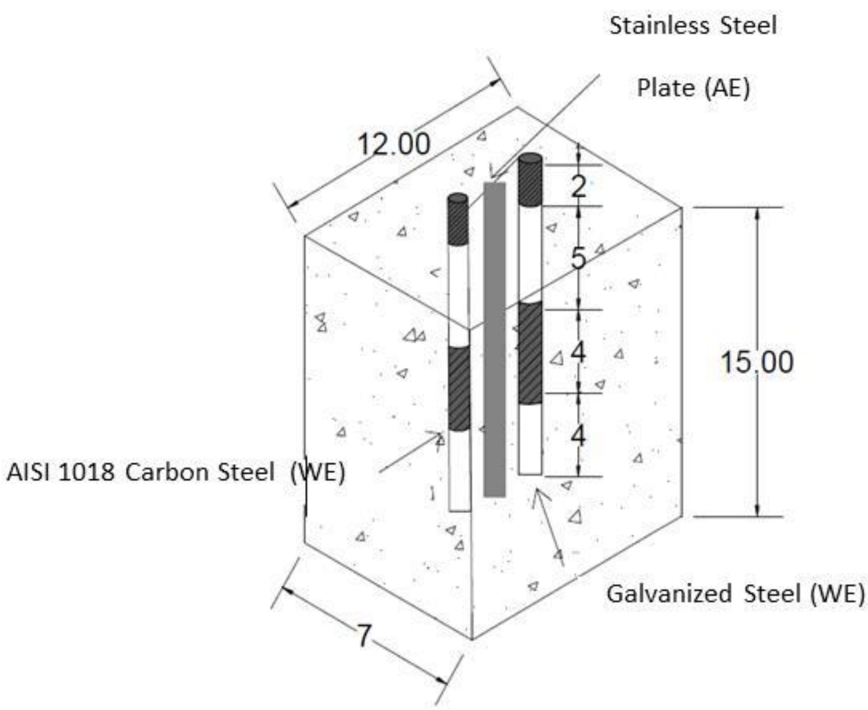

Figure 1. Characteristics of specimens and reinforcing steels in cm.

The bars reinforcing steel AISI 1018 and galvanized steel they were cleaned and prepared as indicated in the literature [21-23].

The manufacture of the test specimens was performed and subjected to curing stage for 28 days, on based standard NMX-C-159-2004 [24]. The nomenclature used for each specimen is shown in in table 4.

Table 4. Nomenclature specimens study

Nomenclature							
A40RG	A40RN	E41RNG	E41RNN	F42RNG	F42RNN	G43RNG	G43RNN
A40RSG	A40RSN	E41RSNG	E41RSNN	F42RSNG	F42RSNN	G43RSNG	G43RSNN

Where:

- A, E, F and G indicates the specimen.
- 4 is the ratio w/c = 0.45 (f´c= 350 kg/cm^2).
- 0, 1, 2 and 3 refer to the concentration of NaCl in the soil of study.
- R indicate the cement CPC 30R used.
- RS indicate the cement CPC 30R RS used.
- N indicates that NaCl as pollutant.
- G indicate the Galvanized Steel as reinforcement
- N indicate the AISI 1018 Steel as reinforcement

Unified Soil Classification System (USCS) was used to classify the type of soil that was used in this research as a means of exposure, according to the USCS, soil used was a poorly graded sand of symbol (SP) [25].

After completion of the step of curing the concrete specimens of this research, thats where placed in the sand with 0, 1, 2 and 3% NaCl, with reference to the 0% indicating sand without the addition of contaminant; the sand is a contact exposure and is for to simulating of reinforced concrete foundations as piles of bridges, isolated footings or bull buildings or foundation slabs in contact with the ground throughout the service life of these structures.

The electrochemical evaluation was for a period of over 260 days and the electrochemical cell based on standard ASTM G59-97, with a Working Electrode (WE), Auxiliary Electrode (AE) and Reference Electrode Cu/$CuSO_4$ (RE). For to use the LPR technique it was used a Gill AC Potentiostat/Galvanostat/ZRA ACM instruments and using its special software for obtain the information of I_{corr} values for each specimen.

3. RESULTS

3.1 Corrosion Potential

The evaluation of corrosion potentials (E_{corr}) was performed as indicated by standard ASTM C876-09, considering a range more when (E_{corr}) values are more negative than -500 mV [26].

Analysing the results presented in figure 2, we have that the A40RN (CPC 30R-1018) and the A40RSN (CPC 30R RS-1018), we observed that both specimens in their curing stage (first 28 days) have homogeneous behaviour with values of potential ranging from -200 mV in the first day with a well defined trend reduction potential more positive or both steel passivation specific values, after an activation step occurs when placed in the aggressive medium, poorly graded sand (SP), in contact with the ground potential of both steels down to more negative values (from day 29 to 50) 1018 reporting the embedded sulphate resisting cement (CPC 30R RS) potential of up to -300 mV which would indicate a 50% chance of corrosion of the steel embedded in ordinary concrete is placed potential to -380 mV which indicates a 90% probability of corrosion according to the standard, then from day 50 to day 98, the potentials of both specimens have a tendency to more positive values reaching near 10% chance of corrosion after 100 days of exposure can identify the benefits it brings resistant cement sulphate (CPC 30R RS), as it is maintained E_{corr} values that indicate a 10% chance of corrosion up to 231 days of exposure, except a drop in the area of uncertainty 170 and 180 days; for the last 20 days of exposure is located in values indicating uncertainty, however the specimen A40RN (CPC 30R-1018) presents after 100 days until day 165 values up to -280 to -290 mV, indicating a 50% chance of corrosion, to present also a drop in the potential to more negative values than -500 mV day 170 to 190, associated with the rupture of the passive film of the steel, the end of the monitoring, day 220 to 270 the trend values indicating severe corrosion is observed.

As regards A40RG (CPC 30R-galvanized steel) and A40RSG (CPC 30R RS-galvanized steel) specimens, similar behaviour to specimens with 1018 with decreased to more positive values of E_{corr} shown in its curing step, and an influence on the values given the type of cement, with an activation step passivation upon contact with the ground (29) and until day 98 when they already have both specimens A40RG and A40RSG values 90% chance of corrosion taking these days (98 to 140), a better performance specimen A40RG to present from day 170 where apparently disrupts the passive layer, E_{corr} values severe corrosion occurs to day 200 to have a passivation period until day 220 and end with a trend to more negative values for the last 50 days, while in the specimen A40RSG, from day 170 begins to see the benefit of using sulphate resistant cement CPC 30R RS showing ranging monitoring until the end (day 270), between -330 and -280 mV, which indicate the standard according to a probability of 50% corrosion unlike presenting A40RG severe corrosion potential.

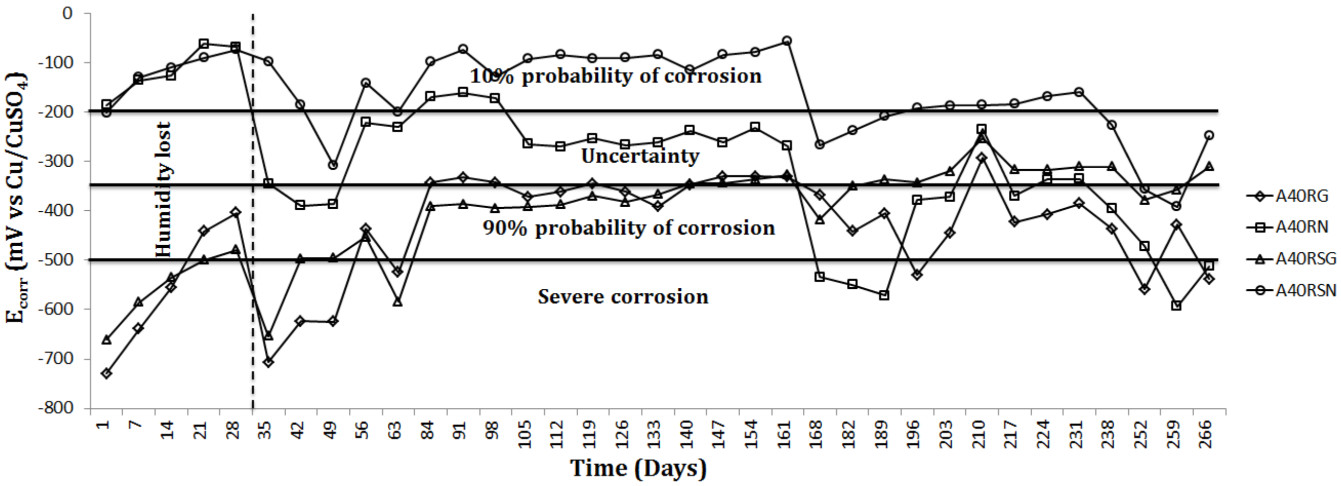

Figure 2. E_{corr}, specimens in exposed to sand without NaCl

In Figure 3 are the results of specimens made with a type CPC 30R cement, steel and galvanized steel 1018 E41RNN and E41RNG specimens exposed to a type SP floor with 1% NaCl as aggressive agent considers himself a marine environment, and with sulphate resisting (CPC 30R RS), in the case of specimens E41RSNG E41RSNN and cement. By analysing these results we have for E41RNN and E41RNG specimens from day 50 the observed chloride attack, presenting a potential drop for both specimens, both for normal cement and sulphate resistant, reporting values of E_{corr} more negative than -350 mV for AISI 1018 steel embedded in concrete with cement type CPC 30R, in the case of concrete prepared with sulphate resisting protection observed for this as E_{corr} presents values of between -200 and -350 mV, indicating uncertainty, behaviour that extends until day 185 of exposure, the benefit of using sulphate resistant cement in 1018 is seen as having a better corrosion performance according to potential obtained in the exposure period, presenting E41RNN specimen from day 100 E_{corr} indicating severe corrosion, unlike the E41RSNN having only uncertainty and severe corrosion to the last week of monitoring. The same behaviour is observed for E41RNG and E41RSNG specimens, where we can see how to get in contact with soil contaminated with 1% NaCl, the system is activated by presenting potential more negative than in the curing stage they were in passive state , is observed in these specimens galvanized steel protective effect by the use of sulphate resistant cement specimen as this presents E_{corr} throughout the period of from -200 mV to -350 mV which indicates an uncertainty of corrosion according to ASTM C-876-09, however the concrete made with the normal values E_{corr} presents indicating severe corrosion from exposure start to the last day of monitoring.

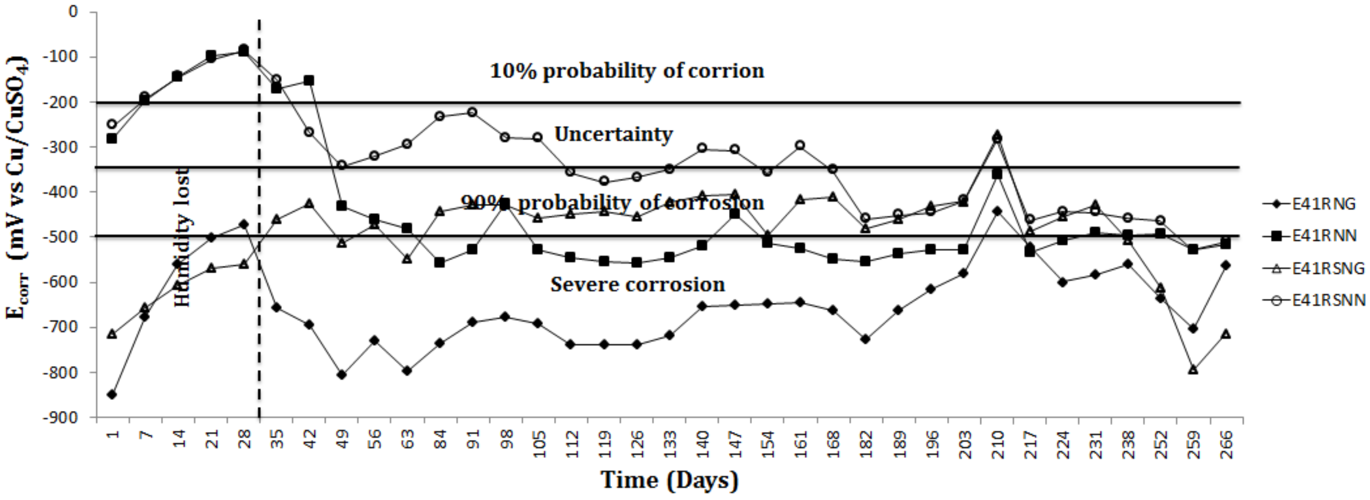

Figure 3. E_{corr} of specimens exposed to sand with 1% of NaCl.

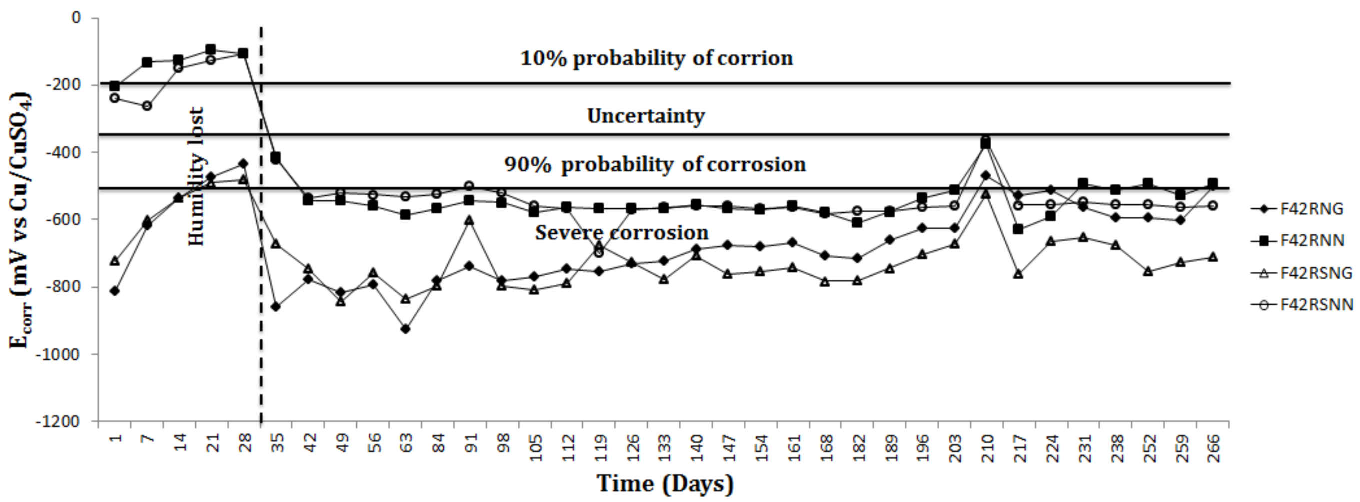

Figure 4. E_{corr} of specimens exposed to sand with 2% of NaCl.

In figure 4 are the results of the specimens with cement type CPC 30R and CPC 30R RS to 1018, for F42RNN and F42RSNN specimens, and galvanized steel for the case of F42RNG and F42RSNG specimens shown in this figure and in figure 4 as the results agree well with the literature in the sense that the chlorides or half chlorides (Marine Environment) is the most aggressive corrosion of reinforcing steel, this statement is observed when analyzed results when the concentration to 2% NaCl in soil type SP of this study was increased.

Corrosion is present in all specimens; presenting with 1018 steel specimens (F42RNN and F42RSNN) after two weeks of exposure to contaminated soils, both values of E_{corr} more negative than -500 mV, this potentials are maintained for 270 days exposure the aggressive environment evidenced and no addition identifying some benefit of using sulphate resistant cement, CPC 30R RS. In the case of galvanized steel specimens have also from the present exposure start of E_{corr} values more negative than -750 mV and F42RSNG and F42RNG, both specimens exhibit that magnitude values until 140 days of exposure, showing a variation with less negative but still in range of severe corrosion F42RNG specimen, specimen normal cement (CPC 30R) having the end values up to -500 mV unlike prepared with sulphate resisting cement that holds E_{corr} to the negative end values -700 mV.

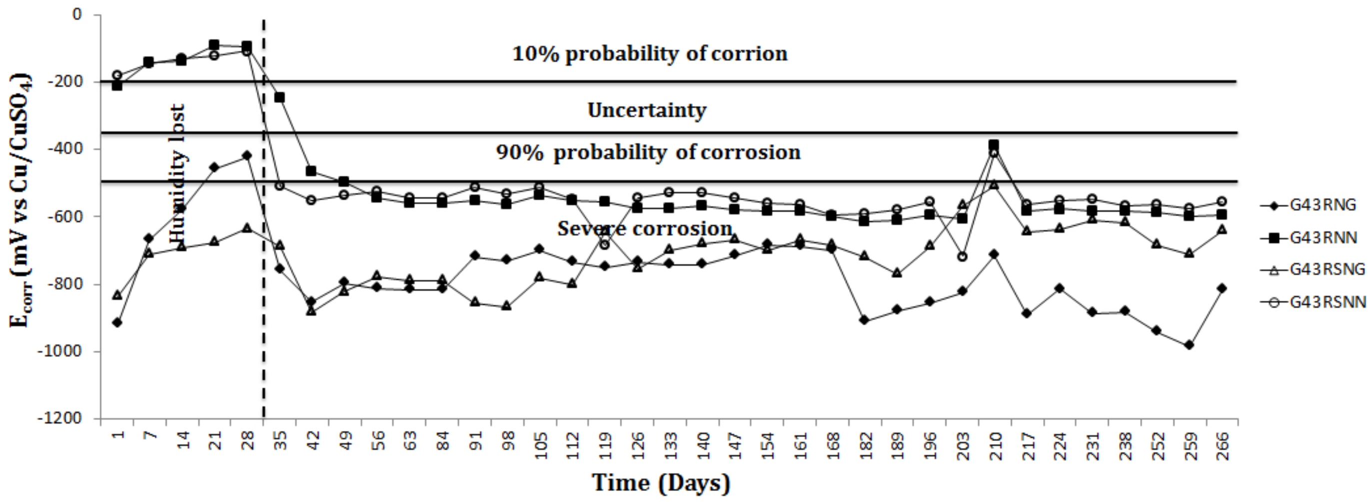

Figure 5. E_{corr} of specimens exposed to sand with 3% of NaCl.

In the case of figure 5 have the specimens with the same characteristics as those discussed in Figure 4 and 5, with type CPC 30R cement and CPC 30R RS to 1018, for G43RNN and G43RSNN specimens, and galvanized steel for and if the G43RNG G43RSNG but SP exposed to soil contaminated with 3% NaCl, specimens which causes a behavior as that observed in specimens exposed to soil with 2% NaCl, corrosion potentials for those steel 1018 (G43RNN and G43RSNN) indicating from day 50 severe corrosion behavior that is maintained until the end of the monitoring reaching values of E_{corr} near -600 mV and observed no difference between the types of cements used, and also for the for specimens with galvanized steel (G43RNG and G432RSNG), we also have corrosion potential of -700 to -800 mV for both until day 170 and no identifying similar behavior influence the type of cement until after this day, wherein the values presented specimen E_{corr} G43RSNG to the end of monitoring -600 mV with little variation, however the normal cement prepared, exhibits greater activity G43RNG corrosion values of -800 mV to -1000mV, in last 100 days of monitoring, which could be associated with the effect of the type of cement in this case, as demonstrated by Joukosky[27] in her worked for to determinate the influence of the cement type and cement content, as well as the concrete cover thickness, in the resistance and durability of reinforced concrete elements exposed to aging in a 3.4 % NaCl aqueous solution, reported what her results are presented for each combination of cement type and content, in terms of the aging time and evaluated by Half Cell Potential and EIS measurements show that concretes made with CPV-ARI RS cement presented the best results, with longer periods necessary to beginning the corrosion.

Pianca[28] , when evaluating three bridges built with galvanized steel, in the Ontario region, Canada, found in the Victoria Street Bridge –Wingham, increases in delaminations 0 to 1.2%, as well as increases in corrosion potential of -360 mV to -440 mV and the corrosion rate, I_{corr}, of 1.07 a 2.55 μA/cm^2, measured by the linear polarization resistence, and considering the results of the other bridges, their conclusion was Galvanized reinforcing bars are not recomennded as the primary or sole means of corrosión protection in the Ontario highway environment.

4. DISCUSSION

4.1 Corrosion Kinetics

Monitoring and interpretation of the Corrosion Kinetics (Corrosion Rate), was performed based on Durar Network Specifications [29].

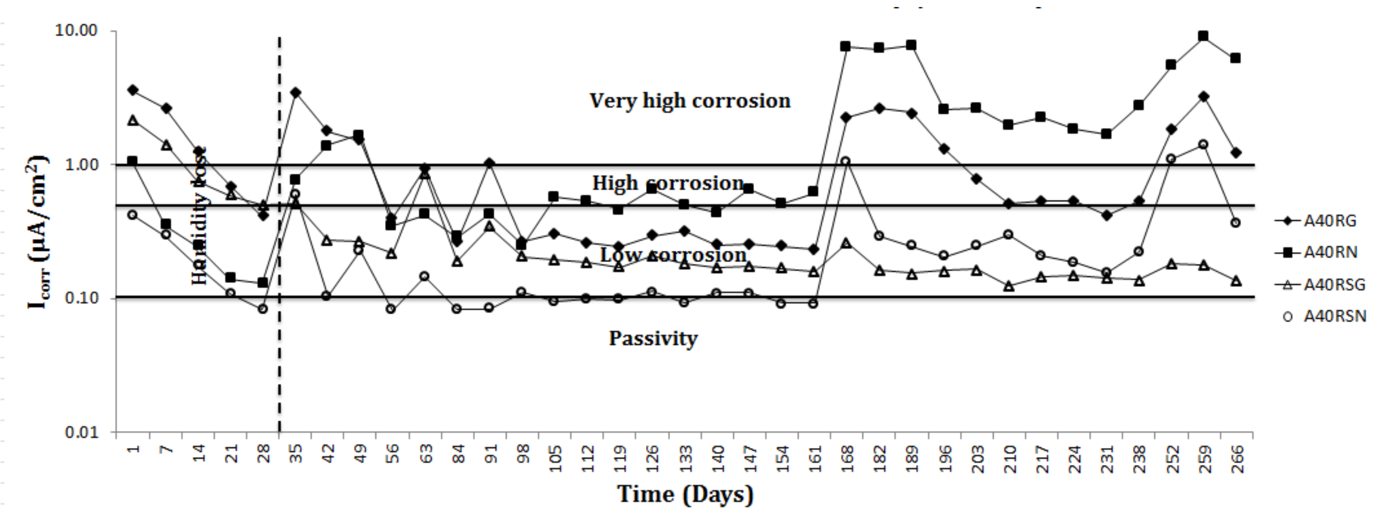

Figure 61. I_{corr} specimens in sand with 0% of NaCl.

In this figure 6 four stages are observed in the 270 days of monitoring, the curing step where four specimens show a reduction in the values of I_{corr} until day 28, related to passivation of steel reinforcement by the protection of concrete in hydration process, then to be placed in the middle of exposure (soil SP) present, the four second activation stage day 35 to day 99, with values ranging I_{corr} in the four levels of corrosion, to enter a stage of stability or protection until the day where 170 is activated again the system in three of the four specimens, only taking a more favourable performance A40RSG specimen, keeping values indicating a moderate corrosion to the last day of exposure, I_{corr} of 0.2 to 0.4 μA/cm^2, this means contact can observe the benefit of using sulphate resistant cement, as in the case of the specimens with 1018, the A40RSN presents I_{corr} values below 0.1 μA/cm^2, until day 170, in the same period the specimen A40RN has high corrosion to take the last 100 days of exposure corrosion kinetics values indicating a high current density above 1 μA/cm^2, this benefit of using cement Sulphate best features with galvanized steel specimens having the values of I_{corr} A40RSG from day 100 to day 270, below 1 μA/cm^2, indicating moderate levels of corrosion, unlike A40RG specimen after 170 days of system activation is presented showing values above 0.5 μA/cm^2 and up to 1 μA/cm^2 indicating extremely high corrosion.

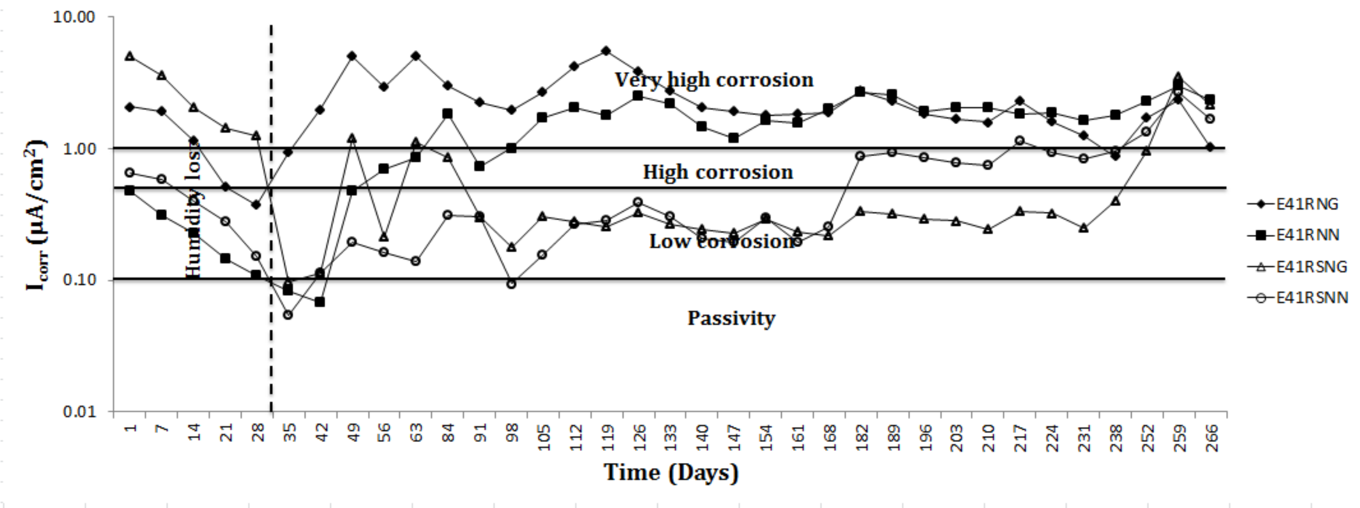

Figure 72. I_{corr} specimens in sand with 1% of NaCl.

Figure 7 presents the results of the corrosion kinetics of specimens with w/c = 0.45 ratio, made with two types of cement, Ordinary (CPC 30R) and sulphate resistant (CPC 30R RS), with steel reinforcement 1018 and galvanized steel, must be those of 1018 are E41RNN and E41RSNN (Ordinary and cement Sulphate best features respectively) and galvanized steel are the E41RNG and E41RSNG.

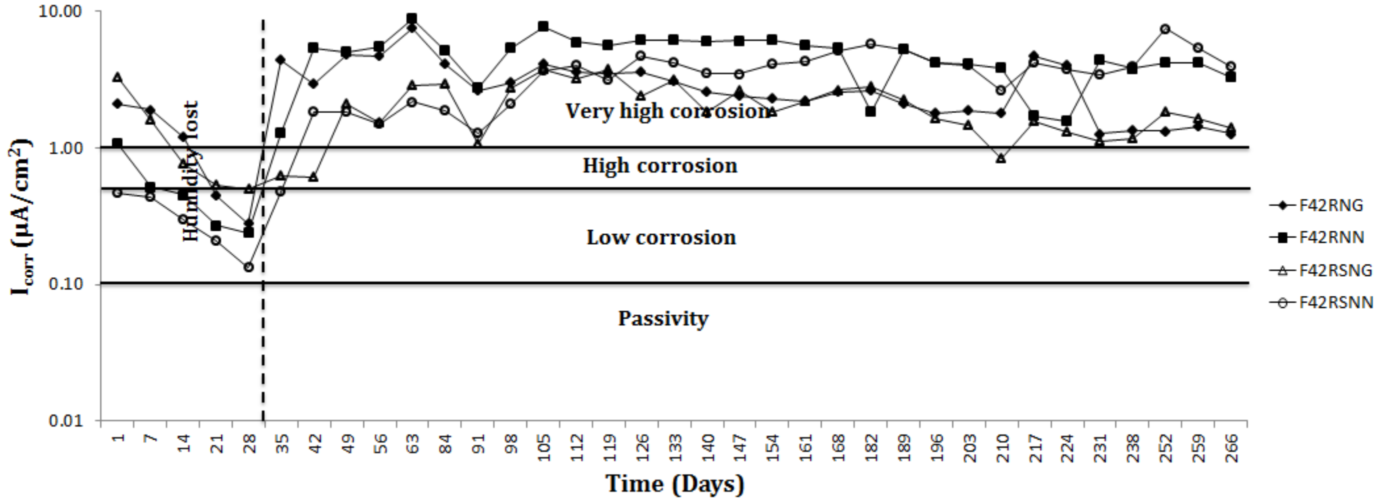

Figure 83. I_{corr} specimens in sand with 2% of NaCl.

In carrying out the analysis of I_{corr} reported for the specimens shown unlike exposed to sand with 1% NaCl, is present from the first week of contact (day 40), an increase in the corrosion rate for all specimens, they indicated that the day 70, for E41RNG and E41RNN specimens prepared with ordinary cement but with galvanized steel and 1018 respectively, have values of I_{corr} above 1 µA/cm^2, indicating a very high corrosion up the end of the exposure period, not presenting a benefit for the use of galvanized, and is seen as worked specimens with sulphate resistant cement (CPC 30R RS), specimens E41RSNN and E41RSNG, presented to the 170 day exposure behaviour better with I_{corr} to date 0.3 to 0.4 µA/cm^2, indicating a moderate level of corrosion and evidenced the positive effect of using this type of cement in soil type SP contaminated with 1% NaCl. As mentioned at the beginning of this paragraph the medium with chloride accelerates corrosion due to their aggressiveness and studied by many researchers, we need to just 1% NaCl in soil after 240 days and the placing concrete with w/c ratio low (0.45), with galvanized steel and sulfate resistant cement is sufficient, given the results obtained with our arrangement, a ground near the sea is very aggressive.

Figure 8 presents the results of corrosion rate of specimens exposed to a ground type SP according to SUCS, but with 2% NaCl, being a very corrosive environment, presenting all specimens with all its variables cement, steel and w/c ratio low, values of I_{corr} or corrosion kinetics, above 1 µA/cm^2 after 50 days, a behavior that is maintained throughout the monitoring period (270 days), with a very high level of corrosion according to the literature. Shown in this arrangement 2% NaCl in soil exposure benefit of using galvanized steel, presenting specimens with this reinforcement (F42RNG and F42RSNG) I_{corr} values, although at very high corrosion but lower those who presented with 1018 steel specimens (F42RNN and F42RSNN), these values are similar to those reported by Maslehuddin [30] when evaluated concrete exposed to soil with NaCl in deterrents concentration. It is important that observed in this research there are the problems generated when the contact medium is dark and very aggressive, that even a good concrete with galvanized steel will achieve a necessary life to consider structures made with these parameters structures with durability criteria, so it is up to the scientific community expert try to find out more about this current problem, not yet visible but which is latent in every structure built in our state near sea and obviously without being designed to last in a marine environment their useful life, whit this results found that the use of sodium nitrite (SN) and diethanolamine (DEA) as inhibitor in galvanized coatings, the system acts helping to delay the corrosion process, Fayala [31]. This protection method protects the steel reinforcement, because the inhibitor reacts with mortar in presence of chloride environment. The values of polarization resistance of reinforcements after 3, 6 and 12 wet - dry cycles, in 3% NaCl solution, indicate that the corrosion rate is low in presence of DEA, and instead the use of SN causes high corrosion rates.

Figure 9 allows us to affirm the provisions of the discussions of Figures 7 and 8 specimens of concrete with w/c=0.45 (f´c=350 kg/cm^2), cement type CPC 30R and CPC 30R RS, 1018 and galvanized steels exposed to soil obtained the Port of Veracruz of 20 m from the sea, contaminated with 1 and 2% NaCl to a lifeline in these conditions, in the presence of chlorides, with only 1% NaCl, performs poorly galvanized steel even with sulphate resistant cement, is seen in this figure as well as in all the other specimens from day 45 present a very high level of corrosion, the values of I_{corr} between 10 to 11 µA/cm^2 for the specimen G43RNN is according with reported by Vedalakshmi[32], who evaluated the corrosion in specimens of mortar ratio w/c = 0.5 exposed to cycles immersion in solution of NaCl at 3%, presenting after 15 cycles of exposure, assessing the realize with three electrochemical techniques obtaining the following values of I_{corr}, 9.92 µA/cm^2 with Harmonic Analysis, 11.47 µA/cm^2 with Electrochemical Impedance Spectroscopy (EIS) and 9.94 µA/cm^2 with Tafel Extrapolation, showing how this research the critical concentration of 3% NaCl present in the middle of exposure of concrete structures, to have high corrosion rates.

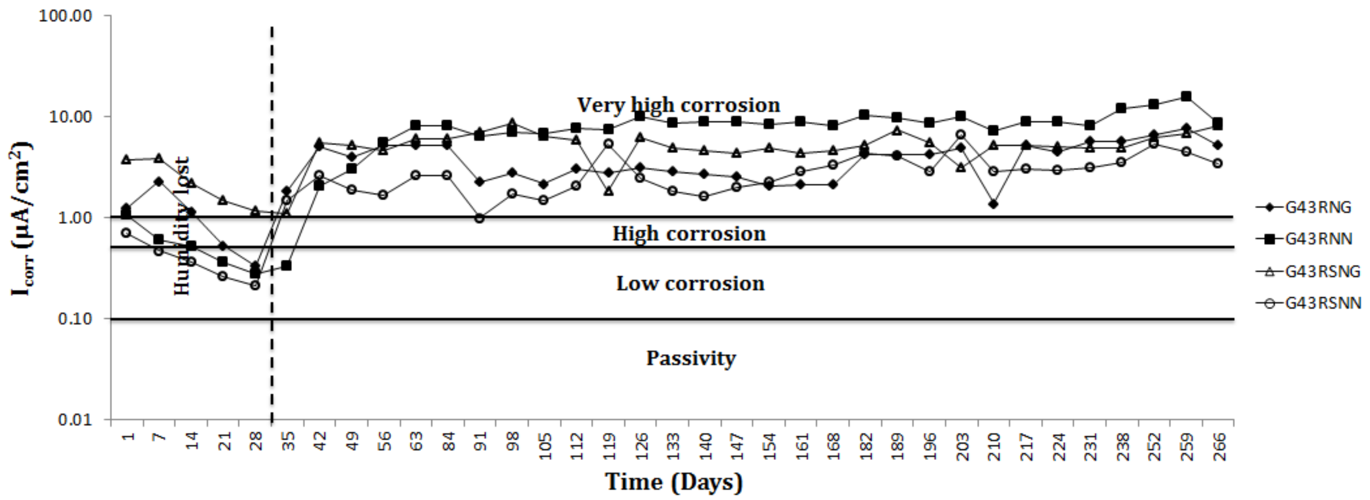

Figure 94. I_{corr} specimens in sand with 3% of NaCl.

Saraswathy[33] evaluated various types of galvanized and stain steels embedded in concrete under macricelle corrosion exposed in 3% NaCl solution, by 10 cycles of exposure, finding that only presented a galvanized steel moderate corrosion resistance, the other three showed a similar behavior to that of common steel with corrosion rates the 0.04 to 0.36 mmpy, reporting also that stainless steel showed the best performance, with a corrosion rate negligible, the above agrees with the results of the present research, with poor efficiency against corrosion of galvanized steel when is embedded in concrete exposed in soil contaminated with 2 and 3% NaCl, as shown in Figures 8 and 9.

Whereby a wall placed at a site structure features and this would be an example the same port of Veracruz, present serious problems by corrosion of reinforcing steel without considering the damage to the concrete matrix by the very presence of other salts such as magnesium sulphate and sodium present in seawater or wastewater, etc . It is confirmed as this site is for the case of buried structures, foundations, very aggressive to its structural integrity that deserves urgent attention of the agencies involved in this type of infrastructure.

5. CONCLUSIONS

From the results obtained in this study it can be concluded that the use of a special sulphate resistant cement (CPC 30R RS), for the manufacture of reinforced concrete when in a contaminated with chlorides environment favours some protection to steel reinforcement by what to considerer more studies on the attack of marine corrosive soils in the foundation of concrete structures and seek a sustainable concrete that can withstand ambient soil coast of Veracruz. Also you can see that the higher is the percentage of chlorides present in the medium increased exposure is the deterioration of reinforcing steel, this deterioration is enhanced or decreased according to the type of cement used as reinforcing steel used, as was observer on the results of this studio, galvanized steel provides moderate protection to the study conditions.

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