Electrochemical Corrosion Resistance Evaluation of Reinforced Concrete Steel Bars Used in Construction in Senegal

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Abstract: This work investigates, , the corrosion resistance of four types of carbon steel (three local steel bars called E1, E2, E3 and an imported steel bar E4 which serves as a reference), used in reinforced concrete constructions in Senegal by electrochemical means. The corrosion tests were carried out by immersing these different steels in an electrolytic solution of hydrochloric acid with a concentration of 0.1M. During their immersion in the HCl solution, the corrosion potential of the different steels is monitored in an open circuit for 1 hour. It will be completed after 1 hour by potentiodynamic polarization which makes it possible to monitor the kinetics of corrosion on the different steels. The results showed that local steels of type E1 and E3 are less resistant to corrosion than imported E4 steel. While local E2 steel has better corrosion resistance compared to imported E4 steel.

Key words: Reinforcement · Local manufacturing · Corrosion kinetics · Performance

INTRODUCTION

Corrosion of concrete reinforcement bars is one of the main phenomena that reduce the service life of reinforced concrete structures and increase the cost of maintaining the damaged structure [1,2]. To improve the tensile, bending, and compressive strength of ordinary concrete structures, concrete is combined with steel bars [3]. The resulting material is called reinforced concrete, Indeed, the premature failure of reinforced concrete structures induced by steel corrosion has attracted a great deal of attention worldwide in recent decades. In 1975, the results of the U.S. National Bureau of Standards field survey showed that the costs of corrosion of steel in concrete accounted for about 40% of the total corrosion loss associated with infrastructure in the United States [4].

A recent study conducted in Switzerland confirmed that the costs of corrosion of road infrastructure pointed out that the US study more than 20 years ago were still valid and also applied to Europe [5]. To reduce this damage and increase the durability of these structures, much in-depth research [6,7] has focused mainly on improving the anti-corrosion properties of newly developed (i.e., new composition or surface-treated) main bars, as well as improving the corrosion resistance of steel [6]. Stainless steels have been developed for this purpose for their high resistance to corrosion [8] relative to their Ni, Cr and Mo contents as corrosion-resistant elements. These steels are classified into three main types: austenitic, ferric and martensitic [9]. Among these stainless steels, corrosion resistances were higher for austenitic Cr-Ni stainless steels and Cr type ferric stainless steels. However, due to the increase in the price

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of Ni due to resource depletion, the use of stainless steels is currently shifting from austenitic steel to Ni-free ferric stainless steel [10].

Studies by El-Basiouny *et al*. [11] and Asami *et al*. [12] have also shown that the corrosion resistance of a steel is fundamentally dependent on the chromium content. According to the work of Shironita et al [13], the addition of chromium (more than 10%) transforms a steel into stainless steel through the formation of an adherent and invisible chromium-rich oxide layer. This oxide layer is formed by the reaction between the chromium in the alloy and the oxygen in the ambient air. This layer gives the steel its stainless character [14]. Their results showed that the corrosion resistance of steel with 22% Cr in an acid solution is as high as that of steel containing 10% nickel, 16% chromium and between 2 and 3% molybdenum [13]. The Cr content significantly affects corrosion resistance. These results clearly show that the corrosion resistance of the steel bar in concrete is a critical factor that must be carefully considered during the design phase of structures. However, the corrosion behaviour of steel bars used in constructions in Senegal is not well known to date. Therefore, this work studies the anti-corrosion performance of four types of steel used in constructions in Senegal. Their anti-corrosion behaviors were compared in a hydrochloric acid solution using electrochemical methods such as open circuit potential (OCP) and linear polarization resistance (LPR).

MATERIALS AND METHODS

This work studies the corrosion resistance of three (03) types of locally manufactured steels (E1, E2, E3) and one type (01) of steel imported from France (E4), which serves as a control material (Fig. 1). This name of these steels has been chosen to guarantee their anonymity. This study compares their anti-corrosion performance in a hydrochloric acid medium (HCl 0.1M). The chemical composition of these steel bars, studied in our previous article [15], is given in Table 1.

Fig. 1: Denomination of the steel bars studied.

Preparation of Working Electrodes (Steel Bars): The preparation of steel bars begins with the removal of the oxide layer using a wire brush. The surface of the steels in contact with the HCl electrolyte solution is then isolated from the rest of the bar by an "Epoxy Steel" resin (Fig. 2). The values of the working electrode surfaces in contact with the solution are given in Table 2. Prior to any measurements, the exposed parts of the steel bars (immersed in the HCl solution) were polished with sandpaper with a grain size of 350 μm and 250 μm, respectively) to remove the oxide films and the various deposits that form on the surface of these steels, then rinsed with distilled water and dried in the open air.

Electrochemical Methods: The experimental set-up used to carry out the electrochemical tests comprises a DropSens Ω Metrohm potentiostat/Galvanostat, coupled to an electrolytic cell and controlled by a computer that allows the diagrams to be visualized. The cell, shown in Fig. 3, consists of the working electrode (WE, HA steel bar), a counter electrode (CE, stainless steel rod) and a saturated calomel reference electrode (RE, DHW).

Measurements start by monitoring the open-circuit free corrosion potential (OCP) until a quasi-steady

Table 1: Chemical compositions of samples – Requirements of standard NF EN 10180.

Samples	Chemical elements - Contents (% mass)										
	C	S	P	N	Cu	Mn	V	Cr	Ni	Mo	Ceq
E1	0.15	0.046	0.036	0.0088	0.220	0.544	0.0028	0.109	0.076	0.013	0.29
E2	0.09	0.012	0.014	0.0100	0.260	0.364	0.0012	0.101	0.125	0.017	0.20
E3	0.31	0.041	0.028	0.0089	0.240	0.706	0.0037	0.181	0.094	0.018	0.49
E4	0.22	0.030	0.022	0.0010	0.450	0.626	0.0021	0.121	0.127	0.02	0.39
Requirements of standard NF EN 10180	0.24	0.055	0.055	0.0140	0.85	-	-	-	-	-	0.52
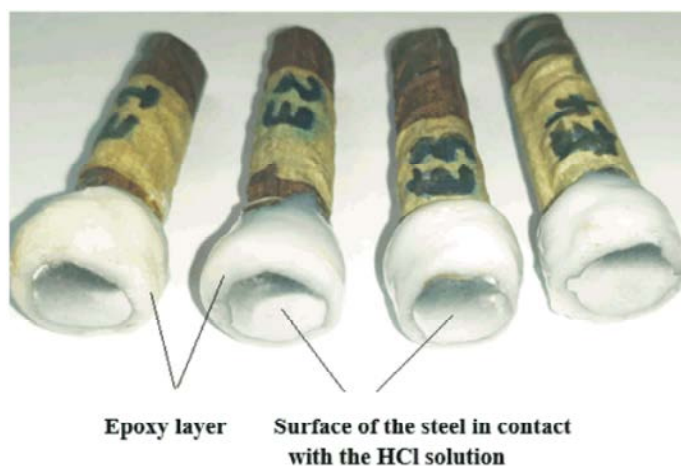
Fig. 2: Preparation of working electrodes.

Table 2: Surface of Steels.

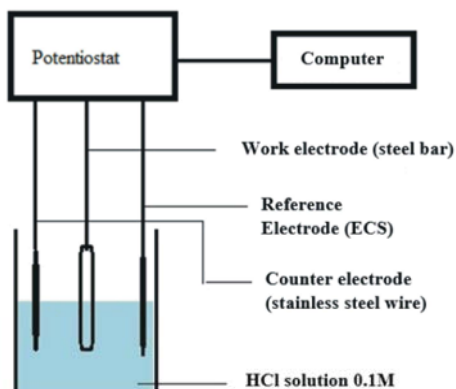| Steel	E1	E2	E3	E4
Surface (mm^2)	71.465	73.594	70.837	77.288

Fig. 3: Experimental device used for electrochemical measurements.

state is established after 1 hour. The potentiodynamic polarization measurements are then started by performing a potential sweep around this OCP value. Scanning is performed in a potential range between -0.25 V and +0.25 V/OCP with a speed of 0.1 mV/s. For each type of steel, three OCP and potentiodynamic polarization measurements were performed. The mean value and standard deviations of the three (03) measurements obtained were calculated for the four (04) types of steel (E1, E2, E3 and E4) studied.

RESULTS AND DISCUSSION

The measurement began by monitoring the corrosion potential of open-circuit steels for 1 hour in a

Table 3 : Corrosion potential values measured at an open circuit after 1 hour in the HCl solution (0.5M).

Steel	E1	E2	E3	E4
Ecor (V/ECS)	-0.322±0.039	-0.312±0.027	-0.338±0.061	-0.314±0.034

0.1M HCl solution. It is complemented by the potentiodynamic polarization method.

Corrosion Potential Monitoring: The corrosion potential (ECOR) of the different steels was measured after one hour in the aggressive HCl solution with a concentration of 0.1M and at room temperature. The corrosion potential values determined after 1 hour of immersion in the HCl solution are shown in Table 3. Table 3 shows that the corrosion potential of E3 steel (-0.338 V/ECS) and E1 steel (-0.322 V/ECS) is more negative than that of E4 steel (-0.314 V/ECS). On the other hand, the corrosion potential of E2 steel (-0.312 V/DHW) is less negative than that of E4. This observation suggests that E1 and E3 steels are less resistant to corrosion than E4 steel. Whereas, E2 steel has better corrosion resistance.

Potentiodynamic Polarization: The polarization curves of the different steels are shown in Figure 4. These are obtained after 1 hour of immersion in the hydrochloric acid solution and at room temperature. The electrochemical parameters derived from these curves are summarized in Table 4.

For E1, E2 and E4 steels, the current density of the cathode and anode branches is almost identical. On the other hand, for E3 steel, the current density of the cathode and anode branches shows an increase compared to that of other steels. This shows that E3 steel is more vulnerable to corrosion. The corrosion potentials of E1
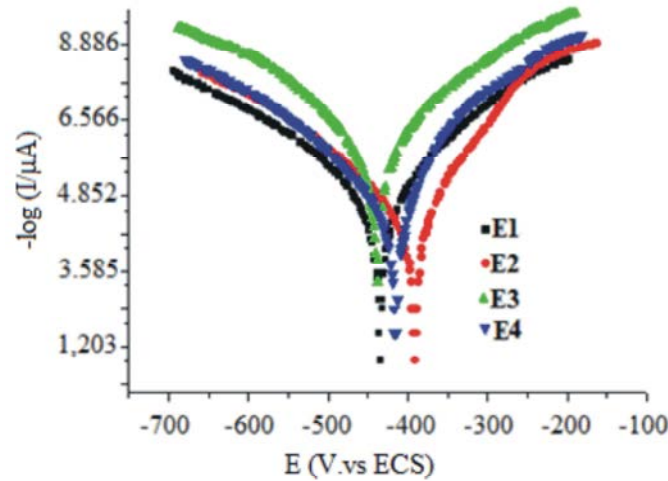
Fig. 4 : Polarization curves of the different steels.

Table 4: Electrochemical parameters from the intensity-potential curves of the different steels in 0.1M HCl medium.

	R_p (kOhm.cm)	E_{cor} (V/ECS)	i_{cor} (µA/cm²)	β_a (V/dec)	β_c (V/dec)	V_{cor} (mm/an)
E1	0.348±0.015	-0.416±0.027	127.656±0.008	0.134±0.022	0.111±0.024	1.486±0.026
E2	0.524±0.021	-0.421±0.023	62.730±0.029	0.123±0.016	0.076±0.028	0.730±0.025
E3	0.254±0.030	-0.425±0.018	222.598±0.033	0.143±0.018	0.127±0.027	2.591±0.016
E4	0.364±0.009	-0.403±0.016	84.245±0.031	0.141±0.020	0.087±0.019	0.981±0.023

and E3 steels are more cathode than that of E4 steel. For E2 steel, there is a shift from E1 and E3 and E4 to the most anodic potentials.

Table 4 shows a higher current density (icor) and corrosion rate (Vcor) of E1 and E3 steels than E4. E2 steel has a lower current density and corrosion rate than E4. The bias resistance (Rp) of E3 steel (0.254 kΩ.cm²) and E1 steel (0.348 kΩ.cm²) is lower than that of E4 steel (0.524 kΩ.cm²). On the other hand, E2 steel has the highest bias resistance (see Table 4). These observations confirm the results of the open-circuit potential monitoring showing that E1 and E3 steels are less resistant to corrosion compared to E4 steel. Whereas, E2 steel has better corrosion resistance.

According to Osozawa and Khorrami [16, 17], the corrosion resistance of steels is related to their Ni, Cr and Mo contents as corrosion-resistant elements. However, according to Table 1 on the chemical composition of steels, the Cr and Mo contents are almost identical to all steels. However, there is a difference in their Ni contents, which provides an explanatory criterion for their difference in corrosion resistance. Thus, Ni contents for E1 and E3 are 0.076% and 0.0094% lower than those of E2 (0.125%) and E4 (0.127%) respectively. This explains their low corrosion resistance compared to E4 and E2 steels. The high carbon content of E4 steel (0.22%) compared to E2 steel could explain the fact that it is less

resistant to corrosion than E2 steel. Table 1 shows a carbon content for E3 steel that exceeds the limit value of 0.24% recommended by the NF EN 10080 standard [18]. This could explain its lower corrosion resistance [19].

CONCLUSION

Through electrochemical methods, the corrosion resistance of four different kinds of carbon steel–three domestic and one imported–used in Senegal reinforced concrete projects could be compared. Open circuit potential (OCP) and potentiodynamic polarization, two electrochemical techniques, were used to test their corrosion resistance in a hydrochloric acid solution.

The findings demonstrated that local E1 and E3 steels are less corrosion-resistant than imported E4 steel. The low Ni concentration of these domestic E1 and E3 steels is the reason for their lower strength when compared to the imported E4 steel. On the other hand, local E2 steel resists corrosion better than imported E4 steel. The carbon content of E4 steel is significantly higher than that of E2 steel, which accounts for its poor strength. E3 steel has the least resistance to corrosion of all the steel varieties, which may be attributed to its high carbon content–which is more than that advised by the French standard NF EN 10080.

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