



Sugarcane Wastes as a Green Additive to Control Corrosion of Steel-Reinforced Concrete Under Different Treatment Conditions

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Abstract

Corrosion rates and resistivity of concrete at different corrosive conditions (exposed to air, partially and totally immersed in water), using various types of steel surface conditions (phosphatized, as-received, and cleaned steels), were evaluated using an electrochemical polarization technique in the presence of different concentrations of sugarcane (bagasse) as a green additive. Electrochemical parameters (corrosion current and resistance) were estimated using a computer program. The addition of bagasse to concrete in dry air conditions increases the half-cell potential to a negative direction, increases the corrosion current, and decreases the resistivity. For concrete samples that partially immersed in water, as bagasse concentrations increase, half-cell potential increases to a positive direction, corrosion current decreases, and electrical resistivity increases, while for totally immersed concrete, the presence of bagasse shifts the potential to a negative direction, corrosion current increases, and resistivity decreases. Phosphatized steel provides better protection than as-received and cleaned steel.

Keywords Steel · Cement · Concrete · Corrosion · Green additive

1 Introduction

Concrete normally affords strengthening steel with a high corrosion resistance. The presence of concrete in the highly alkaline media results in the formation of a strongly adhering film, which passivates and protects the steel from corrosion. Furthermore, the low permeability of concrete can reduce the penetration of corrosive species and also increase the electrical resistivity of concrete, which impedes the electrochemical corrosion currents flow [1]. Due to these inherent protective layers, steel corrosion does not happen in the majority of concrete structures. However, steel corrosion

can occur if the concrete is not of suitable quality and the structure was not correctly designed for the service environment, or the environment was not as expected or changes during the concrete service life [2]. The corrosion of steel in concrete has received significant attention in recent years because of the high cost of concrete repairs and occurrence in certain types of structures. Steel reinforcement corrosion was first detected in chemical manufacturing plants and marine structures [3–5]. The consequent extensive researches on the role of chloride and other corrosive ions have increased our understanding of concrete corrosion [6]. Application of researches will result in fewer occasions of corrosion in new concrete structures and improved methods of repairing and maintenance in existing structures. In addition to data available in the literature, and for these enhancements to happen, the information must be collected from individuals responsible for the construction, design, and maintenance of concrete structures [7]. Several environments can cause severe concrete corrosion problems. Ions of chloride are considered to be the main cause of premature corrosion of reinforcement steel. Corrosion can happen in some circumstances in the absence of chloride ions; however, for example, concrete carbonation results in the reduction of its alkalinity, thereby allowing corrosion of embedded steel [8]. However, corrosion due to carbonation

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is not as common as corrosion prompted by chloride ions. Chloride ions are common in nature, and small amounts are usually accidentally contained in the mix ingredients of concrete. It may also be deliberately added most often as a constituent of accelerating admixtures. Chloride ions also may penetrate into unprotected hardened concrete in structures exposed to marine environments. The corrosion rate of steel embedded in concrete is also strongly affected by environmental factors. Both moisture and oxygen must be present if electrochemical corrosion is to happen [9]. Other factors that affect the rate and level of corrosion are heterogeneities in the concrete and the steel, pH of the concrete pore water, carbonation of the Portland cement paste, cracks in the concrete, stray currents, and galvanic effects due to contact between dissimilar metals. Design features also play an important role in the corrosion of embedded steel. Mix proportions, depth of cover over the steel, crack control measures designed specifically for corrosion protection are some of the factors that control the onset and rate of corrosion [10]. Concrete deterioration results in corrosion because the products of corrosion inhabit a greater volume than the steel and exert substantial tensile stresses on the surrounding concrete. The outward manifestations of the rusting include staining, cracking, and spalling of the concrete. Consequently, the steel cross section is reduced. Gradually, and with time, distress of structural may happen either by a bond loss between the steel and concrete due to cracking or as a result of the steel cross-sectional area reduction. Last effect can be of distinct anxiety in structures containing high-strength prestressing steel in which a small amount of metal loss could possibly induce ligament failure [11]. Many corrosion controlling methods have been proposed to slow or delay the process corrosion, such as galvanized steel bars [12], epoxy coatings [13], application of stainless-steel reinforcing bars [14], use of concrete with low permeability [15], systems of cathodic protection [16], use of fiber glass [17], and silica fumes [18]. The aim of all the mentioned techniques is to increase the service life of concrete constructions. Another important and promising technique is the use of corrosion inhibitors. Organic compounds represent the most known inhibitors due to the presence of heteroatoms like nitrogen, oxygen, sulfur, and several bonds that are responsible for the adsorption on the metal surface [19–21]. Asaad et al. [22] prepared an eco-friendly and nontoxic silver nanoparticle (AgNPs)-doped palm oil leaf (*Elaeis guineensis*/EG) extracts (EG/AgNPs) as a corrosion inhibitor. The inhibitor was incorporated in cement composite and examined against steel corrosion in seawater. Corrosion resistance was enhanced by the addition of 5% green EG/AgNPs inhibitor into the steel-reinforced concrete due to the formation of a protective thin barrier over the steel-reinforced surface with the maximum inhibition efficiency of 94.74%.

Recently, the utilization of concrete with natural additives in construction is increasingly implemented by the construction industry [23, 24]. Various forms of concrete with natural additives are available, such as concrete with high-volume fly ash, high-performance concrete, and lightweight concrete [25]. Joshaghani and Moeini [26] studied the effect of sugarcane bagasse ash (SCBA) and nanosilica on the durability and mechanical properties of mortar. Samples were prepared with a 10–30% replacement of cement weight with sugarcane bagasse ash. The addition of SCBA did not have a significant effect on mortar performance according to lower strength and durability at early ages. Cordeiro et al. [27] studied the effect of sugarcane bagasse ash in addition to concrete as a potential pozzolanic material. There was no measurable change in mechanical behavior of high-performance concrete in partial replacement of Portland cements (10, 15, and 20% by mass). However, rheology and resistance to penetration of chloride ions were improved. Cordeiro et al. [28] investigated the binary and ternary blended cement concretes containing ultrafine residual rice husk ash (RHA) and sugarcane bagasse ash (SCBA). Binary mixture contains SCBA or RHA with cement at concentration of 0% and 20% (cement replacement by mass), while ternary mixtures contain cement, RHA, and SCBA (60–20–20%). Ternary mixture offered lower electric charges (test of chloride ion penetration) and an intermediate behavior between the RHA and reference concretes. The change is attributed to the pozzolanic activity of RHA and SCBA, and to the modification in the distribution of pore size in relation to the reference concretes.

For the above reasons, the present research is an attempt in the direction of using a sugarcane (bagasse) as a green environment-friendly additive with dual function effect, green cement filler, and corrosion inhibitor. Furthermore, research program was made with the aim of studying the corrosion process of steel reinforcement in the concrete structure and the ways to control it. The main aim of this study is to investigate the effect of changing the exposure conditions (corrosive mediums) of concrete samples (exposed to air, partially and totally immersed in a corrosive media) and also to study the effect of changing the surface conditions of steel surface (phosphatized, as-received, and cleaned steels). A comparison was made with concrete without any additives and concrete.

2 Experimental Work

2.1 Materials

The corrosion of different surface-treated reinforced steel in concrete containing concentrations of sugarcane (i.e., waste from sugar industry called locally as bagasse) as a corrosion

inhibitor and pozzolanic cement has been tested and investigated by electrochemical measurement technique. Environmental conditions tested were dry air, partially immersed and totally immersed conditions. The electrode potentials are expressed relative to saturated calomel electrode (SCE). An iterative computer program was used to find the corrosion rate and the concrete resistance. Mild steel reinforcement bars were used as a working electrode (specimens test). The chemical analysis (wt%) of the steel bars was C; 0.1, Si; 1.5, Mn; 0.83, Cr; 0.06, Ni; 0.1, Al; 0.01, Cu; 0.34, Fe is the balance. The specimens were 10 cm length and 1.2 cm in diameter, and a small hole was drilled at a distance 1 cm from the top of each bar, which was 0.4 cm in diameter. In this study, three types of reinforcing steel bars were used according to their surface conditions; the first one is phosphatized steel by applying a chemical coating on its surface by using 5% diluted phosphoric acid. The second one is as-received steel, which was taken directly from its source with keeping it as it was because there was a layer of rust (ferric oxide) on its surface covering it due to its contact with air. The third one is cleaned steel surface by pickling in 30% diluted hydrochloric acid. Saturated calomel electrode (SCE) was used as a reference electrode to record the change in electrode potentials. Stainless-steel container was used as an auxiliary electrode (counter electrode), which contained the corrosive solution. Sulfate-resisting Portland cement was used in these experiments, and the chemical analysis (wt%) of this type of cement is CaO; 63.51, SiO₂; 19.99, SO₃; 1.95; MgO 3.61; R₂O₃; 9.55, L.O.I; 1.29. The sulfate-resisting Portland cement was mixed with sand, gravel, and water in the following proportion 1: 1.5: 3: 0.5 to produce concrete. Stabilized power supply (6236B triple-output power supply, Hewlett-Packard, USA) was used as a power source. Resistance box (type DR41 ABCD): 100 to 0.1 μΩ was used to change the resistance, and digital voltmeter and ammeter were used to record the voltage and current, respectively.

2.2 Preparation, Casting, and Curing of the Specimen Test

After producing the three types of reinforcing steel bars, phosphatized, as-received and cleaned steels, they were cast in a cylindrical shape of 5 cm diameter and 10 cm length, and in the center of each cylinder, a reinforcing steel bar was placed, and only 8 cm of the steel bars was in contact with concrete. The exposed part of the steel bars was coating with paint except a small hole was drilled for the electrical connection. After casting, the samples were kept in the mold for 24 h, and then, they were removed from molds and were kept in tap water for 28 days for curing. Then, the concrete samples were exposed to three conditions: some samples were exposed to air, other samples were kept partially immersed in water, and the rest were kept totally

immersed in water. The water used in these experiments was taken from the Third River pumping station in the South of Nasiriyah (Dhi Qar Governorate, Iraq). All preparations to the experiments and test conditions were carried out at room temperature (approximately 25 °C). The chemical analysis (ppm) and specification of the water are: pH 8.25, nitrate 4.2, CO₃ 26.4, bicarbonate 237, sulfate 2100, chloride 2068, potassium 8.2, sodium 1392, magnesium 382, calcium 312. In this experiment, concrete samples were cast using different concentrations of bagasse (0, 8, 11, 14, and 17%) by weight of cement. The chemical analysis (wt%) of sugarcane (bagasse) was SiO₂ 43.7, Fe₂O₃ 2.65, Al₂O₃ 6.14, FeO 0.95, CaO 9.82, MgO 4.9, SO₃ 3.9, N₂O 4.45, K₂O 9.5, Cl 1.45, P₂O₅ 1.82, and the balance is other impurities. The sugarcane (bagasse) contains high concentrations of SiO₂ and Al₂O₃, which reduce the heat of hydration that resulting from the cement–water reaction. Additionally, this material is considered as a filler material, which increases concrete durability and reduces its permeability and prevents the corroding ions from reaching to the steel.

2.3 Electrochemical Setup and Measurements

The electrochemical potential of the sample was measured relative to a saturated calomel electrode (SCE). The testing instrument used for corrosion potential measurements consists of a saturated calomel electrode, a digital voltmeter, and connection wires. The sample is connected to the positive terminal of the ammeter, while the reference electrode bridged by a Luggin–Haber probe was connected to voltmeter. The testing method is accomplished by placing the Luggin–Haber capillary at a distance of 1 mm from the concrete surface. The voltmeter is turned on D.C., and then, corrosion potential can be read directly from the digital voltmeter. Polarization was carried out in a cell and with an electrical circuit designed and is described in Fig. 1a. The polarization measurements were taken in the counter electrode (stainless-steel container), working and the reference electrodes as shown in Fig. 1b. After supplying the test solution to the cell, the corrosion potential was measured every 2 min for the first 10 min and then every 5 min for the remaining 1 h by a digital voltmeter. Then, the power supply was switched on and the resistances were put to a maximum. For the cathodic polarization, the potential was changed by about 30 mV for each step and an ammeter measured the current. After allowing time for equilibrium, the potential was recorded and steady state had been achieved. However, 1 min was noted after each step. After the cathodic polarization is finished, the connection to the power supply was inverted and the polarization began in anodic direction by a change of the potential in the positive direction in 30 mV steps from the potential of about zero current density, and at each step the current was observed when it was stabled

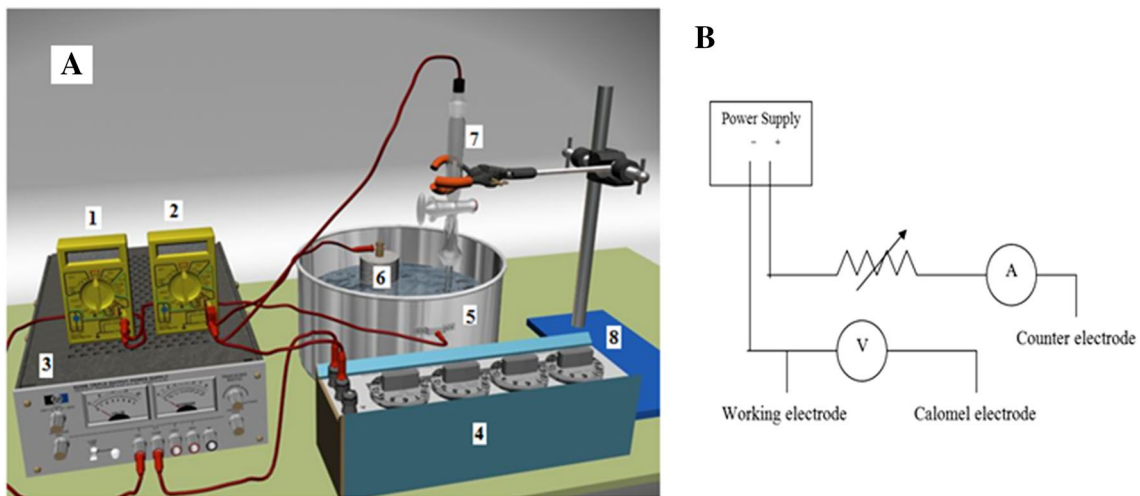


Fig. 1 a Electric circuit for polarization measurements. b Diagram for polarization test connections. 1. Ammeter, 2. voltmeter, 3. power supply, 4. resistors, 5. the counter electrode, 6. working electrode, 7. reference calomel electrode, 8. stand

after about 1 min. The procedure adopted in this work is that the potential was changed manually at a nearly constant rate and the current value was noted when stability was achieved. The time required to reach this stability ranged from a few seconds to 1 min.

3 Results and Discussion

The corrosion of steel embedded in concrete contains different concentrations of sugarcane (bagasse), immersed in corrosive media, and had been investigated by using polarization measurements. The electrode potential was expressed relative to the SCE.

3.1 Corrosion Potential Measurements

The corrosion potential measurements relative to a SCE for phosphatized steel exposed to dry air conditions are shown in Fig. 2, which indicate the potential of steel embedded in concrete was shifted to more active value after subjecting to a corrosive medium. In such cases, the high negative potentials are not indicative of high corrosion activity. This behavior is probably due to the higher moisture content of concrete samples after 28 days of curing in a tap water. Similar behavior was observed for as-received and cleaned steel-reinforced concrete. From the curves, a trend of decreasing, through fluctuating, positive potentials could be observed throughout the experimental period. There is an indication that as the bagasse concentration increases, the corrosion potential increases negatively to an active value. According to American Standard 173/ANSI/ASTM c876-77, which stated that the corrosion

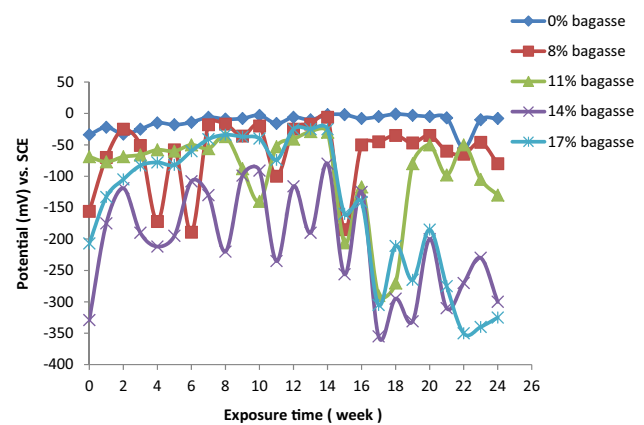


Fig. 2 Corrosion potential/exposure time plot for phosphatized steel exposed to air

potential for steel embedded in concrete for 0% bagasse, although the surface condition of steel is changed, seems to be more positive than -140 mV and that is indication more than 90% corrosion is not occurring. If steel potential (volt, SCE) is more positive than -0.14 V, the probability of corrosion is 90% not occurring. If between -0.14 and -0.290 V, there is an uncertain corrosion activity. If steel potential is more negative than -0.29 V, the probability of corrosion is 90% occurring. The present work results showed that phosphatized steel containing a different concentration of bagasse is still passive, but the passivity is break down for as-received and cleaned steels and 90% of corrosion probability is occurring, and there is an indication that cleaned steel is corroded more than as-received steel. Figure 3 shows the curves of corrosion potential against the exposure time for phosphatized

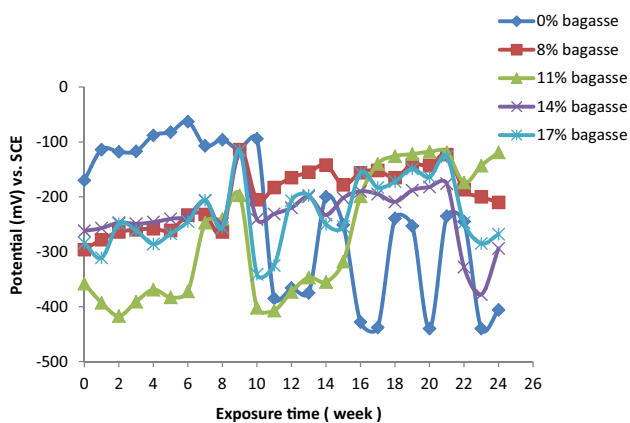


Fig. 3 Corrosion potential/exposure time plot for phosphatized steel partially immersed in water

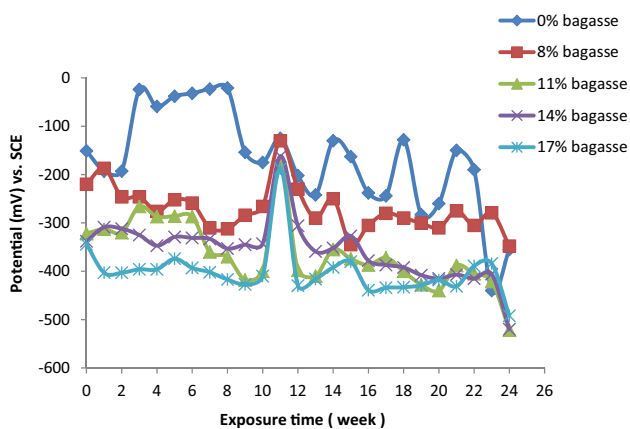


Fig. 4 Corrosion potential/exposure time plot for as-received steel totally immersed in water

steel samples with a different concentration of bagasse in partially immersed in the corrosive media containing aggressive ions. Similar behavior was observed for as-received and cleaned steel-reinforced concrete samples. Again, phosphatized steel is less corroded than as-received and cleaned steels and that corrosion activity is more pronounced on cleaned steel. Figure 4 illustrates the curves of corrosion potential against the exposure time (in weeks) for as-received steel. In this case, the concrete samples containing the embedded steel were totally immersed in the corrosive media. It can be said as bagasse concentration increases the corrosion potential increases to negative values of an active potential. The presence of bagasse may make concrete more porous. Porosity increases the diffusion rate of water and corrosive species through the concrete and makes the concrete more susceptible to corrosion. Or the presence of bagasse in concrete may retain water and electrolyte that lead to higher probability for corrosion.

3.2 Polarization Measurements

Concrete is a fundamental part of the whole corrosion process, and it plays an important role in corrosion reactions. Therefore, it is important to consider the potential difference across the electrolyte (concrete) which is often referred to as the ohmic or IR drop and may be large if either the current or the resistance of the electrolyte is large. A mathematical model as derived was used to determine numerically the unknowns, i_{corr} and $R_c A$ by deriving linear equations and solving them by the method of averages; the full derivation was mentioned in the work of Khadom [29]. The obtained Eqs. 1–3 are solved using a computer program. The program was written in a BASIC language, and a minimum of three data points was required. To complete the values of the unknowns, 15 data points were used in the program spaced equally at 10 mV starting from $\Delta E = 50$ mV from E_{corr}

$$i_c = \frac{b_c i_{corr} \exp\left(\frac{2.303 \Delta E}{b_c}\right)}{b_c + 2.303 i_{corr} R_c A \exp\left(\frac{2.303 \Delta E}{b_c}\right)} \tag{1}$$

$$i_c = \gamma i_{corr} \exp\left(\frac{2.303 \Delta E}{b_c}\right) \tag{2}$$

where γ is IR drop correction factor:

$$\gamma = \frac{1}{1 + \left(\frac{2.303 R_c A}{b_c}\right) i_c \exp\left(\frac{2.303 \Delta E}{b_c}\right)} \tag{3}$$

where i_{corr} is the corrosion current, and b_c represents the cathodic Tafel slope. Results obtained using the above equations and procedures are presented in Tables 1, 2 and 3. Polarization curves for as-received steel embedded in concrete are presented in Figs. 5, 6 and 7 after 24 weeks of exposure dry air, partially immersed, and totally immersed corrosive media for different concentration of bagasse, respectively. Similar figures were obtained at other conditions. Polarization figures present the anodic and cathodic curves for resisting Portland cement containing different concentrations of bagasse by weight (i.e., the samples were in a laboratory dry conditions for 24 weeks after removal from curing water) and for phosphatized, as-received and cleaned embedded steels in concrete, respectively. The results indicate that the anodic and cathodic current density requirements for samples with no bagasse are much lower than for samples containing up to 17% bagasse, but this situation is less pronounced in as-received embedded steel. The cathodic parts of these polarization curves indicate that at -400 mV (SCE), the current requirements for the samples are not the same. In case of resisting, Portland cement concrete contains embedded steel samples with

Table 1 Corrosion current density and concrete resistance of embedded steel in dry air conditions for Portland cement in corrosive media

Time (week)	Bagasse concentration	Cleaned steel		As-received steel		Phosphatized steel	
		i_{corr} ($\mu\text{A}/\text{cm}^2$)	R_c (Ω)	i_{corr} ($\mu\text{A}/\text{cm}^2$)	R_c (Ω)	i_{corr} ($\mu\text{A}/\text{cm}^2$)	R_c (Ω)
4	0	0.08	2054.49	0.04	1269.232	0.03	2631.186
	8	0.16	6111.797	0.05	4271.577	0.03	1242.406
	11	0.22	1525.883	0.07	1421.086	0.05	37.302
	14	0.25	476.959	0.07	2376.101	0.05	5055.27
	17	0.27	2855.034	0.15	983.934	0.06	746.046
8	0	0.04	1498.69	0.07	1531.360	0.04	2268.756
	8	0.04	5009.556	0.1	1940.087	0.06	4.145
	11	0.24	2026.101	0.22	1294.811	0.06	1.243
	14	0.05	24.868	0.08	1347.824	0.03	658.696
	17	0.18	2180.562	0.33	50.123	0.05	99.473
12	0	0.04	1333.69	0.05	2589.078	0.03	33.158
	8	0.08	4329.792	0.17	2640.304	0.05	99.473
	11	0.14	1876.319	0.25	1170.743	0.05	5.135
	14	0.05	26.099	0.05	3202.482	0.14	426.369
	17	0.22	1498.449	0.24	1235.156	0.06	4.145
16	0	0.06	2218.3	0.1	1246.759	0.05	3161.928
	8	0.09	290.103	0.12	2440.955	0.06	1181.408
	11	0.12	3087.746	0.25	804.772	0.06	51.257
	14	0.07	16.579	0.07	2420.574	0.15	174.906
	17	0.24	211.909	0.07	2032.403	0.19	122.927
20	0	0.06	1057.129	0.13	1455.718	0.07	8.289
	8	0.07	41.447	0.1	3610.995	0.12	1977.386
	11	0.21	1904.148	0.23	1752.044	0.07	8.289
	14	0.04	3262.511	0.07	3144.784	0.13	895.540
	17	0.16	485.043	0.24	677.477	0.09	211.676
24	0	0.06	82.894	0.16	1479.781	0.06	49.736
	8	0.03	3602.354	0.07	2901.244	0.05	248.682
	11	0.01	1511.779	0.13	3044.627	0.04	49.736
	14	0.03	20.723	0.04	4583.362	0.09	1138.824
	17	0.14	1733.806	0.11	544.305	0.06	503.724

various bagasse contents in partially immersed conditions for 24 weeks (after removal from curing water). The data indicate that the anodic and cathodic current density requirements for concrete samples with no bagasse are higher than samples containing bagasse for phosphatized, as-received and cleaned embedded steels. In the same time, it is clear that the potential shifts to a more positive direction as bagasse concentration increases in samples containing phosphatized steel, while this behavior is not the same for as-received and cleaned steel samples, but is little mixed to some extent. A comparison among polarization figures indicates that the anodic and cathodic polarization curves of same treated steel, under different exposure conditions in concrete, are not alike (i.e., the shape and position of anodic and cathodic curves are different for these two types of exposed conditions) for phosphatized steel, while for as-received and cleaned steels, the current density requirements are little mixed. In case of totally immersed conditions, the

results show that the cathodic current requirements for all different surface-treated steel decrease as bagasse concentrations increase, while the situation is exactly the opposite for anodic density requirements. These figures also show that current density requirements for zero and 8% bagasse concerning as-received steel are the same; the situation is alike with 11, 14, and 17% bagasse. Also for cleaned steel under totally immersed conditions, the current density requirements for 8, 14, and 17% bagasse are approximately the same and generally less than 0% bagasse samples. Accordingly, the different embedded steels in concrete exposed to air with higher bagasse contents require higher current density compared to samples with lower bagasse contents. This may be due to the fact that concrete samples with lower bagasse contents retain more water than samples with higher bagasse contents. This may be due to the deliquescent property of bagasse, which absorbs moisture. Therefore, the moisture may be more uniformly distributed along the steel rod in the

Table 2 Corrosion current density and concrete resistance of embedded steel in partially immersed conditions for Portland cement in corrosive media

Time (week)	Bagasse concentration	Cleaned steel		As-received steel		Phosphatized steel	
		i_{corr} ($\mu\text{A}/\text{cm}^2$)	R_c (Ω)	i_{corr} ($\mu\text{A}/\text{cm}^2$)	R_c (Ω)	i_{corr} ($\mu\text{A}/\text{cm}^2$)	R_c (Ω)
4	0	0.1	913.238	0.04	2216.076	0.03	1451.835
	8	0.34	448.142	0.15	1192.591	0.19	968.723
	11	0.39	309.956	0.3	1137.503	0.11	1093.189
	14	0.31	795.437	0.15	1458.587	0.12	962.858
	17	0.28	656.701	0.28	526.758	0.26	592.627
8	0	0.13	1167.569	0.05	1560.845	0.04	461.912
	8	0.46	322.802	0.28	511.767	0.23	933.828
	11	0.53	289.673	0.38	600.321	0.28	297.149
	14	0.37	689.979	0.3	482.429	0.14	519.395
	17	0.33	437.537	0.38	298.299	0.29	397.779
12	0	0.21	1172.215	0.1	903.458	0.24	571.352
	8	0.36	548.824	0.21	683.253	0.15	1171.043
	11	0.89	236.674	0.35	623.569	0.3	331.724
	14	0.36	609.180	0.2	908.433	0.11	977.658
	17	0.35	489.720	0.37	409.962	0.19	472.959
16	0	0.16	736.991	0.33	171.630	0.47	305.030
	8	0.25	732.929	0.24	1217.952	0.16	1470.747
	11	0.43	391.074	0.34	6868.786	0.25	406.952
	14	0.3	812.156	0.27	1555.756	0.1	1011.535
	17	0.27	791.919	0.35	621.213	0.24	512.990
20	0	0.61	324.342	0.45	255.138	0.62	264.712
	8	0.36	964.570	0.22	536.443	0.13	2250.188
	11	0.35	470.307	0.31	566.162	0.28	394.256
	14	0.32	1218.454	0.24	564.252	0.07	1553.131
	17	0.27	839.721	0.33	476.043	0.38	339.706
24	0	1.05	222.509	0.73	199.049	0.77	235.072
	8	0.11	1686.907	0.13	1671.112	0.05	4385.513
	11	0.23	1086.156	0.27	830.261	0.12	1067.741
	14	0.15	1866.666	0.13	1162.550	0.04	2737.293
	17	0.15	1423.308	0.24	617.387	0.12	1293.288

sample with lower, and the possibility of a corrosion cell due to moisture difference is lowered. However, in the sample with higher bagasse contents, an electrochemical cell may be set up along the steel rod, because of a moisture gradient along the steel rod. As a result, a local action current will flow between anodic and cathodic regions. The same behavior can be seen in the partially and totally immersed embedded steel samples in concrete. The Cl^- and O_2 ions in the corrosive media play a very important role in the current requirement and its relation with a breakdown in the passive film. Five theories were described by Foley [30] to explain chloride attack:

1. Penetration of chloride into the oxide film which is otherwise protective.
2. Formation of a complex between chloride ions and some form of an ion.
3. The effect of field of absorbed chloride ions that pulling Fe^{++} ions out of the metal.
4. Privileged adsorption of chloride ions rather than a passivating species.
5. Catalysis of the corrosion reaction by the bridging structure.

The chloride attack by any of the above means causes an increase in current density. The fact that oxygen is necessary for the corrosion mechanism in concrete seems obvious from the type of failure always reported. The steel corrodes, producing a corrosion product of greater volume than the steel consumed in the reaction. This corrosion product literally has no place to go so that it produces large internal pressures in the structure and cracks the concrete. In a rigid mass such as concrete, it is difficult to see how this increase in volume could occur unless atoms migrate in from the outside. This

Table 3 Corrosion current density and concrete resistance of embedded steel in totally immersed conditions for Portland cement in corrosive media

Time (week)	Bagasse concentration	Cleaned steel		As-received steel		Phosphatized steel	
		i_{corr} ($\mu A/cm^2$)	R_c (Ω)	i_{corr} ($\mu A/cm^2$)	R_c (Ω)	i_{corr} ($\mu A/cm^2$)	R_c (Ω)
4	0	0.04	87.855	0.06	24664.47	0.04	592.797
	8	0.28	34.176	0.33	198.945	0.7	476.024
	11	0.5	243.599	0.38	389.810	0.26	437.652
	14	0.7	297.930	0.39	319.385	0.33	329.885
	17	0.64	238.244	0.68	310.290	0.19	513.119
8	0	0.03	4007.129	0.05	62862.19	0.03	2645.211
	8	0.54	212.191	0.38	370.487	0.16	452.137
	11	0.59	232.289	0.81	202.703	0.39	412.230
	14	0.59	227.263	0.4	274.349	0.42	333.615
	17	0.82	170.868	0.62	228.993	0.42	371.381
12	0	0.17	590.842	0.13	22499.98	0.15	791.799
	8	1.54	111.848	0.5	204.640	1.48	175.693
	11	1.14	137.344	1.6	86.618	0.78	226.847
	14	1.28	135.518	0.61	135.007	0.87	202.239
	17	1.65	112.943	1.29	151.445	0.82	227.141
16	0	0.38	399.036	0.24	13668.39	0.05	456.106
	8	1.31	117.232	0.63	250.907	0.56	267.595
	11	1.21	164.253	1.28	178.354	0.71	255.262
	14	0.97	134.799	0.78	174.063	0.81	207.866
	17	0.97	123.218	1.33	168.344	0.96	207.741
20	0	0.17	911.927	0.27	10700.01	0.38	322.131
	8	0.22	113.370	0.42	331.349	0.42	341.227
	11	0.71	294.992	1.01	195.018	0.68	257.052
	14	0.85	216.009	0.63	238.811	0.54	355.386
	17	0.89	181.848	0.99	187.749	0.61	290.838
24	0	0.14	771.970	0.98	5327.53	0.52	250.579
	8	0.9	169.376	0.34	470.693	0.35	435.636
	11	0.61	309.755	0.76	218.753	0.75	267.877
	14	0.79	234.317	0.69	284.779	0.47	365.821
	17	0.93	213.074	0.81	237.186	0.44	377.952

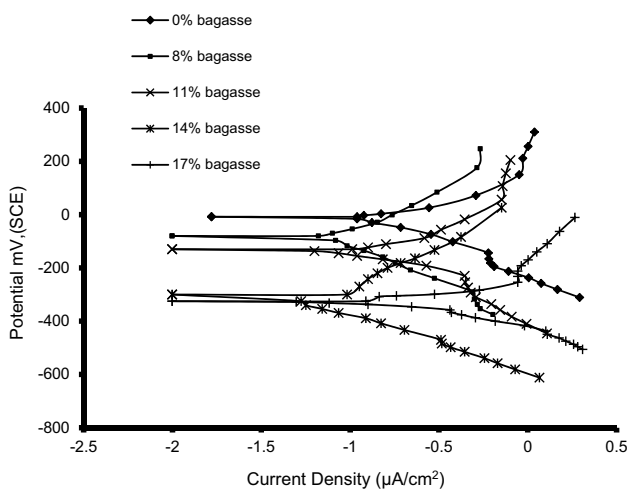


Fig. 5 Polarization curves of as-received steel embedded in concrete containing different concentrations of bagasse, after 24 weeks of exposure to air

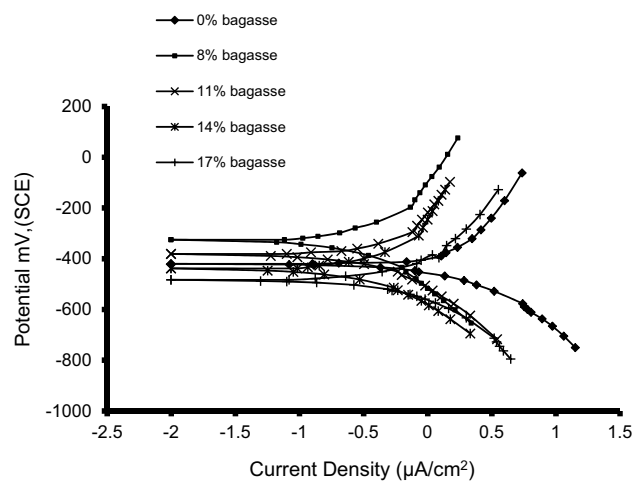


Fig. 6 Polarization curves of as-received steel embedded in concrete containing different concentrations of bagasse, after 24 weeks of partially immersed in water

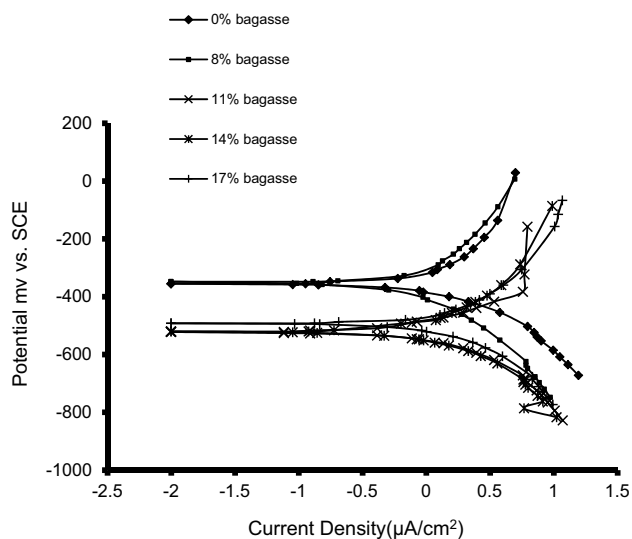


Fig. 7 Polarization curves of as-received steel embedded in concrete containing different concentrations of bagasse, after 24 weeks of totally immersed in water

is most easily explained by the diffusion of oxygen. It is doubtful that there has ever been a case of seriously corroded reinforcing steel in concrete sufficiently impermeable to prohibit access of oxygen to the steel.

3.3 Corrosion Current Measurements

Tables 1, 2, and 3 show the corrosion current results. These results indicate that, generally, corrosion currents show a significant reduction and increase with exposure time. This means that the decrease in corrosion current results the development of passive layer with time, and the increase in corrosion current the breakdown of passive layer and onset of corrosion. Rodriguez et al. [31] reported that corrosion rates less than $0.2 \mu\text{A}/\text{cm}^2$ indicate reinforcement in the passive condition, values up to $0.5 \mu\text{A}/\text{cm}^2$ indicate low-to-moderate rates, values in the range of $0.5 \mu\text{A}/\text{cm}^2$ to $1.0 \mu\text{A}/\text{cm}^2$ indicate moderate-to-high rates, and values greater than these are indicative of high corrosion rates. According to these ranges, the results obtained from computer program can be explained according to the type of and condition of steel in the absence and presence of bagasse.

3.3.1 Dry Air Conditions Steel

The results show that for the three types of steel embedded in concrete containing 0% bagasse and exposed to dry air conditions they were in the passive conditions for all times of exposure. Figure 8a–i shows the relationship between the corrosion rate of phosphatized, as-received and cleaned steels embedded in concrete containing a different concentration of bagasse, and exposure time (in a weeks). For dry

conditions (Fig. 8a–c) that concrete containing 8 and 14% bagasse, the results show that phosphatized steel is in the passive condition for all times of exposure. For concrete containing 11% bagasse, the results indicate that, for the first 6 weeks of exposure time, steel in the passive region, and after that and until 8 weeks of exposure to dry air condition, the result shows low corrosion rate. At the end of exposure time, the data show that steel returns to passive condition. For concrete containing 17% bagasse, the results indicate steel is in passive condition for the first 10 weeks, and after that and until 12 weeks of exposure, the results indicate very low corrosion rates of steel, and then, for 2 weeks later steel returns to passive condition, and after that and until 2 weeks the results indicate low corrosion rate values; at the end of exposure time, steel returns to passive condition. For concrete containing 8 and 14% bagasse, the results indicate that steel is in passive condition for all times of exposure. For concrete containing 11% bagasse, the data show that for the first 8 weeks of exposure to dry air conditions, results indicates low corrosion rate values for steel, and after that and until 10 weeks, the results indicate passive condition for steel, then low corrosion rate values were obtained for steel until 20 weeks, and at the end of exposure the result show that steel returns to passive condition. The relationship is between corrosion rate and exposure time for as-received steel embedded in concrete containing different concentrations of bagasse exposed to dry air conditions. For concrete containing 17% bagasse, the results indicate for the first 4 weeks of exposure steel is in a passive condition, after that and until 12 weeks of exposure the result shows low corrosion rates for steel and then steel returns to passive condition until 16 weeks, after that and until 20 weeks low-to-moderate corrosion rate values are obtained and at the end of exposure time steel returns to a passive region. The results indicate that cleaned steel embedded in concrete containing different concentrations of bagasse is in passive condition for all times of exposure.

3.3.2 Partially Immersed in Water Conditions Steel

For corrosion rates of concrete samples partially immersed in water (Fig. 8d–f) for phosphatized steel (Fig. 8d) at 0% bagasse, the data from these figures show that for the first 10 weeks steel is in passive condition, after that and until 14 weeks of exposure time, the results indicate low corrosion rate values, then steel returns to passive condition at time equal to 16 weeks, after that and until 20 weeks the results indicate moderate-to-high corrosion rate values, and at the end of exposure time steel has high corrosion rate values. For concrete containing 8% bagasse, the results show low-to-moderate corrosion rate values until 22 weeks of exposure, and then, at the end of exposure time steel returns to passive conditions. For concrete containing

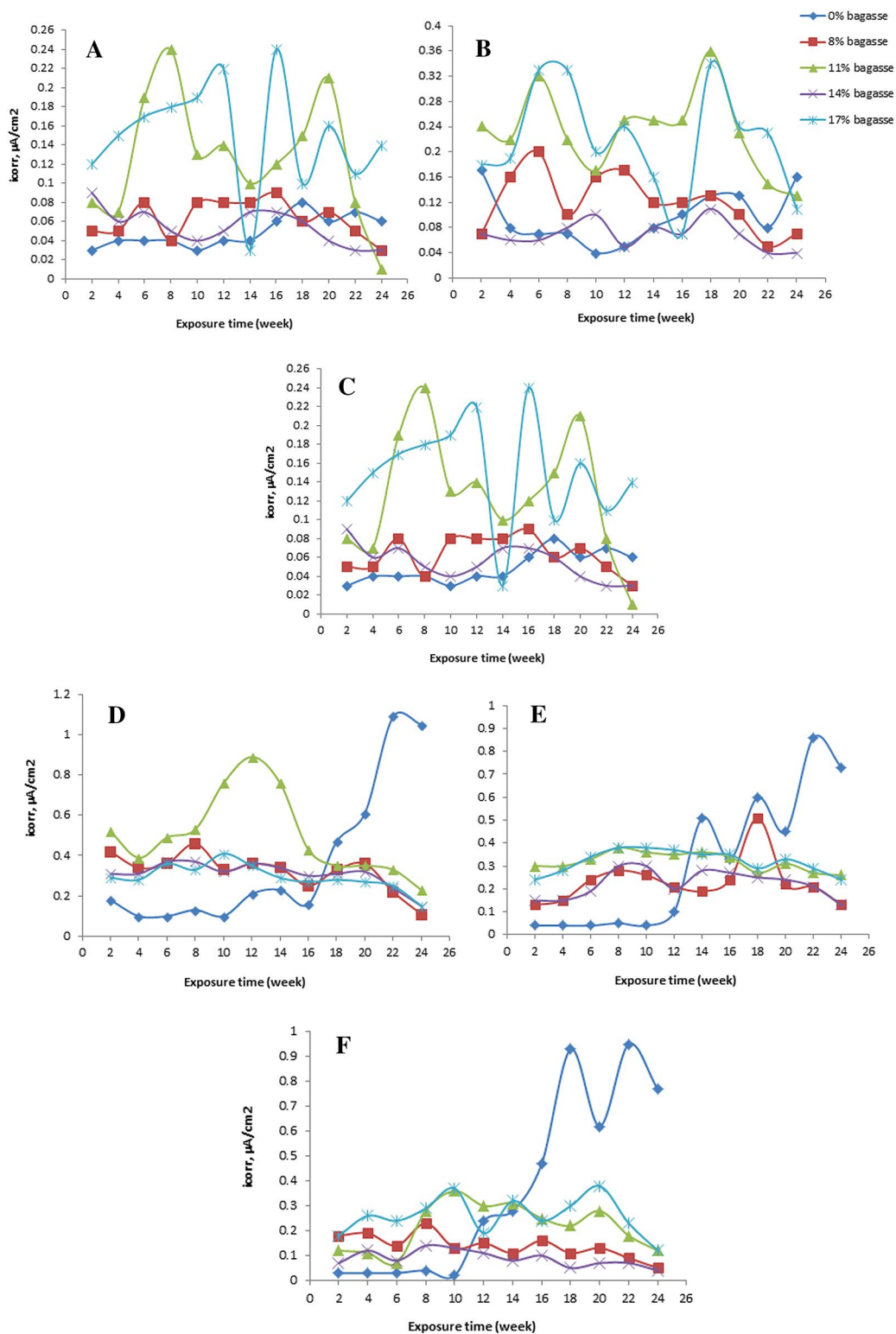


Fig. 8 Relationship between the corrosion rates of steel embedded in concrete containing different concentrations of bagasse. **a** Phosphatized steel at dry air conditions. **b** As-received steel exposed to dry air conditions. **c** Cleaned steel exposed to dry air conditions. **d** Phosphatized steel in partially immersed conditions. **e** As-received

steel in partially immersed conditions. **f** Cleaned steel in partially immersed conditions. **g** Phosphatized steel in totally immersed conditions. **h** As-received steel in totally immersed conditions. **i** Cleaned steel in totally immersed conditions

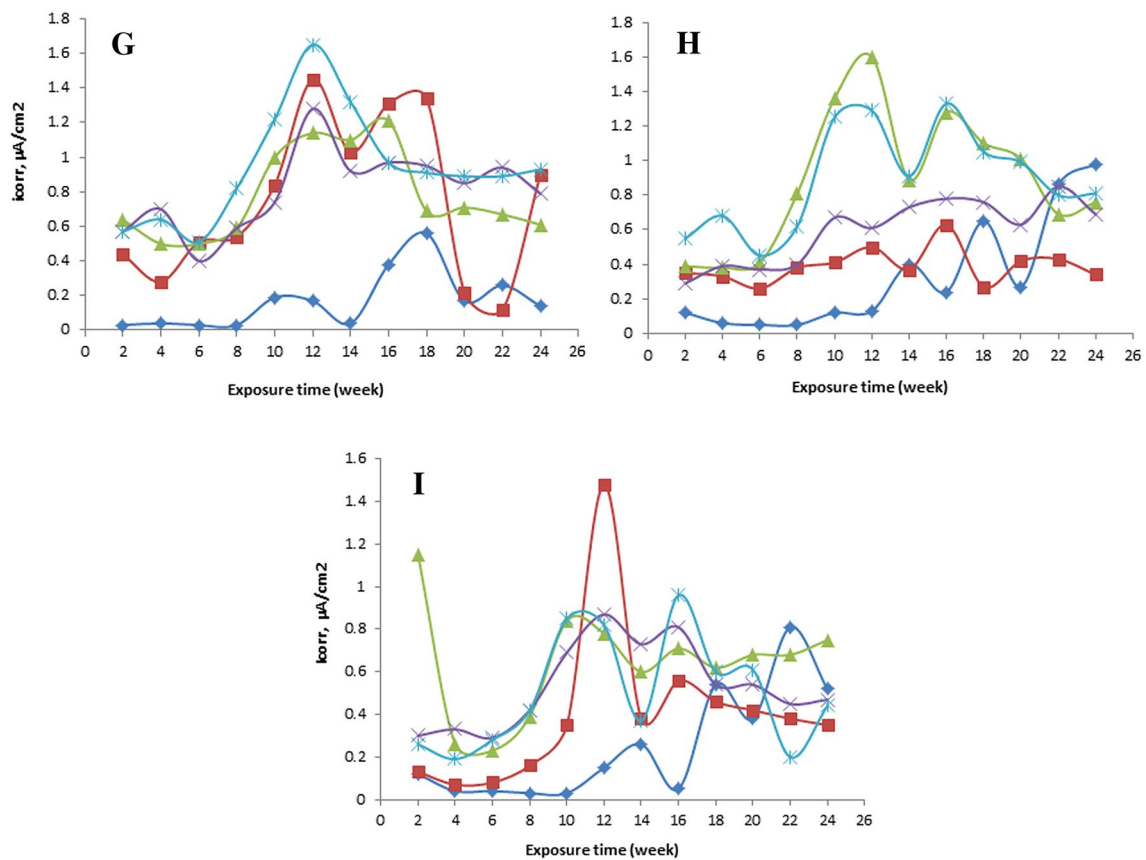


Fig. 8 (continued)

11% bagasse, for the first 8 weeks of exposure, the results indicate low-to-moderate corrosion rate values, after that and until 14 weeks moderate-to-high corrosion rates are observed, and then, at the end of exposure time steel returns to low-to-high-moderate corrosion rate values. For concrete containing 14 and 17% bagasse, the results indicate that low-to-moderate corrosion rate values are maintained on steel until 22 weeks of exposure to corrosive media, and then, at the end of exposure time steel is in passive conditions. For as-received steel (Fig. 8e) embedded in concrete containing different concentrations of bagasse, and exposure time. For concrete containing 0% bagasse, the results indicate that passive condition of steel is maintained on steel until 12 weeks of exposure, after that and until 16 weeks of exposure the data show low-to-moderate corrosion rate values, then moderate-to-high corrosion rate values are found for 2 weeks, the steel returns to low-to-moderate values until 20 weeks, and after that and until the end of exposure time the corrosion rates return to moderate-to-high values. For concrete containing 8% bagasse, the results indicate that for the first 4 weeks of exposure, steel is in a passive condition. After that and until 20 weeks, the result shows low-to-moderate values of corrosion rate. At the end of exposure time, steel

returns to passive condition. For concrete containing 11 and 17% bagasse, the data indicate low corrosion rate values of steel for all times of exposure. For concrete containing 14% bagasse, the results indicate that for the first 6 weeks of exposure, steel is in a passive condition. After that and until 22 weeks of exposure, the results show a low corrosion rate. At the end of exposure time, steel returns to passive condition. For cleaned steel (Fig. 8f) embedded in concrete containing different concentrations of bagasse, and exposure time. For concrete containing 0% bagasse, the results indicate that for the first 10 weeks of exposure, steel is in a passive condition. After that and until 16 weeks of exposure, the results show low-to-moderate corrosion rate values, and then, at the end of exposure time, the results indicate moderate-to-high value of corrosion rate. For concrete containing 8% bagasse, the results indicate that for the first 6 weeks, steel is in a passive condition. After that and until 10 weeks of exposure, the data indicate low corrosion rate values. At the end of exposure time, steel returns to the passive region. For concrete containing 11% bagasse, the results indicate that for the first 6 weeks, steel is in a passive condition. After that and until 20 weeks, the results indicate low-to-moderate corrosion rate values. At the end of exposure time,

steel returns to passive condition. For concrete containing 14% bagasse, the results indicate that steel is in passive condition for all times of exposure. For concrete containing 17% bagasse, the results indicate that for the first 22 weeks of exposure, low-to-moderate corrosion rate for steel is found. At the end of exposure time, steel is in a passive condition.

3.3.3 Totally Immersed in Water Conditions Steel

Figure 8g–i shows the relationship of corrosion rate in totally immersed conditions. For phosphatized steel (Fig. 8g) at 0% bagasse, the data presented in this figure show that for the first 14 weeks of exposure, steel is in a passive condition, and then, low-to-moderate corrosion rate values are obtained for 2 weeks. After that and until 18 weeks, the results indicate moderate-to-high corrosion rate values. At the end of exposure time, steel returns to the passive region. At 8% bagasse, the results indicate for the first 4 weeks, low-to-moderate corrosion rate values are found. After that and until 10 weeks, the results indicate moderate-to-high corrosion rate values. Then, high corrosion rate values are found until 18 weeks of exposure, then until 22 weeks the results indicate that steel is in a passive condition. At the end of exposure time, the data show moderate-to-high corrosion rate values. For concrete containing 11% bagasse, the results show for the first 8 weeks moderate-to-high corrosion rate values for steel. After that and until 16 weeks, the results indicate high corrosion rate values for steel. At the end of exposure time, steel returns to moderate-to-high corrosion rates. For concrete containing 14% bagasse, the results indicate for the first 4 weeks moderate-to-high corrosion rate values for steel. After that and until 6 weeks, the results indicate low-to-moderate corrosion rate values for steel. Then until 10 weeks of exposure, the data indicate moderate-to-high values of corrosion rates. Then, there is a sudden increase in corrosion rate to high values at a time equal to 12 weeks. At the end of exposure time, the corrosion rate of steel returns to moderate-to-high values. For concrete containing 17% bagasse, the results indicate that for first 8 weeks moderate-to-high corrosion rate values are found. After that and until 14 weeks, the data indicate high corrosion rate values. At the end of exposure time, corrosion rate values return to moderate-to-high region. Figure 8h shows as-received steel in concrete containing 0% bagasse; the results indicate that for the first 12 weeks steel is in a passive condition. After that and until 16 weeks of exposure, the results indicate low-to-moderate corrosion rate values. Then, moderate-to-high values of corrosion rate continued for 4 weeks. At the end of exposure time, there is a sudden increase in corrosion rate to high values for steel. At 8% bagasse, the results indicate that for the first 14 weeks, low-to-moderate corrosion rate values are found. After that and until 16 weeks, the data indicate moderate-to-high

corrosion rates. At the end of exposure time, steel returns to low–moderate corrosion rate values. For concrete containing 11% bagasse, the results indicate that for the first 6 weeks, low-to-moderate corrosion rate values are found. After that and until 8 weeks, the data indicate moderate-to-high corrosion rates. Then very high corrosion rate values are observed at a time equal to 12 weeks. After that and until 14 weeks of exposure, the results show moderate-to-high corrosion rate, and then, high corrosion rate values are found at a time equal to 20 weeks. At the end of exposure time, steel returns to low–moderate corrosion rate values. For concrete containing 14% bagasse, for the first 8 weeks, the results indicate low-to-moderate corrosion rates. At the end of exposure time, the data show moderate-to-high corrosion rate values. For concrete containing 17% bagasse, for the first 4 weeks, the results show moderate-to-high values of corrosion rate. After that and until 6 weeks, the data indicate low-to-moderate corrosion rate. Then at a time equal to 8 weeks the values return to moderate–high corrosion rate. After that and until 12 weeks of exposure, the results show high corrosion rate values. Then at a time equal to 14 weeks of exposure, the values ranged between moderate and high values. After that and until 20 weeks, corrosion rate values become high. At the end of exposure time, the results indicate another return to moderate–high corrosion rate values. Figure 8i shows the relationship between the corrosion rate of cleaned steel embedded in concrete containing different concentrations of bagasse and exposure time. At 0% bagasse, the results indicate that for the first 12 weeks steel is in a passive condition. After that and until 14 weeks of exposure, the results indicate low-to-moderate corrosion rate values. Then steel returns to the passive state until 16 weeks of exposure. At the end of exposure time, the results indicate moderate-to-high values of corrosion rate. For concrete containing 8% bagasse, the results indicate that for first 8 weeks steel is in a passive condition. After that and until 10 weeks of exposure, the results indicate low-to-moderate corrosion rate values. Then there is a sudden increase in corrosion rate to high values at 12 weeks. At the end of exposure time, the results indicate that steel returns to low-to-moderate values. For concrete containing 11% bagasse, for the first 2 weeks the results indicate high corrosion rate values for steel. After that and until 8 weeks of exposure, the results indicate low-to-moderate corrosion rate values. At the end of exposure time, the data show moderate-to-high values of corrosion rate. For concrete containing 14% bagasse, for first 8 weeks, the results indicate low-to-moderate corrosion rate values for steel. After that and until 20 weeks of exposure, the results indicate moderate-to-high corrosion rate values. At the end of exposure time, the data show that steel returns to low-to-moderate corrosion rates. For concrete containing 17% bagasse, for the first 8 weeks, the results indicate low-to-moderate corrosion rate values for steel. After that and until

12 weeks of exposure, the results indicate moderate-to-high corrosion rate values. Then, the results return to low-to-moderate corrosion rates. After that and until 20 weeks, the data indicate moderate-to-high values. At the end of exposure time, the data show that steel returns to low-to-moderate corrosion rates. According to Tables 1, 2 and 3 and Fig. 8, there are indications that concrete samples exposed to air are in passive conditions at the end of exposure time. This means that no corrosion is occurring on the steel surface. While samples that are partially immersed in water, for 0% bagasse the results indicate the onset of corrosion and at the end of exposure time corrosion progressively increased to high values. But concrete that containing bagasse, as bagasse concentrations increase the passivity is found on the steel surface. For concrete samples that totally immersed in water, the results indicate that steel surface is in passive condition at the end of exposure time for concrete containing 0% bagasse, while concrete containing different concentrations of bagasse the corrosion is between moderate and high values.

3.4 Electrical Resistance of Concrete

Electrical resistance values for concrete samples are listed in Tables 1, 2 and 3, and are shown in Fig. 9a–i. There is a significant decrease in resistance values for 0% bagasse samples for all times of exposure to different corrosive conditions for different surface conditions of steel. There is an indication that resistance values of cleaned steel are lower than phosphatized and as-received steels for different corrosive conditions. Also, the results indicate that resistance values of concrete samples exposed to dry air conditions are much higher than samples that immersed partially and totally in corrosive media (water). This indicates that the attack of aggressive ions on the passive film is severe in concrete with higher moisture content because the higher moisture content increases the ionic conductivity of the concrete. As a consequence, the steel corrodes because of a lower resistivity (10^3 – 10^4 O cm) [32]. In dry concrete, the resistivity is high, in the range (10^7 – 10^{10} O cm) [32]. Therefore, the flow of local action current between the anode and cathode is low and corrosion of steel is reduced. Startfull [33] explained that in the measurements of the potentials and resistivity of the concrete on the structure two factors came apparent: (1) the greater the potential differences between the anodes and the cathodes, the greater the probability of severe corrosion, (2) the lower the electrical resistance of the corrosion, then again the greater the probability of corrosion attack. For phosphatized steel embedded in concrete containing different concentrations of bagasse and exposed to dry condition, the best electrical resistance values that are found at the end of exposure time can be obtained at concentrations 8, 17, 11, 0, and 14% bagasse, respectively, as shown in Fig. 9a, while

for as-received steel the higher values of electrical resistance can be obtained at concentrations 14, 11, 8, 0, and 17% bagasse, respectively, as shown in Fig. 9b, but for cleaned steel the higher values of electrical resistance are obtained at concentrations 14, 17, 8, 11, and 0%, respectively, as shown in Fig. 9c. For phosphatized steel embedded in concrete containing different concentrations of bagasse, these samples are partially immersed in water, the best electrical resistance values that are found at the end of exposure time can be obtained at concentrations 14, 8, 17, 11, and 0% bagasse as shown in Fig. 9d, while for as-received steel the higher values of electrical resistance can be obtained at concentrations 8, 14, 11, 17, and 0% bagasse, respectively, as presented in Fig. 9e, but for cleaned steel the higher values of electrical resistance are obtained at concentrations 8, 14, 17, 11, and 0%, respectively, as shown in Fig. 9f. For phosphatized steel embedded in concrete containing different concentrations of bagasse, these samples are totally immersed in water; the best electrical resistance values that are found at the end of exposure time can be obtained at concentrations 0, 14, 11, 17, and 8% bagasse as shown in Fig. 9g, while for as-received steel the higher values of electrical resistance can be obtained at 0% bagasse for all times of exposure as shown in Fig. 9h, but for cleaned steel the results indicate that electrical resistance values are approximately the same for all times of exposure as shown in Fig. 9i.

4 Conclusions

The addition of sugarcane (bagasse) to the concrete samples exposed to dry air conditions shows a large shift in the half-cell potential to the negative direction, decreases in electrical resistance and increases the corrosion current, for all concentrations of bagasse and all types of steel surface conditions. While in partially samples, a large shift in the half-cell potential to the positive direction was recorded, electrical resistance increases and corrosion current reduces compared with the absence of bagasse, in totally immersed concrete samples, a large shift in the half-cell potential to the negative direction was observed, electrical resistance decreases, and corrosion current increases compared with 0% bagasse; except for phosphatized steel, the reverse has occurred. In general, the results of this study showed that bagasse is not recommended as an additive to the cement from a corrosion point of view (for samples exposed to dry air conditions and totally immersed in water). The corrosion rate of different surface conditions of embedded steel in concrete exposed to different corrosive conditions can be made in the following order: samples exposed to air < samples partially immersed in water < samples totally immersed in water, while the surface treatment effectiveness for steel embedded in concrete

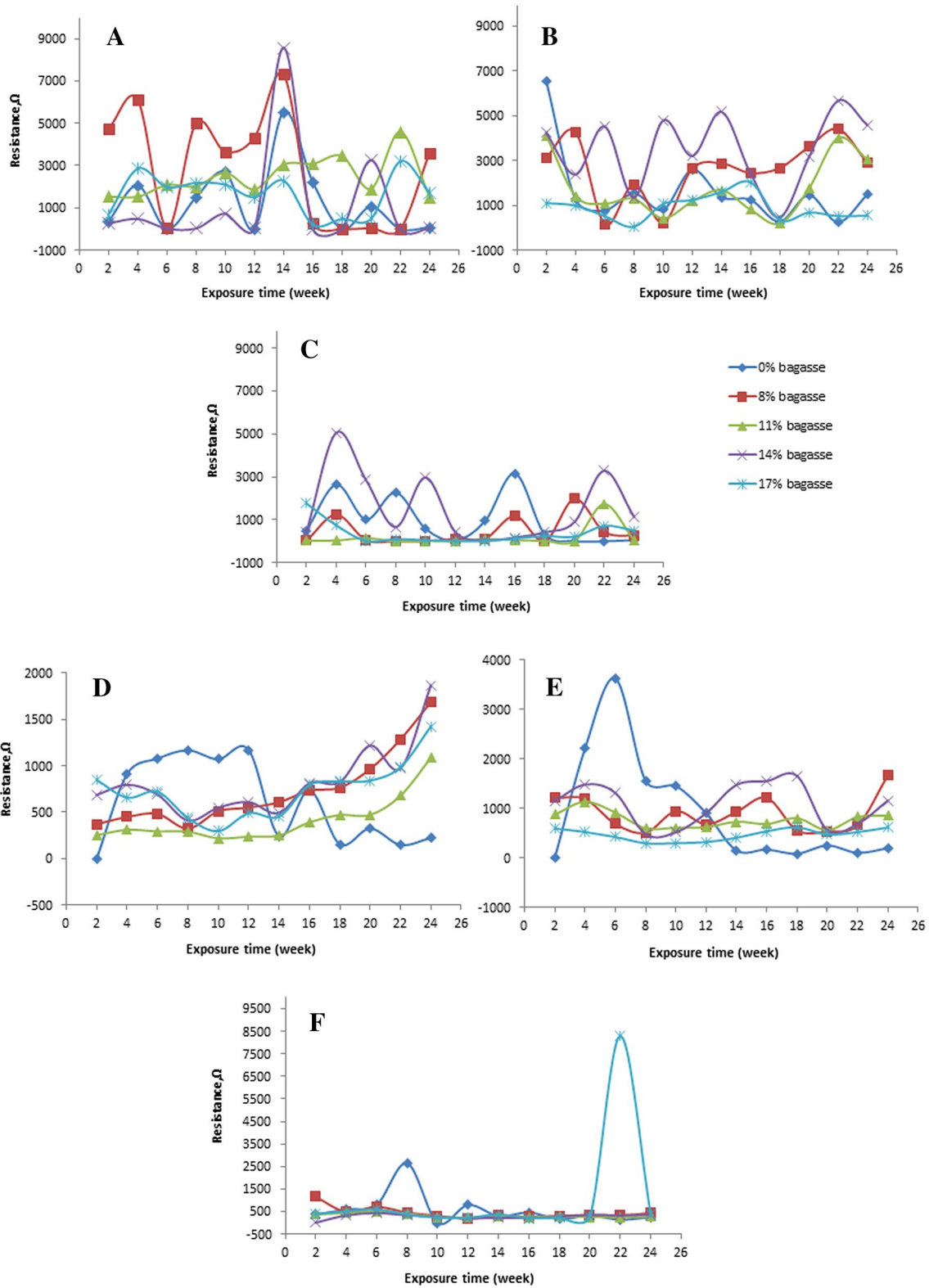


Fig. 9 Relationship between resistances of steel embedded in concrete containing different concentrations of bagasse. **a** Phosphatized steel at dry air conditions. **b** As-received steel exposed to dry air conditions. **c** Cleaned steel exposed to dry air conditions. **d** Phosphatized steel in partially immersed conditions. **e** As-received steel in

partially immersed conditions. **f** Cleaned steel in partially immersed conditions. **g** Phosphatized steel in totally immersed conditions. **h** As-received steel in totally immersed conditions. **i** Cleaned steel in totally immersed conditions

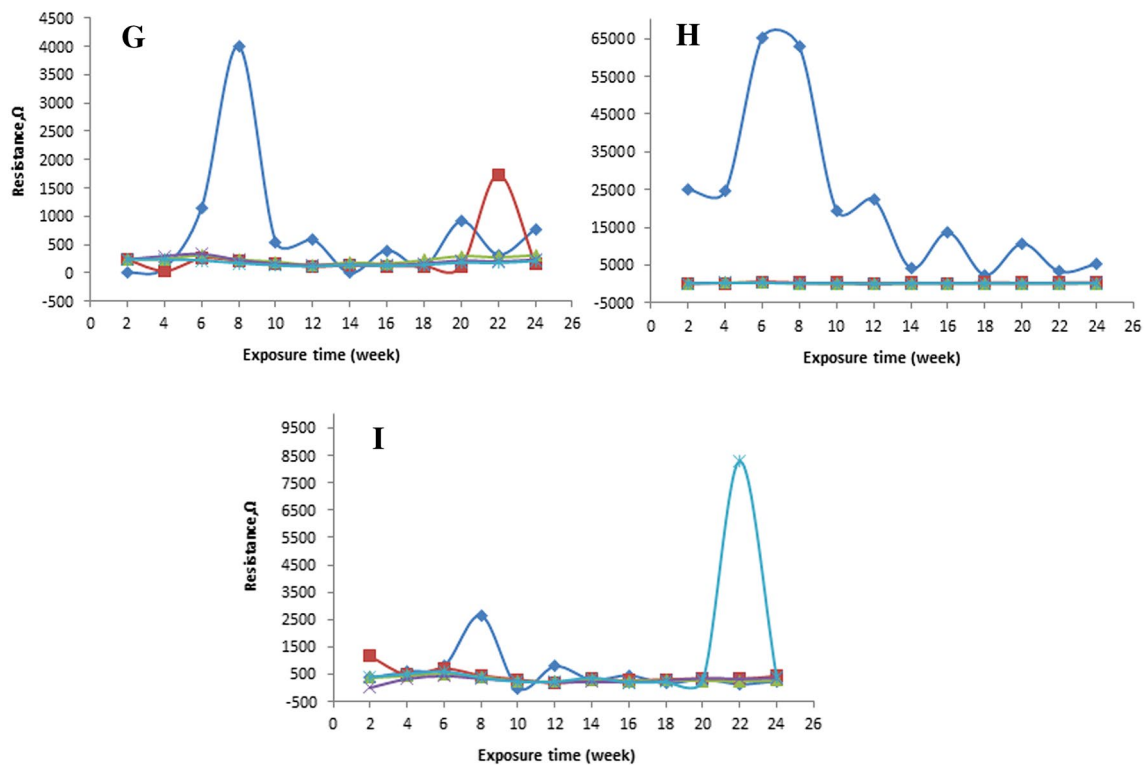


Fig. 9 (continued)

samples toward decrease the corrosion rates which were in the order: phosphatized steel > oxidized steel > cleaned steel.

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Compliance with ethical standards

Conflict of interest There are no conflicts of interest arising from the involvement of other parties either internal or external to the university.

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