S. RAJENDRAN[1], T.S. MUTHUMEGALA[1],
A. KRISHNAVENI[2], M. MANIVANNAN[3],
B. SHYAMALA DEVI[4], B. NARAYANA SAMY[5],
N. HAJARA BEEVI[6], A LEEMA ROSE[7]

Corrosion behaviour of mild steel in simulated concrete pore solution

The corrosion resistance of three metals, namely, mild steel (MS) galvalnised steel (GS) and SS 316L, in simulated concrete pore solution, namely, saturated calcium hydroxide solution has keen evaluated by electrochemical studies such as polarization study and AC impedance spectra. The corrosion resistance of the metals in simulated concrete pore solution is SS 316 L > GS > MS.

Keywords: *Concrete corrosion, corrosion of mild steel, SS 316L, simulated concrete pore solution, saturated calcium hydroxide solution.*

INTRODUCTION

Reinforced concrete is widely used for building materials and plays a significant role in economic development. However, the premature degradation of reinforced concrete structures due to the reinforcing steel corrosion has become a serious problem in modern society, which results in a huge economic loss [1], [2] and [3].

Under normal conditions, reinforcing steel in concrete can be protected from corrosion by forming a compact passive film on its surface in concrete pore solution with high alkalinity (pH 12.5-13.5). However, the passive film can be locally damaged and the localized corrosion of reinforcing steel takes place when pH and/or the chloride concentration at the steel/concrete interface reach the critical values for corrosion [4-9]. The pH of concrete pore solution decreased during concrete carbonation due to the neutralization of $Ca(OH)_2$ in the interstitial solution with the acidic gases (CO_2, SO_2, etc.) which diffuse into the steel/concrete interface from the air [8]. The pH value of concrete pore solution is one of the most important parameters affecting the corrosion behaviour of reinforcing steel in concrete.

In spite of the extensive studies of corrosion behaviours of reinforcing steel [4], [6], [9] and [10], the exact mechanism of its depassivation is still unclear. Even though the effect of pH on the corrosion of reinforcing steel was discovered decades ago, there were only a few studies focusing on the depassivation of the steel caused by decreasing pH of concrete pore solution during the carbonation process [8], [11], [12] and [13]. In the urban and industrial areas, the acidic gases (CO_2, SO_2, NO_2, etc.) can make the local atmosphere acidic, and attack the hydrated concrete. The reactions of neutralization in concrete may decrease the pH value of concrete pore solution, induce the steel surface depassivation, and consequently cause the steel corrosion.

Several research papers have investigated the corrosion behaviour of metals in presence of simulated concrete pore (SCP) solutions [14-25]. Usually steel robars have been used in such studies. The present study is undertaken to investigate the corrosion behaviour of three materials, namely, mild steel (MS), galvanized steel (GS) and SS 316L in simulated concrete pore (SCP) solution. A saturated solution of calcium hydroxide is used as SCP solution [26-30]. Electrochemical studies such as polarization study and AC impedance spectra have been used to evaluate the corrosion resistance of the materials under investigation.

MATERIALS AND METHODS

Metal specimens

Mild steel (Composition (wt %): 0.026 S, 0.06 P, 0.4 Mn, 0.1 C and balance iron [31]), galvanized steel, and SS316L (Composition (Wt%): 18 Cr, 12 Ni, 2.5Mo, < 0.03 C and balance iron [32]) wires of 1mm diameter are used in the present study.

Address authors: [1]Corrosion Research Centre, Post Graduate and Research Department of Chemistry, GTN Arts College, Dindigul-624 005, Tamilnadu, India, [2]Department of Chemistry, Yadava College, Madurai, India, [3]Department of Chemistry, Chettinad College of Engineering and Technology, Karur, India, [4]Department of Chemistry, Vivekanandha Institute of Engineering and Technology, Thiruchengode, Tamil Nadu, India, [5]Department of Chemistry, Theigarajar College of Enginnering, Madurai, India., [6]Department of Chemistry, B.S. Abdur Rahman University, Vandalur, Chennai – 600 048, India, [7]Department of Chemistry, Holy Cross College, Trichy, India

Simulated Concrete Pore (SCP) Solution

A saturated calcium hydroxide solution is used in the present study, as SCP solution. The electrodes made of the said wires were immersed in the SCP solution and polarization study was carried out and AC impedance spectra were recorded.

Potentiodynamic polarization

Polarization studies were carried out in a CHI – Electrochemical workstation with impedance, Model 660A. A three-electrode cell assembly was used. The working electrode was one of the three metals. A saturated calomel electrode (SCE) was the reference electrode and platinum was the counter electrode. From the polarization study, corrosion parameters such as corrosion potential (E_{corr}), corrosion current (I_{corr}) and Tafel slopes (anodic = b_a and cathodic = b_c) were calculated.

AC impedance spectra

The instrument used for polarization study was used to record AC impedance spectra also. The cell setup was also the same. The real part (Z') and imaginary part (Z") of the cell impedance were measured in ohms at various frequencies. Values of the charge transfer resistance (R_t) and the double layer capacitance (C_{dl}) were calculated.

RESULTS AND DISCUSIONS

Corrosion behaviour of three materials, namely, mild steel (MS), galvanized steel (GS) and SS 316 L, immersed in simulated concrete pore solution (SCP), (saturated calcium hydroxide solution) have been investigated by polarization study and ACC impedance spectra.

Polarization Study

The polarization curves of metals immersed in simulated concretre pore solution are shown in Figs 1 to 3. The corrosion parameters such as corrosion potential (E_{corr}), Tafel slopes (b_c = cathodic; b_a = anodic), Linear polarization resistance (LPR), and corrosion current (I_{corr}) are given in Table 1.

Table 1 - Corrosion parameters of metals immersed in simulated concrete pore solution (saturated calcium hydroxide solution), obtained by potentiodynamic polarization study.

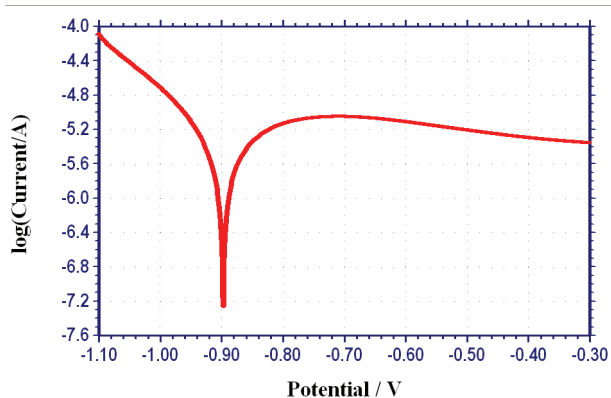| System	E_{corr} mV vs SCE	b_c mV/decade	b_a mV/decade	LPR ohm cm^2	I_{corr} A/cm^2
MS	-897	147	344	8362	5.344 x 10^{-6}
GS	-889	164	342	24531	1.968 x 10^{-6}
SS 316 L	-646	98	673	1195399	0.03113 x 10^{-6}

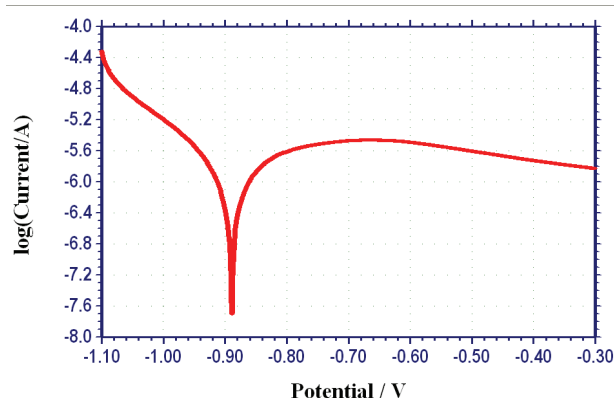*Fig 1 - Polarization curve of MS immersed in concrete pore solution.*

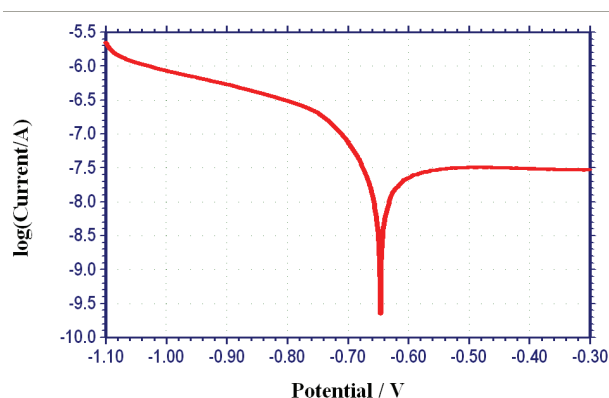*Fig 2: Polarization curve of GS immersed in concrete pore solution.*

Fig 3 - Polarization curve of SS 316 L immersed in concrete pore solution.

When corrosion rate of a metal decreases, LRP value increases and corrosion current value decreases [33-37]. It is observed from Table 1 that the decreasing order of LPR values is SS 316 L > GS > MS.

It is inferred that SS 316 L is more corrosion resistant than GS in concrete solution; GS in turn is more corrosion resistant than MS, in concrete solution. The LPR value of SS 316 L is very high (1195399 ohm cm^2), when compared with that of MS (8362 ohm cm^2).

These results are supported by the value of corrosion current. The decreasing order of corrosion current is: MS > GS > SS 316 L. This suggests that the corrosion resistance of the metals is in the order : SS 316 L > GS > MS. It is observed that the corrosion current for SS 316L is very small (0.03113 x 10^{-6} A/cm^2) when compared with that of MS (5.344 x 10^{-6} A/cm^2). It is also observed that the corrosion potential of SS 316 L is shifted to more noble side (–646 mV vs SEC), when compared with GS (–899 mV vs SCE) and MS (–897 mV vs SCE). This indicates that the anodic reaction of metal dissolution is prevented more effectively in SS 316 L than in the case of GS and MS. The decreasing order of corrosion resistance is SS 316 L > GS > MS.

Thus it is concluded from polarization study that the corrosion resistance of materials in concrete solution is SS 316 L > GS > MS.

AC impedance Spectra

The AC impedance spectra of various metals immersed in simulated concrete pore solution are shown in Figs 4 to 9. The Nquist plots are shown in Figs. 4, 6 and 8. The Bode plots are shown in Figs 5, 7 and 9. Change transfer resistance (R$_t$) and double layer capacitance (C$_{dl}$) values are derived from Nyquist plots. Impedance values, log (z/ohm) are derived from Bode plots. The results are summarized in Table 2.
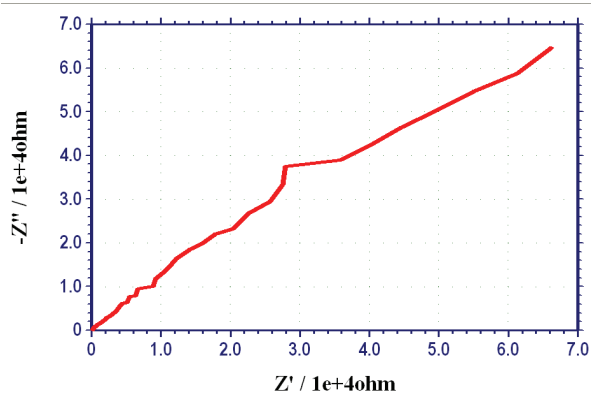

Fig 4 - AC impedance spectrum of MS immersed in concrete pore solution, (Nyquist plot)
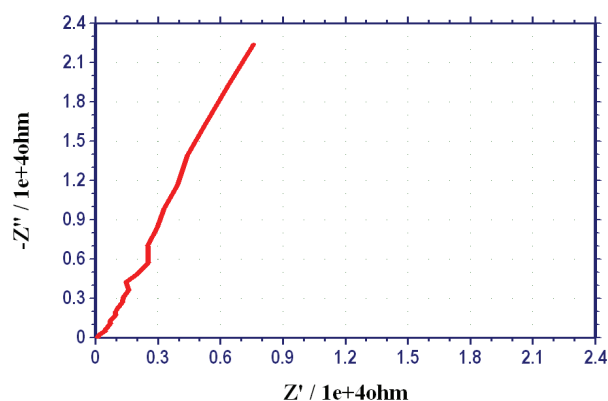

Fig 6 - AC impedance spectrum of GS immersed in concrete pore solution (Nyquist plot)
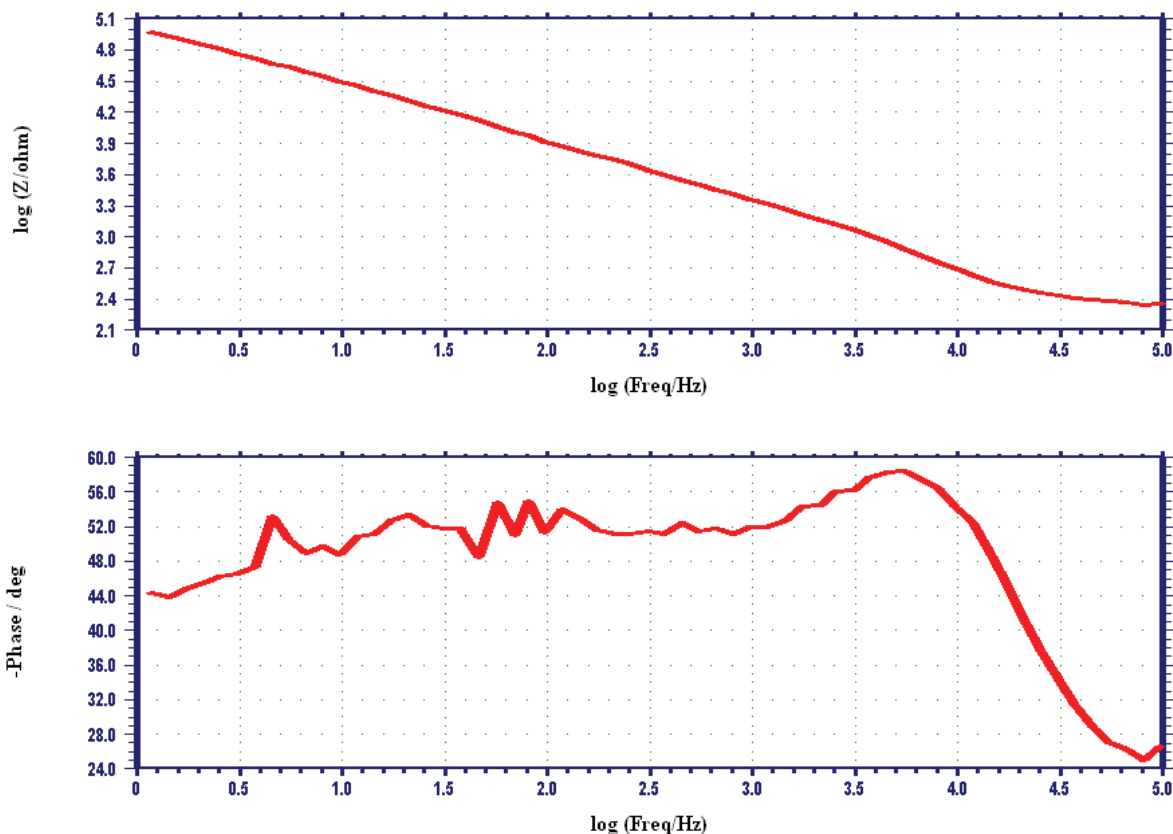
Fig 5 - AC impedance spectrum of MS immersed in concrete pore solution (Bode plot)
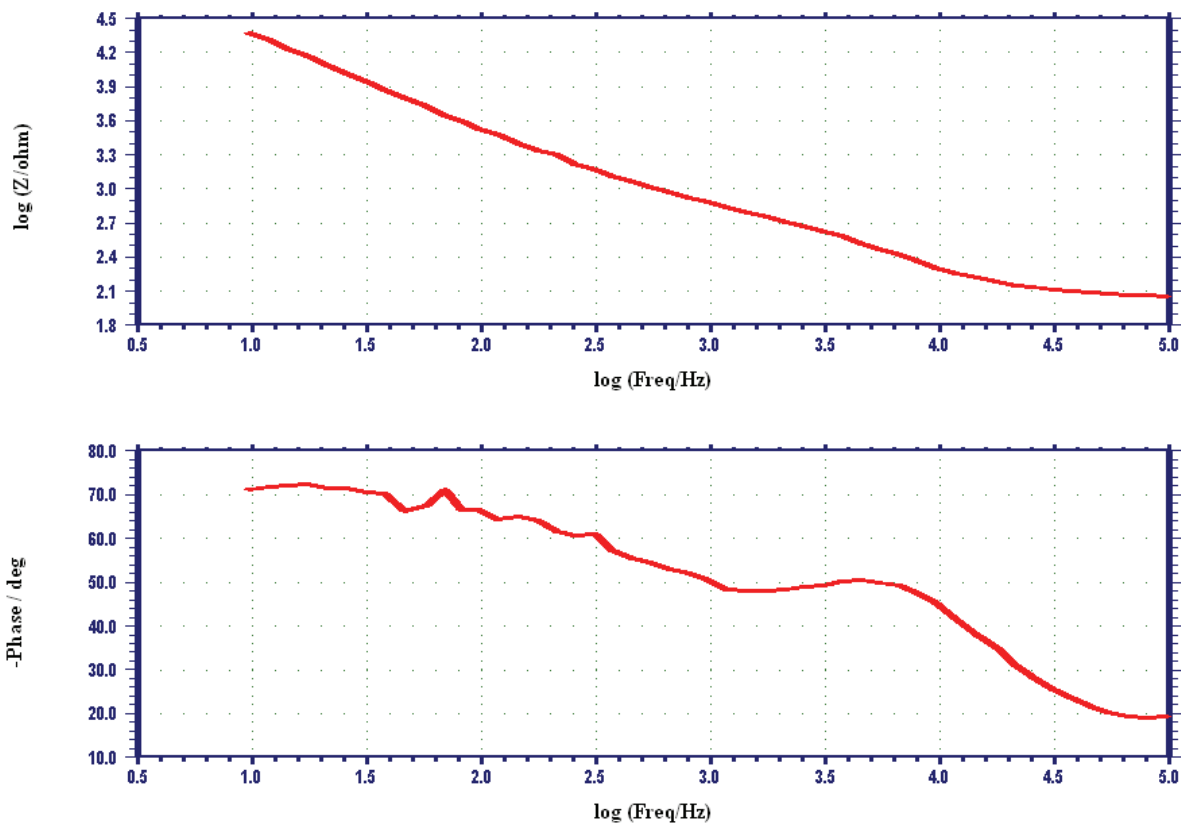

Fig 7 - AC impedance spectrum of GS immersed in concrete pore solution (Bode plot)
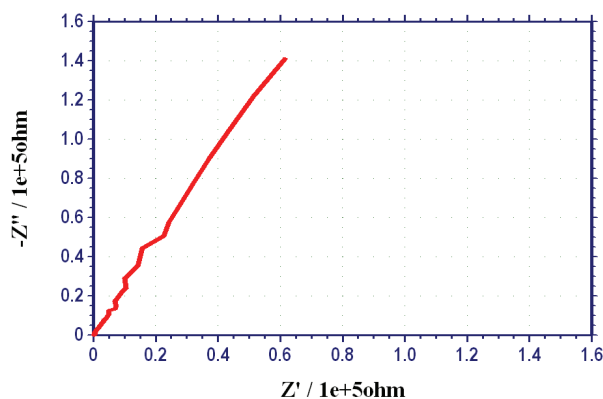
Fig 8 - AC impedance spectrum of SS 316 L immersed in concrete pore solution (Nyquist plot)
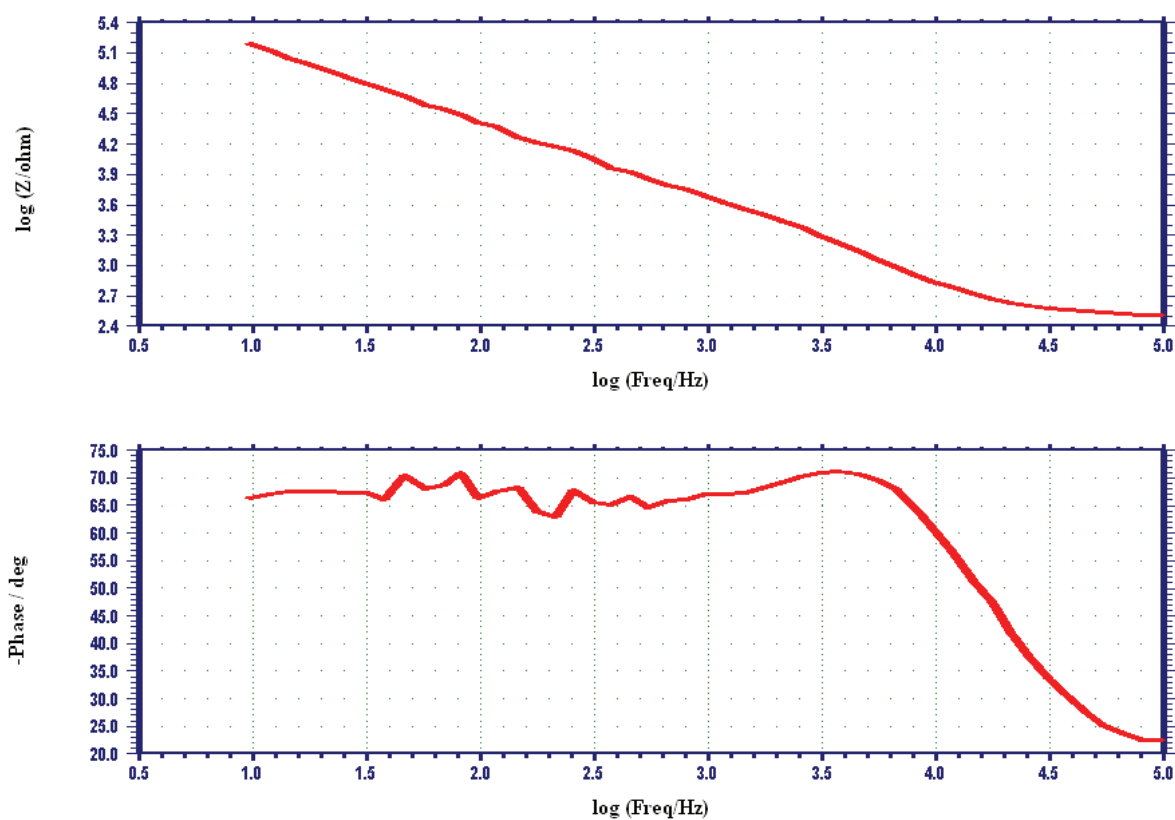

Fig 9 - AC impedance spectrum of SS 316 L immersed in concrete pore solution (Bode plot)

When corrosion rate decreases, due to formation of protective film, the charge transfer resistance value increases and double layer capacitance value decreases; the impedance value log (z/ohm) increases [38-42].

It is observed from Table 2 that MS has the highest R_t value and GS has the lowest value. Hence it is concluded that the decreasing order of corrosion resistance of the metals under investigation, in simulated concrete pore solution is MS > SS 316L > GS.

Table 2 - Impedance parameters of metals immersed in simulated concrete pore solution (saturated calcium hydroxide solution), obtained by AC impedance spectra.

System	R_t ohm cm^2	C_{dl} F/cm^2	Impedance log (z/ohm)
MS	66290	7.693×10^{-11}	5.0
GS	7658	66.60×10^{-11}	4.366
SS 316 L	61910	8.237×10^{-11}	5.20

It is observed from Table 2 that MS has the highest R_t value and GS has the lowest value. Hence it is concluded that the decreasing order of corrosion resistance of the metals under investigation, in simulated concrete pore solution is MS > SS 316L > GS.

This is supported by the double layer capacitance values also (7.693 x 10^{-11} , 8.236 x 10^{-11}, and 66.60 x 10^{-11} respectively). SS 316 L has the highest impedance value of 5.2. The slight decrease in the impedance value of GS, when compared with MS may be explained by the fact that the film formed on the GS surface is porous and arnorphous.

SS 316 L and MS have nearly same impedance [log (z/ohm)] value (5.20 and 5.0 respectively). GS has the lowest value (4.366).

AC impedance spectra lead to the conclusion that the corrosion resistance of the metals in simulated concrete pore solutions is in the order MS > SS 316 L > GS.

CONCLUSION

The corrosion resistance of three metals, namely, mild steel (MS) galvanized steel (GS) and SS 316 L, in simulated concrete pore solution, namely, saturated caslcium hydroxide solution has been evaluated by electrochemical studies such as polarization study and AC impedance spectra. The corrosion resistance of the metals in simulated concrete pore solution is SS 316 L > GS > MS.

REFERENCES

[1] S. Ahmad, Cement Concrete Comp. 25 (2003), p. 459.

[2] M.V. Biezma and J.R. San Cristobal, Corros. Eng Sci. techn. 40 (2005), p. 344.

[3] K. Thangavel, Corros. Rev. 22 (2004), p. 55.

[4] M. Moreno, W. Morris, M.G. Alvarez and G.S. Duffo, Corros. Sci. 46 (2004), p. 2681.

[5] V. Kumar, Corros. Rev. 16 (1998), p. 317.

[6] M. Maslehuddin, M.M. Al-Zahrani, M. Ibrahim, M.H. Al-Mehthel and S.H. Al-Idi, Constr. Build. Mater. 21 (2007), p. 1825.

[7] R.G. Du, R.G. Hu, R.S. Huang and C.J. Lin, Anal, Chem. 78 (2006), p. 3179.

[8] B. Huet, V.L'Hostis, F. Miserque and H. Idrissi, Electrochim. Acta 51 (2005), p. 172.

[9] C. Alonso, M. Castellote and C. Andrade, Electrochim. Acta 47 (2002), p. 3469.

[10] O. Poupard, A. Ait-Mokhtar and P. Dumargue, Cement Concrete Res. 34 (2004), p. 991.

[11] G.S. Duffo, W. Morris, I. Raspini and C. Saragovi, Corros. Sci. 46 (2004), p. 2143.

[12] W.C. Yeih and J.J. Chang, Constr. Build. Mater. 19 (2005), p. 516.

[13] P. Garces, M.C. Andrade, A. Saez and M.C. Alonso, Corros, Sci. 47 (2005), p. 289.

[14] X. Zhou, H.Y. Yang, F.H. Wang, Corrosion Science and Protection Technology 22 (4), (2010), pp. 343-347.

[15] S. Fajardo, D. M. Bastidas, M. P. Ryan, M. Criado, D. S. McPhail, J.M. Bastidas, Applied Surface Science 256 (21), (2010), pp. 6139-6143.

[16] W. Chen, R. G. Du, C-Q. Ye, Y-F. Zhu, C-J. Lin, Electrochimica Acta 55 (20) (2010), pp. 5677-5682.

[17] L. Wang, Y-L. Zhao, Tiedao Xuebao/Journal of the China Railway Society 32 (4) (2010), pp. 96-101.

[18] C. Chastre, M.A.G. Silva, Engineering Structures 32 (8) (2010), pp. 2268-2277.

[19] K. Suh, G. Mullins, R. Sen, D. Winters, Journal of Composites for Construction 14 (4) (2010), pp. 388-396.

[20] J. X. Zhang, H.H. Sun, Y.M. Sun, N. Zhang, Journal of Zhejiang University Science A 11 (5) (2010), pp. 382-388.

[21] V.T.N. Dao, P. F. Dux, P.H. Morris, A. H. Carse, ACI Materials Journal 107 (3) (2010), pp. 291-296.

[22] P. Ghods, O. B. Isgor, G. A. McRae, G.P. Gu, Corrosion Science 52 (5) (2010), pp. 1649-1659.

[23] Y. F. Fan, Z. Q. Hu, Y. Z. Zhang, J. L. Liu, Construction and Building Materials 24 (10) (2010), pp. 1975-1983.

[24] A. Kenny, A. Katz, Advanced Materials Research 95 (2010), pp. 69-72.

[25] B. Huet, V. L'Hostis, L. Tricheux, H. Idrissi, Materials and Corrosion 61 (2), (2010) pp. 111-124.

[26] S. R. Allahkaram, M. Khodayari, Anti-Corros. Methods Mater. 55 (2008) 250.

[27] M.M. Mennucci, E.P. Banczek, P.R.P. Rodrigues, I.Costa, Cement Concrete Compos, 31 (2009) 418.

[28] C.J. Kitowski, H.G. Wheat, Corrosion 53 (1997), p. 216.

[29] M.F. Hurley, J.R. Scully, Corrosion 62 (2006) 892.

[30] L. Li, A.A. Sagues, Corrosion 60 (2004) p. 195.

[31] J. Arockia Selvi, S. Rajendran, V. Garga Sri, A. John Amalraj and B. Narayanasamy, Portugaliae Electrochimica Acta, 27 (2009), 1.

[32] I. Gurappa, Materials Characterization 49 (2002), p 73.

[33] Noreen Anthony, H. Benita Sherine and S. Rajendran, International Journal of Engineering Science and Technology, 2 (2002) p. 2774.

[34] S. Rajendran, P. Chitradevi, S. Johnmary, A. Krishnaveni, S. Kanchana, Lydia Christy, R. Naga-lakshmi and B. Narayanasamy, Corrosion behaviour of SS 316 L in artificial saliva in presence of electral , Zastita Materijala, 51 (2010) p. 149.

[35] Noreen Anthony H. Benita Sherine and Susai Rajendran, The Arabian Junal for Science and Engineering, 35 (2010) p. 41.

[36] S. Rajendran, M. Kalpana Devi, A. Peter Pascal Regis, A. John Amalraj, J. Jeyasundari and M. Manivannan, Zastita Materijala, 50 (2009) p. 131.

[37] A. Raji, S. Rajendran, P. Sivaprabha, J. Arockia Selvi, B. Narayarasamy and J. Jeyasunderi, Zastita Materijala, 50 (2009) p. 153.

[38] A. Leema Rose, Noreen Antony, Felicia Rajarnmal Selva Rani, A. Peter Pascal Regis and S. Rajendran, Zastita Materijala, 50 (2009) p. 167.

[39] S. Rajendran, M. Kanagamani, M. Sivakalaivani, J. Jeyasunderi, B. Narayanasamy and K. Rajam, Zastita Materijala, 49 (2008) p 19.

[40] J. Sathiyabama, S. Rajendran, J. Arockia Selvi and J. Jeyasunderi, The Open Corrosion Journal, 2 (2009) p. 76.

[41] S. Agnesia Kanimozhi and S. Rajendran, International Journal of Electrochemical Science, 4 (2009) p. 353.

[42] R. Kalaivani, B. Narayanasamy, J.A. Selvi, A.J. Amalraj, J. Jeyasunderi and S. Rajendran, Portugaliae Electrochimica Acta, 27 (2009) p. 177.