

CORROSION BEHAVIOUR OF A NEW LOW-NICKEL STAINLESS STEEL IN SATURATED CALCIUM HYDROXIDE SOLUTION

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Abstract

Corrosion behaviour of low-nickel stainless steel (SS), AISI 304 SS and carbon steel was studied using cyclic anodic polarization curves and electrochemical impedance spectroscopy (EIS). Saturated calcium hydroxide ($\text{Ca}(\text{OH})_2$) solution was used to simulate a concrete pore solution at room temperature. The effect of up to 5.0% sodium chloride (NaCl) concentration in the test solution on the passivity of the alloys was studied. Experimental results showed that low-nickel SS exhibits similar behaviour to conventional AISI 304 SS, with E_{corr} and R_{ct} values of the same order and higher corrosion resistance than traditional carbon steel.

Key Words: Low-nickel stainless steel; saturated calcium hydroxide; passivity; polarization curves; EIS

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1. INTRODUCTION

Steel reinforcements embedded in concrete are protected from corrosion by a thin oxide film formed on their surfaces and maintained by the highly alkaline environment of the surrounding concrete, usually with a pH of 12-13 [1,2]. However, the presence of chlorides can lead to damaging effects on passivity and the appearance of pitting corrosion when chloride ions reach the metal/concrete interface. Chloride ions are commonly found in construction and building materials and may be due to the use of contaminated water in concrete production, contaminated aggregates, or even the external environment, as in the case of marine environments, de-icing salts and acid rain [3].

Together with cathodic protection, corrosion inhibitors and galvanized steel, stainless steel (SS) reinforcements are a reliable way to guarantee the durability of reinforced concrete structures (RCS) in extremely aggressive environments [4-6]. Although SS reinforcements may be the most economical solution in the long term [7,8], the initial cost involved has so far limited their use.

Austenitic SSs are alloys with high corrosion resistance and of great interest in technological applications, offering exceptional advantages for certain applications in construction by combining intrinsic durability with aesthetics, strength, ductility and formability. The stability of the surface oxide (passive film) formed on an austenitic SS depends mainly on the alloy composition, temperature, passivation time and working environment. Previous studies have revealed that these passive oxide films, formed of iron and chromium oxides, are of the order of only 1-4 nm thick [9,10], and their corrosion resistance is therefore a challenge. However, the use of SS rebars has been limited due to their high cost compared to traditional carbon steel. Nickel is one of the alloying elements that significantly increases the cost of austenitic SSs. Its price has

risen by 79% in the last five years, reaching a historic high of ~38000 euros/t in 2007. For this reason, new SSs, in which the nickel content (subject to considerable price fluctuations due to stock market factors) is partly replaced by other elements [11,12], are being evaluated as possible alternatives to traditional carbon steel [7,13,14]. This new low-nickel SS could mean a saving of about 15-20% compared to conventional AISI 304 SS.

Low-nickel austenitic SSs exhibit attractive properties, comparable to those of conventional austenitic SSs, such as good corrosion resistance, high strength and ductility, and a low tendency towards grain sensitization [15]. Low-nickel SSs can be highly nitrogen alloyed and have a well-balanced two-phase structure: 40% ferrite (α)-60% austenite (γ) up to 60% α -40% γ . In their production the addition of manganese increases nitrogen solubility in the melt and significantly retards the tendency for nitride precipitation, e.g. as chromium nitride (Cr_2N).

Passive film breakdown has been reported to occur non-uniformly on the surface of SS rebars, starting from a number of activated sites where the reaction products are a voluminous non-protective hydroxide [16]. Several authors have studied the effect of manganese on corrosion resistance, noting that it reduces the pitting resistance of 18% chromium, 5% nickel, 10% manganese and 0.07-0.35% nitrogen alloy [17,18]. Lowering the nickel content, which essentially serves as a γ -stabiliser to improve pitting corrosion resistance [19], can be compensated by increasing the nitrogen content. Manganese is also a good γ -stabiliser and contributes to improving nitrogen solubility [11]. It is well-known that both manganese and nickel promote austenitic microstructures that are more corrosion resistant in chloride media than ferritic microstructures [19].

The different models proposed to describe the mechanisms that lead to breakdown of the passive film can be classified into two groups attributing a specific role to chloride ions: adsorption of chloride ions on the passive film and migration or penetration of chloride ions through the passive film to the metal surface [20-22].

Potentiodynamic tests have been as one of the main electrochemical methods widely used in the study of corrosion. Although many researchers have used this method to study carbon steel and SS in alkaline solutions [5,22], the literature contains very little information about the corrosion behaviour of these materials (especially low-nickel SS) in alkaline saturated calcium hydroxide (Ca(OH)_2) simulating a concrete pore (SCP) solution. Electrochemical impedance spectroscopy (EIS) has also been used to characterize the electrical properties of passive films formed on the surface of these alloys.

The aim of this paper has been to investigate the corrosion behaviour of a new low-nickel SS in saturated calcium hydroxide solution (a SCP solution) polluted with sodium chloride (NaCl) in order to evaluate its possible use as reinforcement in RCS. Conventional AISI 304 SS and carbon steel materials have also been studied for comparative purposes, being the most common austenitic SS and the material traditionally used in reinforcements, respectively.

2. EXPERIMENTAL

The test specimens consisted of 5.0 cm × 2.0 cm plates of low-nickel austenitic SS, AISI 304 austenitic SS and carbon steel. The decision to use plates instead of traditional bars was due to the design of the electrochemical cell. An Avesta type cell was used, which allows crevice corrosion to be avoided or minimised [23] by replacing the chloride solution in the microcrevice between the specimen and the specimen holder with small quantities of distilled water.

The low-nickel and AISI 304 SS samples were supplied by ACERINOX SA (Palmones, Cádiz, Spain). Table 1 shows the chemical composition of the three materials determined by analytical analysis. The specimens were ground using a series of silicon carbide (SiC) emery papers down to grade 600, and then ultrasonically cleaned with ethanol and rinsed with high-purity water.

Table 1. Chemical composition (wt.%) of the tested low-nickel austenitic SS, AISI 304 austenitic SS and carbon steel.

A saturated calcium hydroxide solution, pH ~12-13, with different NaCl concentrations (0.0, 0.4, 1.0, 2.0, 3.0 and 5.0 wt.%), was used to study corrosion behaviour in a wide range of experimental conditions. The chemical products used to prepare the solutions were laboratory grade reagents: NaCl purisimum CODEX supplied by Panreac and Ca(OH)₂ for analysis supplied by Merck. All the solutions were prepared with distilled water.

A PARC 273A potentiostat (EG&G Instruments) was used to perform the electrochemical experiments. The Avesta cell was used in a three-electrode configuration with the sample as the working electrode, a saturated calomel electrode (SCE) as reference, and a platinum mesh as counter electrode. All the potentials were thus referred to the SCE.

The corrosion potential (E_{corr}) of the samples was monitored for 40 min in each test solution. This was the time needed to reach a stable potential. Pitting corrosion susceptibility was characterized by means of cyclic anodic polarization curves. A potential scan rate of 0.1667 mV s⁻¹ was used [24]. The current limit for reversing the

potential scan was 10^{-3} A cm^{-2} . The pitting potential (E_p) was defined as the potential value at which the current density sharply rises.

EIS measurements were recorded at E_{corr} in a frequency range from 10^5 Hz to 10^{-3} Hz with a logarithmic sweeping frequency of 5 points per decade. The EIS method involved the imposition of a 10 mV rms amplitude excitation voltage. A 1250 Solartron Frequency Response Analyser linked to an EG&G PARC 273A potentiostat was used for EIS measurements. All the experiments were performed at room temperature and in triplicate.

3. RESULTS AND DISCUSSION

Fig. 1 shows E_{corr} vs NaCl concentration for low-nickel SS, AISI 304 SS and carbon steel. It can be seen that after immersion the potential was negative for all the samples. In the absence of chloride ions the three materials presented very similar E_{corr} values of around -300 mV vs SCE. When chloride was added, the low-nickel and AISI 304 SSs behaved in practically the same way throughout the studied NaCl concentration range. The E_{corr} increased with the chloride level until reaching a steady state value of ~ -200 mV vs SCE for a NaCl concentration of more than or equal to 1.0%. These results are in good agreement with the studies performed by other authors [25]. However, carbon steel exhibited an E_{corr} threshold at 0.4% NaCl of ~ -300 mV vs SCE. At chloride ion levels above 0.4% the E_{corr} decreased significantly (~ -600 mV vs SCE), reaching a stable value.

Fig. 1. Variation in corrosion potential (E_{corr}) with NaCl concentration for low-nickel SS, AISI 304 SS and carbon steel in $\text{Ca}(\text{OH})_2$ saturated solution.

Figs. 2-4 show the cyclic anodic polarization curves for low-nickel SS, AISI 304 SS and carbon steel. For low-nickel SS in the absence of chlorides, no sign of attack could be observed using this technique (see Fig. 2). The sudden increase in the current density for this material at potentials above 600 mV vs SCE was caused by the oxidation of hydroxyl ions in the solution ($4\text{OH}^- \rightarrow \text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^-$) [2]. In the presence of chloride ions, the potential where the current density suddenly rose was similar to in the absence of chloride ions. This suggests that no E_p was reached, as oxygen evolution occurred before any local breakdown of the passive film took place. An exception is seen for 5% NaCl (see Fig. 2). In this case the E_p was observed at ~500 mV vs SCE, approximately 50 mV less than the oxidation potential of hydroxyl ions. Furthermore, pits were observed on the low-nickel SS surface at the end of the experiment for the 3% NaCl concentration. The large hysteresis loop exhibited was consistent with the presence of micropits formed during the anodic polarization scan and developed during the reverse scan at a NaCl concentration of more than or equal to 3%.

Fig. 2. Cyclic anodic polarization curves for low-nickel SS in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Potentiodynamic results show that the low-nickel SS (Fig. 2), AISI 304 SS (Fig. 3) and carbon steel (Fig. 4) behaved in the same way in the absence of chlorides. Similar E_{corr} values were obtained and no E_p was reached before oxygen evolution occurred. However, when chloride ions were present in the solution, important differences were seen between the two SSs and the carbon steel. Both SSs exhibited similar behaviour in the tested NaCl concentration range, with large hysteresis loops at

a NaCl concentration of more than or equal to 3%. As observed for low-nickel SS, pits at these NaCl concentrations were present on the surface at the end of the experiment. This is in agreement with the presence of micropits formed during the anodic polarization scan which undergo to stable pits during the reverse scan. Nevertheless, E_p potential for AISI 304 SS at 5% NaCl remained similar to those observed at the rest of NaCl concentrations, see Fig. 3. In contrast, pitting attack could clearly be detected on the carbon steel when anodic polarizations were imposed (see Fig. 4). At higher chloride concentrations E_p tended to fall to less noble values, approaching the E_{corr} value. Thus the $E_p - E_{corr}$ difference for the carbon steel became smaller as the chloride ion content increased. For a NaCl concentration of more than 1.0%, no E_p was defined, indicating that for NaCl concentrations above 1.0% no passivity was shown by the carbon steel at any potential. It can also be seen that in accordance with the increase in the chloride ion concentration, the current density in the passive region (i_p) increased gradually until no passivity could be detected (see Fig. 4). No repassivation of the pits was observed when the potential scan was reversed in any of the chloride containing Ca(OH)_2 solutions.

Fig. 3. Cyclic anodic polarization curves for AISI 304 SS in Ca(OH)_2 saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Fig. 4. Cyclic anodic polarization curves for carbon steel in Ca(OH)_2 saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Fig. 5 shows Nyquist plots for low-nickel SS in Ca(OH)_2 saturated solution with different NaCl concentrations. Capacitive behaviour can be observed, characterized by a well defined depressed semicircle. Diffusion processes were defined at low frequencies.

Thus, a Warburg diffusion element was defined. Fig. 6 shows Nyquist plots for AISI 304 SS observing the same tendency as for low-nickel SS (Fig. 5). In contrast, a lack of diffusion processes can be observed for carbon steel, see Fig. 7.

Impedance data has been modelled using the equivalent circuits (EC) depicted in Fig. 8a for carbon steel and in Fig. 8b for low-nickel and AISI 304 SSs. The ECs of Fig. 8 contain a constant phase element (CPE). A CPE unit is often used instead of an ideal capacitor to account for a non-ideal capacitive response from the steel/electrolyte interface. This is generally due to dispersion of the time constant caused by irregularities on the steel surface, surface roughness, fractal surface and in general certain processes associated with an irregular distribution of the applied potential [26]. R_e is the electrolyte resistance between the reference electrode and the working electrode, and R_{ct} is the charge transfer resistance, which may be inversely associated with the corrosion process. In addition to these elements, Fig. 8b also contains a finite length Warburg diffusion element to describe mass transport processes through the diffusion layer. A model like Fig. 8a has been proposed for carbon steel in the literature [27]. Although a two time constant EC has been proposed by some authors to describe the behaviour of SS in an alkaline medium [28] and in $\text{Ca}(\text{OH})_2$ solution with and without chloride ions [29], the EC of Fig. 8b was preferred as it provided better fitting of the impedance data. A one time constant EC containing a finite length Warburg diffusion element has previously been used by other authors to describe the behaviour of SS in chloride containing solutions [30]. Table 2 reports the fitting of impedance data for carbon steel, AISI 304 SS and low-nickel SS in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl additions yielded using the EC of Fig. 8.

Fig. 5. Nyquist plots for low-nickel SS in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Fig. 6. Nyquist plots for AISI 304 SS in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Fig. 7. Nyquist plots for carbon steel in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Fig. 8. Electrical circuit (EC) used to fit impedance data, (a) for carbon steel, and (b) for low-nickel SS and AISI 304 SS.

Table 2 shows that the R_e value decreased as NaCl was added to the solution. The conductivity of a water solution is highly dependent on the concentration of dissolved salts and other chemical species that ionize in the solution. Thus, as NaCl was added to the $\text{Ca}(\text{OH})_2$ saturated solution its conductivity grew, leading to a lower R_e value. This phenomenon was independent on the material studied, as carbon steel and both SSs presented practically identical R_e values.

The impedance results for low-nickel SS in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl additions presented typical capacitive behaviour, with a semicircle at high frequencies. Nevertheless, as can be seen in Fig. 5, the radii of the semicircles decreased as the NaCl concentration increased, indicating a less protective passive layer and, therefore, a descent in passivity with the presence of chloride ions. This behaviour was also shown by AISI 304 SS and carbon steel, although the decrease in the semicircle radii was more pronounced for carbon steel than for either SS. The above trend can be further supported by the quantified R_{ct} values seen in the fitted data in Table 2. It is true that carbon steel was stable in $\text{Ca}(\text{OH})_2$ saturated solution without NaCl, as its R_{ct} value was similar to the low-nickel and AISI 304 SSs, which according

to the polarization results both presented passivity in the studied potential range. However, carbon steel was unstable and corrosion took place when NaCl was added, as is indicated by the one order of magnitude decrease in R_{ct} values. These results were consistent with the polarization tests, where general corrosion was observed for carbon steel from the lowest NaCl concentration studied. Low-nickel SS and AISI 304 SS also showed a decrease in R_{ct} values as the NaCl content in the $\text{Ca}(\text{OH})_2$ saturated solution increased, but less notably than carbon steel. Both SSs were less stable as chlorides were added to the $\text{Ca}(\text{OH})_2$ saturated solution but still conserved their passivity.

Table 2. Fitting impedance data using EC of Fig. 8a for carbon steel, and EC of Fig. 8b for low-nickel SS and AISI 304 SS in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations.

The effect of chloride ions can also be evaluated in terms of Y_0 and α , which are parameters of the CPE unit. The impedance of a CPE (Z_{CPE}) is defined by the expression: $Z_{CPE} = \frac{1}{Y_0(j\omega)^\alpha}$, where Y_0 is a real frequency-independent constant, $j^2 = (-1)$, ω is the angular frequency, and α is a dimensionless fractional exponent ($-1 \leq \alpha \leq 1$). Therefore, the CPE-parameters Y_0 and α can reflect the change of a metal electrode surface relating to an electrochemical double-layer [26]. A number of studies have revealed that these parameters vary with the homogeneity of the electrode surface: higher Y_0 values and lower α values ($\alpha=1$ for an ideal capacitor) were characteristic of non-homogeneous surfaces [31-33]. For low-nickel SS, Y_0 values increased with the addition of NaCl. The variation in Y_0 values from the non-chloride containing solution to the maximum studied NaCl concentration was of the same order of magnitude (see Table 2). This may be a sign of the loss of homogeneity on the surface of the electrode

due to the effect of chloride ions. Additionally, this could indicate an increase in the surface area, induced by the corrosion process which increases the surface roughness. However, the small variation in Y_0 from chloride-free to the maximum tested chloride concentration (~2 units) suggests that low-nickel SS was able to retain its passivity in these adverse environments in unpolarized conditions. In terms of the α parameter, low-nickel SS showed no trend as it varied around $\alpha \sim 0.90$, exhibiting no influence of the NaCl concentration in the Ca(OH)_2 saturated solution. AISI 304 SS and carbon steel showed the same tendency, although it was more pronounced in the latter case. Comparing the Y_0 parameter for low-nickel SS and AISI 304 SS, very similar values were yielded, with the exception of that corresponding to the Ca(OH)_2 saturated solution without NaCl. With regard to carbon steel, it was worth noting that from the maximum studied NaCl concentration the Y_0 increased by one order of magnitude (see Table 2). This fact means that the double-layer changed and indicates the gradual breakdown of the passive film in the presence of chloride ions, even from the lowest tested NaCl addition. In terms of the α parameter, the slight decrease as NaCl was added to the alkaline solution, showed that the carbon steel surface may become less homogeneous due to the chloride attack.

At low frequencies, diffusion was the controlling process for both SSs (see Figs. 5 and 6). The Warburg diffusion coefficient (σ_w) results from mass transport of the species through the passive layer. As referred by Burstein et al. [34,35], the ability of a corrosion pit to grow is limited by the transport of chloride ions from the bulk electrolyte down to the pit channel. The origins of this phenomenon arise from the fact that pits in SS grow under diffusion control [35,36]. In the stable growth state, the diffusion barrier is provided by the depth of the pit itself, and this condition enables the pit anolyte to maintain the saturated metal salt concentration necessary to sustain metal

dissolution. As the chlorides increase in the solution, the salt concentration in the pit becomes higher. This originates a more effective diffusion barrier, therefore, leading to bigger σ_w values. If the chloride ions concentration is insufficient, the activated sites die out by repassivation and no longer proceed to a stable state.

The σ_w values yielded from the impedance data fitting showed that low-nickel SS exhibited similar values ($1.82-1.90 \times 10^{-3} \Omega \text{ cm}^2 \text{ s}^{-1/2}$) when the NaCl concentration was lower than or equal to 2.0% (see Table 2). The fact that σ_w values in the solution in the absence of chlorides (where it is not possible, therefore, their diffusion) is similar to those up to 2.0% NaCl, indicates that a concentration of NaCl lower than or equal to 2.0% is insufficient for an activated site to achieve stability. However, when the NaCl concentration is 3.0% and 5.0%, an increase in the σ_w values was observed. According to these results, for these NaCl concentrations, a diffusion barrier is observed, indicating that the activated sites on the surface evolved into stable micropits. This can be seen in Fig. 9, where SEM micrographs of low-nickel SS after 15 days of immersion in two different test solutions are presented. Samples were immersed that period of time in order to achieve significant differences among them. Fig. 9a shows the surface after exposure to a no-chlorides containing $\text{Ca}(\text{OH})_2$ solution. No pits can be observed. However, micropits can be clearly detected after exposure to a 3.0% NaCl solution (see Fig. 9b).

If σ_w is compared for both SSs, it can be seen that for NaCl concentrations of less than or equal to 2.0%, low-nickel SS showed lower σ_w values, probably indicating a more protective passive film than AISI 304 SS. Nevertheless, when the chloride ion concentration increased in the alkaline solution a similar σ_w value was yielded for both low-nickel and AISI 304 SSs.

4. CONCLUSIONS

Electrochemical tests have been performed on a new low-nickel SS in a $\text{Ca}(\text{OH})_2$ saturated solution (a simulated concrete pore (SCP) solution) polluted with sodium chloride. E_{corr} tended towards more noble values as the chloride level increased in the alkaline solution until reaching a stable state for a NaCl concentration of more than or equal to 1.0%. In terms of passivity, low-nickel SS remained in the passive state for all the studied NaCl concentrations. EIS results showed that R_{ct} values decreased with the addition of NaCl. Nevertheless, R_{ct} values were so high that low-nickel SS preserved its passivity at the E_{corr} value, exhibiting high corrosion resistance. Diffusion processes were observed for low-nickel SS. The σ_w values obtained showed that for a NaCl concentration higher than or equal to 3.0% a less protective passive film was formed.

Low-nickel SS presented higher corrosion resistance than carbon steel, and very similar corrosion behaviour to conventional austenitic AISI 304 SS. If further experimental results obtained in mortar or concrete with the new material in the form of ribbed rebars confirm this data, the low-nickel SS presented in this paper may be a viable material to be used as reinforcement in RCS in aggressive environments.

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6. REFERENCES

- [1] D.M. Bastidas, A. Fernández-Jiménez, A. Palomo, J.A. González, *Corros. Sci.*, 50 (2008) 1058-1065.
- [2] A. Bautista, G. Blanco, V. Velasco, *Cement Concrete Res.*, 36 (2006) 1922-1930.
- [3] M.A.G. Tommaselli, N.A. Mariano, S.E. Kuri, *Constr. Build. Mater.*, 23 (2009) 328-333.
- [4] R. Montoya, W. Aperador, D.M. Bastidas, *Corros. Sci.*, 51 (2009) 2857-2862.
- [5] M.B. Valcarce, M. Vázquez, *Electrochim. Acta*, 53 (2008) 5007-5015.
- [6] Z.Q. Tan, C.M. Hansson, *Corros. Sci.*, 50 (2008) 2512-2522.
- [7] N.R. Baddoo, *J. Constr. Steel Res.*, 64 (2008) 1199-1206.
- [8] A. Bautista, G. Blanco, F. Velasco, M.A. Martínez, *Constr. Build. Mater.*, 21 (2007) 1267-1276.
- [9] S. Fajardo, D.M. Bastidas, M.P. Ryan, M. Criado, D.S. McPhail, J.M. Bastidas, *Appl. Surf. Sci.*, 256 (2010) 6139-6143.
- [10] E.E. Rees, D.S. McPhail, M.P. Ryan, J. Kelly, M.G. Dowsett, *Appl. Surf. Sci.*, 203-204 (2003) 660-664.
- [11] R. Merello, F.J. Botana, J. Botella, M.V. Matres, M. Marcos, *Corros. Sci.*, 45 (2003) 909-921.
- [12] L. Freire, X.R. Nóvoa, G. Pena, V. Vivier, *Corros. Sci.*, 50 (2008) 3205-3212.
- [13] D. Trejo, P.J. Monteiro, *Cement Concrete Res.*, 35 (2005) 562-571.
- [14] L. Veleza, M.A. Alpuche-Aviles, M.K. Graves-Brook, D.O. Wipf, *J. Electroanal. Chem.*, 537 (2002) 85-93.
- [15] A. Di Schino, J.M. Kenny, *J. Mater. Sci. Lett.*, 21 (2002) 1969-1974.
- [16] B.O. Elfström, *Mater. Sci. Eng.*, 42 (1980) 173-180.

- [17] M. Janik-Czachor, E. Lunarska, Z. Szklarska-Smialowska, *Corrosion*, 31 (1975) 394-398.
- [18] E. Lunarska, M. Janik-Czachor, Z. Szklarska-Smialowska, *Corrosion*, 31 (1975) 231-234.
- [19] G.S. Frankel, *J. Electrochem. Soc.*, 145 (1998) 2186-2198.
- [20] T.P. Hoar, *Corros. Sci.*, 7 (1967) 341-355.
- [21] Z. Szklarska-Smialowska, *Corrosion*, 27 (1967) 223-233.
- [22] M. Vuković, *Corros. Sci.*, 37 (1995) 111-120.
- [23] R. Quafort, *Corros. Sci.*, 28 (1988) 135-140.
- [24] ASTM G61-86 (2009) Standard, Test Method for Conducting Cyclic Potentiodynamic Polarization Measurements for Localized Corrosion Susceptibility of Iron-, Nickel-, or Cobalt-Based Alloys.
- [25] D. Addari, B. Elsener, A. Rossi, *Electrochim. Acta*, 53 (2008) 8078-8086.
- [26] V. Feliu, J.A. González, C. Andrade, S. Feliu, *Corros. Sci.*, 40 (1998) 975-993.
- [27] F. Zhang, J. Pan, C. Lin, *Corros. Sci.*, 51 (2009) 2130-2138.
- [28] C.M. Abreu, M.J. Cristobal, R. Losada, X.R. Nóvoa, G. Pena, M.C. Pérez, *J. Electroanal. Chem.*, 572 (2004) 335-345.
- [29] G. Blanco, A. Bautista, H. Takenouti, *Cement Concrete Comp.*, 28 (2006) 212-219.
- [30] T. Hong, G.W. Walter, M. Nagumo, *Corros. Sci.*, 38 (1996) 1525-1533.
- [31] W. Chen, R.-G. Du, C.-Q. Ye, Y.-F. Zhu, C.-J. Lin, *Electrochim. Acta*, 55 (2010) 5677-5682.
- [32] U. Rammelt, G. Reinhard, *Electrochim. Acta*, 35 (1990) 1045-1049.
- [33] M. Leibig, T.C. Halsey, *Electrochim. Acta*, 38 (1993) 1985-1988.
- [34] G.T. Burstein, P.C. Pistorius, S.P. Mattin, *Corros. Sci.*, 35 (1993) 57-62.
- [35] P.C. Pistorius, G.T. Burstein, *Corros. Sci.*, 33 (1992) 1885-1897.

[36] T. Hong, N. Nagumo, *Corros. Sci.*, 39 (1997) 285-293.

CAPTIONS FOR ILLUSTRATIONS

Fig. 1. Variation in corrosion potential (E_{corr}) with NaCl concentration for low-nickel SS, AISI 304 SS and carbon steel in $\text{Ca}(\text{OH})_2$ saturated solution.

Fig. 2. Cyclic anodic polarization curves for low-nickel SS in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Fig. 3. Cyclic anodic polarization curves for AISI 304 SS in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Fig. 4. Cyclic anodic polarization curves for carbon steel in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Fig. 5. Nyquist plots for low-nickel SS in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Fig. 6. Nyquist plots for AISI 304 SS in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Fig. 7. Nyquist plots for carbon steel in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations: (a) 0.0, 0.4, 1.0%, and (b) 2.0, 3.0, 5.0%.

Fig. 8. Electrical equivalent circuit (EEC) used to fit impedance data, (a) for carbon steel, (b) for low-nickel SS and AISI 304 SS.

Fig. 9. SEM micrograph for low-nickel SS after 15 days of immersion in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations: (a) 0.0%, and (b) 3.0%.

TABLES

Table 1. Chemical composition (wt.%) of the tested low-nickel austenitic SS, AISI 304 austenitic SS and carbon steel.

Table 2. Fitting impedance data using EEC of Fig. 8a for carbon steel, and EEC of Fig. 8b for low-nickel SS and AISI 304 SS in $\text{Ca}(\text{OH})_2$ saturated solution with different NaCl concentrations.

Table 1. Chemical composition (wt.%) of the tested low-nickel austenitic SS, AISI 304 austenitic SS and carbon steel.

| Material | C | Si | Mn | P | S | Cr | Ni | Mo | Cu | N |
|--------------|-------|------|------|-------|-------|-------|------|------|------|-------|
| Low-Nickel | 0.082 | 0.48 | 7.26 | 0.027 | 0.001 | 16.56 | 4.32 | 0.07 | 0.13 | 0.075 |
| AISI 304 | 0.049 | 0.32 | 1.75 | 0.028 | 0.001 | 18.20 | 8.13 | 0.22 | 0.21 | 0.050 |
| Carbon Steel | 0.450 | 0.22 | 0.72 | <0.01 | 0.022 | 0.13 | 0.13 | – | 0.18 | – |

The balance was Fe

Table 2. Fitting impedance data using EEC of Fig. 8a for carbon steel, and EEC of Fig. 8b for low-nickel SS and AISI 304 SS in Ca(OH)₂ saturated solution with different NaCl concentrations.

| Material | NaCl/% | $R_e/\Omega\text{cm}^2$ | $R_{ct}/\times 10^6 \Omega\text{cm}^2$ | $Y_0/F\text{cm}^{-2}\text{s}^{-(1-\alpha)}$ | α | $\sigma_w/\times 10^{-3} \Omega\text{cm}^2\text{s}^{-1/2}$ |
|--------------|--------|-------------------------|--|---|----------|--|
| Carbon Steel | 0.0 | 177.3 | 0.212 | 2.06×10^{-6} | 0.92 | – |
| | 0.4 | 99.2 | 0.013 | 4.44×10^{-5} | 0.91 | – |
| | 1.0 | 66.3 | 0.008 | 4.58×10^{-5} | 0.92 | – |
| | 2.0 | 42.3 | 0.007 | 5.08×10^{-5} | 0.91 | – |
| | 3.0 | 29.9 | 0.006 | 6.13×10^{-5} | 0.88 | – |
| | 5.0 | 19.9 | 0.005 | 7.38×10^{-5} | 0.87 | – |
| AISI 304 | 0.0 | 178.7 | 0.292 | 2.57×10^{-5} | 0.93 | 3.57 |
| | 0.4 | 99.3 | 0.241 | 2.97×10^{-5} | 0.89 | 3.86 |
| | 1.0 | 67.1 | 0.235 | 3.20×10^{-5} | 0.91 | 3.35 |
| | 2.0 | 41.9 | 0.186 | 3.22×10^{-5} | 0.92 | 3.99 |
| | 3.0 | 30.5 | 0.175 | 3.26×10^{-5} | 0.92 | 4.51 |
| | 5.0 | 19.9 | 0.160 | 3.34×10^{-5} | 0.90 | 4.82 |
| Low-Nickel | 0.0 | 176.9 | 0.332 | 1.00×10^{-5} | 0.89 | 1.82 |
| | 0.4 | 93.8 | 0.325 | 2.91×10^{-5} | 0.91 | 1.76 |
| | 1.0 | 62.6 | 0.270 | 3.00×10^{-5} | 0.90 | 1.54 |
| | 2.0 | 37.9 | 0.236 | 3.08×10^{-5} | 0.88 | 1.90 |
| | 3.0 | 29.7 | 0.231 | 3.25×10^{-5} | 0.88 | 4.75 |
| | 5.0 | 19.8 | 0.212 | 3.28×10^{-5} | 0.89 | 4.32 |