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Behavior of the electrogalvanized and painted carbon steel and low Cu and Cr carbon steel during cyclic and field corrosion tests

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Abstract The corrosion behavior of aluminum killed mild steel, aluminum killed carbon steel with copper and chromium additions, and electrogalvanized steels with substrate of aluminum killed mild steel, and aluminum killed carbon steel with copper and chromium additions is studied. All steels were phosphatized and painted in an industrial plant. The corrosion resistance evaluation was performed using accelerated tests, and field tests at industrial weathering sites. The average cosmetic corrosion results, obtained in the field test during a 24-month period, with an application of a saline solution spray are similar to those of the GM 9540P/B cyclic test with 40 cycles. The corrosion mechanism was evaluated, and the role that chromium and copper play in corrosion processes was discussed. Concerning the tests used, it was verified that the cyclic tests and the field test with saline solution spray are appropriate for the atmospheric corrosion resistance evaluation of steel and its painting system as well as for the civil construction material selection.

Introduction

Steel frames used in civil construction may show low corrosion resistance, which results in low service life. This is partially due to the fact that the Mercosul's and Brazil's technical standards do not foresee any specific requirement or tests as far as corrosion resistance is concerned.

Aluminum killed mild steels of commercial quality are used in the manufacture of window and door frames for providing the required mechanical strength, weldability and formability properties [1]. In order to improve the performance of aluminum killed mild steels, new steels have been developed with increased atmospheric corrosion resistance, such as the conventional aluminum killed mild steels with additions of alloying elements such as copper and chromium [2]. The mild steels with copper and chromium additions have been produced by Brazilian industry since the early 80's, and their metallurgical and corrosion resistance properties have turned them into a good choice for the manufacture of window and door frames when compared to aluminum killed mild steels [3].

Another steel class that is widely applied in the construction industry is the zinc coated steels. These steels may be produced either by hot dipping or electrodeposition processes. The zinc layer protects the metallic substrate against corrosion through a mechanism that combines barrier protection and cathodic protection.

In order to evaluate the corrosion resistance of painting systems employed in steel frames, the civil construction industries usually adopt the salt spray test method. However, as this method does not properly reproduce the corrosion mechanism observed during

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the steel exposure to natural weathering conditions, it has been replaced by cyclic tests. In previous investigations [4, 5], the authors showed that the use of the salt spray test, to evaluate the corrosion resistance of phosphatized and painted steels, leads to inconsistent results, especially if the metallic substrate is zinc coated steel. Such investigations showed that, after testing in the salt spray cabinet, the cosmetic corrosion of the mild steel with copper and chromium additions was statistically similar to that of electrogalvanized steels for a significance level of 5% [5, 6]. This result was unexpected, as electrogalvanized steels usually present a lower average cosmetic corrosion than uncoated steels. The reason for the similarity between the average cosmetic corrosion results of electrogalvanized steels and aluminum killed carbon steels with copper and chromium additions is the corrosion mechanism inherent to testing in the salt spray cabinet, which enhances the chemical dissolution of the zinc and phosphate layers, as the corrosion front is alkaline and is always wet.

The phosphate coating of the carbon steel with copper and chromium additions is more resistant to the alkaline media than the phosphate layer of electrogalvanized steels, because the phosphate layer on the mild steel with copper and chromium additions is more compact and adherent, and presents the phosphophyllite and hopeite phases. The lack of zinc coating in the steels with copper and chromium additions is offset by the lower solubility of its phosphate layer when compared to electrogalvanized steels, thus resulting in similar performances when such phosphatized and painted steels are submitted to corrosion tests that do not have wet–dry cycles, as is the case of the salt spray test.

Contrary to the salt spray test, the corrosion mechanism of steels either coated or not with zinc, phosphatized and painted, when exposed to natural weathering or submitted to cyclic corrosion tests, is based on the cathodic delamination associated to the wedge effect caused by the corrosion products. In this case, the effect of the corrosion product volume is more important than the effect of the phosphate layer solubility because the test specimen surface does not remain wet the whole time and for that reason zinc coated steels show increased corrosion resistance [4, 7].

In this context, the objective of this work consists in determining corrosion test methodologies suitable to the material selection process in civil construction. Four corrosion tests were investigated, three being accelerated corrosion tests (Cycle I and GM 9540P/B cyclic tests and the field test with saline solution spray) and one non-accelerated corrosion test in industrial atmosphere.

Four steels were used in this research project: aluminum killed mild steel of commercial quality, aluminum killed carbon steel with copper and chromium additions, and two electro galvanized steels whose substrate was the same as non-galvanized steels. All the steels were phosphatized and painted.

Experimental

The metallic materials used in this investigation were: aluminum killed mild steel of commercial quality (CC); aluminum killed carbon steel with copper and chromium additions (RIII); and electrogalvanized steels with aluminum killed mild steel substrate (EG) and using as a substrate aluminum killed carbon steel with copper and chromium additions (EG/Plus). The test specimen dimensions were 100 mm × 150 mm, with a thickness ranging from 0.55 to 1.20 mm.

The test specimens were degreased with an alkaline product at 80 °C and subsequently washed with distilled water. Then these samples were dipped in titanate-based refining solution and phosphatized by immersion in zinc phosphate solution for 4 min, in the case of CC and RIII steels, or for 2 min, in the case of EG and EG/Plus steels. Finally the test specimens were dipped in a chromate-based passivating solution. The samples were painted by immersion using alkydic paint. The wet paint film was cured in two stages. First, it was submitted to accelerated solvent evaporation in an oven at 120 °C for 11 min; second, the paint film itself was cured by oxidation in air for 72 h.

The metallic substrate's chemical composition was determined by plasma spectrometry. The weight and chemical composition of the zinc and phosphate coats were determined by removing the coat layers from five samples and analyzing the removing solution by means of plasma spectrometry. The solution used to remove the zinc coat was HCl 1:1 v/v. For removing the phosphate coat a CrO_3 0.5% p/v solution was used at 70 °C.

The dry paint film thickness was measured in five samples of each steel grade studied, using Fishers's magnetic induction thickness measuring device, model Fischerscope MMS (Multi Measuring System), in accordance with ASTM E 376/89 Standard. The paint film adherence was measured using the tape test method according to ASTM D 3359/97 Standard, in dry condition, after immersion in water and after exposure in the wet cabinet, as well as the tensile method. The phosphate layer porosity of the carbon steels was measured using an electrochemical technique of polarization. The electrolyte was a solution of

NaOH 40 g l^{-1} [8]. The porosity of the phosphate layer of the electrogalvanized steels was measured using a voltametric anodic dissolution technique in $KHCO_3$ solution [9]. The EG&G Princeton potentiostat (273 A model) was used. The current density values of the carbon steels were obtained in the –550 mV (SCE) potential, and the current densities of the electrogalvanized steels were obtained in the peak of the anodic dissolution curve.

Three accelerated corrosion tests were performed: Cyclic I, GM9540P—Method B, and the field-test with saline solution spray. The fourth test method was a non-accelerated corrosion test in industrial atmosphere.

Cyclic accelerated corrosion test Cyclic I

The Cyclic I test is comprised of the moistening and drying cycles of the painting system similar to the case of the natural weathering test. Ten samples of each steel grade were tested. The duration of the Cyclic I test was 5 and 10 cycles, each cycle lasting 168 h.

The following test procedure was adopted for the Cyclic I test: on the first day, the test specimens were exposed to a saline solution in the salt spray cabinet, solution NaCl 5% w/v, pH from 6.5 to 7.0, at a temperature of (35 ± 2)°C for 24 h. From the second up to the fifth day, the samples were exposed in the wet cabinet for 8 h, relative humidity higher than 95% and at a temperature of (40 ± 3)°C; and for 16 h in the same cabinet, switched off, and opened. On the sixth and seventh day the test specimens remained exposed in a laboratory environment. The wet surface period in this test was 33% [4].

Cyclic accelerated corrosion test GM 9540P—method B

The cyclic test GM 9540P/B was developed by General Motors, and its duration was 40 cycles and 80 cycles, which correspond respectively to 5 and 10 cycles of the Cyclic I test.

Ten test specimens of each steel grade were tested. Each cycle of the GM 9540P/B test has five stages. The first stage was repeated four times prior to going to the second stage. It comprised four applications of mixed saline solution spray (0.9% w/v NaCl plus 0.1% w/v $CaCl_2$ plus 0.25% w/v $NaHCO_3$, with pH ranging from 6.0 to 8.0) for 15 min each, followed by 75 min intervals at (25 ± 2)°C without application of a saline solution spray. In the second stage, the samples were exposed for 120 min in a dry chamber with relative humidity below 30% at a temperature of (25 ± 2)°C. In the third stage, the material remained 8 h in the wet chamber with relative humidity between 95 and 100% and at a temperature of (49 ± 2)°C. Then, they were exposed for 7 h in a dry chamber with relative humidity below 30% at a temperature of (60 ± 2)°C and 1 h in a dry chamber with relative humidity below 30% at a temperature of (25 ± 2)°C. The wet surface period in this test was 37% [4].

Field accelerated corrosion test with saline solution spray

The field corrosion test with saline solution spray was performed in accordance with the ISO 11474 Standard. Ten test specimens of each steel grade were exposed at the mini-weathering site at the Usiminas steelworks, Ipatinga, Minas Gerais, Brazil. This site is classified as light/medium industrial according to the ISO 11474 Standard. Once a week a NaCl 5% w/v solution was sprayed on the samples. The wet surface period in this test was 50% [4].

Non-accelerated corrosion test in industrial atmosphere

The non-accelerated corrosion test was performed in accordance with the NBR 7011 Standard, using thirty test specimens from each steel grade investigated. This test was performed in the Usiminas' atmospheric corrosion station, in a location whose elevation is above that of the industrial plant. This site is classified as light/medium industrial according to the ISO 11474 Standard. The wet surface period in this test was 50% [4].

In every test the sample corrosion resistance was evaluated by determining the average cosmetic corrosion (scribe creepback measurement) and the maximum corrosion penetration according to the NBR 8754 Standard.

Results and discussion

Materials characterization

Table 1 shows that the RIII steel does not have copper and chromium contents compatible with those of weathering steels (Cu: 0.25% w/w to 0.50% w/w and Cr: 0.40% w/w to 0.65% w/w) [10], although they are higher than the corresponding contents of aluminum killed mild steel.

The zinc coating weight (63.2 g/m^2) of the EG/Plus steel was higher than that of EG steel (52.5 g/m^2),

Table 1 Chemical composition of the steels

Steel grade	Chemical composition (% w/w)									
	C	S	Mn	P	Si	Al_{sol}	Al_{insol}	N	O	Ni + Cu + Cr
CC	0.060	0.014	0.26	0.020	0.009	0.052	0.002	0.0027	0.0035	0.055
RIII	0.047	0.013	0.20	0.016	0.013	0.031	0.002	0.0064	0.0035	0.128
EG	0.047	0.007	0.21	0.013	<0.005	0.063	0.002	0.0066	0.0034	0.060
EG/Plus	0.034	0.007	0.27	0.010	0.016	0.060	0.003	0.0064	0.0032	0.122

Table 2. The result of the zinc coating chemical analysis did not show the presence of foreign elements in this layer [4]. It was identified the crystalline phase eta (η - Zn pure) formed by small randomly oriented hexagonal crystals [4].

The phosphate layer weight of electrogalvanized steels was on average 2.7 times more than that of carbon steels, as shown in Table 2. The reason for such difference resides on surface reactive of theses steels and the phosphatization process adopted. X-ray diffractometric analysis found just the crystalline hopeite phase [$Zn_3(PO_4)_2.4H_2O$] in the phosphate layer of such steels [4]. However, the presence of iron in the phosphate layer of CC and RIII steels indicates the existence of compounds containing this element and that they do not show a differentiated crystalline structure. The phosphate layer of RIII steel showed the lowest porosity compared to the layers deposited on CC, EG and EG/Plus steels, Table 2. Miranda et al [11] reported that the value of the reduction current density of hydrogen ions increases with the copper content up to contents of about 0.10% w/w. Therefore, copper addition favors the reduction reaction of hydrogen ions, thus accelerating the phosphatization. As a consequence, it was found that the porosity of the phosphate layer of RIII steel is lower than that of the phosphate layer deposited on CC steel, which confirms the result obtained in the present work.

The samples have an average dry paint film thickness of (24.8 ± 4.0) µm, Table 2. The dry paint film adherence to the steels under investigation was very good in the dry tests and after exposure in the wet cabinet. However, when tested after immersion in water the electro galvanized steels presented detachment “grade 1”. In the adherence test under tension [4] the dry paint film of RIII steel showed the highest value, affording a tension of 1.22 MPa. On the other hand, the EG/Plus steel presented the lowest resistance, 0.76 MPa, which may be attributed to the phosphate coat weight.

Accelerated cyclic corrosion test Cyclic I

From the results shown in Fig. 1, it can be seen that after five test cycles it is possible to distinguish the various samples as far as their corrosion resistance is concerned.

EG and EG/Plus steels present average cosmetic corrosion values below those of CC and RIII steels. Such result confirms that zinc provides a cathodic protection to steel.

Shastry and Townsend [12] have proposed that during accelerated testing, the majority of the under paint area is anodic, however, the delamination front remains cathodic. The cathodic delamination of the dry paint film was explained by Furbeth et al [13, 14]. The

Table 2 Measurement results of zinc and phosphate coating weight, and dry paint film thickness and adherence

Steel grade	Zinc weight (g/m^2)	Phosphate layer			Dry paint film			
		Weight (g/m^2)	Poro sity (%)	Thickness (µm)	Adherence rate			
					Tape test[a]			Tension (MPa)
					Dry	Water[b]	Wet chamber[c]	
CC	Nil	2.1	35.8	24.5	grade 0	grade 0	grade 0	0.97
RIII	Nil	2.3	10.5	24.8	grade 0	grade 0	grade 0	1.22
EG	52.2	5.8	27.4	25.3	grade 0	grade 1	grade 0	1.10
EG/Plus	63.2	6.5	23.5	24.5	grade 0	grade 1	grade 0	0.76

[a] Grade 0 corresponds to no detachment in the grid area and “grade 4” corresponds to detachment of approximately 65% of the evaluated area

[b] Adherence measured after 24 h of immersion in distilled water at 40 °C

[c] Adherence measured after 24 h of exposure in wet cabinet with moisture above 95% at 40 °C

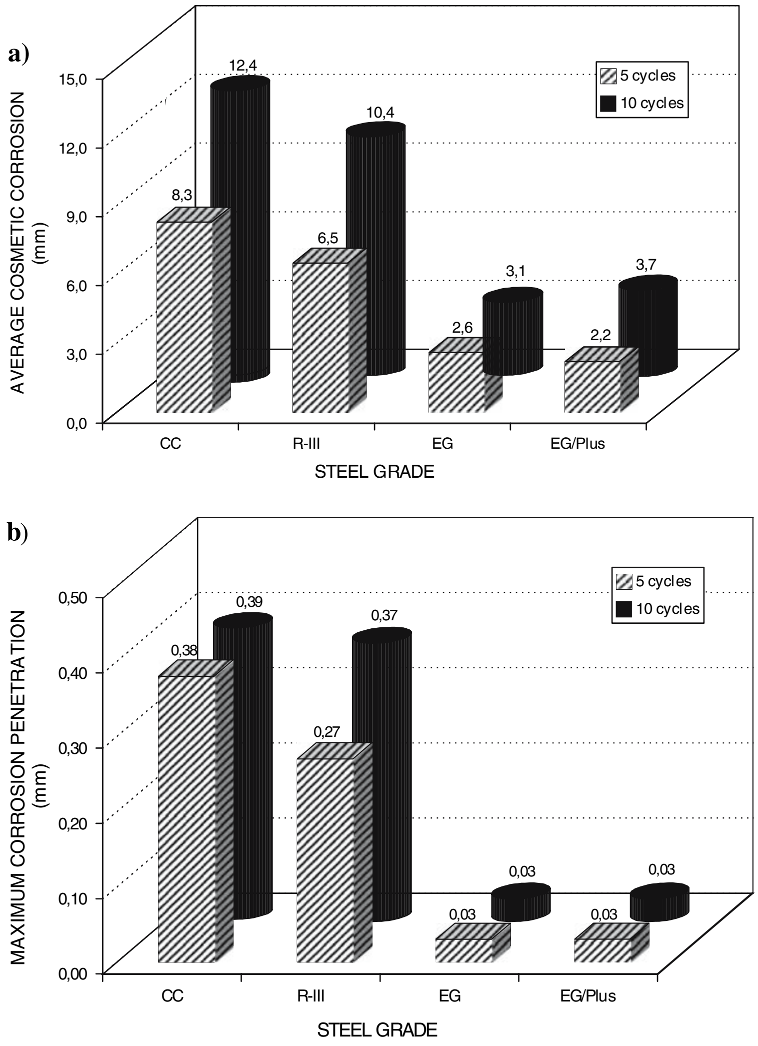


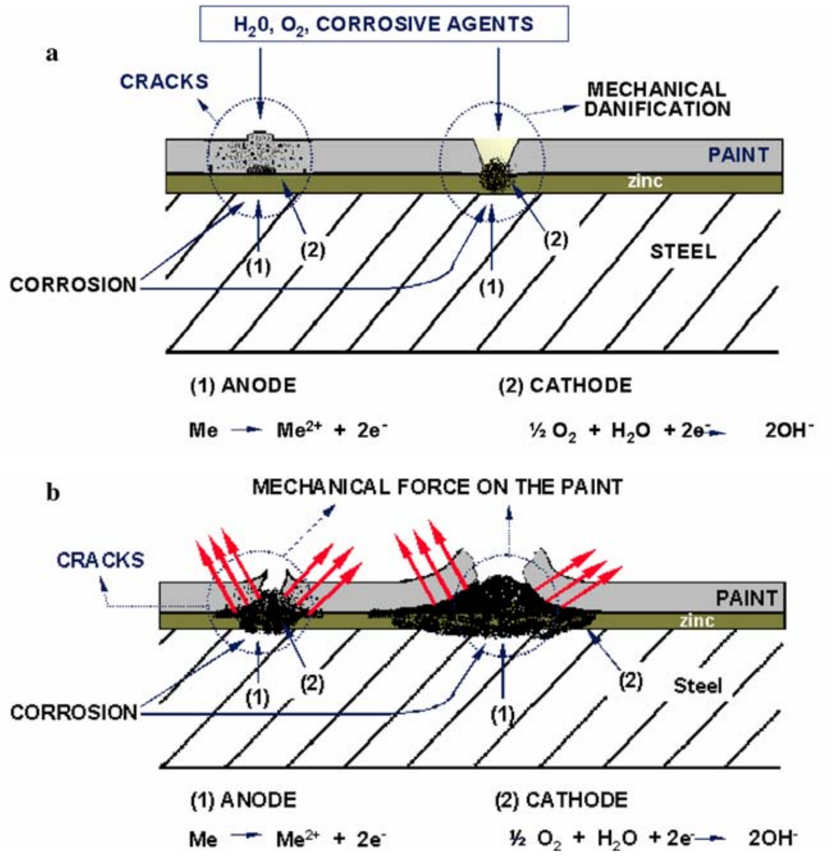
Fig. 1 Average cosmetic corrosion (**a**) and maximum corrosion penetration (**b**) of phosphatized and painted steels after 5 and 10 cycles of Cyclic I Test

defect area is an anodic zone (Fig. 2a), which occurs the zinc dissolution. The oxygen reduction occurs in the region close to the defect, under painting, where the zinc layer was still unchanged (Fig. 2a). Water and oxygen can permeate to the zinc-painting surface in a high rate (Fig. 2a). The balancing of the zinc cations formation is done by the OH^- production in the cathodic zone close to the defect area, or by the ions transportation from the defect zone to the cathodic region. Electrons produced by the zinc dissolution can reduce oxygen in micro-cathodes in the defect zone or in an area under painting close to the anodic region (Fig. 2a). Water and oxygen, which permeate the paint layer, come together and react in a region at the head of the defect. The corrosion products inhibit zinc dissolution. Process kinetics is complex and depends on the cathodic region and the zinc layer thickness. During the early stages of delamination, there was an electrochemical cell with a distinct anodic and cathodic zone. The later stages may be more complicated when voluminous corrosion products are formed that can exert a mechanical force on the paint from underneath [15], as shown in Fig. 2b. As the time increases, zinc dissolution near to the defect zone inhibits the cathodic protection of the iron.

The corrosion mechanism of the galvanized steels in which the steel substrate is exposed to the environment is a result of steel corrosion and cathodic delamination, Fig. 2. In the early stages, the steel is protected by zinc. Corrosion products have an significant effect in the corrosion propagation. The best performance of the galvanized steels in relation to the carbon steels is due to the small zinc oxide volume produced under the paint layer, to the barrier protection of the oxides and to the cathodic protection of steel by zinc.

According to Leidheiser [16], there was a difference between metals relative to their catalytic properties for the cathodic reaction of oxygen reduction. Copper, iron, and zinc are excellent catalysts for the oxygen reduction reaction, increasing the cathodic

Fig. 2 Cathodic delamination mechanism



delamination. Electrogalvanized carbon steel with copper showed a good corrosion resistance. This steel showed copper that is a good catalyst for the oxygen reduction, but this steel also showed a thicker zinc and phosphate layers.

Carbon steel showed the higher oxide volume and the higher mechanical force on the paint from underneath. Figure 3 shows transversal section of the carbon steel and electrogalvanized carbon steel after 10 cycles of Cyclic I test. Chloride ions presence in the corrosion front that was identified using an EDS analysis (Fig. 3) confirms that the delamination mechanism is cathodic. Chloride ions are attracted by zinc cations, and goes to the corrosion front as the delamination is developing. Delamination occurs due to the mechanical force of the corrosion products and to the dissolution of the zinc and phosphate layers.

Scanning electronic microscopy and EDS analysis showed that there were calcium and titanium in the corrosion front of carbon steel. In the phosphatizing process, the samples were degreased with an alkaline product at 80 °C and subsequently washed with distilled water. Then these samples were dipped in titanate-based refining solution and phosphatized. The presence of titanium can be due to the phosphatizing process.

Regarding the maximum corrosion penetration results (Fig. 1), five test cycles were enough to distinguish EG and EG/Plus steels from CC and RIII steels in terms of corrosion resistance in the studied medium. The samples of EG and EG/Plus steels showed maximum corrosion penetration values much lower than those obtained for the samples of CC and RIII steels. After the 10th cycle the maximum corrosion penetration value of RIII steel was close to the value reached for the CC steel.

In order to properly evaluate the service life of EG and EG/Plus steels by means of the Cyclic I corrosion test using the maximum corrosion penetration measurements it is necessary to use more than 10 cycles, since the maximum corrosion penetration achieved for such steels after 10 testing cycles was equivalent to the mechanical damage of the test specimens, therefore being deemed insignificant.

Accelerated cyclic corrosion test GM 9540 P—method B

Figure 4 shows that the average cosmetic corrosion in CC and RIII steels was of a higher magnitude than that obtained for electrogalvanized steels. After 40 test cycles, the CC steel presented full perforation. RIII

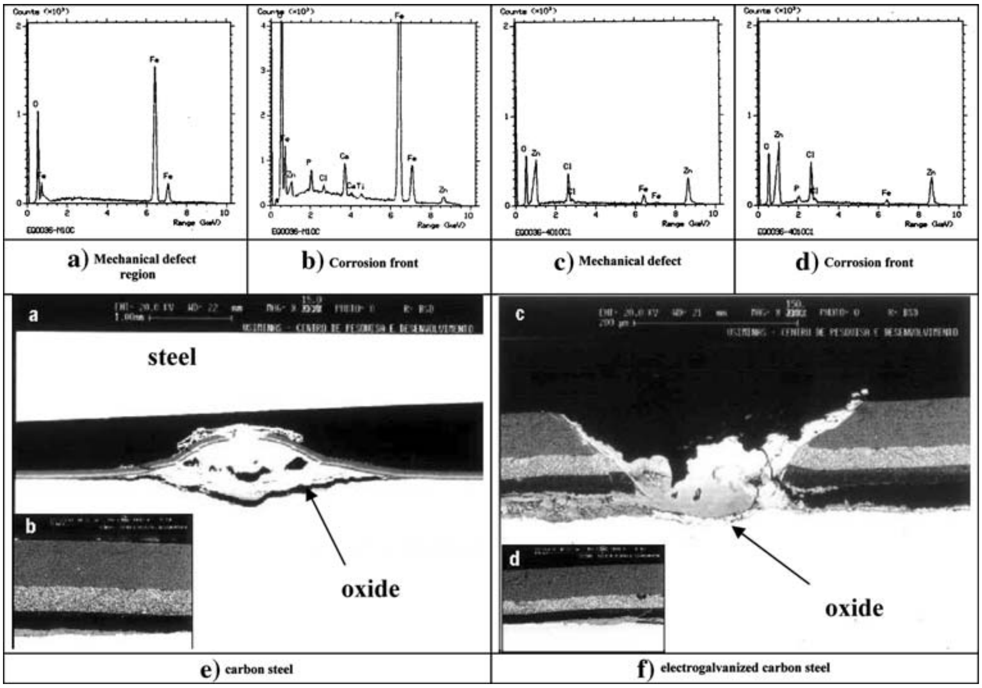


Fig. 3 Transversal section of the phosphatized and painted carbon and electrogalvanized carbon steels after 10 cycles of Cyclic I test

steel presented a maximum corrosion penetration of 54% of its initial thickness, whereas for EG steel this percentage was only 8%. The maximum corrosion penetration of EG/Plus steel was of a magnitude similar to the mechanical damage of the samples, therefore being deemed insignificant.

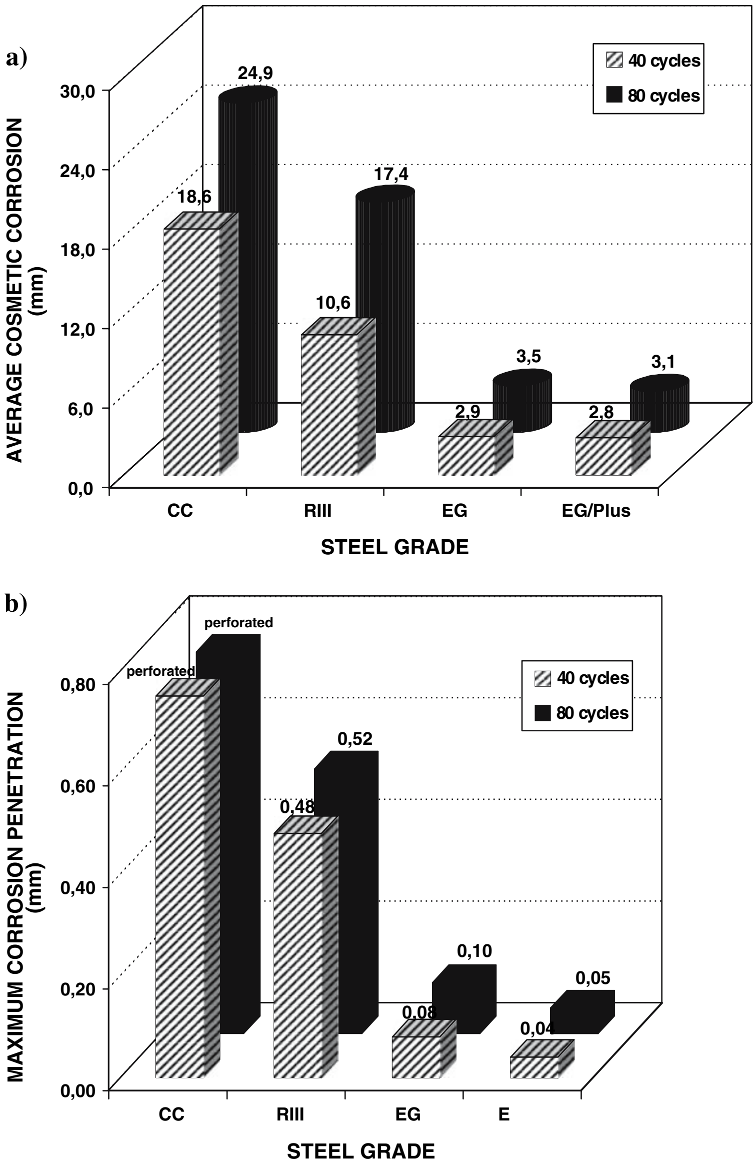
The results given in Fig. 4 show the capability of the cyclic test GM 9540P/B distinguishing the atmospheric corrosion resistance of zinc coated and uncoated steels.

Besides, this test method was also capable of evidencing the differences in the corrosion resistance between CC and RIII steels, either coated or not with zinc.

Evans and Taylor [17] and Stratmann et al [18, 19] proposed a mechanism for the atmospheric corrosion of a mild steel. They reported that during the wetting, initial stage of the wetting–drying cycle, the anodic dissolution of iron is mainly balanced by the reduction of ferric species within the rust layer and very little oxygen is reduced. So, oxygen reduction cannot provide the large corrosion rates observed during the wetting stage. Another available oxidizer is γ—FEOOH present in the rust layer. The γ –FEOOH phase reacts with an electron and hydrogen cation to give γ –Fe·OH·OH. The next stage, wet stage, begins and is characterized by oxygen reduction as the major cathodic reaction. At the end of the drying, the third stage of the cycle, the species reduced during the first stage and other ferrous compounds produced by the corrosion process are re-oxidized by oxygen. This mechanism can operate during the cyclic accelerated corrosion test GM 9540P—method B when the oxidation of zinc and the formation of zinc corrosion products inhibit the cathodic protection of steel, which starts its corrosion process. During the initial exposition of samples in a salt spray chamber, the anodic reaction of iron was the oxidation of iron to produce Fe^{2+}, and the cathodic reaction could be the reaction of the γ –FEOOH phase with an electron and hydrogen cation to give γ –Fe·OH·OH. In the third stage of the GM 9540P test, the material remained 8 h in the wet chamber with relative humidity between 95 and 100% and at a temperature of (49 ± 2)°C, and the oxygen reduction could be the major cathodic reaction, instead of the γ –FEOOH reduction [18, 19]. At the end of the drying, the fourth and the fifth stage of the cycle, the species reduced during the wet stages are re-oxidized by oxygen, regenerating the γ –FEOOH.

According to Stratmann et al [20, 21], the reduced lepidocrocite (γ –Fe·OH·OH) would be a compound of same chemical formula as iron hydroxide but keeping the same crystallographic structure as its mother phase γ –FEOOH. It would be a Fe^{2+} doped lepidocrocite: Fe [II] being in Fe sites and OH^{-} being in O sites. The Fe^{2+} doping turns the reduced lepidocrocite into an electronic conductor [21]. Roberge [22] related that weathering steels generally perform best when they are freely exposed to the open air in industrial environments. Copper and chromium additions influence the rate of rusting by raising the potential of the surface to more noble values, encouraging passivation [22]. It is possible that there was a doping of chromium ad

Fig. 4 Average cosmetic corrosion (**a**), and maximum corrosion penetration (**b**) after 40 and 80 cycles of the cyclic corrosion test GM 9540P—method B



copper of Fe[II] doped lepidocrocite, and these cations could stabilize the reduced lepidocrocite and then decrease its re-oxidation at the end of drying, decreasing the corrosion rate.

Finally, the electrolyte film evaporates, thus slowing down the electrochemical corrosion. The corrosion rate and the rust layer modifications are thus correlated to the number and frequency of the wet–dry cycles. The GM 9540P/B test was more aggressive than the Cyclic I test (Figs. 1, 4), probably because It has more wet-dry cycles of short duration.

The corrosion mechanism observed in the GM 9540P/B test was the cathodic delamination, together with a wedge-type mechanic effect caused by the corrosion products [4, 7]. The delamination mechanism also occurred in the field tests. The better corrosion performance of RIII steel compared to CC steel may be explained by its corrosion mechanism. The presence of copper in the RIII steel provides a remarkable reduction in the critical corrosion current density, thus resulting in lower tendency to anodic dissolution of this steel grade. Moreover, the porosity of the phosphate layer deposited on the RIII steel surface is lower that that of CC steel, which provides the former with increased corrosion resistance.

After 80 test cycles, the EG/Plus steel showed a higher corrosion resistance than did the EG steel. Such result may be explained not only by the fact that EG/Plus steel zinc layer is heavier than that of the EG steel, but also, and particularly, because the metallic substrates of such materials are RIII and CC steels, respectively. Increased corrosion resistance of RIII steel results in a lower maximum corrosion penetration, and as a consequence, a lower average cosmetic corrosion ($i_{\text{corrosion}} = i_{\text{cosmetic}} + i_{\text{penetration}}$) [4].

Accelerated corrosion field test with saline solution spray

Figure 5 shows that the field test with application of saline solution spray is an efficient method to distinguish the corrosion resistance performance of coated and uncoated steel as well as to determine such performance as a function of the metallic substrate.

EG and EG/Plus steels showed an average cosmetic corrosion much lower than that of CC and RIII steels, and their corresponding values were of significance only after 12 months of exposure. On the other hand the cosmetic corrosion of CC and RIII steels was measurable after 3 months of exposure. Figure 5 shows a typical variation of corrosion rate with time. The corrosion rate of the phosphatized and painted carbon steel and the phosphatized and painted carbon steel with low copper and chromium is initially high, followed by a gradual decrease and finally became constant. These results are according to the literature [23]. Concerning the maximum corrosion penetration, CC steel presented full perforation after 12-month exposure, whereas RIII steel presented the same perforation only after a 24-month exposure. The maximum corrosion penetration values of galvanized steels were not significant up to 24-month exposure. In order to better highlight the difference in performance of EG and EG/Plus steels it is necessary to increase either the weekly frequency of saline solution spay or the test duration.

The data in Figs. 4 and 5 show that the average cosmetic corrosion results, obtained in the field test during a 24 month period, with an application of a saline solution spray are similar to those of the GM 9540P/B cyclic test with 40 cycles.

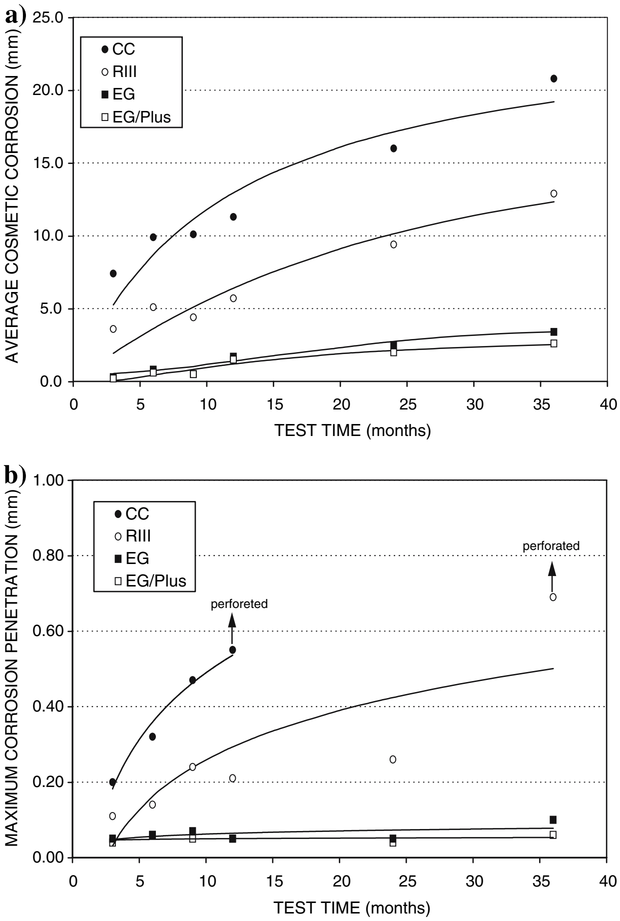


Fig. 5 Average cosmetic corrosion (**a**) and maximum corrosion penetration (**b**) of phosphatized and painted steels exposed to an accelerated corrosion field test with saline solution spray

Non-accelerated corrosion test with exposure to industrial atmosphere

Figure 6 shows that the corrosion resistance of RIII steel is higher than that of CC steel. After a 3-year exposure, the average cosmetic corrosion and the maximum corrosion penetration of CC steel are 1.5 and 1.7 times the cosmetic corrosion and penetration of RIII steel, respectively. The non-accelerated corrosion test also evidenced the improved performance of EG and EG/Plus steels in relation to CC and RIII steels as far as the atmospheric corrosion resistance is concerned. When comparing the results of Figs. 6 and 5, it can be concluded that the saline solution spray has the effect of accelerating the test, providing a faster differentiation of the corrosion resistance of the steels studied. The analysis of the corrosion product shows that the corrosion mechanism for the two steels is basically the same [4].

As expected, when compared to uncoated steels, the electrogalvanized steel showed better performance in the tests carried out during this study as far as atmospheric corrosion resistance is concerned.

Among the cyclic tests carried out, GM 9540P/B cyclic test proved to be suitable to evaluate the atmospheric corrosion resistance of steels and their corresponding painting systems. This test method is capable of distinguishing the corrosion resistance of uncoated steels from that of zinc-coated steels as well as among uncoated steels or among the zinc-coated steels. Moreover, GM 9540P/B test demands a minimum testing period of forty days, whereas the non-accelerated

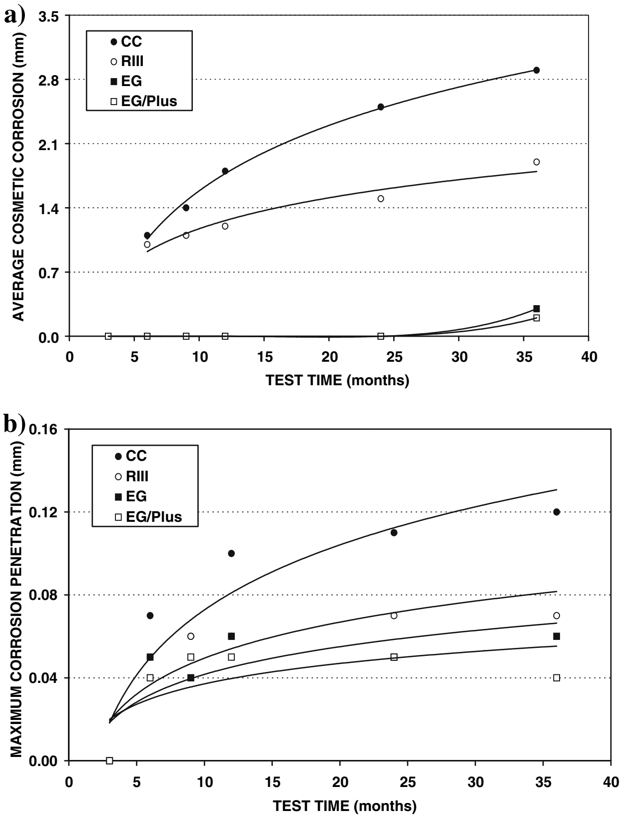


Fig. 6 Average cosmetic corrosion (**a**) and maximum corrosion penetration (**b**) of the phosphatized and painted steels after exposure to industrial atmosphere

corrosion test requires an exposure period in excess of 2 years.

The corrosion field test with saline solution spray has also proven to be efficient in evaluating the atmospheric corrosion resistance of steels and their corresponding painting systems. This test requires an exposure time, which is lower than that of the non-accelerated corrosion test, and its test cost is lower compared to the cyclic corrosion tests. Depending on the number of weekly spray applications on the test pieces, the test duration may be reduced without affecting the corrosion mechanism, as evidenced in works carried out for the automobile industry [13]. Nevertheless, in the case of the civil construction industry, it is convenient to carry out more research regarding test time in order to optimize test duration while providing significant results in terms of average cosmetic corrosion and maximum corrosion penetration.

The utilization of RIII steel as an evaluation parameter of civil construction materials is justified in view of its increased corrosion resistance as compared to the CC steel, taking into consideration its potential application in the construction of low cost housing.

Conclusions

- As expected, when compared to uncoated steels, the electrogalvanized steel showed better performance in the tests carried out during this study as far as atmospheric corrosion resistance is concerned.
- Among the cyclic tests carried out, GM 9540P/B cyclic test proved to be suitable to evaluate the atmospheric corrosion resistance of steels and their corresponding painting systems. This test method is capable of distinguishing the corrosion resistance of uncoated steels from that of zinc coated steels as well as among uncoated steels or among the zinc coated steels. Moreover, GM 9540P/B test demands a minimum testing period of forty days, whereas the non-accelerated corrosion test requires an exposure period in excess of 2 years.
- The corrosion field test with saline solution spray has also proven to be efficient in evaluating the atmospheric corrosion resistance of steels and their corresponding painting systems. This test requires an exposure time, which is lower than that of the non-accelerated corrosion test, and its test cost is lower compared to the cyclic corrosion tests.
- The utilization of RIII steel as an evaluation parameter of civil construction materials is justified in view of its increased corrosion resistance as compared to the CC steel, taking into consideration its potential application in the construction of low cost housing.

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