Synthesis and characterization of a protective coating against corrosion based on scale and iron pigment

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Received: 23 July 2019 / Accepted: 20 November 2019 / Published online: 25 November 2019
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Abstract

The objective of this work is to characterize two materials in order to synthesize anticorrosive coating. These materials are an oolitic iron oxide pigment containing phosphorus and scale which is a by-product of steel making that should be recycled. The characterization of these two components took place in the URASM/CRTI-Annaba laboratories. Chemical analysis showed that the pigment contains 53.18% iron and a siliceous gangue. The scale contains 73.83% iron as iron oxides (FeO , Fe_3O_4 and Fe_2O_3). Grinding tests have shown that the scale is much more suitable for grinding than pigment. Particle size analysis gave a volume distribution of particles ranging in size from 0.7 to 32 microns for the scale and from 0.6 to 40 microns for the pigment; their specific surfaces are between 1.6 and 1.5 m^2/g . TGA and DTA analyses have shown that the pigment loses weight with phase dissolution by consuming energy as the temperature increases. Scale is gaining weight by forming a new phase with heat. At SEM, the iron pigment is in the form of an aggregate of grains surrounded by gangue. Scale showed a homogeneous structure composed of iron oxide grains of sizes and shapes ranging from 1 to 10 μm . X-ray diffraction analysis showed that the iron contained in the pigment was in the form of hematite and goethite. A tiny portion is combined with silica as Fe_2SiO_4 . Iron in Scale is in the form of three oxides (FeO , Fe_2O_3 and Fe_3O_4). Spectrophotometric tests showed that for both materials absorption is nil and reflection is maximal (100%) in the visible range. The different coating formulations used have shown that a mixture of 71.43% pigments and 28.57% scale has the best corrosion resistance, resulting in low current and low corrosion rate.

Keywords Pigment iron · Scale · Simultaneous thermal analysis · X-ray diffraction · Spectrophotometry · Electrochemistry

1 Introduction

The pigments are iron ore deposits. Their use in the field of coatings is dictated by certain technical conditions.

Scale counts among the fatal productions of secondary materials generated by the steel industry. Umadevi and Chen [1, 2] showed that the scale is formed by oxidation at high temperature during the cooling of the products in continuous cast steel and during the reheating treatment and hot forming.

Pigments are chemical compounds with absorption only at certain wavelengths of the visible spectrum. This property makes their role as best coating.

The pigments are mainly in the form of fine dry particles and are almost dispersible in all solvents. There are different types of pigments:

- Nature: plants, earth, animals, flowers, trees.
- Chemical product: obtained by mixing or melting various materials.

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The use of pigments is clearly growing. They are widely used in the following applications: coating, toner, paint, ink, plastic, rubber, textile, cosmetics, food and pharmaceutical. Fabrice [3] showed that the analysis of the granulometry of the pigments could influence the properties of the final products such as: optical properties, color, shade, opacity, viscosity, gloss, durability and sedimentation.

Hematite has a dark red color and a granulometric analysis which are sufficient properties to be used as a chromophore for encapsulation in pigment production, this is demonstrated by.

Della et al. [4]. Pigments production is still carried out according to classical mechanical methods. The lands are extracted first manually from careers then cleaned, dried and finely ground. Their purity and fineness of their grinding determine the later possibilities of use as was described by Philip [5].

Husband et al. [6] wrote that pigments are usually powders. The fineness and the shape of the particles can considerably modify the properties of the ground pigment by acting on the proportion of light rays reflected by the surface of the grains.

Particle size has an effect on:

- The optical properties. The size of pigment particles can affect the final aspect of the coated surface. For example, a coating can be glossy, matte or satin, depending on the size of the particles. This effect is related to the phenomena of diffusion, reflection and refraction of light.
- The final performance of the coating. The ease of application of a pigment is determined by the particle size distribution of the elements. Particle size directly determines the intensity or depth of the coating.
- Rheological properties. For example, work done by Annemieke et al. [7] on the influence of the shape of the pigment particles on the tensile properties in the plane of the Kaolin-based coating layers, have shown that the intrinsic viscosity (μ) of particles having the same volume is directly related to their aspect ratio. The viscosity is increased by the presence of finer particles, which allows limiting the sedimentation and flocculation. These two phenomena can notably modify in a significant way the intensity of the formulation.

Coating applications are used to combat corrosion that is the result of the interaction between the base metal which is steel and the oxidant which may be a solution as has been demonstrated by Landolt [8], Latanision [9] and Benard et al. [10]. Among the most used protection methods against corrosion, we distinguish non-metallic coatings to isolate the metal from the corrosive medium.

Our objective in this study is to characterize mixtures for the synthesis of scale-based coating. In this part, we will determine the microstructure of two components, the *grindability* and finally the size of the particles by laser granulometry. Differential thermal analysis (TGA) and thermal variation of enthalpy (DTA) are measured and X-ray diffraction analysis is performed. Visible light spectrophotometer tests are carried out and finally electrochemical analysis on coatings is studied.

2 Used materials and methods

The studied materials, scale and iron oxide pigment, are characterized by different techniques and under various conditions. Chemical analysis was used to determine their iron content. Scanning electron microscopy observations were used to control their morphology, the shape and fineness of their grains, and their compactness. The particle size analysis was used to give information on the volume distribution of the grain size constituting them. Simultaneous thermal analysis (TGA and DTA) was performed by analyzing materials from ambient temperature up to 1200 °C to examine the mass and heat variations for both materials and their mixtures. The determination of the phases constituting the scale and the pigment of iron oxide is carried out by X-ray diffraction. Optical measurements have been made in this work in order to estimate the absorbing, transmitting and reflecting power of the light when are exposed to radiation.

The chemical analysis of the materials is carried out using a SIEMENS SRS-3000 spectrometer. This method is fluorescence spectrometry operating by wavelength dispersive analysis. A control of grain size is carried out after each grinding session with a mesh of 32 microns.

The particle size distribution is studied using a "Master-sizer 2000/Malvern" laser microgranulometer. This works with the Hydro MU sample preparer.

The study of the contribution of the laser granulometric analysis in the physical characterization of the calcareous loads of Michel and Courard [11] shows that it is an indirect measurement technique commonly used to determine the particle size of distribution of powdered materials.

Indeed, it has been shown that the rheological properties depend on the fineness of the grains [6].

Thermogravimetric analysis was used as a reference method to determine the amount of reacting material for the formation of the pigment mixture and phenomena that may occur during heating.

Simultaneous thermal analysis was performed by a device of TA-Instruments SDT.Q.600 type.

A scale amount is added in the range of (5, 10, 15, 20, 25% and 35%) to optimize the synthetic blend. According

to the experimental procedures of TGA and DTA cited by Thirion [12], the heating is provided at 50 °C per minute up to a temperature of 1100 °C in an alumina crucible for the measurement of TGA and DTA.

The scanning electron microscope used in mineralogical quantification is a type of Quanta 250 microscope with an Ametek analyzer.

Ambient temperature transmission measurements (absorption and reflection) were performed by an Agilent Carry 5000 UV–visible–IR spectrophotometer.

UV–visible Spectrophotometry is an optical characterization technique. It provides information on the optical properties of the sample to be analyzed, such as light transmission, absorption and reflection rates. This technique gives us information about wavelength domains where transmission, reflection and absorption are important or weak.

When a material has an order in the three directions of space, crystalline material (case of the pigment) or semi-crystalline, it has the property of diffracting the X-rays. X-ray diffraction is thus a technique particularly well adapted for the structural characterization of iron pigments.

The diffractogram or diffraction spectrum obtained is composed of the lines diffracted by the different families of crystalline planes (hkl) of the crystal lattice of the analyzed material.

The acquisition is performed by a control unit and the processing of diffractograms or spectra is performed using software (PDXL-2.5: X-Ray Powder Diffraction Software) based on ASTM data sheet data (American Society for Testing and Materials), matching interplanetary distances d_{hkl} to recorded angles.

The crystallographic structure of our materials was studied using a Rigaku diffractometer, equipped with a copper anticathode tube.

For coatings blending tests:

Steel samples produced at the El-Hadjar complex were prepared and polished to which a coating formulation was applied. These formulations were the subject of mixing work in the URASM/CRTI-Annaba laboratory. The coating is sprayed onto the steel samples using a pneumatic gun at a pressure of 2.5 bar, as described by Benali [13].

Several formulations based on scale and iron pigment (natural or calcined) have been implemented. For the comparative study, we have chosen as reference a anticorrosive coating based on iron oxide “Glyfer”. The ratios of the formulations are shown in Table 2.

The fineness is measured using the fineness gauge. The viscosity is determined by a CoupFord4 type viscometer (CF4). The density is measured by means of a pycnometer. The surface condition of the samples after immersion in a solution of NaCl is observed by means of a Nikon Eclipse LV150 N type optical microscope. The electrochemical study was carried out at the level of corrosion laboratory with a potentiostat–galvanostat of the “EGG instrument versastat” type controlled by “softcorr3” software.

3 Results and discussion

3.1 Chemical analysis

Both materials mainly contain iron oxides. Like all minerals, the pigment contains gangue oxides. The analysis is given in Table 1.

The hematite and magnetite in the pigment are calculated from the total iron and ferrous iron contents.

A simplified calculation shows that the pigment contains 72.48% hematite and 3.44% magnetite.

$$\text{Total Hematite} = (\text{FeT} - \text{Fe}^{+2}) \times 1.43 \quad (1)$$

$$\text{Magnetite} = \text{FeO} \times \left(\frac{232}{72} \right) \quad (2)$$

$$\text{Hematite combined} = \text{FeO} \times \left(\frac{232}{72} \right) - \text{FeO} \quad (3)$$

$$\text{Hematite not combined} = \text{Total Hematite} - \text{Hematite combined}.$$

3.2 Grinding

The choice of the particles size has consequences on the modes of dispersions stability.

Indeed, the micrometric size particles are attracted by the Van der Waals force of high intensity comparable to their sizes.

According to Cabane [14] and particularly particle shapes have a significant effect on the mechanical properties of aggregated dispersions.

The sampling and grinding conditions are the same for both materials, namely:

Table 1 Chemical analysis of iron pigment and scale

	FeT	FeO	CaO	SiO ₂	MgO	Al ₂ O ₃	MnO	P ₂ O ₅	ZnO	Fe ₂ O ₃	Fe ₃ O ₄
Pigment	53.18	1.07	0.76	4.23	0.36	2.13	0.64	1.63	0.75	72.48	3.44
Scale	73.83	56.9	0.42	0.14	0.37	–	–	–	–	–	–

- Raw materials crushed to less than 160 microns.
- Drying at 200 °C.
- Sample masse 10 g ± 0.3
- Screening time: 03 min (suction) through a mesh sieve of 32 microns.
- Depression (suction) of 1500 Pascal.

We retain initial results that the scale has a better yield of grindability than the pigment. The grinding of the pigment is carried out at 3, 5, 8, 12 and 15 min. The results are shown in Fig. 1. For this reason, grinding of the scale is carried out at 1, 2, 3, 4 and 5 min. The results are shown in Fig. 2. We conclude that the optimal time for grinding the pigment and scale is 5 and 1 min, respectively.

3.3 Particle size

As noted above, the particle size has an effect on the optical properties, the final performance and the rheological properties of the coating. The viscosity is increased by the presence of finer particles, which allows limiting the sedimentation and flocculation. These two phenomena can notably change the intensity of formulation. According to the work of Bohic [15], the particle size is generally between 0.1 and 50 microns. D_{50} is between 1 and 10 microns.

Particle size analysis measured by a laser granulometer (Hydro 2000MU) gave us a volume distribution with particle size between 0.7 and 32 microns for scale and between 0.6 and 40 microns for the pigment. Thus, as can be seen, the average diameters (D_{50}) are 6.31 microns for the scale and 7.97 microns for the pigment. Their specific areas are 1.6 and 1.5 m²/g.

Fig. 1 Grindability of iron pigment

Fig. 2 Grindability of the scale

3.4 Simultaneous thermal analysis

Simultaneous Thermal Analysis for scale shows an increase in weight (3.602%) between 400 and 1000 °C, which is attributed to the oxidation reaction of iron oxides (new phase formation) according to the reaction.

Between 850 °C and 1150 °C, the system remains stable, according to the reaction.

This oxidation is accompanied by a weight gain and a heat generation (exothermic reaction) respectively of 3.602% and 1.128 W/g, it is shown by Fig. 3.

For iron pigments, this analysis shows a loss of mass by evaporation of the water combined in the iron matrix as hydroxide FeOOH. This decrease of 11.05% is recorded

Fig. 3 Simultaneous thermal analysis of the scale

between temperatures 289 °C and 349 °C. It is accompanied by heat absorption (endothermic reaction) equal to 1 926 W/g, as shown in Fig. 4.

According to Goss [16], kinetic of phase transformation of αFeOOH into $\alpha\text{Fe}_2\text{O}_3$ during heating above 255 °C is evidenced by a dehydration mechanism, thus the weight loss in the TAG test. Hematite only starts to grow from a 3.97% weight loss with synthetic goethite. The transformation of the product is from the surface towards the interior of the grains by the formation of pores releasing water vapor.

In this figure, we notice that there's a first small endothermic peak corresponding to the fact of a quantity of heat required to evaporate moisture from the pigment at temperature lower than 200 °C.

Thermal analysis mixtures synthesized with the addition of (5, 10, 15, 20, 25 and 35%) of scale in the natural iron pigment showed a weight loss fall. This can be explained by the decrease in the amount of pigment in favor of the scale. Loss of weight is proportional to the rate of addition of mill scale, when the injection rate of scale increases, the weight loss decreases.

Fig. 4 Simultaneous Thermal Analysis of the iron pigment

Fig. 5 Size and morphology of the crushed grains **a** oxide scale and **b** iron pigment

The energy expended for the dissolution of iron hydroxides (goethite dissociation) in the pigment is offset by the energy released by the scale (oxidation reactions).

3.5 Scanning electron microscope

The SEM observation of scale showed a homogeneous structure composed of iron oxide grains with sizes and forms ranging from 1 and 10 micrometers (Fig. 5a). Chemical analysis on all ranging in observation given by EDS (Fig. 6) shows the dominant existence of iron with very little of manganese and some traces of silicon and aluminum. Iron is the main component of steel from which the scale was formed (oxidized iron), manganese is important in the chemical composition of the steel. Traces of Si and Al can originate either from the chemical composition of the iron-carbon alloy (steel) or from the powder of the continuous casting.

Scanning electron microscope image of pigment shows a grain aggregate rounded formed at least of iron oxide and gangue (Fig. 5b). The EDS analysis (Fig. 7) shows a predominance of iron with a rather important gangue

Fig. 6 EDS spectrum of scale

Fig. 7 EDS spectrum of iron oxide pigment

Fig. 8 X-ray diffractogram of scale (FeO-Cubic, Fe₂O₃-Orthorhombic and Fe₃O₄-trigonal)

containing the four predominant oxides (silicon, calcium, aluminum and magnesium).

3.6 X-ray diffraction analysis

The X-ray diffractogram (Fig. 8) shows that the scale contains a mixture of crystalline phases of wustite, magnetite and hematite. Wustite (Fe_{0.94}O) has cubic structure, magnetite (Fe₃O₄) has orthorhombic crystal and hematite (Fe₂O₃) has trigonal structure.

The X-ray diffractogram of pigment (Fig. 9) shows that the crystalline phases are also mixtures of 6 phases. These phases are goethite, hematite, fayalite, silica, phosphorus pentoxide, and hausmannite respectively.

Fig. 9 X-ray diffractogram of Iron pigment (FeOOH, Fe₂O₃, Fe₂SiO₄, Mn₃O₄, SiO₂, P₂O₅)

Fig. 10 Absorbance spectra of raw materials and their mixture

3.7 Spectrophotometric analysis

The absorption spectra of two raw materials and their mixture (Fig. 10) showed the presence of two peaks in each one's. The first and weakest one at a wavelength of 320 nm while the maximum absorption is done a higher wavelength at 365 nm, these peaks are located in same place and located in the near ultra-violet region. These materials does not absorb in the visible part of the spectrum. In the visible region (380–780 nm), we observe an almost zero absorbance. A coloring substance is most often defined by its ability to absorb visible light.

Fig. 11 Reflectance spectra of materials and their mixture

The reflectance spectra of these materials in the visible region has shown an excellent reflectance, note that the curve is on average 120% (Fig. 11).

This indicates that the constituents of these materials themselves become sources of radiation that can be added to the total reflected radiation. The incident radiation is totally reflected.

4 Tests of corrosion protection coating

4.1 Sample preparation

The different characterization techniques used in this work are presented below. Shape and surface quality were taken into consideration.

- Shape: Machining of samples as a circle, square and rectangle.
- Polishing: Cleaning the surface of the samples by means of a disk polisher with abrasive paper.
- Acetone cleaning: improvement of the surface condition of the sample.

We report that the samples were coated with a self-hardening resin in which a copper wire is fixed on the test plate (Fig. 12).

4.2 Coating formulation

Several formulations based on scale and pigment (natural or calcined) have been implemented. For the comparative study, we have chosen as reference an anticorrosive coating based on iron oxide "Glyfer". The ratios of the formulations are shown in Table 2.

The procedure is as follows:

Fig. 12 Coated steel samples

- Weighing the materials used in the formulation (pigment, scale, resin (binder), solvent).
- Blend powder ingredients (filler + pigment) according to the choice of formula with resin and solvent. The mechanical agitation is actuated until a fineness of 6 is obtained according to the standards.
- Dilution and mixing of the ingredients with addition of siccatives, anti-skin and gel for 15 min.

4.3 Characterization of formulations

4.3.1 Fineness

The fineness is measured during the manufacture of the coating to check the good dispersion of the grains. The measurement range from 0 to 8. When the value of the fineness is high, the particle size will be small. The duration of obtaining the desired fineness which is equal to 6 is different for each formula, this is due to the presence of 4.23% silica and 2.13% alumina in the pigment composition. These two elements are very hard to grind. Samples 100P and P28.57C were milled for 75 min. The scale composed only of iron oxides is very suitable for grinding.

4.3.2 Viscosity

The viscosity of the coatings is determined with a Coup-Ford4 type viscometer (CF4) as a function of the flow time in seconds at a room temperature that ranged in 20–25 °C. The results are given in Table 3. We note that only the viscosity of the formula 1 is almost equal to that of the standard Glyfer.

4.3.3 Density

The density of the formulations is measured by a pycnometer and it given in Table 3. We notice that all density values are equal and close to the value of the standard Glyfer.

Table 2 Designation and compositions of different coating formulations

Type of formula	Designation	Iron pigment	Scale	Calcined Iron pigment	Calcined Scale
Formula 1	100P	100	–	–	–
Formula 2	100C	–	100	–	–
Formula 3	100Pc	–	–	100	–
Formula 4	P28.57C	71,43	28.57	–	–
Formula 5	P42.85C	57.15	42,85	–	–
Formula 6	Pc28.57Cc	–	–	71,43	28,57

Table 3 Measured characteristics of different formulations

Sample	100P	100C	100Pc	P28.57C	P42.85C	Pc28.57Cc	Glyfer
Fineness/duration	6/75	5.5/0.0	6/0,0	5/75	6/0,0	6.5/0,0	6
Viscosity (s/cSt)	165/70.62	128/54.78	131/56.07	377/161.36	240/102.72	268/114.7	150/64.2
Density (g/cm ³)	1.42	1.45	1.42	1.45	1.42	1.43	1.49
Dry extract (%)	77.7%	77.7%	77.7%	77.7%	72.2%	77.7%	71 ± 1
Thickness (μm)	124.2	139.2	110.6	98.1	148.6	110.8	97.9

4.3.4 Determination of the dry extract

We denote the dry extract all quantity of non-volatile matter. These are the materials of the mixture that do not evaporate when subjected to a temperature of 150 °C for 1h30. They constitute the protective film against corrosion. The results are given in Table 3. The value of the solids content for all the formulations is identical except for the fifth formulation, which is slightly greater than that of the standard one.

4.3.5 Thickness measurement

Thickness is one of the first criteria used to qualify a coating. There are many methods to measure it. Equipment used in coating thickness measurement is based on the magnetic principle (magnetic induction or Foucault currents). The apparatus used is a portable magnetic thickness gauge. The thickness values are given in Table 3. We notice that the thickness of the formulation 4 is equal to that of the Glyfer reference system.

5 Corrosion tests

A comparative study of each of the coatings prepared is carried out with the reference coating (Glyfer). All samples were immersed in 3.5% NaCl solution at room temperature (Fig. 13). These tests are performed to determine the best corrosion protection formulas for steel.

5.1 Macrographic observation

After 20 days of immersion in a 3.5% NaCl solution, we observed small bubbles in the form of swellings on the surface of the coated steel with the exception of the reference sample (Glyfer) which has a puncture corrosion. The coating composed of 28.57% of scale gave the best surface quality. Rouibah [17] and Lamoureux [18] describe these types of corrosions that observed as localized corrosions.

5.2 Optical microscope observation

To better evaluate on of the corrosion resistance of the coated surface, we used a Nikon Eclipse LV150N type optical microscope. The observation of the samples after 20 days of immersion is illustrated in Fig. 14. These observations show that the coating formulation containing 28.57% scale has the best resistance in a corrosive medium at 3.5% NaCl. The surface is very sharp with some tiny bubbles that are barely visible.

5.3 Electrochemical analysis

The electrochemical study is carried out in the corrosion laboratory using a software-controlled EGG versastat potentiostat–galvanostat (softcorr3). All tests were performed with a set of three electrodes. The electrochemical cell used is a double-walled Pyrex glass.

The operating conditions are as follows:

- Waiting time before polarizing the sample: 60 min.

Fig. 13 Coated steel samples emerged in solution 3.5% NaCl

- Scanning range: $E_i = 0$ to ± 250 mV/E.C.S.
- Sweep speed: 1 mV/s.
- Surface of the working electrode: 1 cm^2 .
- Electrolyte: 3.5% NaCl solution maintained at room temperature.

The polarization curves (plot of the Tafel curve: $\log i = f(E)$) of the different formulations are presented in Fig. 13. The values of the corrosion potentials (E), as indicated by the studies of Casenave [19], the polarization resistance (R_p) and the corrosion current (I_{cor}) are obtained from the treatment of the polarization curves (method of extrapolation of the Tafel straight lines) and are reported in Table 4.

Figure 15a shows that the coating of the formulation which contains 28.57% scale has the best characteristics with respect to other coatings. Its corrosion current is lower than that of the comparison reference system. The value of its corrosion potential is very close to that of the reference system. The currents and the corrosion potentials of the different coatings are illustrated in Fig. 15b.

The results given in Table 4 show that the coating formulations (100C, P42.85 and P28.57) have a high corrosion potential with the exception of P28.57C sample. The current and the corrosion rate have larger values.

- Formulations based on calcined pigment do not have a resistance to corrosion.
- The formula P28.57C has the greatest corrosion potential compared to the others and the closest to that of the reference (Glyfer).

6 Conclusion

The scale has a uniform structure composed of 98% iron oxides. The pigment contains in addition to iron a siliceous gangue. Grinding time of the iron pigment is

greater than the scale. The analysis of the particle size shows a particle distribution between 0.7 and 32 μm for the scale and 0.6–40 μm for the pigment.

The average diameter $D_{(50)}$ is 6.31 μm for the scale and 7.97 μm for the pigment, their specific surface area is 1.6 and 1.5 m^2/g . The simultaneous thermal analysis for the scale shows an increase in mass (3.602%) between 400 and 1000 $^\circ\text{C}$, attributable to the oxidation reaction of iron oxides. For iron pigments, this analysis shows a loss of mass attributed to the evaporation of water formation in iron hydroxides.

The observations of the SEM show a homogeneous structure composed of iron oxide grains ranging in size from 1 to 10 μm for scale and rounded grain aggregate for the pigment.

The X-ray diffractogram shows that the phases composing the scale are wustite, magnetite and hematite. The crystalline phases of the iron pigment are goethite, hematite, fayalite, silica, phosphorus pentoxide and hausmannite.

The optical measurement spectra show that the three compounds do not absorb any visible radiation and absorb significant fluxes in the near UV. They reflect the totality of the incidental radiation in the visible but reflect very little the radiations of the near UV.

Several coating formulations based on scale and iron pigment are prepared. Characterization tests have shown that the density and solids content meet international standards but the viscosity is slightly higher. Obtaining the desired fineness required more preparation because of the presence of SiO_2 and Al_2O_3 . Immersion in a corrosive medium for 20 days at a concentration of 3.5% NaCl showed slight swelling at the sample surface levels. The optical microscope observation showed that the 28.57% scale sample is the most resistant and this result is confirmed by electrochemical analysis with a low corrosion current and a high potential close to the reference.

Fig. 14 Images showing the results of immersions in NaCl solution at 3.5% of the samples under an optical microscope

Table 4 Electrochemical parameters obtained after corrosion tests

Sample	100P	100C	100Pc	P28.57C	Pc28.57Cc	P42.85C	Glyfer
I_{Cor} (nA)	184.56	8529	164.8	10.28	241.6	6671	97.62
E_{Cor} (mV)	-519.5	-571	-590.6	-509.8	-673.4	-547.4	-434.5
V_{Cor} (μ mpy)	2.14	0.04	1795	0112	2633	0073	1064
R_p (Ohm)	231.4 K	5.158 M	131,8 K	2.111 M	89.87 K	3.255 M	222.4 K

Fig. 15 Potentiodynamic polarization curve of the different coated samples immersed in 3.5% NaCl

Funding This study was funded as part of the research projects of the Industrial Technologies Research Center. The number of the research team is 39. The team leader is the corresponding author. The financing of the project is provided by our guardianship. We are permanent researchers working in a state institution who will receive a monthly salary. This institution is the center of research in industrial technologies itself financed by the Ministry of Higher Education and Scientific Research of the Algerian state.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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