

## **AC INTERFERENCE EFFECTS ON POLARISED STEEL**

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### **Abstract**

This paper illustrates the results of laboratory tests on the influence of AC interference on carbon steel at different polarisation conditions: anodic polarisation (DC stray current interference and galvanic coupling with copper grounding system) and cathodic polarisation (cathodically protected structures). The environments used for the experiments were sulphate solutions simulating low resistivity soils. AC was overlapped to the testing specimens at different current densities, ranging from 10 to 1,000 A/m<sup>2</sup>. Cathodic protection level was varied from -0.85 V CSE to -1.5 V CSE as true potential. Anodic polarisation, obtained by galvanic coupling with copper and stainless steels and by external polarisation was ranging from free corrosion conditions to 10 A/m<sup>2</sup>.

### **INTRODUCTION**

Studies on AC interference grew in the last 30 years, although AC corrosion it was well known since the beginning of the XX century [1]. Today main concern is the frequent parallelism between buried pipelines and AC high tension transmission lines in combination with the use of highly dielectric coatings like extruded polyethylene or polypropylene. However, in the near future, at least in Italy, new interference conditions are expected because of the overlapping of high current AC traction systems (25 kV and 50

Hz) and the traditional DC traction system that have been operating for about a century.

For stray direct current corrosion on buried structures, for instance interfered pipelines, there is large agreement on criteria to be used for corrosion mitigation and international standards are available since many years [2]. For AC corrosion, different approaches are used and different opinions still exist. The European approach is the specification of the maximum allowable AC density to be measured by means of corrosion coupons (the threshold value so far proposed is  $30 \text{ A/m}^2$ ) [3]; others are based on the maximum AC voltage (for instance, 15 V). It is agreed that the AC intensity threshold value obtained in laboratory tests is of the order of 20 to  $100 \text{ A/m}^2$ , and meanwhile, few data are available on the influence of the simultaneous presence of AC and DC current on steel corrosion in soil and in concrete [4]. The results reported in this paper evaluate the effect of AC current on freely corroding conditions, and under cathodic and anodic polarisation in soil simulating solutions.

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### **EXPERIMENTAL**

The aim of the experimental work was to study the influence of AC current on cathodic and anodic overpotential by means of the following tests:

- overlapping of AC on galvanic couplings, as shown in Figure 1;
- overlapping of AC and DC through two independent electric circuits, as shown in Figure 2;
- determination of the anodic and cathodic polarisation curves in presence of AC.

Potentials were measured by means of a Lugging capillary, in order to limit the IR drop contribution. This because of difficulties for the application of the ON-OFF technique, since the instant-off potential reading was affected by spikes.

#### **Tests on galvanic couplings**

The AC current effect was studied in a soil simulating solution by applying an AC voltage across two identical galvanic couplings (carbon steel and AISI 304 stainless steel) in a cell  $150 \times 150 \times 100 \text{ mm}$ . Steel specimens were  $30 \times 30 \times 1 \text{ mm}$ ; copper cable was glued on the surface by means of conductive resin, and the connection was insulated with epoxy resin (the tested net surface was  $900 \text{ mm}^2$ ) (Figure 1). The

galvanic coupling was obtained through a shunt in order to measure the galvanic current. Potential was measured using a high impedance voltmeter (200 M $\Omega$ ) with a suitable AC filtering device, with an acquisition frequency of 1 Hz.

The AC feeding system was 50 Hz, 220 V and 4.5 A maximum and the AC current density on the carbon steel specimen was in the range of 50–150 A/m<sup>2</sup>. Test solutions were 0.25 g/L and 0.5 g/L of Na<sub>2</sub>SO<sub>4</sub>, simulating different soil resistivity values, maintained at 20°C ( $\pm$  1°C) by using a cryostat.

Tests followed this sequence:

- measurement of rest potential of both carbon and stainless steel, before the coupling;
- galvanic coupling for 3 days, without AC application;
- AC application with step increases up to 150 A/m<sup>2</sup>. Minimum one day test was allowed for each AC density;
- potential and macrocouple current measurements after AC switch off.

### **Tests on separated circuits**

In order to separate the two signals [6], the electric circuit of Figure 2 was used, where the AC was limited to about 1.1% on the DC circuit by means of a 10 H inductance and, on the other hand, the DC was halted on the AC circuit by means of a 500  $\mu$ F capacitor side. Shunts were installed to measure the flowing currents.

The test cell was the same of galvanic coupling experiments, test solution was 4 g/L of Na<sub>2</sub>SO<sub>4</sub>. Carbon steel specimens with different surface areas (900 and 1,600 mm<sup>2</sup>) were used. The AC current densities ranged from 30 to 1,000 A/m<sup>2</sup>. The DC current densities ranged from 0.1 to 10 A/m<sup>2</sup> for cathodic polarisation and from 1 to 10 A/m<sup>2</sup> for anodic polarisation.

Tests were performed following this sequence:

- rest potential measurement;
- cathodic or anodic polarisation (for at least 1 hour);
- application of AC current; three steps, each at least 2 hours long, until the AC current density reached 1,000 A/m<sup>2</sup>;
- switch off of the AC current, and after 2 hours switch off of the DC current.

### **Polarisation curve determination**

In order to separate the two signals, the electric circuit previously described was used (Figure 2). The test

cell, the solution, the steel specimens and the AC current densities applied were the same as the tests on separated circuits. The DC current densities ranged from 0.001 to 20 A/m<sup>2</sup>.

In each experiments, the DC polarisation were started about 12 hours after the working electrode immersion in the solution and the AC application, in order to allow the stabilisation of the rest potential.

Tests followed this sequence:

- rest potential measurement;
- AC application at a fixed value (30, 100, 300 or 1,000 A/m<sup>2</sup>);
- application of DC anodic polarisation from 20 to 0.001 A/m<sup>2</sup> (eight steps, each 10 minutes long), started 12 hours after the AC imposition. Measurement of steel potential;
- application of DC cathodic polarisation from 0.001 to 20 A/m<sup>2</sup> (eight steps, each 10 minutes long). Measurement of steel potential.

## **RESULTS**

### **Galvanic couplings**

Macrocouple currents and potential measurements are reported in Table 1 and Figure 3. Since the surfaces of carbon and stainless steel specimens are equal, the rate of the anodic process ( $I_A$ ) is double with respect to the measured macrocouple current ( $I_{MC}$ ). The application of an AC current lowers the carbon steel DC potential (Figure 3), and increased the corrosion rate (Table 1): the higher the AC density, the higher the measured macrocouple current.

### **Separated circuits**

The separated circuits system allowed studying both anodic (as in previous experiment) and cathodic processes, simulating the influence on cathodic protection conditions. Figure 4 and Table 2 report the AC influence on the DC potential of cathodically and anodically polarised steel, at different DC current density.

On 0.1 A/m<sup>2</sup> cathodically polarised steel, the DC potential is lowered after the AC application (Figure 4a) and this effect is enhanced at higher current densities. A different behaviour was obtained when the DC cathodic current density was in the range of 1 to 10 A/m<sup>2</sup>. After the AC application the DC potential increased (Figure 4b) as AC current density increased.

In the anodic polarisation tests (1–10 A/m<sup>2</sup>), the steel DC potential lowered as the AC current increased, reaching -770 mV SCE when AC was 1,000 A/m<sup>2</sup> (Table 3 and Figure 4b).

### **Polarisation curves**

The determination of the polarisation curves allowed to evaluate the influence of AC on the kinetic parameters like: exchange current densities ( $i_{0,a}$ ,  $i_{0,c}$ ), Tafel slopes ( $\beta_a$ ,  $\beta_c$ ) and corrosion current density ( $i_{corr}$ ). The experimental results of polarisation curves are reported in Figure 5; the regression curves obtained from the experimental data are also reported. Values of Tafel slopes, exchange current densities, corrosion rate and corrosion potential obtained by regression of the experimental data are reported in Table 4.

The alternating current does not have considerable effect on Tafel slopes (Figure 6 and Table 4), both on cathodic and anodic process, whereas the effect on the exchange current density is quite relevant for AC current densities higher than 100 A/m<sup>2</sup>, leading to a decrease on  $E_{corr}$  (about 30 mV) and a considerable increase on  $I_{corr}$  (Table 4 and Figure 7).

## **DISCUSSION**

The mechanism by which AC current effects the corrosion process is not very well known. The most reliable theory is the influence on anodic and cathodic overpotentials [6]. In accordance with this theory, the main effects of AC current interference should be a DC potential reduction in case of anodic polarisation (Figure 8a) and a DC potential increase on a cathodically polarised steel (Figure 8b).

### **AC effects on galvanic couplings**

By means of the galvanic coupling between carbon and stainless steel, the separation of the anodic and the cathodic processes is obtained, allowing to study separately the influence of the AC current overlapping. As far as the effects on overpotential is concerned, a reduction of both the anodic and cathodic overpotential should be expected, resulting in an increase of the macrocouple current (i.e., the corrosion rate).

Experimental data confirmed these hypotheses, as the application of AC lowers the carbon steel DC potential of about 30 mV and 100 mV at 45 and 145 A/m<sup>2</sup> AC current density respectively; at the same time, the higher the AC current density and the higher the macrocouple current, then the higher the steel corrosion rate (Table 1).

No significant influence was observed on stainless steel, where the cathodic process takes place.

### **AC effects on cathodic polarisation**

In cases of DC cathodic current density between 1 and 10 A/m<sup>2</sup>, the carbon steel potential is lower than -1.1 V SCE (Figure 4a), and so the cathodic process is hydrogen evolution. Carbon steel potential variation ( $\Delta\Psi$ ) after the application of AC can be related to a reduction of the cathodic overpotential (Figure 8b), where the potential change is about 50 mV or 200 mV, at an AC current density in the range 30–100 A/m<sup>2</sup> and 1000 A/m<sup>2</sup>, respectively (Figure 9a).

Polarisation tests (Figure 6a) show that the main effect of AC is to increase the exchange current of the cathodic process, while no significant variation was measured on the Tafel slope.

### **AC effects on anodic polarisation**

When carbon steel is anodically polarized (DC anodic current density between 1 and 10 A/m<sup>2</sup>), the overlapping of AC leads to a DC potential lowering (Table 3 and Figure 4b) that has to be related to the reduction of the anodic process overpotential, as schematically shown in Figure 8a.

Figure 9b illustrates the carbon steel potential variations ( $\Delta\Psi$ ) obtained in sulphate solutions. DC potential lowering is about 30 mV at low AC current density (30 A/m<sup>2</sup>) and it is close to 100 mV at higher AC current densities (100–1000 A/m<sup>2</sup>).

Polarisation tests (Figure 6b) show that the overpotential reductions are due to the increase of the exchange current density in presence of the alternate current.

### **CONCLUSIONS**

The influence of the simultaneous presence of AC and DC current on carbon steel in corrosion simulating soil conditions was studied. The main results confirmed that AC current overlapped to a cathodically or anodically polarised steel leads to a reduction of both cathodic and anodic overpotential, by increasing the exchange current of both the cathodic and anodic reaction. No significant variation was measured on the Tafel slope.

In CP conditions, the effect of the AC is the changing of the potential toward the more positive values of about 200 mV. This may lead to a partial protection condition.

In presence of anodic interference due to the presence of stray current, the effect of the AC is the changing of the potential toward less positive values down to about -0.75 V

SCE. This situation is very dangerous, since at such negative potentials no significant corrosion rate is usually associated, instead the anodic current density was as high as 1 A/m<sup>2</sup> corresponding to a corrosion rate of 1 mm/y.

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TABLE 1 - GALVANIC COUPLING TESTS: CARBON STEEL POTENTIAL (mV vs SCE) AND ANODIC CURRENT DENSITY (mA/m<sup>2</sup>)

	0.25 g/L Na <sub>2</sub> SO <sub>4</sub>		0.50 g/L Na <sub>2</sub> SO <sub>4</sub>	
	Rest	E (mV) / I <sub>a</sub> (mA/m <sup>2</sup> )	Rest	E (mV) / I <sub>a</sub> (mA/m <sup>2</sup> )
<b>W (No AC)</b>	-685	-720 / 0	-690	-735 / 80
<b>AC (45 A/m<sup>2</sup>)</b>		-754 / 0		-757 / 230
<b>AC (90 A/m<sup>2</sup>)</b>		-765		-774 / 380
<b>AC (145 A/m<sup>2</sup>)</b>				-767 / 560

TABLE 2 - CATHODIC POLARISATION TESTS: CARBON STEEL POTENTIAL (mV vs SCE)

	CARBON STEEL POTENTIAL (mV vs SCE)
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<i>DC</i> (A/m <sup>2</sup> )	<b>Applied AC (A/m<sup>2</sup>)</b>			
	<b>0</b>	<b>30</b>	<b>100</b>	<b>1,000</b>
0.1	-751	-725	-935	-915
1.0	-1100	-1070	-1042	-970
10	-1148	-1151	-1126	-934

TABLE 3 - ANODIC POLARISATION TESTS: CARBON STEEL POTENTIAL (mV vs SCE)

<i>DC</i> (A/m <sup>2</sup> )	CARBON STEEL POTENTIAL (mV vs SCE)			
	<b>Applied AC (A/m<sup>2</sup>)</b>			
	<b>0</b>	<b>30</b>	<b>100</b>	<b>1,000</b>
1.0	-676	-707	-772	-769
10	-621	-654	-694	-739

TABLE 4 - CARBON STEEL: KINETIC PARAMETERS OBTAINED FROM POLARISATION CURVES

<i>AC</i> (A/m <sup>2</sup> )	$\beta_a$ (V/dec)	$\beta_c$ (V/dec)	$i_{0,a}$ (A/m <sup>2</sup> )	$i_{0,c}$ (A/m <sup>2</sup> )	$i_{corr}$ (mA/m <sup>2</sup> )	$E_{corr}$ (mV SCE)
0	0.063	0.123	6.7 10 <sup>-3</sup>	2.2 10 <sup>-3</sup>	39	-805
30	0.055	0.120	5.9 10 <sup>-3</sup>	2.0 10 <sup>-3</sup>	44	-808
100	0.064	0.124	2.0 10 <sup>-2</sup>	3.1 10 <sup>-3</sup>	72	-820
300	0.065	0.129	5.4 10 <sup>-2</sup>	6.4 10 <sup>-3</sup>	151	-828
1,000	0.066	0.131	8.6 10 <sup>-2</sup>	1.3 10 <sup>-2</sup>	276	-823



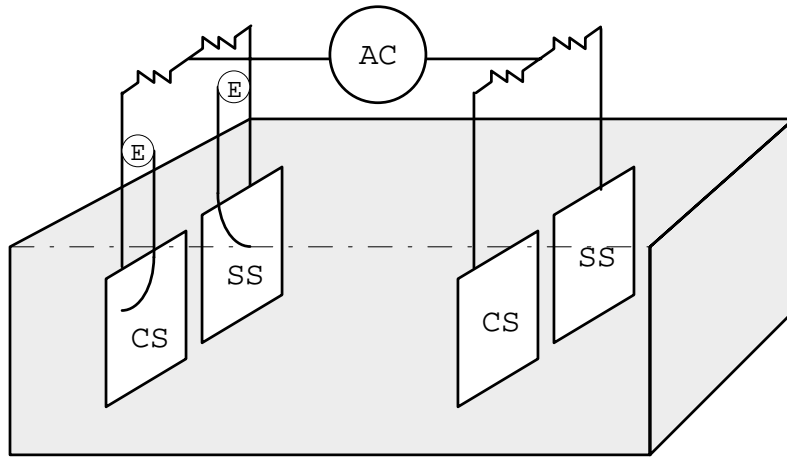


FIGURE 1- Schematic view of the cell for galvanic coupling tests

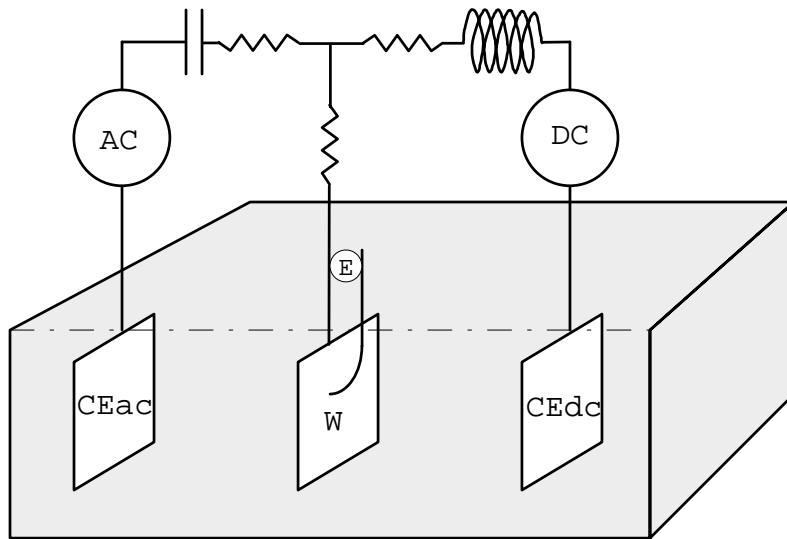


FIGURE 2 - Electric circuit diagram with DC and AC separation

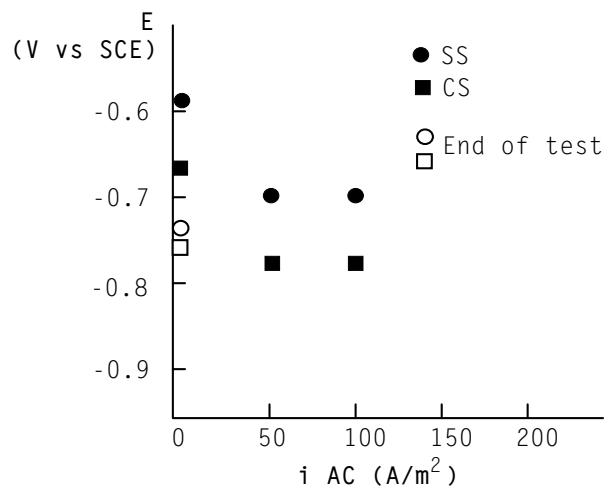


FIGURE 3 - Galvanic coupling tests in 0.5 g/L  $Na_2SO_4$  solution: influence of AC on carbon steel (CS) and stainless steel (SS)

potential

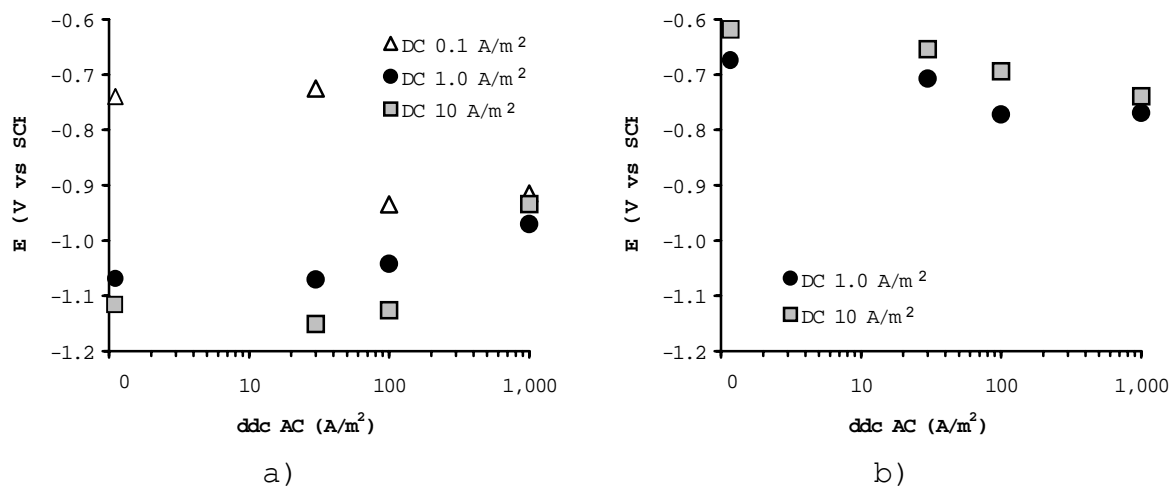


FIGURE 4 - Effect of AC on (a) cathodically and (b) anodically polarised steel, in 4 g/L Na<sub>2</sub>SO<sub>4</sub> solution in tests with separated circuits

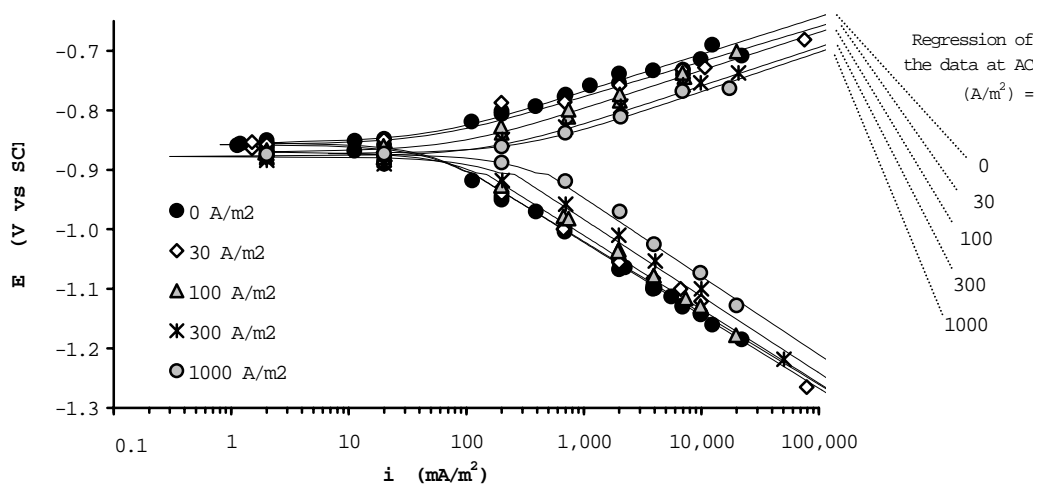
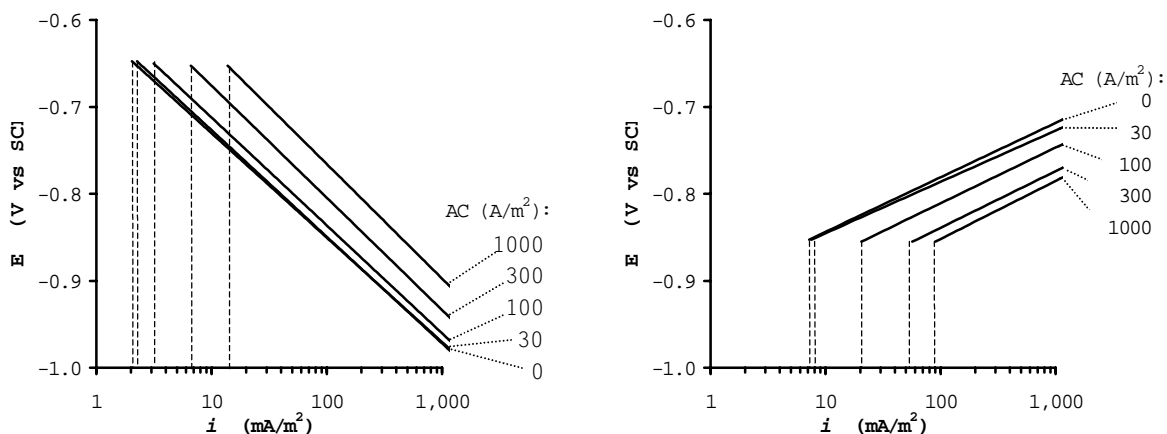


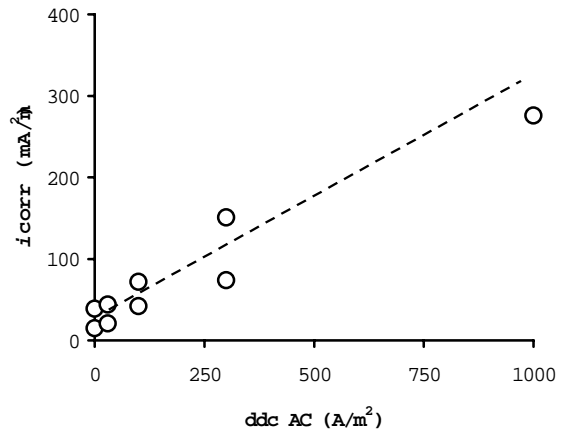
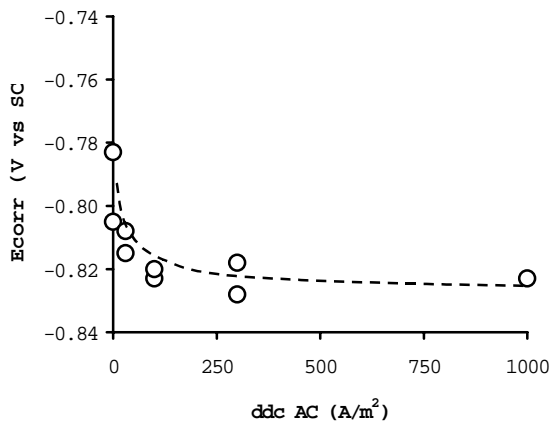
FIGURE 5 - Effect of AC on polarisation curves of carbon steel in 4 g/L Na<sub>2</sub>SO<sub>4</sub> solution: experimental data and regression curves



a)

b)

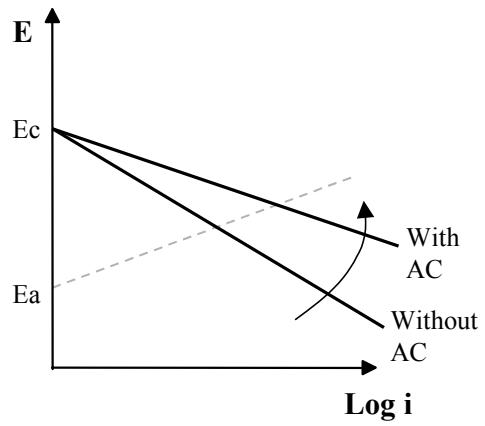
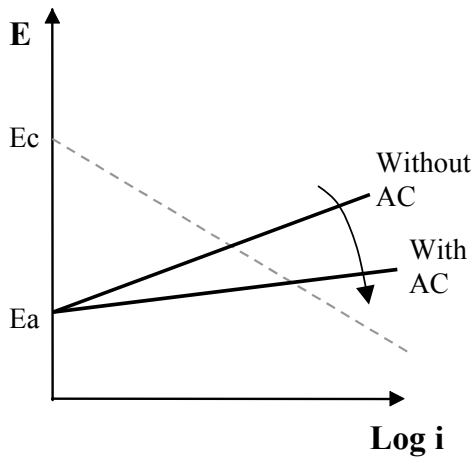
FIGURE 6 - Effect of the AC on (a) the cathodic process and on (b) the anodic process, in 4 g/L Na<sub>2</sub>SO<sub>4</sub> solution



a)

b)

FIGURE 7 - Effect of the AC on (a) free corrosion potential ( $E_{corr}$ ) and on (b) corrosion rate ( $i_{corr}$ ) of carbon steel in 4 g/L Na<sub>2</sub>SO<sub>4</sub> solution



a)

b)

FIGURE 8 - Schematic effect of AC on (a) anodic and (b) cathodic overpotential

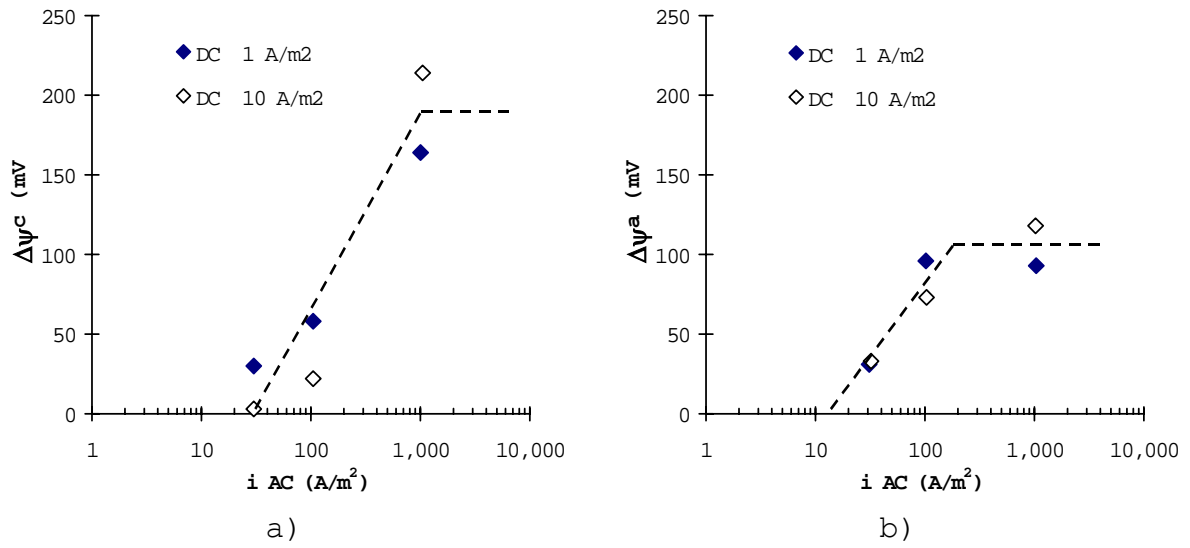


FIGURE 9 - Overpotential reduction in (a) cathodic and (b) anodic polarisation tests