

## Corrosion protection of steel with DMEA-based organic inhibitor



E. Rakanta<sup>1</sup>, Th. Zafeiropoulou<sup>\*</sup>, G. Batis<sup>1</sup>

National Technical University of Athens, School of Chemical Engineering, Department of Materials Science and Engineering, 9, Iroon Polytechniou St., Zografou Campus, GR-157 80 Athens, Greece

### HIGHLIGHTS

- DMEA-based organic corrosion inhibitor for protection of rebars in artificial concrete pore solution.
- Electrochemical evaluation in synthetic concrete pore solution, contaminated with chloride ions.
- Determination of corrosion rate, corrosion current density  $i_{corr}$ , polarization resistance  $R_p$  and pitting potential  $E_{pitt}$ .
- Comparison between electrochemical parameters and metal loss determination.

### ARTICLE INFO

#### Article history:

Received 17 October 2012  
Received in revised form 25 February 2013  
Accepted 4 March 2013  
Available online 13 April 2013

#### Keywords:

Organic corrosion inhibitor  
Concrete  
Electrochemical evaluation

### ABSTRACT

The aim of this study is to examine the protective effect of N,N-dimethylaminoethanol (DMEA – organic corrosion inhibitor) against rebar corrosion in the presence of chloride ions. The inhibiting properties of DMEA based corrosion inhibitor were evaluated in artificial concrete pore solution and in cement mortar specimens. The electrochemical measurements were performed using synthetic concrete pore solution which was contaminated with chloride ions in order to simulating the concrete interstitial electrolyte. Corrosion parameters such as corrosion rate, corrosion current density  $i_{corr}$ , polarization resistance  $R_p$  and pitting potential  $E_{pitt}$  of reinforcing steel have been evaluated by electrochemical measurements and compared with that obtained from metal loss determination. Results indicated that the addition of N,N-dimethylaminoethanol to the artificial concrete pore solution as well as into the concrete contaminated with chloride ions decreases the corrosion rate of steel reinforcement.

© 2013 Elsevier Ltd. All rights reserved.

### 1. Introduction

Corrosion of reinforcing steel embedded in concrete is becoming a significant structural and financial problem. As it is known in Greece many historical buildings and structures are located in coastal regions (islands) where the weather is characterized by pollutants such as chloride ions ( $\text{Cl}^-$ ) and carbon dioxide ( $\text{CO}_2$ ). This leads to an increased incidence of spalling, delamination and as a consequence the deterioration of concrete in reinforced structures. The use of chemical admixtures, which act as corrosion inhibitors, is a method for preventing and delaying the onset of rebar corrosion. An ideal corrosion inhibitor has been defined as “a chemical compound which when added in adequate amounts to concrete can prevent corrosion of embedded steel and has no adverse effect on the properties of concrete”. Nowadays chemical corrosion inhibitors present an easily implemented solution to the growing problem of corrosion of reinforcing steel

in concrete. However, to be considered viable, these additives should not only prevent or delay the onset of corrosion they must not have any detrimental effect on the properties of concrete itself such as strength, setting time, workability and durability. It must be clarified that corrosion inhibitors do not totally stop corrosion but rather increase the time to the onset of corrosion and reduce its eventual rate. Drawbacks of corrosion inhibiting admixtures are that they may not remain in the repair area, potentially reducing the concentration of the inhibitor below necessary values and secondly, when used in a limited area along a continuous reinforcing bar there is the potential for microcell corrosion development [1–6]. The effect of N,N-dimethylaminoethanol (DMEA) on the corrosion of steel due to chloride ingress was experimentally investigated in this paper. The aim of this study was to examine the protective effect of DMEA (organic corrosion inhibitor) against rebar corrosion in cement mortar specimens and in artificial concrete pore solution containing corrosion inhibitor in the presence of chloride ions. Corrosion parameters such as corrosion rate, corrosion current density ( $i_{corr}$ ), polarization resistance  $R_p$  and breakdown potential of reinforcing steel were evaluated by electrochemical measurements and compared with that obtained from metal loss determination.

<sup>\*</sup> Corresponding author. Tel.: +30 693685972.

E-mail addresses: [erakanta@central.ntua.gr](mailto:erakanta@central.ntua.gr) (E. Rakanta), [dia\\_zaf@mail.ntua.gr](mailto:dia_zaf@mail.ntua.gr) (Th. Zafeiropoulou), [gbatis@central.ntua.gr](mailto:gbatis@central.ntua.gr) (G. Batis).

<sup>1</sup> Tel.: +30 210 772 3099; fax: +30 210 772 3184.

## 2. Materials and evaluation methods

### 2.1. Mortar specimens

#### 2.1.1. Materials

The test specimens were prepared with cement, sand and water in ratio 1:3:0.6. The mean value of the sand grains diameter was  $250 \mu\text{m} < d < 4 \text{ mm}$ . Greek Portland cement was used in all the specimens. Table 1 presents the chemical and mineralogical composition of the cement.

Cylindrical steel rebars of type S500s (Vanadus type steel) which meet Greek specification for weldable reinforcement were used for all test specimens with dimensions of 12 mm in diameter and 10 mm high [7]. Fabrication of the steel for the test specimens simply involved cutting to the consistent length of 100 mm. The chemical composition of steel is given in Table 2.

Drinking water from Athens water supply network and DMEA corrosion inhibitor were used in the preparation of the specimens. DMEA based corrosion inhibitor was in liquid form and the solid content was 29 wt.% and it was mixed in the mixing water at two dosages of 1 wt.% and 2 wt.% of cement. Two categories of cement mortar specimens were prepared. The first category included chloride contaminated cement mortars which were produced with the addition of sodium chloride to the mixing water, thus producing specimens with chlorides at 1 wt.%, 2 wt.%, 3 wt.%, 4 wt.% and 5 wt.% of cement. The second category consisted of mortars with both corrosion inhibitor and chlorides. For corrosion inhibitor at 1 wt.% of cement the chlorides were 1.5 wt.%, 2 wt.%, 2.5 wt.% of cement and for specimens with corrosion inhibitor at 2 wt.% of cement the chlorides were 2 wt.%, 2.5 wt.%, 3 wt.% of cement. The proportions of the materials used and the code names of the specimens are given in Table 3.

#### 2.1.2. Casting of the specimens

The test specimens considered for the present study were cylindrical 100 mm in height and 40 mm in diameter. One steel rebar was axially embedded in each cement mortar as shown in Cement, sand and water were mixed in a mortar mixer for approximately 5 min until a uniform consistency was achieved. The molds (100 mm in height and 40 mm in diameter) were filled with mortar and vibrated for consolidation using a vibrating table. Copper wire cables were connected to the steel bar in order to receive electrochemical measurements. Steel rebars were cleaned prior their installation into the mortars according to ISO/DIS 8407.3 Standard [8]. In particular the surface of the steel bars was washed with water and then immersed in strong solution of HCl (500 ml HCl, density  $\rho = 1.19 \text{ g/ml}^3$  in 1000 ml distilled water) with organic corrosion inhibitor (3.5 g hexamethylene tetramine in 1000 ml distilled water) for 15 min, washed with water and washed thoroughly with distilled water to eliminate traces of the corrosion inhibitor and chloride ions. Following that, the surface was cleaned with alcohol and acetone and finally weighed to accuracy of 0.1 mg. Thereafter the bars were placed in cylindrical molds, as shown in Fig. 1, where the mortar was cast and stored at ambient conditions in the laboratory for 24 h. After being demolded the specimens were placed in water in curing room (RH > 98%,  $T = 20 \pm 1.5^\circ\text{C}$ ) for 24 h and then kept for an additional 7 days at ambient temperature in a laboratory environment to stabilize internal humidity. Epoxy resin was placed in the region shown in Fig. 1 in order to avoid atmospheric corrosion. Finally the specimens were partially immersed in 3.5 wt.% NaCl solution up to 20 mm from the bottom. The objective of partially immersing the cement mortar specimens was to provide an increase of required moisture

**Table 1**  
Oxide and compound compositions of OPC cement.

Oxide composition of cement (wt.% of cement)		Compound composition (per cent)	
Oxide	Content (%)	Compound	Content (%)
SiO <sub>2</sub>	20.67	C <sub>3</sub> S	56.80
Al <sub>2</sub> O <sub>3</sub>	4.99	C <sub>2</sub> S	16.49
Fe <sub>2</sub> O <sub>3</sub>	3.18	C <sub>3</sub> A	7.85
CaO	63.60	C <sub>4</sub> AF	9.67
MgO	2.73		
K <sub>2</sub> O	0.37		
Na <sub>2</sub> O	0.29		
SO <sub>3</sub>	2.414		
CaO <sub>(f)</sub>	2.41		
LOI	2.52		

**Table 2**  
Chemical composition of microelements in the steel bars S500s, type of Vanadus.

	C	Mn	S	P	Si	Ni	Cr	Cu	V	Mo
%	0.22	1.24	0.044	0.032	0.28	0.10	0.10	0.52	0.075	0.028

and oxygen for the initiation and acceleration of reinforcement corrosion. The chloride concentrations of the exposure solutions were selected to avoid leaching of chloride ions casted into cement mortar as contamination. The experimental duration of this study was 7 months.

### 2.2. Steel reinforcements in artificial concrete pore solution

For the electrochemical measurements disk-shaped steel specimens were prepared with 12 mm diameter and 10 mm of thickness and their chemical composition is given in Table 2. The steel disks were cleaned according to ISO/DIS 8407.3 Standard [8]. Prior to the electrochemical tests steel specimens were exposed to saturated Ca(OH)<sub>2</sub> solution containing salt and inhibitor for 24 h. The code numbers and the composition for the different sets of the artificial pore solutions used in this study as a corrosion medium for the electrochemical measurements are shown in Table 4.

SCH: Saturated Calcium Hydroxide, Ca(OH)<sub>2</sub>.

The first number "0" indicates the wt.% concentration of corrosion inhibitor in the solution and the second number "1" the wt.% concentration of chloride ions added as NaCl.

### 2.3. Evaluation methods

Methods used to assess cement mortar specimens' performance included the measurement of corrosion potential, corrosion rate and mass loss. The corrosion potentials for each of the test specimens were recorded at regular intervals versus a saturated calomel reference electrode (SCE). The measurements were initially recorded on an everyday basis until equilibrium conditions were established and then they were recorded on a weekly basis. In order to evaluate the corrosion of steel rebars corrosion rate and %weight change of the steel rebars were estimated according the following equations:

$$\% \text{weight change} = \frac{m_{\text{initial}} - m_{\text{final}}}{m_{\text{initial}}} \quad (1)$$

$$\text{Corrosion rate } (\mu\text{m/y}) = \frac{8.76 \times 10^7 \times W}{A \times T \times D} \quad (2)$$

where  $W$  is the metal loss (g),  $A$  the rebars' surface (cm<sup>2</sup>),  $T$  the time of exposure (h) and  $D$  the density of steel (g/cm<sup>3</sup>). The total exposure time was 7 months while the determination of the mass loss of the bars was made in intervals of 91, 183 and 210 days. The corroded surface of the steel rebars was also examined with an optical fiber microscope and specifically with the Picoscope system by Moritex. Steel rebars were also electrochemically examined in order to evaluate reinforcement corrosion after their immersion in the synthetic concrete pore solution with the aforementioned concentrations of corrosion inhibitor and sodium chloride (Table 4). The computer program "Softcorr III" developed by EG&G Princeton Research was used for applying the potential scan and analyzing the parameters  $i_{\text{corr}}$ ,  $R_p$ . For each polarization test the steel specimens were transferred to a standard electrochemical cell containing the working solution (Table 4) and then corrosion current density, corrosion rate and breakdown potential were measured. The corrosion rate of reinforcing steel was determined according to Stern-Geary electrochemical method at the same exposure ages (24 h). Linear polarization method (LPR) can be used to measure the active rate of corrosion of steel reinforcements. To apply the LPR technique a small perturbation is applied to the reinforcing steel specimen and the resulting response is measured. Although the corrosion of steel in concrete is an electrochemical process and does not obey to Ohm's law it has been shown that Ohm's law is approximately true if polarization applied to the steel does not exceed  $\pm 20 \text{ mV}$ . Thus

**Table 3**  
Categories of specimens – composition ratio wt.% of cement.

Code name	NaCl wt.% of cement	Corrosion inhibitor wt.% of cement
A0	–	–
C11	1	–
C12	2	–
C13	3	–
C14	4	–
C15	5	–
A1C11.5	1.5	1
A1C12	2	1
A1C12.5	2.5	1
A2C12	2	2
A2C12.5	2.5	2
A2C13	3	2

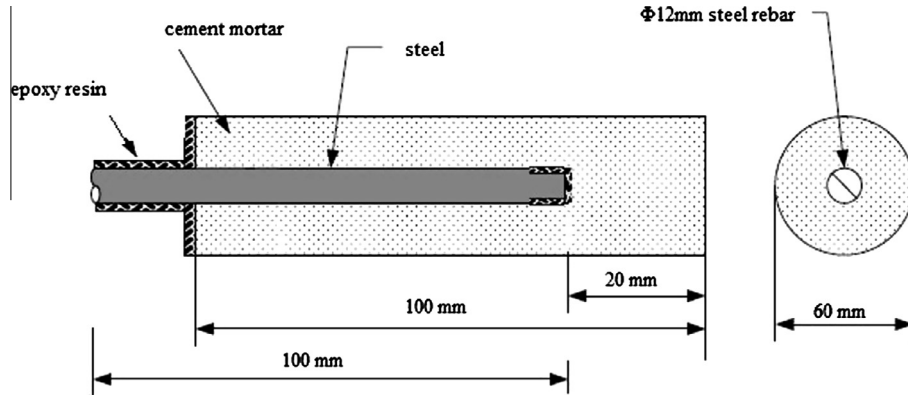


Fig. 1. Schematic representation of reinforced mortar specimen.

**Table 4**  
Results of electrochemical measurements of steel reinforcements in artificial concrete pore solution.

Code name	Chemical composition of artificial concrete pore solution		Electrochemical parameters			
	Corrosion inhibitor (wt.%)	NaCl concentration (wt.%)	LPR technique			Cyclic polarization
			$i_{corr}$ ( $\mu\text{A}/\text{cm}^2$ )	$R_p$ (k Ohms)	Corrosion rate (mpy)	Pitting potential (mV)
SCH 0_0	0	0	0.4870	44.57	0.4461	535
SCH 0_1*		1	1.732	12.54	1.586	419
SCH 0_2		2	5.730	3.790	5.246	185
SCH 0_3		3	6.042	3.594	5.532	119
SCH 0_4		4	10.74	2.021	9.836	117
SCH 0_5		5	13.24	1.640	12.12	85
SCH 1_0	1	0	0.2494	87.08	0.2283	660
SCH 1_1		1	0.763	28.44	0.6992	570
SCH 1_2		2	4.056	5.353	3.714	496
SCH 1_3		3	5.235	4.148	4.793	233
SCH 1_4		4	5.453	3.982	4.993	131
SCH 1_5		5	5.640	3.850	5.164	114
SCH 2_0	2	0	0.172	126.244	0.1574	757
SCH 2_1		1	0.717	30.284	0.6564	658
SCH 2_2		2	2.896	7.497	2.6515	458
SCH 2_3		3	3.202	6.781	2.9317	263
SCH 2_4		4	4.298	5.0521	3.9352	220
SCH 2_5		5	5.195	4.1797	4.7565	134

the resulting current is linearly plotted versus potential. The  $R_p$  polarization resistance, which is the slope of the potential-current curve at  $E_{corr}$  is related to  $i_{corr}$  through the Stern-Geary relationship.

$$i_{corr} = \frac{B}{R_p} \quad (3)$$

where  $B$  is the Stern Geary constant equals to  $\frac{\beta_a \times \beta_c}{2.3(\beta_a + \beta_c)}$ . The  $\beta_a$  and  $\beta_c$  are the anodic and cathodic Tafel constants, respectively. For steel in concrete, a value of  $B = 52$  mV for steel in passive condition and a value equal to  $B = 26$  mV for steel in active conditions are normally used.

From Faraday's law:

$$\text{Corrosion\_rate} = \frac{E.W \times i_{corr} \times t}{\rho \times z \times F} \quad (4)$$

the following equation can be derived, which is used to calculate the corrosion rate once  $i_{corr}$  is determined,

$$\text{Corrosion\_rate} (\mu\text{m}/\text{y}) = \frac{3.27 \times i_{corr} \times E.W}{d} \quad (5)$$

where  $i_{corr}$  is the corrosion current density ( $\mu\text{A}/\text{cm}^2$ ),  $E.W.$  the equivalent weight of steel (g) (for iron  $E.W. = 27.92$  g),  $\rho$  the density of iron ( $\text{g}/\text{cm}^3$ ) ( $\rho = 7.95$   $\text{g}/\text{cm}^3$ ) and  $t$  the time in seconds [9]. The linear polarization resistance of steel reinforcement was evaluated at a scan rate of 0.15 mV/s. The values reported are the average of the polarization resistance measured in each set of artificial pore solution according to corrosion inhibitor percentages ratio and sodium chloride concentration. For each set of solution, there were 10 disk-shaped steel specimens. For all the electrochemical measurements a standard corrosion cell was used. The steel reinforcements were fitted with a standard size disk specimen holder which exposes

100 mm<sup>2</sup> area of specimen surface. The corrosion cell consisted of a reference electrode which was a Saturated Calomel Electrode (SCE) in luggin capillary filled with the same solution as the corrosion medium, a working electrode which was the reinforcing steel and a counter (auxiliary) electrode with a surface of approximately 2 cm<sup>2</sup>. A platinum mesh sheet was used as counter electrode. In this technique, the reinforcing steel bar is polarized to  $\pm 20$  mV of the open circuit potential ( $E_{corr}$ ), the potential within which the current varies linearly with applied potential. Cyclic polarization curves were used to calculate the pitting potential value for each of the above mentioned working solutions with corrosion inhibitor and sodium chloride concentration. The tests were run with the potentiostat using the following parameters: Initial potential = 100 mV more negative than the open circuit corrosion potential  $E_{corr}$ , Return potential = 900 mV more positive than  $E_{corr}$  and Final potential = 100 mV more negative than  $E_{corr}$ , at polarization scan rate of 0.7 mV/s.

### 3. Results and discussion

#### 3.1. Steel reinforcement embedded in contaminated cement mortar

The potential shift is a function of the durability of the protective layer on steel surface. Thus, the corrosion potential of rebars in concrete is a good indication of either the depassivation or activation of corrosion. The corrosion potential measurements given in Figs. 2 and 3 are for specimens without and with inhibitor respectively. According to the guidelines involved in ASTM C876-87 [10] the probability of corrosion initiation is greater than 90% when corrosion potentials are more negative than  $-350$  mV relative to the

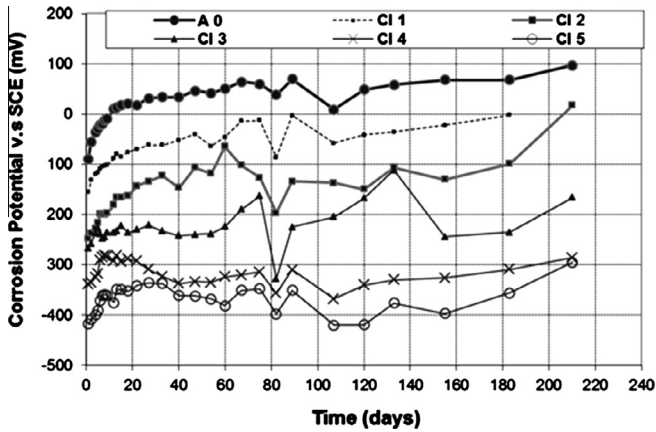


Fig. 2. Half-Cell Potential measurements versus time in specimens contaminated with various concentrations of chloride ions (0, 1, 2, 3, 4 and 5 wt.% of cement).

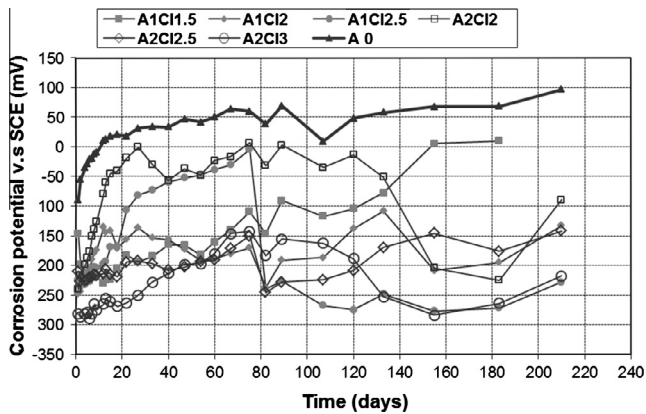


Fig. 3. Half-Cell Potential measurements versus time for mortar specimens with chloride ions and inhibitor treated. The first number is indicative of the concentration of the inhibitor whereas the second displays the contamination of chloride ions.

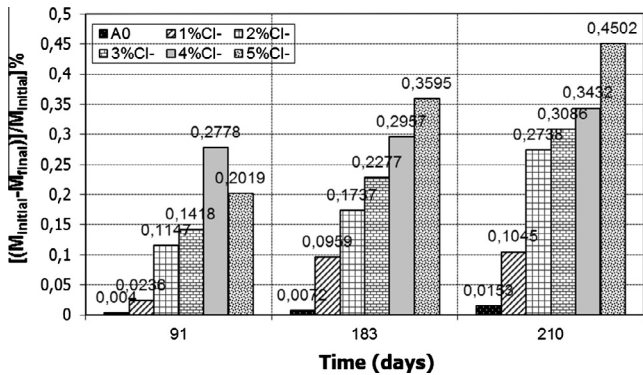


Fig. 4. Mass loss measurements versus time in mortar specimens contaminated with various concentrations of chloride ions (0, 1, 2, 3, 4 and 5 wt.% of cement).

copper–copper sulfate (CSE) and  $-270$  mV relative to the Saturated Calomel Electrode (SCE).

Figs. 2 and 3 illustrate the variation of corrosion potential for the rebars embedded in mortar contaminated with  $\text{Cl}^-$  ions and immersed in 3.5 wt.% sodium chloride solution. Regarding the untreated cement mortar specimens contaminated with chloride ions it is observed that as the concentration of the chloride ions

increases, the corrosion potential values shift towards to more electronegative values (Fig. 2).

On the contrary, for the inhibitor treated cement mortar specimens contaminated with chloride ions it is evident (Fig. 3) that all these values of corrosion potential measurements are in the range of  $-300$  mV to  $-100$  mV vs SCE. These values suggest a high probability of 90% of a passive stage. The results of mass loss measurements of reinforcing steel after 7 months of exposure to chloride solution are given in Figs. 4–6. From these results the improvement of the corrosion performance of steel rebars when the amino alcohols corrosion inhibitor was added is evident. The DMEA decreases the steel rebar mass loss after 91, 183 and 210 days of exposure by approximately 17.96%, 62.29% and 48.90%, respectively in inhibitor treated cement mortar specimens (2 wt.% of cement). It has been reported that DMEA (N,N'-dimethylethanolamine) provides protection by forming an adsorbed layer on the steel surface which hinders the dissolution of the steel [11]. Moreover DMEA was found to partially displace chloride ions from the oxide surface of the steel rebar, forming a durable passive film. Consequently aminoalcohols, although they are generally absorbed on non-corroding sites, they can also be absorbed on potentially anodic sites as well [11]. Overall, weight loss and corrosion potential measurements performed on mortar specimens indicated that the addition of DMEA-based corrosion inhibitor reduces the rate of corrosion in chloride-contaminated cement mortars (2 wt.% DMEA) as it is shown to the following figures.

### 3.2. Fiber optical microscope observations

Further analysis was performed after 7 months by fiber optical microscope. The cement mortar specimens were destroyed and steel rebar surface was inspected by fiber optical microscope to assess its state (passive or active). Fig. 7a illustrates the surface morphology of steel reinforcement embedded in contaminated mortar with chloride ions (2 wt.% NaCl). Direct visual observation indicates that the corrosion process has already been activated. The reinforcing steel surface is not homogenous because the whole surface has not undergone the same mechanisms. Two distinct areas were observed, one presenting a pitting corrosion and another one without corrosion products. Pitting corrosion was observed to be the predominant form of localized corrosion. Brief examination of the steel surface indicated that pits were formed under the rusted surface (Fig. 7a–c) and the microstructure of the layer of the iron oxides seems to be porous. However, comparing the surface morphology of untreated and treated specimens with corrosion inhibitor, steel reinforcement embedded in cement mortar with DMEA, exhibit substantially better performance against corrosion (see Fig. 7b and c). Overall, after 7 months of immersion in

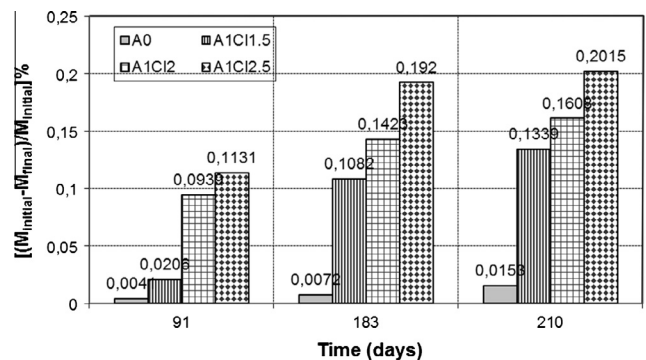


Fig. 5. Mass loss measurements versus time in inhibitor treated specimens (1 wt.% of cement) and various concentrations of chloride ions (0, 1.5, 2, 2.5 wt.% of cement).

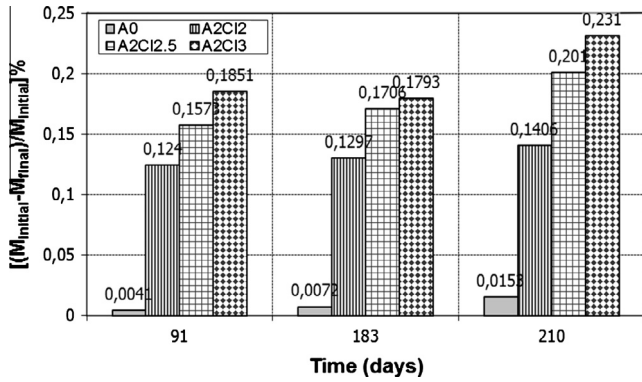


Fig. 6. Mass loss measurements versus time in inhibitor treated specimens (2 wt.% of cement) and various concentrations of chloride ions (0, 2, 2.5, 3 wt.% of cement).

3.5 wt.% sodium chloride solution the corrosion scale produced on steel rebar surface embedded in cement mortars treated with DMEA (1 wt.% and 2 wt.%) was less than that on the steel bars in the specimens without inhibitor.

3.3. Steel reinforcement in artificial pore solution

Reinforcing corrosion in concrete is an electrochemical process that involves the transfer of electrically charged ions between passive and active locations. In the absence of chloride ions, the anodic dissolution reaction of iron is balanced by cathodic oxygen reduction. The Fe<sup>2+</sup> ions produced at the anodes combine with the OH<sup>-</sup> ions from the cathodic reaction to ultimately produce a stable passive film. Chloride ions in the pore solution, having the same

charge as OH<sup>-</sup> ions, compete with these anions to combine with Fe<sup>2+</sup> cations. The resulting iron chloride complexes are thought to be soluble therefore metal dissolution is not prevented and ultimately the buildup of voluminous corrosion products takes place. Therefore, the electrochemical measurements of steel rebars in artificial concrete pore solution allowed to evaluate the behavior and the protective efficiency of the DMEA based corrosion inhibitor. This behavior was assessed through linear polarization and cyclic polarization techniques. Table 4 shows the results of electrochemical parameters which were measured by LPR and cyclic polarization techniques for all the types of artificial pore solution with varying concentrations of corrosion inhibitor and varying amounts of Cl<sup>-</sup> ions. The test results indicated that DMEA retards reinforcement corrosion in the presence of chloride ions. After 24 h of immersion the corrosion rates were 12.12, 5.164, 4.756, 4.565 mils per year (mpy) in solutions containing 0 wt.%, 1 wt.%, 2 wt.% and 3 wt.% corrosion inhibitor, respectively and 5 wt.% NaCl. It is also observed that the polarization resistance, R<sub>p</sub>, of steel reinforcements decreases as the chloride content increases. This is due to the presence of chloride ions in the working solution which are typically responsible for the local breakdown of the passive layer on steel surface. The corrosion current density of steel reinforcement in artificial pore solution containing various amounts of corrosion inhibitors and chlorides is presented in Fig. 8. It is shown that corrosion current density on steel in solutions without inhibitor is higher than that in the solutions with the inhibitor. This indicates that N,N-dimethylaminoethanol inhibitor retards reinforcement corrosion. The critical potential for pit initiation is a function of the nature and concentration of aggressive and inhibiting molecules. Furthermore, the pitting potential is more positive as the concentration of the aggressive anions decreases (catalyzing the anodic metal dissolution) and as the concentration of the

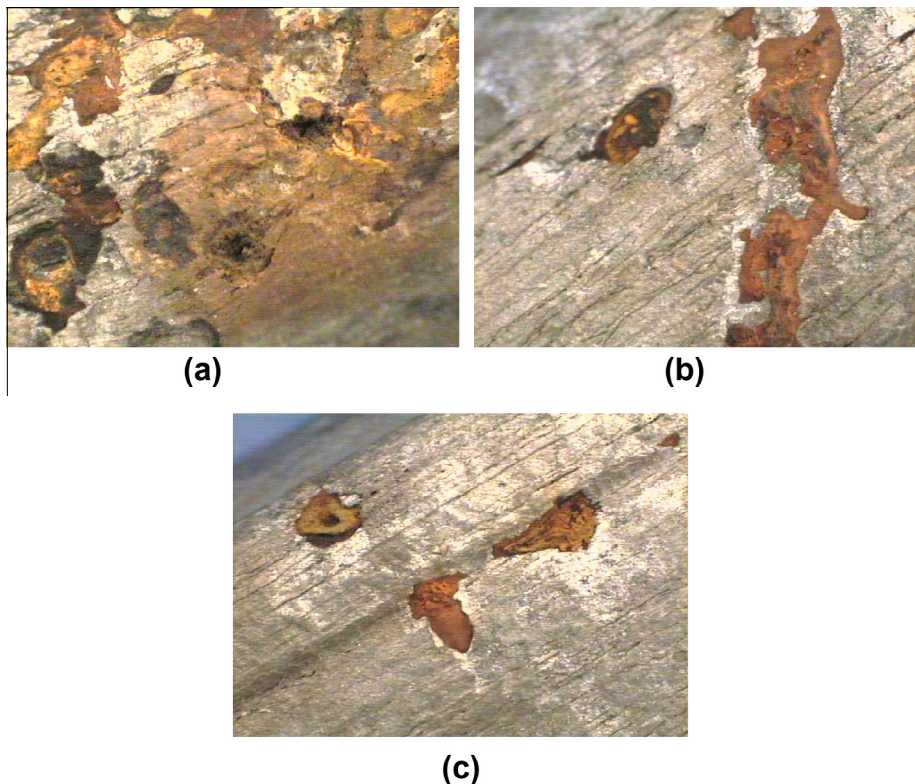


Fig. 7. Fiber optical microscope images after 7 months partially immersion in 3.5 wt.% NaCl solution. Surface morphology of (a) steel reinforcement embedded in contaminated mortar with chloride ions (2 wt.% of cement), (b) steel reinforcement embedded in contaminated mortar with chloride ions (2 wt.% of cement) treated with corrosion inhibitor (DMEA 1 wt.% of cement) and (c) steel reinforcement embedded in contaminated mortar with chloride ions (2 wt.% of cement) treated with corrosion inhibitor (DMEA 2 wt.% of cement). For all the steel reinforcements the magnification used was ×50.

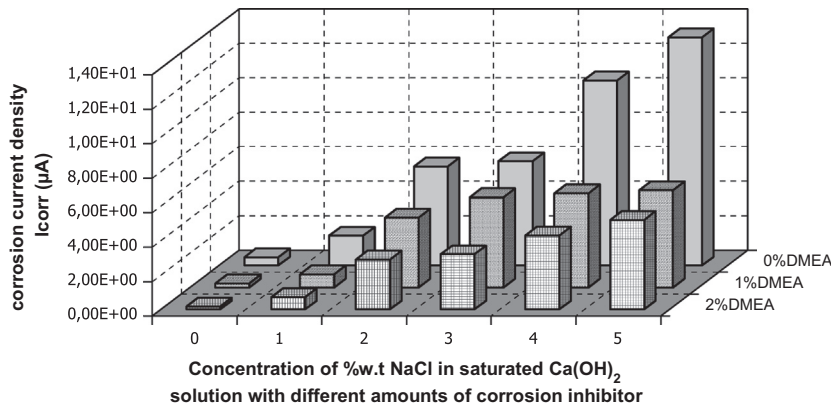


Fig. 8. Corrosion current density of steel rebars immersed in Saturated  $\text{Ca}(\text{OH})_2$  (artificial concrete pore solution) versus wt.% corrosion inhibitor and wt.% NaCl concentration.

inhibiting molecules increases (inhibiting the anodic metal dissolution). Fig. 9 depicts the cyclic polarization curves obtained in the artificial pore solution with 2 wt.% DMEA contaminated with varying amounts of chloride ions. Corresponding to Fig. 9 in artificial concrete pore solution with 2 wt.% DMEA a straight increase of current intensity at approximately 754 mV is observed. The curves with chloride ions at varying amounts of 1 wt.%, 2 wt.%, 3 wt.%, 4 wt.% and 5 wt.% showed a significant increase of corrosion current density at approximately 658, 458, 263, 220 and 134 mV, respectively. As expected, chloride ions are typically responsible for the breakdown of passive film on the rebar surface. Chloride-induced reinforcement corrosion tends to be localized corrosion process with the original passive surface being destroyed locally under the influence of chloride ions. In cyclic polarization curves the probability of localized corrosion is related to the difference between the repassivation,  $E_{\text{rep}}$ , and corrosion potentials,  $E_{\text{corr}}$ , thus the higher the difference the lower the probability of pitting corrosion [12–17].

Overall, the experimental results obtained on the steel rebars immersed in saturated calcium hydroxide solution with varying amounts of chloride ions showed that in absence of DMEA inhibitor the corrosion activity on the steel surface strongly increases with the increase of chloride ion content leading to high corrosion rates and low pitting potentials as observed in Table 4. However, the addition of DMEA inhibitor to the working solution, once corrosion

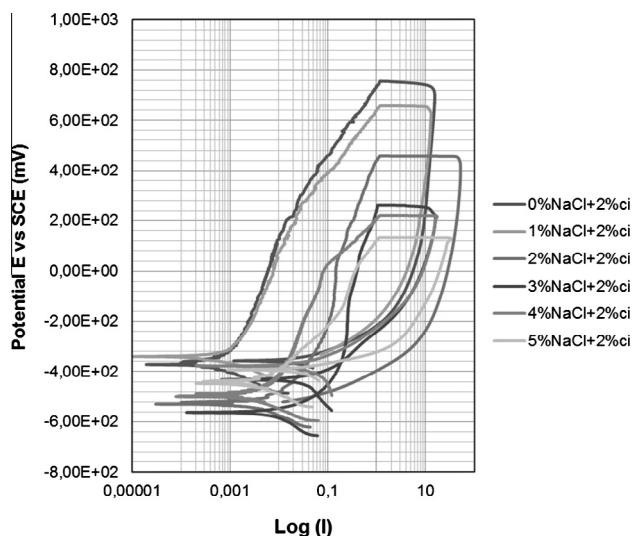


Fig. 9. Cyclic polarization curves obtained in the artificial pore solution, with 2 wt.% DMEA, contaminated with varying amounts of chloride ions.

was initiated, leads to a reduction of this activity. Thus the results of electrochemical measurements suggested that inhibitor molecules are able to reduce the corrosion rate and pit initiation due to presence of chloride ions. The results of the electrochemical measurements for calculating the corrosion rate in steel reinforcements in artificial concrete pore solution are certified and confirmed by the results of the calculations of the reinforcements mass loss in the mortars for a 7 month corrosion period.

#### 4. Conclusion

Based on the findings of this study, the following main conclusions could be obtained:

1. The corrosion potentials in cement mortar specimens contaminated with chloride ions shift to more negative values as the chloride concentration increases. On the other hand, when corrosion inhibitor is added, the corrosion potentials shift towards more positive values.
2. The addition of 2 wt.% of cement DMEA inhibitor decreases the mass loss of the steel rebar about 43%.
3. The corrosion current density on steel in solutions containing  $\text{Cl}^-$  ions is higher than that in solutions with the same  $\text{Cl}^-$  ion and no inhibitor is higher than that on steel in the saturated  $\text{Ca}(\text{OH})_2$  and inhibitor. This indicate that N,N'dimethylaminoethanol retards reinforcement corrosion.
4. The corrosion rate of steel reinforcement increases as chloride concentration increases. However, the corrosion rate of the rebars decreases as the concentration of the corrosion inhibitor increases.
5. The surface of the steel rebars that were embedded in contaminated cement mortar specimens were examined with a fiber optical microscope after 7 months of exposure. The results revealed that under the presence of inhibitors the area of the rebar that suffered from pitting corrosion was restricted.
6. Overall, the addition of N,N'dimethylaminoethanol to the artificial concrete pore solution contaminated with NaCl decrease the corrosion rates of steel reinforcements due to the fact that this type of organic inhibitor forms a stable interfacial layer on steel surface which is able to keep the interface in a passive state.

#### References

- [1] Nmai CK. Multi-functional organic corrosion inhibitor. *Cem Concr Compos* 2004;26:199–207.
- [2] Wombacher F, Maeder U, Marazzani B. Aminoalcohols based mixed corrosion inhibitors. *Cem Conc Compos* 2004;26:209–16.

- [3] Trepanier SM, Hope BB, Hansson CM. Corrosion inhibitors in concrete. Part III: Effect on time to chloride – induced corrosion initiation subsequent corrosion rates of steel in mortar. *Cem Concr Res* 2001;31:713–8.
- [4] Mammoliti L, Hansson CM, Hope BB. Corrosion inhibitors in concrete. Part II: Effect on chloride threshold values for corrosion of steel in synthetic pore solutions. *Cem Concr Res* 1999;29:1583–9.
- [5] Batis G, Rakanta E, Theodoridis B, Sideris KK, Psomas K, Barbari X. Influence of N,N-dimethylethanolamine corrosion inhibitor on carbonation and chloride-induced corrosion of steel. In: Malhotra, editor. *Proceedings seventh CANMET/ACI*. Berlin. ACI SP-217; 2003. p. 469–78.
- [6] de Rincon OT, Perez O, Paredes E, Caldera Y, Urdaneta C, Sandoval I. Long-term performance of ZnO as a rebar corrosion inhibitor. *Cem Concr Compos* 2002;24:79–87.
- [7] Hellenic Organization for Standardization ELOT 971/94. Weldable steel rebars for concrete reinforcement, 2000.
- [8] ISO/DIS 8407.3. Procedures for removal of corrosion products from corrosion test specimen, 1986.
- [9] Broomfield JP. Corrosion of steel in concrete understanding, investigation and repair. E & FN SPON; 1997.
- [10] ASTM C876–09. Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete, 2009.
- [11] Gaidis JM. Chemistry of corrosion inhibitors. *Cem Concr Compos* 2003;25:181–9.
- [12] Saremi M, Mahallati E. A study on chloride-induced depassivation of mild steel in simulated concrete pore solution. *Cem Concr Res* 2002;32:1915–21.
- [13] Dhouibi LL, Triki E, Raharinaivo A. The application of electrochemical impedance spectroscopy to determine the long-term effectiveness of corrosion inhibitors for steel in concrete. *Cem Concr Compos* 2002;24:35–43.
- [14] Qian S, Cusson D. Electrochemical evaluation of the performance of corrosion-inhibiting systems in concrete bridges. *Cem Concr Compos* 2004;26:217–33.
- [15] Andrade C, Garcus P, Martvnez I. Galvanic currents and corrosion rates of reinforcements measured in cells simulating different pitting areas caused by chloride attack in sodium hydroxide. *Corros Sci* 2008;50:2959–64.
- [16] Garcus P, Saura P, Zornoza E, Andrade C. Influence of pH on the nitrite corrosion inhibition of reinforcing steel in simulated concrete pore solution. *Corros Sci* 2011;53:3991–4000.
- [17] Söylev TA, McNally C, Richardson M. Effectiveness of amino alcohol-based surface-applied corrosion inhibitors in chloride-contaminated concrete. *Cem Concr Res* 2007;37:972–77 [2004;26:217–33].