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Cathodic protection of reinforced steel bars imbedded in Portland cement concrete using Al-3.25Zn-3.12Mg sacrificial anode

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الملخص

فى هذا البحث تم اجراء عدة تجارب على تاكل الصلب الكربونى المستخدم فى انتاج الخرسانة المسلحة فى وجود وغياب القطب الانودى المضحى المصنوع من سبيكة الالمونيوم-الزنك-الماغنسيوم. وقد استخدم فى هذه الدراسة مكعبات خرسانية ذات ابعاد 15 *15*15 . كما استخدمت الطرق الحديثة فى تقييم القطب الانودى المضحى. حيث شملت هذه التجارب استخدام الميكروسكوب الضوئى والاشعة السينية وكذلك الطرق الكهروكيمائية المختلفة. وقد تم دراسة البنية المجهرية والبناء الداخلى للقطب الانودى المضحى كذلك تم دراسة تأثيرالعوامل المؤثرة على الحماية الكاثودية للصلب داخل الخرسانة المسلحة وتلك العوامل تشمل المسافة التى تفصل الكاثود عن الانود ونسبة مساحة الكاثود الى الانود. وقد اثبتت النتائج ان القطب الانودى المضحى المصنوع من سبيكة الالمونيوم-الزنك-الماغنسيوم يعمل بكفاءة عالية و بتكليفه منخفضة مقارنة بالانواع الاخري . كما اوضحت النتائج انه للحفاظ على كفاءة الانود يجب ان تكون المسافة الفاصلة بين الكاثود و الانود لا تزيد عن 5سم ونسبة مساحة الكاثود الى الانود لا تزيد عن 300

Abstract

In the present investigation, the evaluation of Al-3.25Zn-3.12Mg as a sacrificial anode for cathodic protection of steel imbedded in Portland cement concrete was performed. Optical microscope, XRD, electrochemical and immersion techniques were used. It was concluded that the investigated anode can be used effectively to minimize the corrosion rate of steel in concrete. Moreover, the results indicated that ncreasing the cathode/anode ratio decreased the corrosion rate of steel imbedded in concrete while the cathodic efficiency decreased with increasing the distance between the cathode and anode.

Keywords: Concrete; Steel; Corrosion; Sacrificial anode

1. Introduction

Reinforced concrete is the most important material in construction applications owing to its lower cost and ease of handling. Moreover, reinforced concrete offers a good service under certain environmental conditions [1,2]. Deterioration of concrete is occurred by corrosion, which results in low mechanical properties, as well as cracking of concrete and thereby reducing the service life of the structure. It was documented that the high alkalinity of concrete chiefly comes from calcium hydroxide which is a product of cement compounds hydration [3]. This alkalinity of concrete offers more protection to the steel. However, the penetration of carbon dioxide decreases the pH of concrete from 13 to 9 [4] causing a uniform corrosion for steel. Moreover, chloride ions come from sea water exposure can destroy the passive layer and cause a pitting corrosion. Owing to the volume expansion of the corrosion products, the cracking of concrete causes a failure for concrete elements and to unprotected steel [5]. Therefore, it is importance to prevent or minimize the corrosion of steel in concrete.

Among the available corrosion control methods is the cathodic protection which is an electrochemical and a major repair technique that has been used for the maintenance of steel bars in concrete structures around the world [6]. Aluminum, magnesium and zinc are the most metals used for the cathodic protection of metallic structures. It is reported that aluminum alloys are the preferred sacrificial anodes for controlling and preventing corrosion in marine environments. The actual limit in the use of magnesium-based sacrificial anodes is their relatively low efficiency, which gives rise to the loss of substantial parts of the required current capacity [7].

Al-Mg-Zn alloy is a multi-component system of Al, Mg and Zn, which has high hydrogen over potential therefore; it has drawn considerable attention from researchers for the design of cathodic protection systems [8]. Therefore, the aim of the present work is to evaluate the Al-3.2Mg-1.9Zn alloy as a sacrificial anode for cathodic protection of reinforced steel bars imbedded in Portland cement concrete.

2. Materials and methods

2.1. Materials

2.1.1 Reinforced concrete

The present study was achieved using a portland cement (type CEM I 42.5 N) supplied from Helwan company meeting the requirements of BS EN 197-1:2000. Natural sand having specific gravity of 2.67 and a fineness modulus of 2.63 was used as fine aggregate. A crushed dolomite with nominal size of 20 mm was used as coarse aggregate. The concrete composition used in the experimental work was as 1/3/2 cement /coarse aggregate/fine aggregate with water/cement ratio of 0.5. The average compressive strength after 28 days was 350 kg/cm^2. Clean and fresh water was used for mixing. Steel bars with chemical composition shown in Table 1 and diameter of 10 mm were cut into lengths of 15 cm.

Table 1.Chemical composition (Wt. %) of steel bar

C	Si	Mn	Ni	Cr	Mo	Fe
0.39	1.43	0.55	1.62	0.70	0.32	Bal.

2.1.2 Sacrificial anodes

The Al-3.25Zn-3.12Mg alloys used in this investigation were produced using casting technique.The samples were cut to dimensions of (5 x 10 x 30 mm) for cathodic protection test.

2.2. Electrochemical corrosion tests

The electrochemical corrosion tests were performed using a Potentiostat/ Galvanostat (EG&G model 273). M352 corrosion software from EG&G Princeton Applied Research was used. A three-electrode cell composed of a concrete specimen as a working electrode, Pt counter electrode, and Ag/AgCl reference electrode were used for the tests (Fig.1).

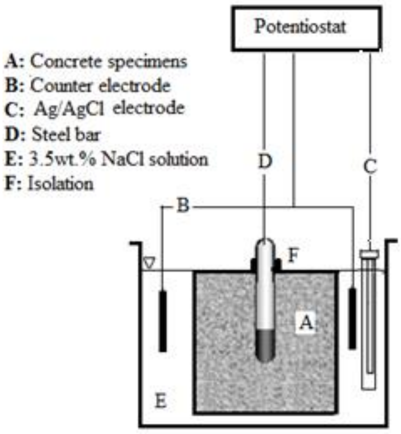

Fig.1. Experimental setup for electrochemical corrosion measurement

Potentiodynamic polarization tests at scan rate of 0.5 mV/s were carried out. PAR Calc Tafel Analysis was used to fit the experimental data. The open-circuit potential (OCP) was recorded with and without sacrificial anode in the test solution for 60 days vs. Ag/AgCl reference electrode (Fig.2).

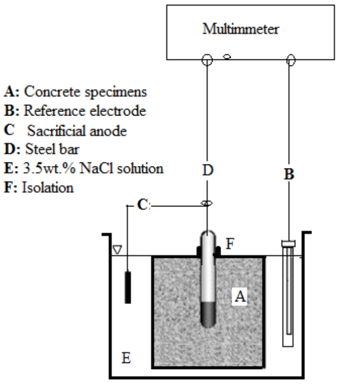

Fig.2. Experimental setup for cathodic protection tests

Before tests each water-cured specimen was taken from water and then rubbed with a clean dry cloth until a dry surface sample was obtained. At the end of electrochemical monitoring, the concrete specimens were broken and the specimens were removed and cleaned with HNO_3 solution for 3 min and dried. After cleaning, the specimens were reweighed and the losses in weights were calculated. The corrosion rates for steel bars and Al-Mg-Zn sacrificial anodes were obtained from following equation [9]:

$$c.r = \frac{K \cdot W}{A \cdot D \cdot t} \qquad (1)$$

where c.r is the corrosion rate expressed in (mpy), K is a constant of (3.45×10^6), t is the time of exposure (h), A is the area (cm^2), W is the weight loss in the nearest 1 mg and D is the density of the material (g/cm^3).All solutions were freshly prepared from analytical grade chemical reagents using distilled water.

2.3. Surface Analysis

The morphology of steel bars after cathodic protection tests was performed using scanning electron microscope (Joel-JXA-840A).

3. Results and Discussions

3.1. Microstructure

The optical micrograph of Al-3.25Zn-3.12Mg sacrificial anode is shown in Fig.3. Obviously, it can be seen that the microstructure contains uniform continuous distribution of intermetallic precipitate along the grain boundaries. The bright area indicates the α-Al and the dark regions indicate the second phases. A phase analysis was carried out using X-ray diffraction (XRD). Fig.4 illustrates that the Al-3.25Zn-3.12Mg sacrificial anode contains α-Al grains with intermetallic compound phases of $MgZn_2$ and $Mg_{32}(Al,Zn)_{49}$. These compounds have potential more negative than Al. Therefore, work as an anode inside the matrix, while α-Al works as a cathode.

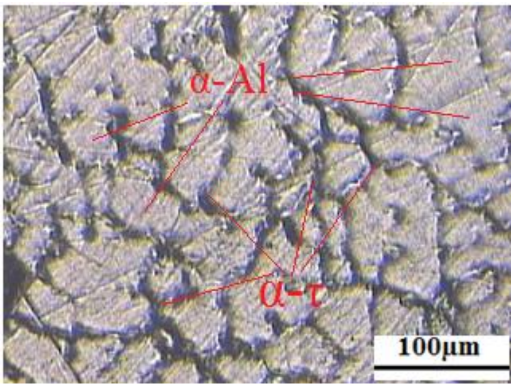

Fig.3. Optical micrograph of the investigated anode

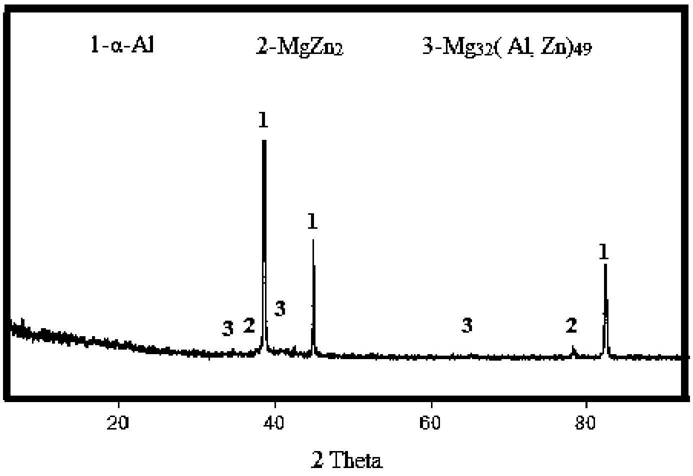

Fig.4. X-ray diffraction of the investigated sacrificial anode

3.2. The self-corrosion

The self-corrosion potentials of steel bars imbedded in concrete and sacrificial anode are shown in Fig. 5. The results show that the potential after 18 days were -570 and -980 for steel bars and sacrificial anode respectively. Fig.6 presents the potentiodynamic polarization curves and corresponding corrosion parameters of steel bars imbedded in concrete and the sacrificial anode. The corrosion potentials were -600 and -990 for steel bar and sacrificial anode respectively. This means that a high potential difference can be obtained by coupling. Therefore the galvanic corrosion between them will occur. In this cell, the steel bar impeded in concrete will work as cathode, while aluminum as anode.

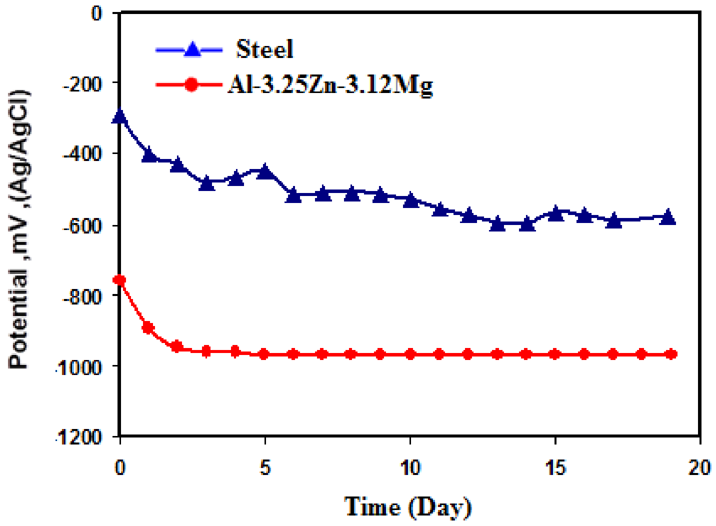

Fig. 5. Potential–time curves of steel imbedded in concrete and sacrificial anode in 3.5 wt. % NaCl solution

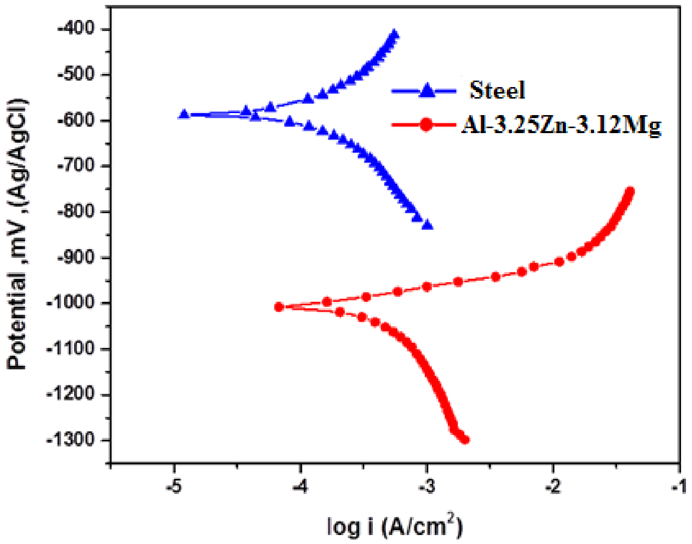

Fig. 6. Tafel polarization curves of steel imbedded in concrete and sacrificial anode in 3.5 wt. % NaCl solution

3.3. Effect of the anode distance

The development of open circuit potential (OCP) for steel bars in concrete with different cathode-anode distance is shown in Fig. 7. It can be seen that increasing distance of the aluminum anode leads to shifting the potential to more anodic values. The corresponding corrosion rate is shown in Fig. 8. It can be seen clearly that the corrosion rate increases with increasing the distance between cathode and anode. These results are in agreement with the OCP. The behavior is attributed to the increment in the ohmic drop IR. Additionally, when the distance between the aluminum anode and the cathodic location increases, the resistance R between the cathode and anode also increases [10]. Therefore, the galvanic current decreases, resulting in low protection efficiency. The morphology of anode after cathodic protection tests are shown in Fig.9. The results show that decreasing the anode distance leads to increasing the galvanic corrosion and the surface of anode heavily corroded with porous corrosion products.

Moreover, Fig. 9 shows that compact corrosion products can be obtained by increasing the anode distance.

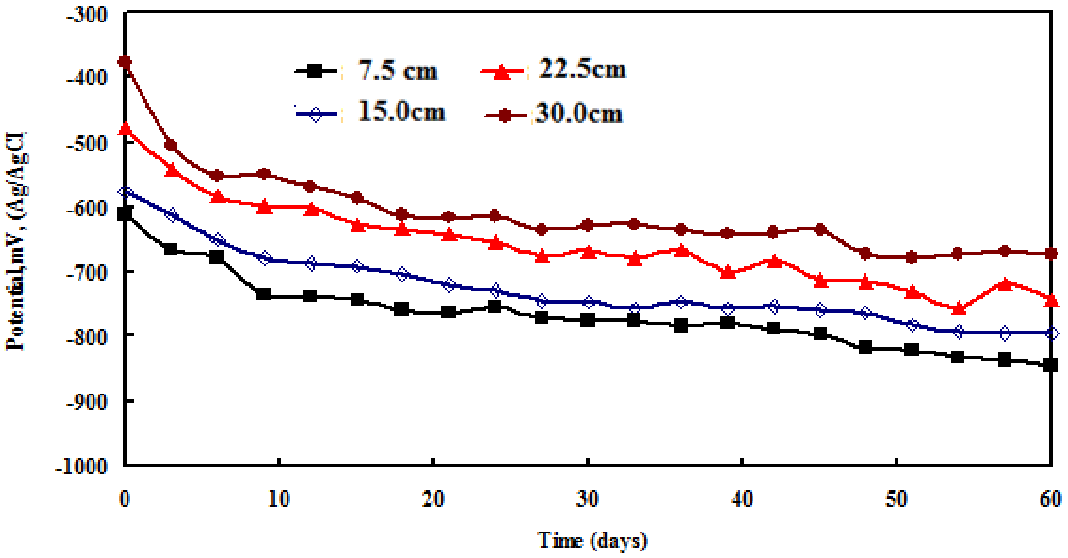

Fig.7. Effect of the anode distance on the OCP of steel bars imbedded in concrete

3.4.Effect of cathode/anode ratio

The development of open circuit potential (OCP) for steel bars in concrete with different cathode/anode ratio is illustrated in Fig. 9. The results illustrate that increasing cathode/anode ratio shifts the OCP to negative direction. The corrosion rate is shown in Fig. 3. It is obvious that the corrosion rate increases with increasing the cathode/anode ratio. This behavior is attributed to the anode current is always equal to the cathode current when the galvanic corrosion occurs, and anode area is smaller, the anode current density is greater. However the morphology of anode with different cathode/anode ratio shows that increasing the cathode/anode ratio leads to increasing the pitting corrosion. This type of corrosion decreases the efficiency of anode and increase the maintenance cost. Therefore, the cathode /anode ratio of 300:1 can be used effectively.

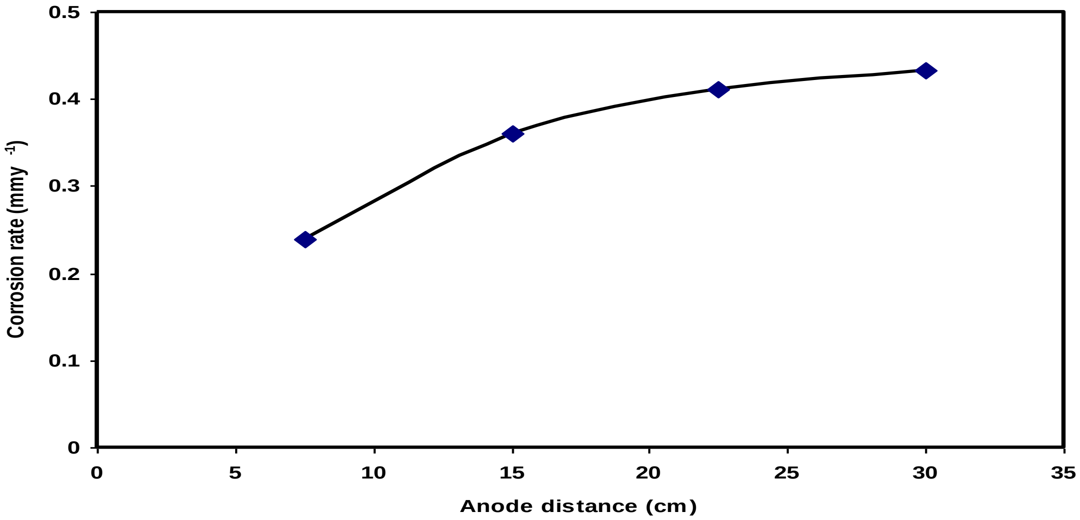

Fig.8. Effect of the anode distance on the corrosion rate of steel bars imbedded in concrete

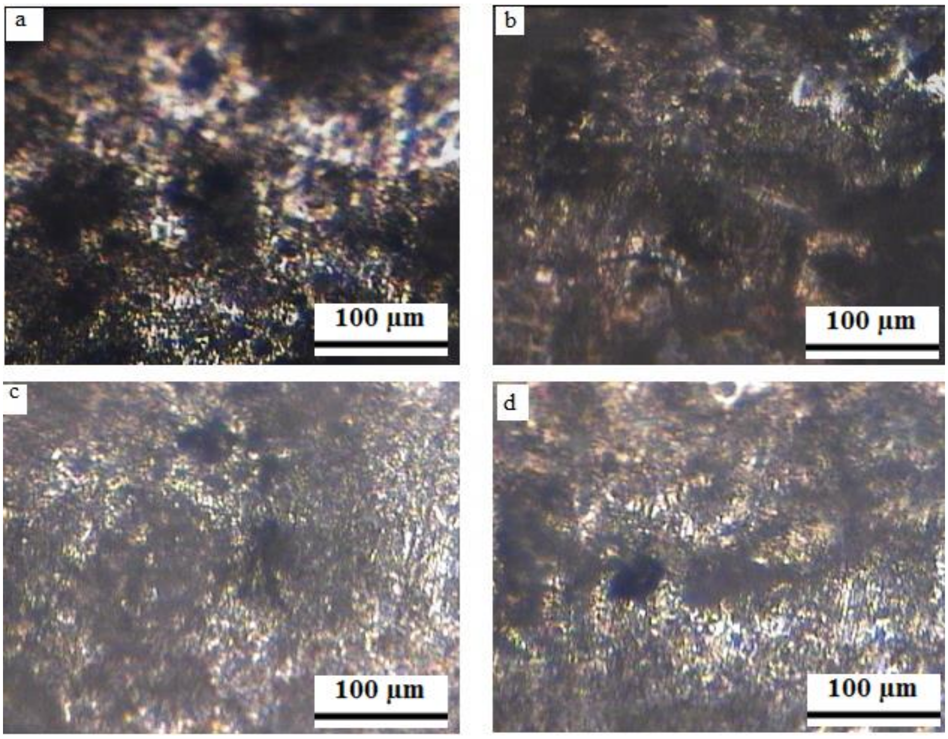

Fig.9. micrographs of surface morphologies of anodes with different cathode-anode distance. (a)7.5cm, (b)15cm, (c)22.5cm and (d)30cm

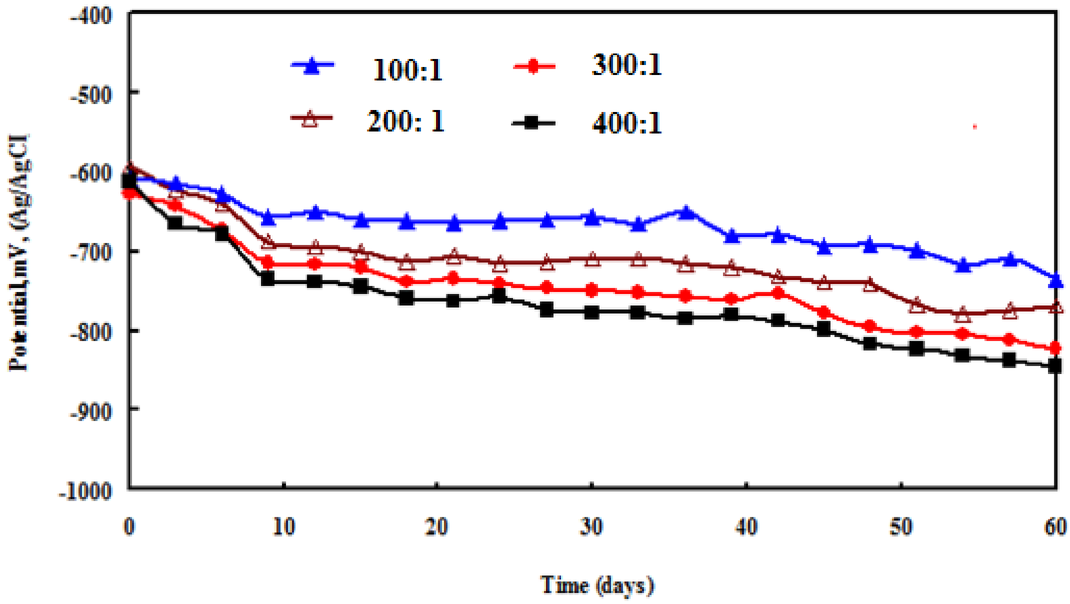

Fig.10. Effect of the cathode/anode ratio on the OCP of steel bars imbedded in concrete

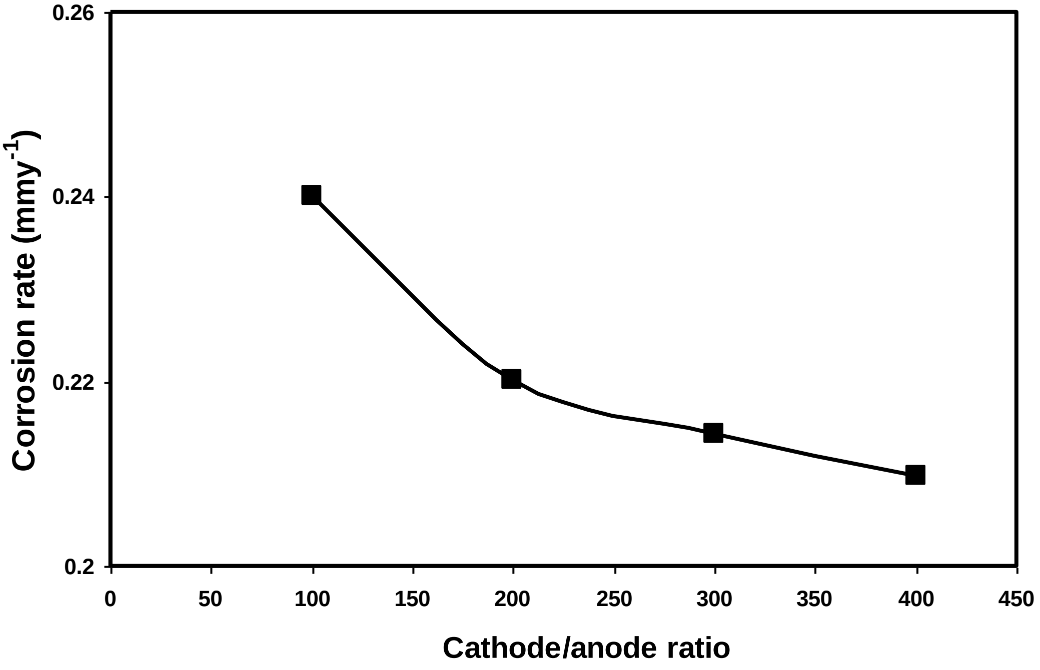

Fig.11. Effect of the cathode/anode ratio on the corrosion rate of steel bars imbedded in concrete

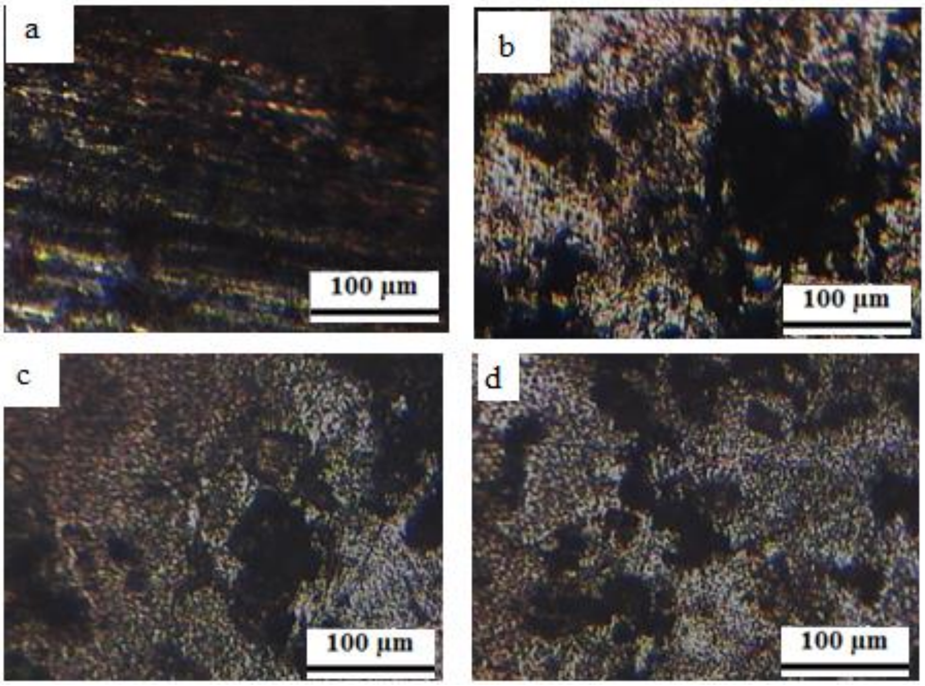

Fig.12. micrographs of surface morphologies of anodes with different cathode/anode ratio, (a)100:1, (b)200:1, (c)300:1and (d)400:1

4. Conclusions

In the present study, Al-3.25Zn-3.12Mg ingot was evaluated as a sacrificial anode in the cathodic protection of steel imbedded in concrete. It was concluded that:

1-Al-3.25Zn-3.12Mg can be used effectively to minimize the corrosion rate of steel in concrete.

2- Increasing the cathode/anode ratio decreased the corrosion rate of steel imbedded in concrete while the cathodic efficiency decreased with increasing the distance between the cathode and anode.

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