Effect of Corrosion Inhibitors Admixtures on Corrosion Rate of Steel Reinforcement in Concrete

تأثيرالإضافات المانعة للصدأ على معدل صدأ حديد التسليح في الخرسانة

By

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ملخص البحث:

إن صدأ حديد التسليح من الأسباب الرئيسية للتفتت والإنهيار المبكر للمنشآت الخرسانية المسلحة . وطرق وأساليب مقاومة صدأ حديد التسليح في الخرسانة الناتج من أملاح الكلوريدات متعددة ، ومن الطرق والأساليب لمنع صدأ حديد التسليح فى الخرسانة هو إستخدام الإضافات المانعة للصدأ التى تضاف أثناء مرحلة خلط الخرسانة . حيث يهدف هذا البحث إلى تقييم أداء هذة الإضافات(سيكا فيروجارد ٩٠١) فى منع حدوث صدأ حديد التسليح ومدى تأثيرها على خواص الخرسانة فى مرحلتيها الطازجة والمتصلدة. وقد تم استخدام هذة الإضافات مع خلطات خرسانية مختلفة النسب والمكونات.

فى هذة الدراسة تم إستخدام عينات خرسانية مكعبة بطول ١٥٠ مم ،عينات الحديد عالي المقاومة (٥٢/٣٦) بقطر ١٠ مم وطول ١٥٠ مم منهم ١٠٠ مم مدفون داخل الخرسانة ، ٥٠ مم خارج الخرسانة وسمك الغطاء الخرسانى لحديد التسليح (٢٥، ٥٠ ، ٧٥ مم) لقياس معدل الصدأ. وبعد إنتهاء مدة المعالجة تم تجفيف العينات لمد ٢٤ ساعة ثم تعريض العينات لعملية تعجيل الصدأ لمدة ٢٤٠ ساعة ، وتمت عملية تعجيل صدأ الحديد بإستخدام التيار الكهربي الناتج من بطارية ٣٠ فولت وبغمر العينات جزئيا فى محلول كلوريد الصوديوم ٦% فى خزان بلاستيك ، وأثناء إجراء عملية تعجيل صدأ حديد التسليح في الخرسانة تم قياس فرق الجهد بالفولت كل ١٢ ساعة بين طرفي مقاومة مقدارها ١٠٠ أوم بإستخدام الأفوميتر، وبمعلومية قيمة فرق الجهد والمقاومة بإستخدام (قانون أوم) تم حساب شدة التيار المار بالأمبير والذى يتسبب في صدأ الحديد. بإستخدام قانون فاراداى حيث يقوم بتحويل التيار المتسبب في عملية الصدأ إلى حساب الشحنات المارة بالكولوم،كتلة الحديد المفقودة نتيجة عملية الصدأ(بالجرام) ،معدل الصدأ (بالمم / العام).

وقد أظهرت النتائج أن زيادة سمك الغطاء الخرسانى يقلل معدل الصدأ لكل الخلطات الخرسانية وإستخدام الإضافات المانعة للصدا بنسبة ٥% من وزن الاسمنت أثناء مرحلة خلط الخرسانة يقلل معدل صداحديد التسليح فى الخرسانة بنسبة ٨٠ % وبدون تأثير على خواص الخرسانة فيما عدا مقاومة التماسك إنخفضت بنسبة ١٠% ، وأنها تعطى نتائج أفضل مع الخلطة التى تحتوى على غبار السيليكا بنسبة ١٥% ونسبة المياة للأسمنت ٠,٣٥،وتقلل سمك الغطاء الخرسانى اللازم لحماية حديد التسليح من الصدأ لنفس مكونات الخلطة من ٧٥ مم إلى ٥٠ مم ، وأنها تعجل شك الخرسانة لذلك تحتاج إلى مؤخرات للشك عند إستخدامها.

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ABSTRACT

Reinforcement corrosion is the main cause of damage and early failure of reinforced concrete structures. The protection system of embedded steel reinforcement from chloride induced corrosion involves several methods and techniques. One of these methods and techniques is using corrosion inhibitors admixtures (CIA) which added to concrete mix during mixing stage of concrete. These research aims to evaluate these admixtures (Sika Ferrogard® -901) in prevent corrosion of steel in concrete and their effect on concrete properties for fresh and hardened concrete. In this paper (CIA) used with different concrete contents and proportions.

In this study, 150-mm concrete cubes specimens with high tensile steel bar grade (36/52) of 10 mm in diameter and 150 mm in length were embedded in each specimen during its casting such that 100 mm was fixed inside the concrete while the reminder 50 mm was kept outside. Three thicknesses of concrete cover were used; 25, 50 and 75 mm. After 28 days of water curing, specimens were transferred to dry for 24 hour, then the specimens were partially submerged in plastic tank filled with 6% NaCl solution Acceleration of corrosion rate test is achieved by continuous electrical current produced from power supply 30 volts for 240 hour, where volts difference was measured in volts between resistance 100 ohm and the reading was record every 12 hour. The corrosion current (I_{corr} in Ampere) was calculated during the accelerated corrosion regime by using ohm's law by knowing measured volts difference and resistance. Faraday's law describes the relationship between section loss and corrosion current. Hence, calculate corrosion rate of steel reinforcement in concrete.

The results show that for all mixes the increasing of concrete cover thickness reduces the corrosion rate of steel. Using 5% (CIA) by weight of cement where the optimum dosage of Corrosion inhibitors admixture from experimental tests is 5% by weight of cement reduce corrosion rate by 80 % with no side effect on concrete properties except bond strength decreased by 10%.(CIA) gave best results with concrete mixes which contains 15% silica fume and water to cement ratio 0.35 . (CIA) decreasing concrete cover required to prevent corrosion from 75 mm to 50 mm. (CIA) accelerate setting time of concrete, so it needs a retarded when used with concrete mixes.

1. INTRODUCTION

A passivating film produced by cement hydration is formed on the steel surface and enables the formation of this thin passive film coating on steel and is maintained in the alkaline environment, The high pH environment in concrete, above 12 where cement paste is alkaline (pH between 12 and 14), will normally protect reinforcing steel from corrosion. Steel passivity can be disrupted by chloride presence in the concrete and decrease in pH and a breakdown of the passive film and destroy this protective layer. It results in the corrosion of the steel-reinforcing bar (rebar) and in the long term, the deterioration of the concrete. Several solutions to this problem have been proposed and tested, some of these methods involve increasing the concrete cover over the rebar, reducing water/cement ratios, using denser concrete, coating the rebar with epoxy, protecting the rebar cathodically, and using corrosion inhibiting admixtures.

2. Objectives

The primary aims of this research are to evaluate the factors affecting on corrosion of steel in concrete and provide designers with deicing support which can improve their judgment in selection and optimization of concrete mix characteristics to prevent corrosion of steel reinforced bars in concrete structures exposed to chlorides salts.

The objectives of study were addressing some of the important matter relating to:

1. What is the optimum ratio of silica fume with regard to corrosion of steel in concrete?
2. Is it necessary to use corrosion inhibitors admixtures to prevent corrosion of steel in concrete?
3. Do corrosion inhibitors admixtures affect the mechanical properties of concrete and durability?

Other aims of this study can be summarized as follows:

1. To clarify the role of corrosion inhibiting admixtures (CIA) on the properties of fresh and hardened concrete.
2. To signify the importance of using corrosion inhibitors admixtures (CIA) on reducing the corrosion activity of reinforcing steel in concrete.

3.Experimental Work

The test program was arranged to determine the effect of corrosion inhibitors admixtures (CIA) on corrosion rate of steel reinforcement in concrete with three thickness of concrete cover (25, 50, 75 mm) and their effect on mechanical properties of both hardened and fresh concrete.

3.1 Corrosion Inhibiting Concrete Admixtures

Sika Ferrogard® -901 as corrosion inhibitors was evaluated in this study. Sika Ferrogard® -901 is mixed with the gauging water or added at the same time into the concrete mixer. It may also be added to the concrete in the transit mixer at the point of discharge. In this case, an additional mixing time of at least 1 minute per m^3 concrete must be observed. Before discharging it, check the concrete visually for uniform consistency. The quantity of Sika Ferrogard® - in the mix design should be taken into consideration when determining the quantity of water for a specific W/C ratio. Sika Ferrogard® -901 is not to be mixed with the dry cement.

4. Tests and Specimens

The consistency of fresh concrete was measured just after mixing by the conventional slump for concrete. After that all moulds were cast, and vibrated to ensure full compaction. To determine the mechanical properties and durability of different mixes the following tests and specimens were used:

- Compression test:

- For concrete at, 7, and 28 days using 150 mm cubes for all mixes
- For concrete at 3, 7, 28 and 365 days using 150 mm cubes to study the influence of corrosion inhibitors admixtures on compressive strength at various ages
- Splitting test: For concrete at, 28 day using 150 x 300 mm cylinders.

- Steel–concrete bond strength by using pullout test

- Concrete specimens were cylinders 15 cm in diameter and 30 cm in length. the steel bars grade (36/52) were placed axially with concrete specimens

- Flexural strength test:

- For concrete at, 28 day using 100 x 100 x 500 mm beams.

- Corrosion rate measurements

In this study, 150-mm concrete cubes specimens with the steel bar of 10 mm in diameter and 150 mm in length were embedded in each specimen during its casting such that 100 mm was fixed inside the concrete while the reminder 50 mm was kept outside and coated by epoxy to protect it from corrosion. The thicknesses of the cover were kept variable 25, 50, and 75 mm as shown in Fig.(1.a,b). For each mixture casting; 6 cubes for compressive test, 3 cylinders for splitting tensile test, 3 cylinders for bond test, 3 beams for flexural test, and 3 cubes for corrosion test. The details of these specimens are given in Fig (2). All the test specimens were demolded after 24 hours and then stored under water in curing tank

4.1 Corrosion Rate

4.1.1 Expression of Corrosion Rate

The corrosion rate is usually expressed as the penetration rate and is measured in mm/year. Often, especially in laboratory tests; it is expressed in electrochemical units, i. e. in mA/m^2 or in $\mu A/cm^2$. Corrosion rate is often expressed in different terms: corrosion current, section loss or corrosion depth, and sometimes, diameter reduction. Faraday's law of electrochemical equivalent states that 10 mA/m^2 or $1 \mu A/cm^2$ corresponds to a cross section loss of carbon steel of approximately 11.60 μm/year.

4.1.2 Acceleration of Corrosion Rate Test

After 28 days of water curing, specimens were transferred to dry for 24 hour, then the specimens were partially submerged in plastic tank filled with 6% NaCl solution (60 gm salt NaCl: 940 gm tap water weight by weight). Acceleration of corrosion rate test was achieved by continuous electrical current produced from power supply 30 volts as shown in Fig.(3). The corrosion current (I_{corr} in Ampere) was calculated during the accelerated corrosion regime by measuring the potential voltage versus time, and was recorded every 12 hour for 240 hours across the known 100-ohm resistance between top and bottom of the bars, then corrosion current can be estimated according to Ohm's as shown in equation (1)

$$V = I * R \qquad (1)$$

Where;

V = Electrical potential difference (volts)

I = Electrical current flow (amperes)

R = Electrical resistance to flow (ohms)

The amount of steel dissolving to form oxide (corrosion) can be calculated from measurements of the current generated by the anodic reaction:

$$Fe \rightarrow Fe^{2+} + 2e^-$$

and consumed by the cathodic reaction:

$$2e^- + H_2O + 1/2O_2 \rightarrow 2OH^-$$

The charge passing (Q) through the reinforcement steel bars at any time during the corrosion regime was calculated by the following equation :

$$Q = \int_0^T Icorr\ dt \qquad (2)$$

Using faraday's equation the cumulative steel mass loss was calculated at any time by the following equation:

Using faraday's equation the cumulative steel mass loss was calculated at any time by the following equation

$$M_s = \frac{Q * E_w}{F} \quad (3)$$

Where:

Q = Charge passing (coulombs)

I_{corr} = Corrosion current (A)

M_s = Mass loss of steel at time T (gm)

T = Corrosion time (sec.)

E_w = Equivalent weight of steel =27.925 (gm /mole of e^-)

F = Faraday's constant = 96486.70 (coulombs/mole of e^-)

The corrosion current density (i_{corr} in $\mu A/cm^2$) is calculated by dividing corrosion current (I_{corr}) by the changing surface area of steel (A_{new}) exposed to the corrosion (ASTM G-102) which could be calculated from the cumulative steel mass loss (M_s) and is given by the following equation.

$$i_{corr} = \frac{I_{corr}}{A_{new}} \quad (4)$$

The corrosion rate was calculated by using one of the following equations, (5) or (6):-

$$P.R. = \frac{8.76*10000*M}{\rho * A * T} \quad (5)$$

Where:

8.76*10000 is the conversion factor of (cm / hour) into (mm/year).

P.R. is the penetration rate in mm/year.

M is mass loss in gm.

A is surface area in cm^2.

ρ is density of steel in gm/cm^3 (7.86 for steel) .

T is exposure time in hour.

$$P.R. = \frac{I_{corr}}{A_{new}} *11.60 \quad (6)$$

Where:

P.R. is the penetration rate in μm /year.

11.60 is the conversion factor of ($\mu A/cm^2$) into (μ m/year).

I_{corr} is corrosion current in μA.

A_{new} is surface area of steel in cm^2.

5. RESULTS AND DISCUSSION

The effect of corrosion inhibitors admixture (CIA) with various concrete Strength on properties of concrete in both fresh and hardened states is discussed, also the effect of corrosion inhibitors admixture (CIA) with various concrete Strength on Corrosion rate of steel reinforcement in concrete were investigated.

5.1 Fresh concrete:

The effect of concrete mixture contents on consistency of fresh concrete are studied, In general consistency of fresh concrete mixtures are measured through the slump cone test as shown in table (3) presents some properties of fresh concrete

5.2 Hardened Concrete:

Some properties of hardened concrete such as compressive strength at 7, 28 days, splitting tensile strength, flexural strength, steel–concrete bond strength and density of concrete at 28 days were studied as shown in table (3). The bond strength decrease with corrosion inhibitors admixture (CIA) by 10% relative to control mix as shown in Fig.(4).compressive strength ,flexural strength and splitting tensile strength are improved with corrosion inhibitors admixtures relative to control mix as shown in Fig.(5), Fig.(6), and Fig.(7). Effect of CIA on properties of concrete at different ages as shown in table (7).

5.3 Corrosion rate of steel measurements:

The corrosion current (Icorr in Ampere) was measured during the accelerated corrosion regime at different concrete cover. By using faraday's law, the average cumulative steel mass loss during the different corrosion regimes was calculated. Hence, corrosion rate of steel reinforcement were calculated. Based on test results of ferrogard 901, it is found that at compressive strength 65 MPa, concrete have a cover 50 mm, has corrosion rate 95% lower than concrete with compressive strength 18 MPa , 63% lowers than concrete with with compressive strength 29 MPa and 42% lowers than concrete with compressive strength 55 MPa as shown in Fig. (8). At compressive strength 65 MPa, concrete have a cover 75 mm, has corrosion rate 96% lower than concrete with compressive strength 18 MPa , 60% lowers than concrete with with compressive strength 29 MPa and 17% lowers than concrete with compressive strength 55 MPa as shown in Fig. (8). At compressive strength 65 MPa, concrete have a cover 25 mm, has corrosion rate 85% lower than concrete with compressive strength 18 MPa , 58% lowers than concrete with with compressive strength 29 MPa and 27% lowers than concrete with compressive strength 55 MPa as shown in Fig. (8) This is because CIA acts as a passivator due to its oxidizing properties and stabilizes the passive film due to its ability to oxidise ferrous ions (Fe^{+2}) to ferric ions (Fe^{+3}), which form poorly soluble iron oxides.

Based on the results in Fig. (9), it is seen that high compressive strength concretes have lower corrosion rate than the normal strength concrete at all covers. This is because corrosion inhibitors admixture give good results with high compressive strength.

Concrete with cover 75 mm gave a significant lower corrosion rate than at 50 mm cover by 15% at compressive strength 65 MPa, 60% at compressive strength 55 MPa, 23% at compressive strength 29 MPa and 28% at compressive strength 18 MPa as shown in Fig. (9). It is recommended to use corrosion inhibitors admixtures with high strength concrete since it gave a significant lower corrosion rate. Based on test results, the concrete mixes with CIA give more reduction in corrosion rate than control mix as shown in Fig.(10), Fig.(11) and Fig.(12)

6. Conclusions

Several conclusions were made after reviewing all data and results from the research, Based on the results and discussions, The following conclusions are drawn from the experimental studies of this investigation:-

1 The results show that for all mixes the increasing of concrete cover thickness from 25 mm to 75 mm reduces the corrosion rate of steel.
2 The adding of corrosion inhibitors admixtures reduces corrosion rate of steel by 69, 90 and 82% for concrete cover 25, 50 and75 mm respectively.
3 The adding of corrosion inhibitors admixtures reduces concrete cover thickness which required for prevent corrosion from 75 mm to 50 mm.
4 Corrosion inhibitors admixture had a beneficial effect on permeability and reduced diffusion of chloride. Significant increase in overall compressive strength was another benefit at different ages of concrete. No particular adverse effects were observed.
5 Use of Corrosion inhibitors admixture, the covering depth required for the nitial corrosion of embedded steel bar in concrete could be reduced.
6 Use of Corrosion inhibitors admixture, improve mechanical properties of hardened concrete except bond strength reduce it by 10%

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Table (1) Experimental program for concrete mixes.

Group	Mix	CIA Cont**	Cement Type	Cement cont*	SF (%)	Water (liter/m³)	SPZ (%)	Aggregate Sand*	Aggregate Gravel*	w/c	Variable effect
A	M1	0	OPC	300	0	165	0	653	1306	0.55	f_c , CIA
	M2			350	0	157.5	1.50	642	1284	0.45	
	M3			400	10	154	2.00	612	1224	0.35	
	M4			450	15	119	3.15	630	1260	0.26	
B	M1-5%	5%	OPC	300	0	165	0	653	1306	0.55	
	M2-5%			350	0	157.5	1.50	642	1284	0.45	
	M3-5%			400	10	154	2.00	612	1224	0.35	
	M4-5%			450	15	119	3.15	630	1260	0.26	

OPC is ordinary Portland cement

f_c is compressive strength

CIA is corrosion inhibitors admixtures (% by wt. of cement)

SF is silica fume,(%by wt. of cement)

w/c is water to cement ratio

SPZ is superplasticizer type F, % (by wt. of cement)

* kg/m³ , ** % (by wt. of cement)

Table (2) Properties of Sika Ferrogard® -901

Trade name	Chemical composition	Color	Density, kg/m³
Sika Ferrogard® - 901	Nitrogen containing organic and inorganic substances.	Green liquid	1060

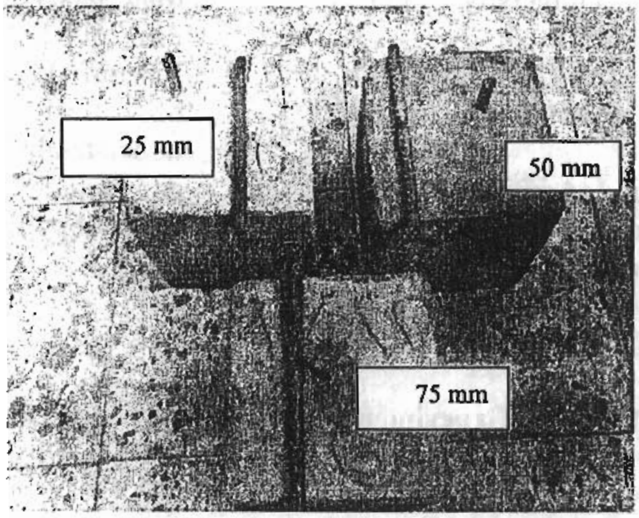

Fig. (1.a) Thickness of concrete cover used with concrete cubic samples

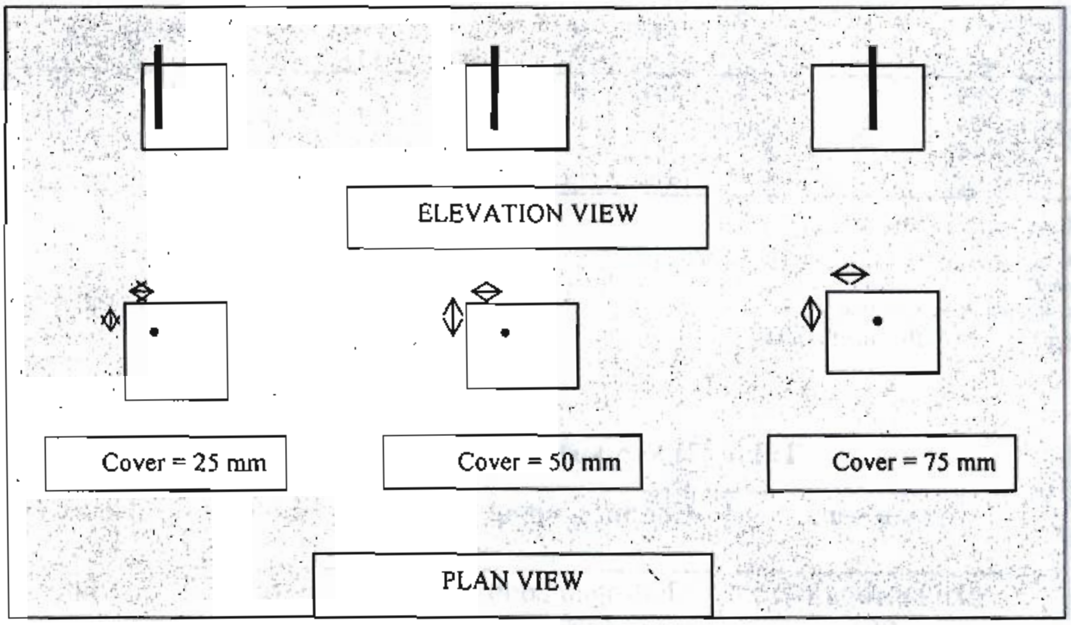

Fig. (1.b) Thickness of concrete cover used with concrete cubic samples

Table (3) Test results of concrete specimens

Mix	S mm	γ 28 days	f_c		f_{sp} 28 days	f_r 28 days	f_b 28 days	parameter effect
			7 days	28 days				
M1	110	2.49	12.5	18.2	1.98	2.95	4.51	
M2	100	2.52	21.5	29.7	2.95	4.75	5.36	
M3	140	2.54	39.2	55.2	5.70	7.84	6.08	
M4	80	2.46	51.3	65.3	6.13	8 .62	7.24	f_c, OPC, CIA (5%)
M1-5%	120	2.49	16.2	20.2	2.2	3.13	4.10	
M2-5%	105	2.50	26.0	33.12	3.32	5.02	4.88	
M3-5%	135	2.52	47.2	62.3	6.34	8.42	5.53	
M4-5%	95	2.53	62.4	70.3	7.02	8.87	6.59	

OPC is ordinary Portland cement

SRC is sulfate resisting cement

S is slump (mm)

f_c is compressive strength (N/mm^2)

f_{sp} is splitting tensile strength (N/mm^2)

f_r is flexural strength (N/mm^2)

f_b is bond strength (N/mm^2)

γ is density of concrete at 28 days (t/m^3)

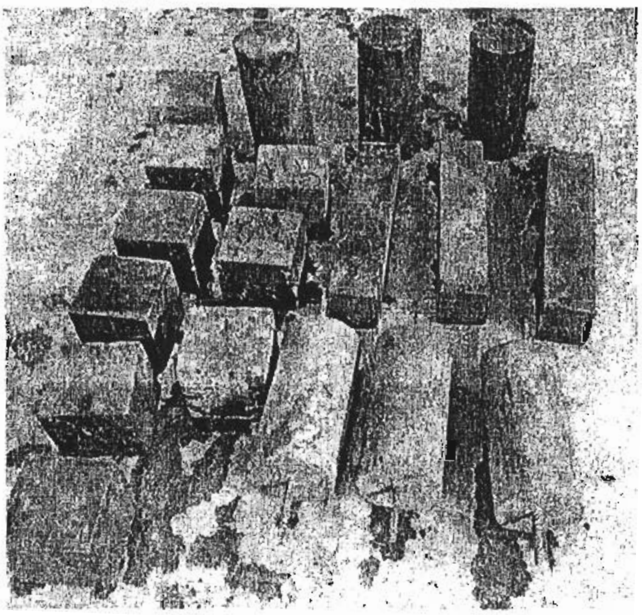

Fig. (2) Concrete specimens for each mixture

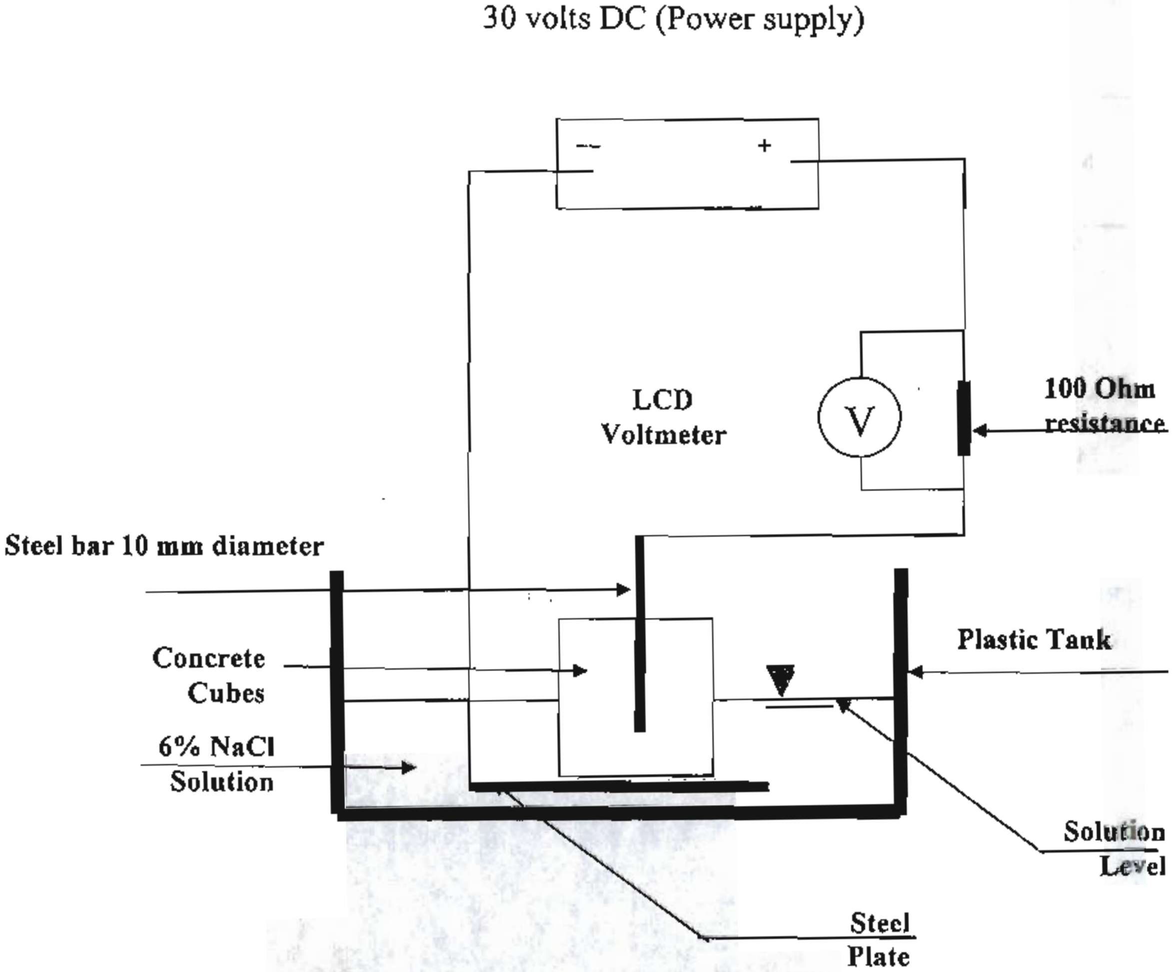

Fig (3) Test configuration of accelerated corrosion set- up [4]

Table (4) Test results of corrosion regime, cover = 25 mm.

Concrete mix	Charge passed (Coulombs)	Mass Loss (gm)	Corrosion current density ($\mu A/cm^2$)	Corrosion rate (mm/year)
M1	1244	0.360	45.90	0.532
M2	864	0.250	31.87	0.370
M3	622	0.180	22.95	0.266
M4	415	0.120	15.30	0.177
M1-5%	898	0.260	33.15	0.385
M2-5%	656	0.190	24.22	0.281
M3-5%	380	0.110	14.02	0.163
M4-5%	138	0.040	5.10	0.059

Table (5) Test results of corrosion regime, cover = 50 mm.

Concrete mix	Charge passed (Coulombs)	Mass Loss (gm)	Corrosion current density ($\mu A/cm^2$)	Corrosion rate (mm/year)
M1	967	0.280	35.70	0.414
M2	656	0.190	24.22	0.281
M3	380	0.110	14.02	0.163
M4	138	0.040	5.10	0.059
M1-5%	656	0.190	24.22	0.281
M2-5%	449	0.130	16.57	0.192
M3-5%	311	0.090	11.47	0.133
M4-5%	31	0.009	1.15	0.013

Table (6) Test results of corrosion regime, cover = 75 mm.

Concrete mix	Charge passed (Coulombs)	Mass Loss (gm)	Corrosion current density ($\mu A/cm^2$)	Corrosion rate (mm/year)
M1	587	0.170	21.67	0.251
M2	380	0.110	14.02	0.163
M3	276	0.080	10.20	0.118
M4	117	0.005	0.64	0.07
M1-5%	484	0.140	17.85	0.207
M2-5%	311	0.090	11.47	0.133
M3-5%	104	0.030	3.82	0.044
M4-5%	21	0.006	0.76	0.009

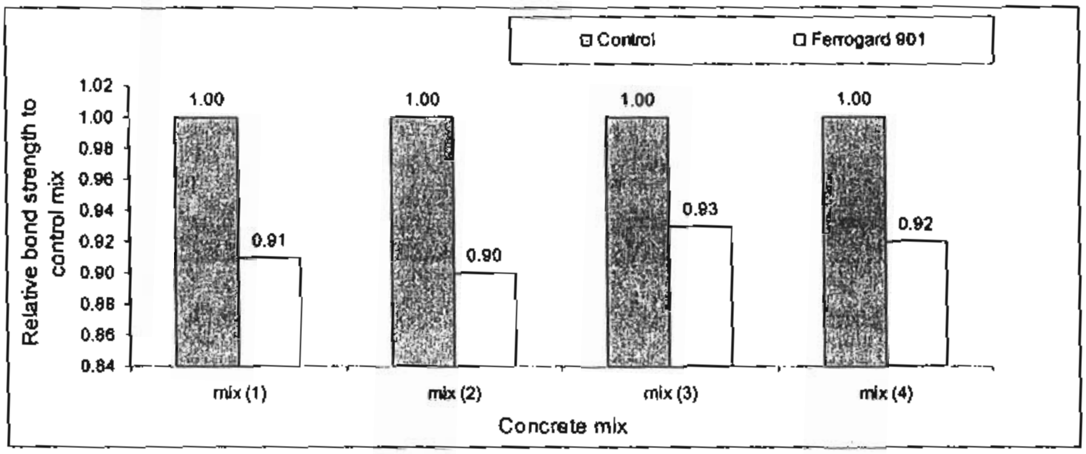

Fig. (4) Effect of type of CIA on bond strength.

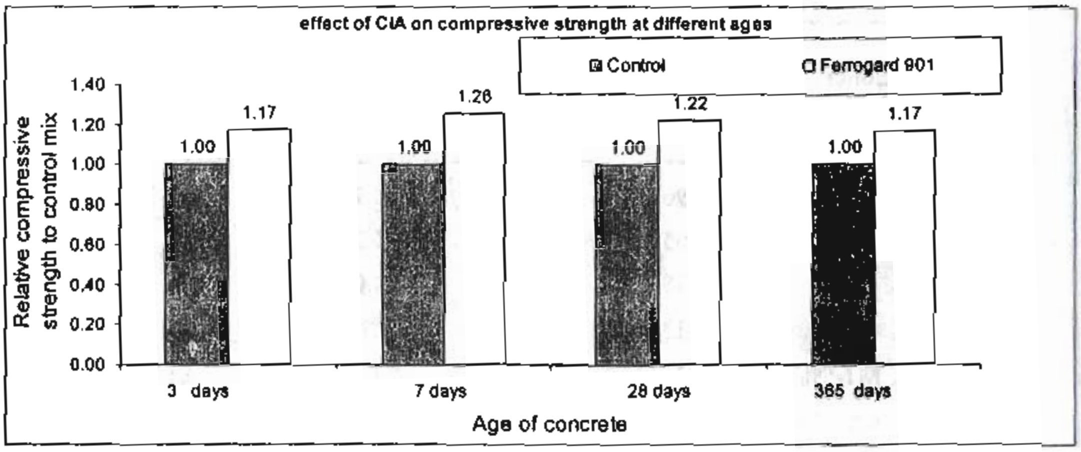

Fig. (5) Effect of CIA on compressive strength.

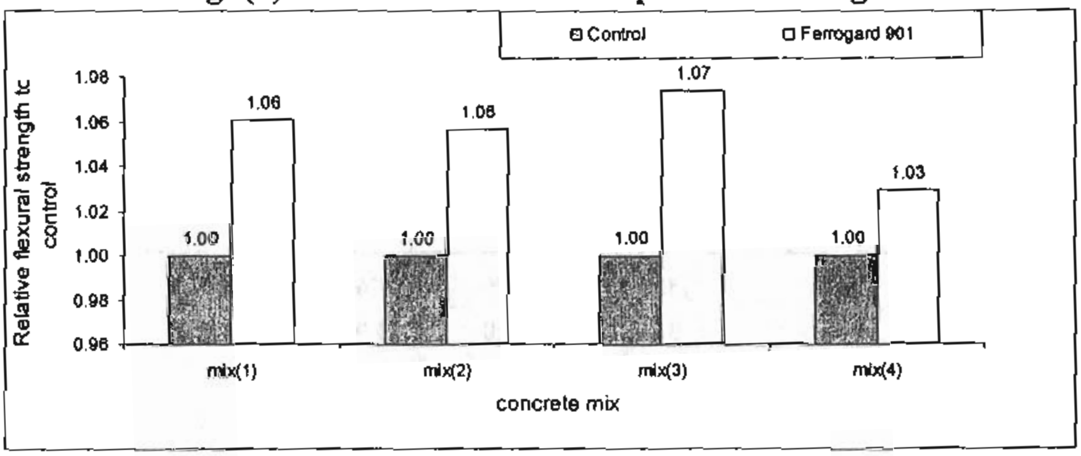

Fig. (6) Effect of CIA on flexural strength.

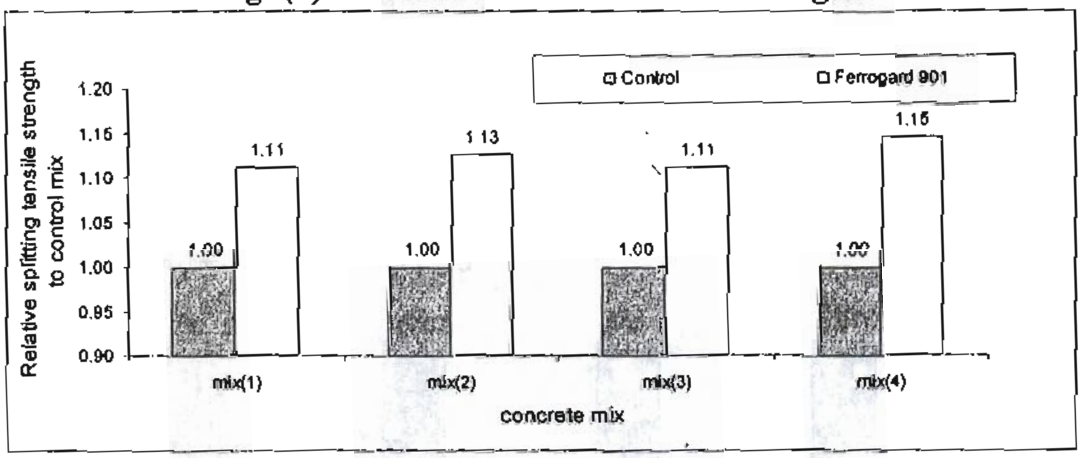

Fig. (7) Effect of CIA on splitting tensile strength.

Table(7) Effect of CIA on concrete properties at different ages

Property \ concrete mixes	M2 (control)	M2 (CIA-5%)
Slump (mm)	92	92
Setting Time:		
Initial, min	85	75
Final, hr - min	4 - 30	3 - 40
Compressive strength, MPa		
3 days	26	30.5
7 days	30.8	38.7
28 days	40.8	49.9
365 days	52.9	61.9

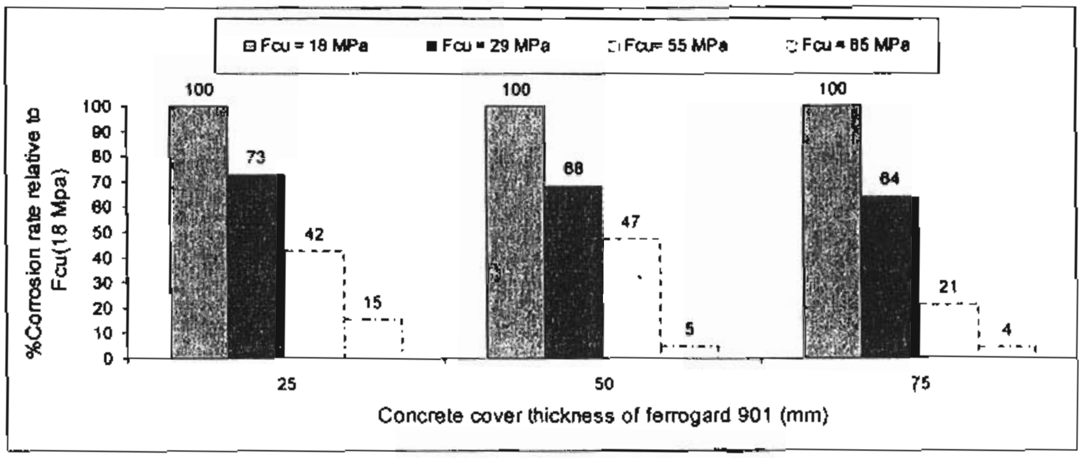

Fig. (8) Effect of concrete cover on reduction of corrosion rate

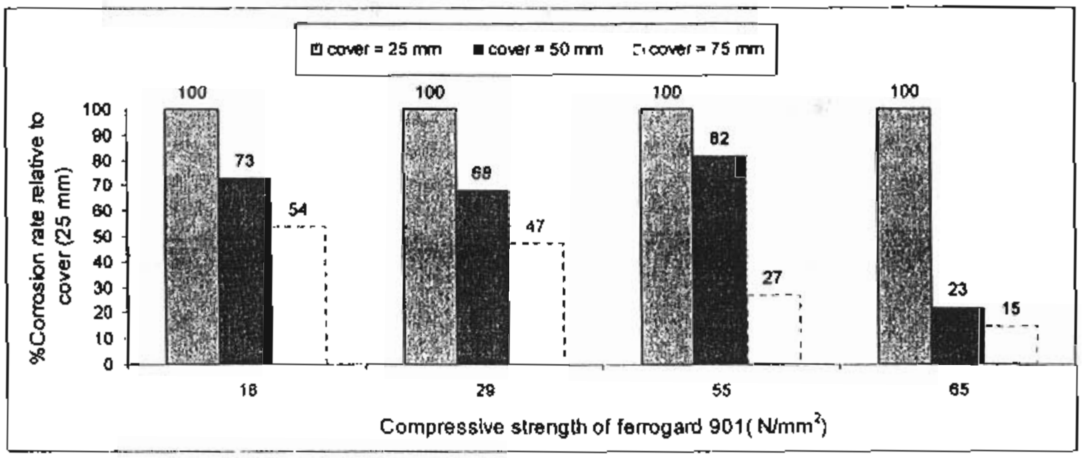

Fig. (9) Effect of compressive strength on reduction of corrosion rate

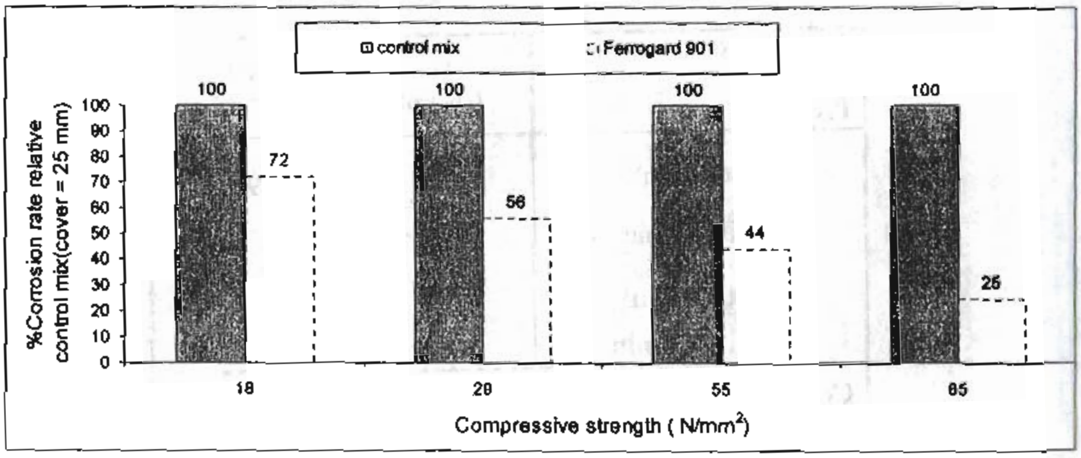

Fig. (10) Effect of CIA on reduction of corrosion for (Cover= 25 mm)

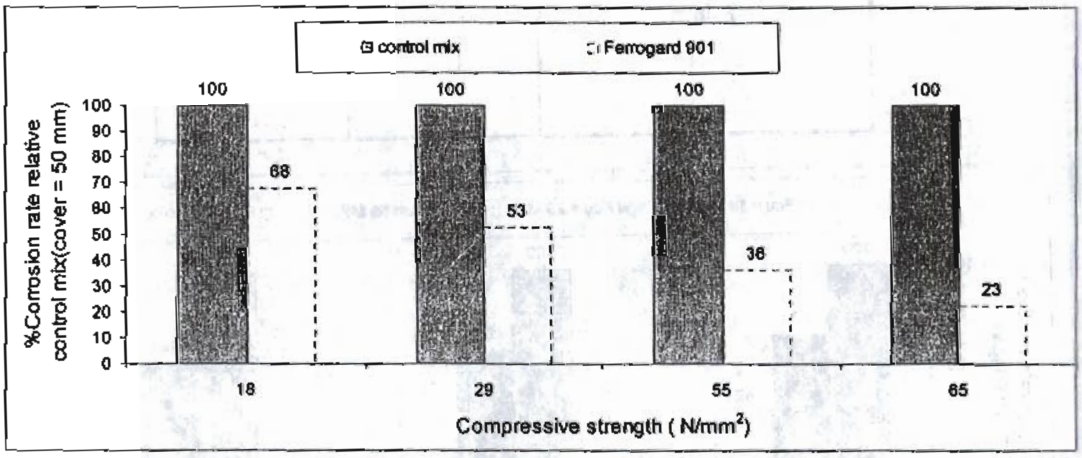

Fig. (11) Effect of CIA on reduction of corrosion for (Cover= 50 mm)

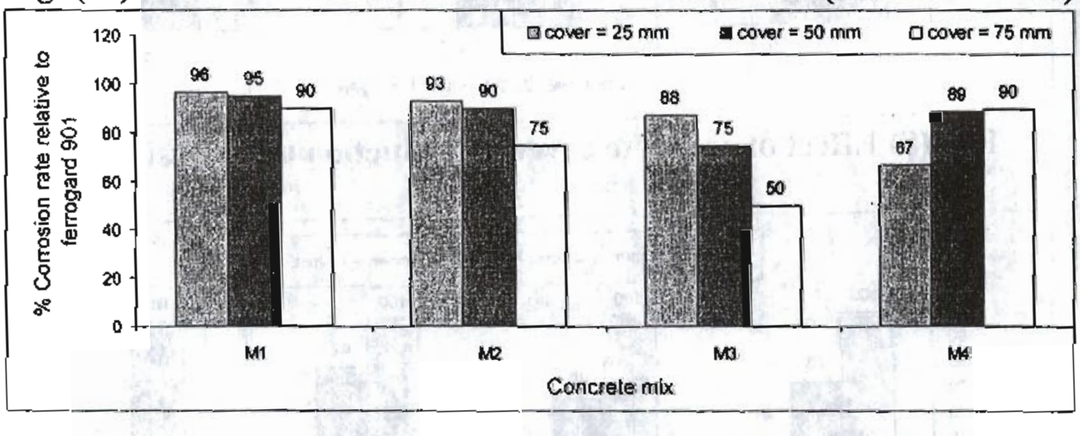

Fig. (12) Effect of CIA (5%) on reduction of corrosion rate

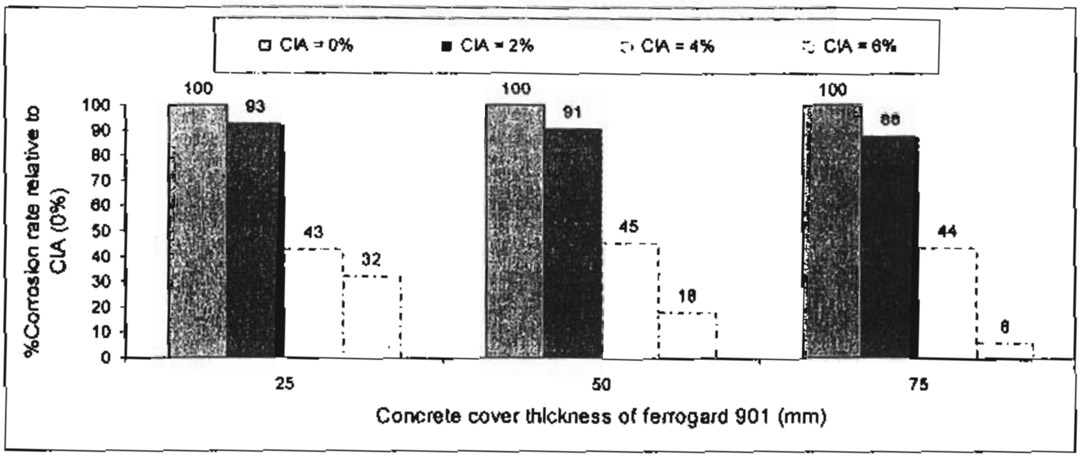

Fig. (13) Effect of cover on reduction of corrosion

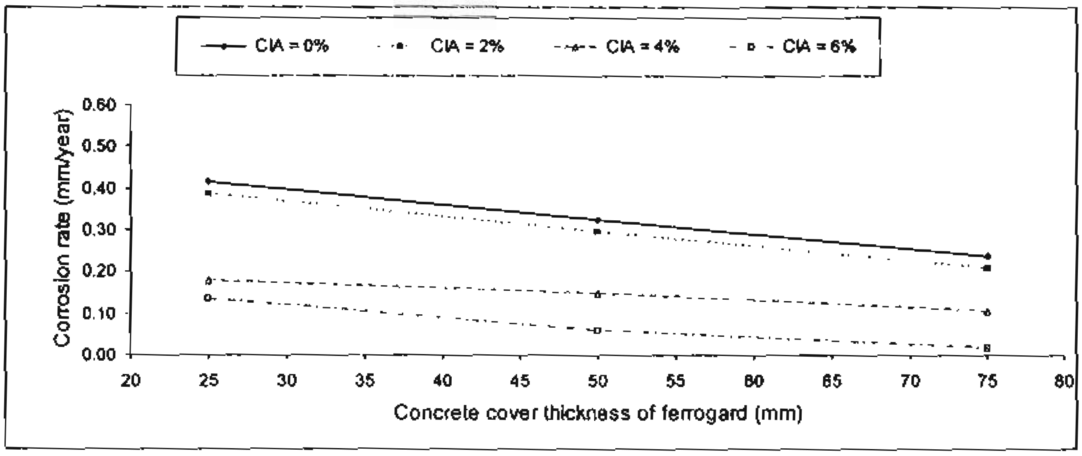

Fig. (14) Effect of cover thickness on corrosion

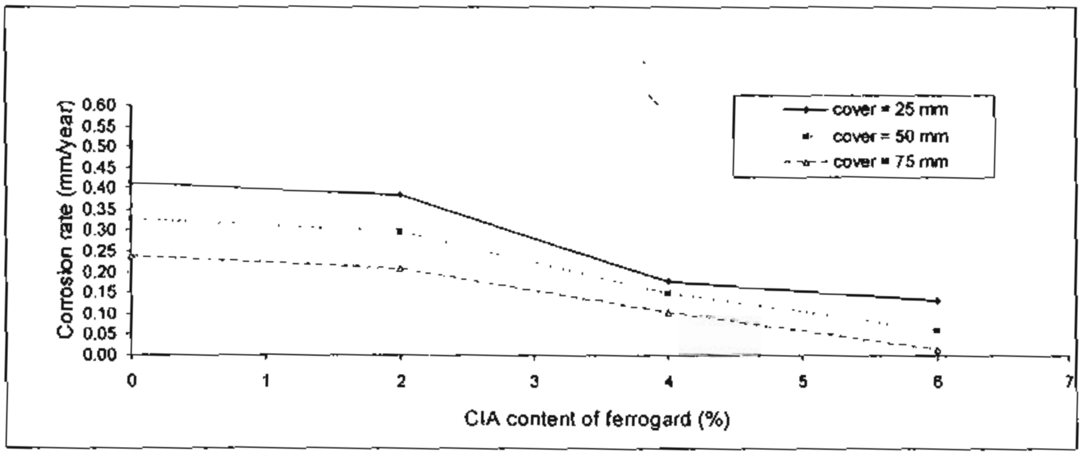

Fig. (15) Effect of CIA content on corrosion rate of