

# CORROSION OF REINFORCING STEEL IN CONCRETE

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## ABSTRACT

The corrosion of reinforcing steel is considered the most critical problem for the durability of reinforced concrete structures. This study shows the experimental results of the corrosion of steel bars in mortar, using an accelerated test. The results indicate that increasing water/cement ratios accelerate the corrosion of reinforcing steel. In addition, increasing curing times decrease steel corrosion rates. The results also show that the cover to bar diameter ratio plays a significant role in determining the corrosion intensity. For the same cover thickness, the corrosion intensity increases as the steel bar diameter increases.

## Key Words

Concrete durability; Steel corrosion; reinforcing steels; Water/cement ratio; Chlorides; Spalling; Cracking; Diffusion

## INTRODUCTION

The corrosion of reinforcing steel in concrete structures depends upon the penetration rates of aggressive ions such as chlorides and sulphates in addition to CO<sub>2</sub> gas. Corrosion of steel in reinforced concrete leads to an increase in the volume of steel, causing spalling and cracking of the concrete cover. The corrosion process depends upon the quality of concrete cover, bar diameter and cover thickness [1-3].

In general, the high alkaline conditions present within concrete (pH of about 12.5) causes a passive oxide film on the steel surface and form a physical barrier to the movement of moisture, oxygen and aggressive ions and prevent steel from further corrosion. This is similar to the oxide film on aluminium surface in normal conditions. The passive layer is destroyed if pH is decreased to 11.0 or below. The alkalinity decreases due to the carbonation reaction in concrete or penetration of chloride ions or other aggressive ions to the steel surface [1-4].

The study aims at investigating the effect of steel bar diameter and cover thickness on corrosion intensity of steel, in addition to factors affecting concrete quality such as curing time and water/cement ratios.

## EXPERIMENTAL DETAILS

### *Materials and mix proportions.*

Table (1) summarises the experimental details of five groups carried out. In group I, the water cement ratio of mortar specimens was varied, whereas the curing time was varied in group II, the diameter of steel bar and the cover thickness were kept constant in both groups. In group III, the specimen diameter was varied at constant bar diameter, curing time and water/cement ratio. Group IV was designed to study the effect of varying the bar diameter and cover thickness on the corrosion intensity. Group V examine the effect of bar diameter, with equal cover thickness, on the steel corrosion.

Through out this study, ordinary portland cement, natural sand and drinking water were used. The corrosion mortar specimens were cylindrical in shape. The water/cement ratio varied from 0.3 to 0.6 while the sand /cement ratio by weight was maintained constant at 1.5. The specimens were cast in steel moulds and demoulded after 24 hours. These specimens were cured in fresh water in the laboratory environment at 25°C, for a specified period before tested for using the accelerated technique.

Table (1). Details of corrosion specimens.

Series No.	Water/Cement Ratio	Curing time (days)	Diameter (mm)		Cover (mm) [c]
			Bar [d]	Specimen [D]	
I	0.3	7	13	75	31
	0.4	7	13	75	31
	0.6	7	13	75	31
II	0.4	3	13	75	31
	0.4	7	13	75	31
	0.4	28	13	75	31
III	0.4	7	13	50	18.5
	0.4	7	13	75	31
	0.4	7	13	100	43.5
IV	0.4	7	26	75	24.5
	0.4	7	6	75	34.5
	0.4	7	13	75	31
	0.4	7	22	75	26.5
V	0.4	7	6	75	34.5
	0.4	7	16	85	34.5
	0.4	7	32	100	34

Measurements of corrosion.

The accelerated corrosion testing technique adopted by Yuan and Chen [4] was chosen in this study. The experimental set-up is shown in Figure (1), where the anode is the sample to be tested and the cathode is a steel bar of same size as anode. The corrosive medium was chemically pure sodium chloride of 5 % concentration by weight. The current impregnated into steel bar was obtained from a DC power supply at constant 5 volt. This volt was sufficient to cause a significant change in current values which were monitored with an ammeter at time intervals up to 14 days. Cracks in the concrete specimens were monitored visually and were accompanied by a sharp increase in current readings. The degree of corrosion intensity was estimated using Farady's law of electrolysis. This law states that mass of any substance liberated by current is proportional to the quantity of electricity which has passed as follows:

$$m \propto I . t$$

where, m, I and t are the mass of substance liberated, the intensity of corrosion and prolonged time, respectively.

According to Heys [5] the law can be expressed in a mathematical form by the following equation:

$$m = E . I . t$$

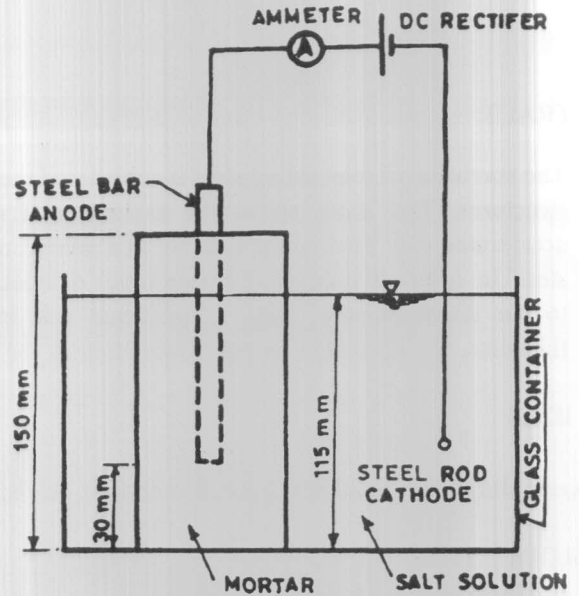


Figure 1. The experimental set-up.

where, E is the proportional constant. The (I . t) represents the area under the current-time relationship and the value of E for mild steel was determined to be 0.0167 gm/Amp-min and the "E" value is not affected by temperature, concentration of electrolyte and size of electrodes [1,5]. From the above equation the weight loss of iron, m, can be determined quantitatively and it is proportional to area under the current-time curve.

RESULTS AND DISCUSSION

Figure (2) shows the effect of water/cement ratio on the current-time relationship for specimens group I. The results indicate that the size of area under the current-time curve increases with increasing water/cement ratio. Therefore, corrosion intensity rises with increasing water/cement ratios. Current is conducted through moist concrete by electrolytic means, therefore, any increase in water percent decreases resistivity and consequently increases current conduction. Moist concrete behaves essentially as an electrolyte with resistivity of order 100 ohm-m (range of semiconductor) on other hand oven dry concrete has resistivity of 10<sup>9</sup> ohm-m which means that it

is reasonably good insulator [6]. The rise in current measured, due to the increase in W/C ratio, can be attributed also to the increase in the permeability coefficient of concrete, since the coefficient increases 20 times as the W/C ratio increases from 0.3 to 0.6 (at 93% cement hydrated). Therefore, the transfer of aggressive ions (Cl) increases causing a severe attack to the steel bars. [1,2]. The amount of iron dissolved due to corrosion of steel bars at different W/C ratios are shown in Table (2). The change of water/cement ratio from 0.3 to 0.6 increases the amount of iron dissolved almost 4.0 times.

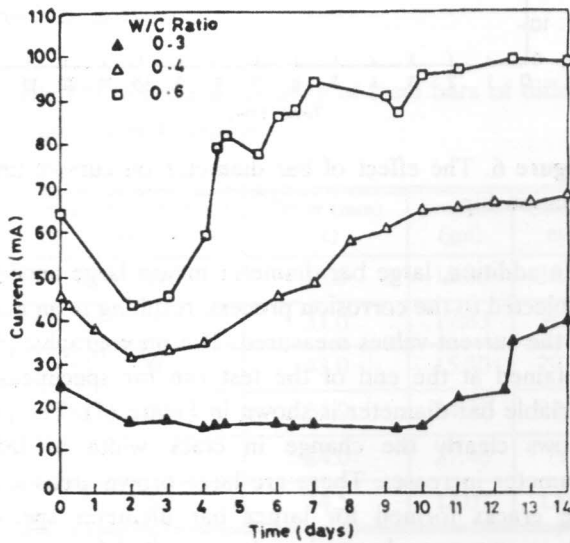


Figure 2. The effect of water/cement ratio on current-time relationship.

Table (2). Corrosion intensity of steel bars at different water/cement ratios and curing times, for 13 mm diameter steel bar and 75 mm specimen diameter.

W/C Ratio	Curing Time (days)	Iron Loss (gm)
0.3	7	6.68
0.4	7	17.83
0.6	7	27.15
0.4	3	22.16
0.4	7	17.83
0.4	28	13.75

Figure (3) is a photographic picture obtained at the end of the test run for the specimens with different water/cement ratios. The picture shows that the crack width increases with increasing water/cement ratio, consequently, corrosion intensity increases.

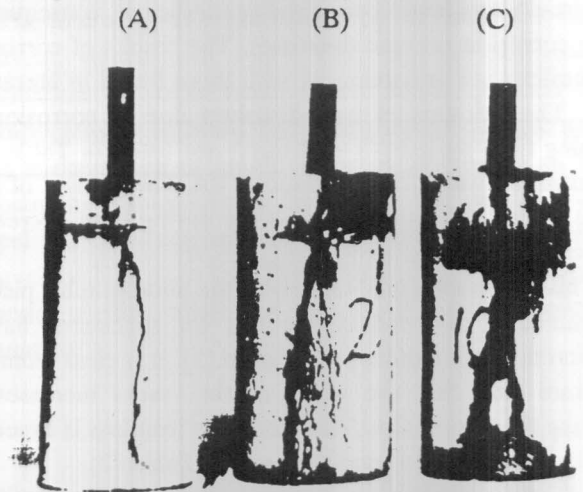


Figure 3. Photographic picture of specimens obtained at the end of the test run; samples from the left are: (A) W/C=0.3, (B) W/C=0.4, (C) W/C=0.6.

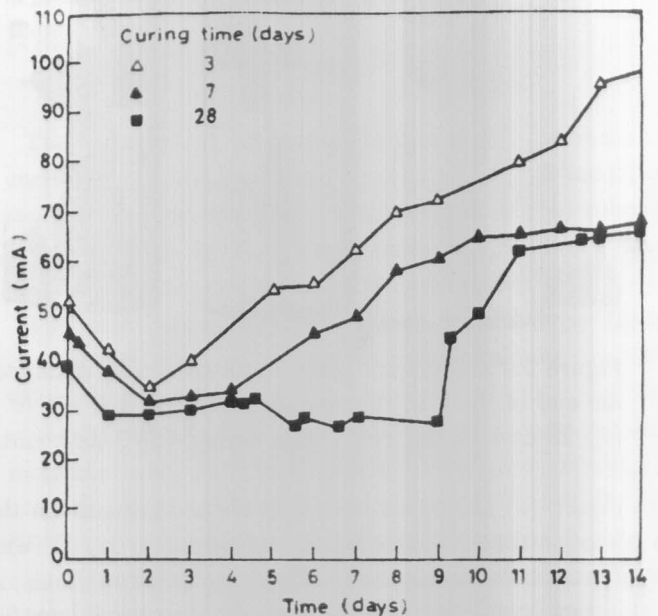


Figure 4. The effect of curing time on current-time relationship.

Figure (4) shows the effect of curing time on the corrosion behaviour of steel bars for specimen group II.

The results indicate that corrosion intensity decreases as the curing time increases. The increase in curing time period enhances the hydration process followed by a decrease in concrete porosity and permeability. A dense and compact concrete will have a higher electrical resistivity and lower permeability coefficient, consequently the corrosion process decreases. The results of corrosion behaviour are in agreement with those found in literature [1]. The amounts of iron dissolved due to corrosion at curing time periods (3 - 28 days) are listed in Table (2), at constant water/cement ratio of 0.4. The amount of iron loss increases almost twice as the curing time decreased from 28 to 3 days.

This is also seen qualitatively by the photographic picture obtained at the end of the test for specimens having different curing times, see Figure (5). It is clear from the picture view that the width of the cracks increases as curing time decreases. Therefore, the iron loss is expected to increase as seen quantitatively in Table (2).

(A) (B) (C)

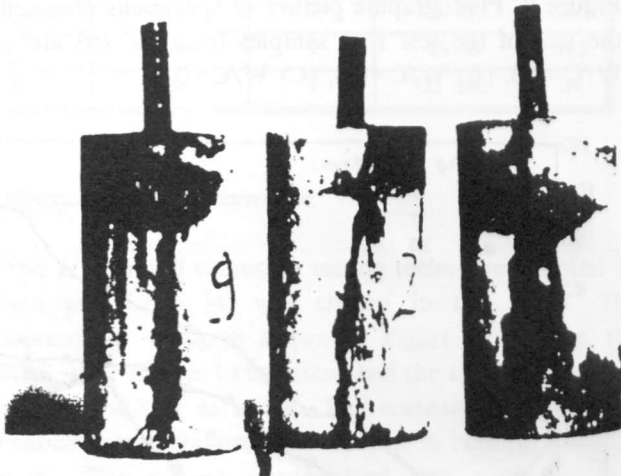


Figure 5. Photographic picture for specimens obtained at the end of the test, run; samples from the left are: (A) 28 days curing, (B) 7 days curing, (C) 3 days curing.

Figure (6) shows the influence of bar diameter on the corrosion-time relationship for specimens group IV with different cover thickness. The results show that, at constant specimen size 75 mm, the corrosion intensity increases as the bar diameter increases. This is clearly shown by the gradual increase of area under current-time curves. The increase in steel bar diameter reduces the cover thickness, consequently, shorten the diffusion path for the chloride ions to penetrate to the steel areas and cause severe attack to the steel bars.

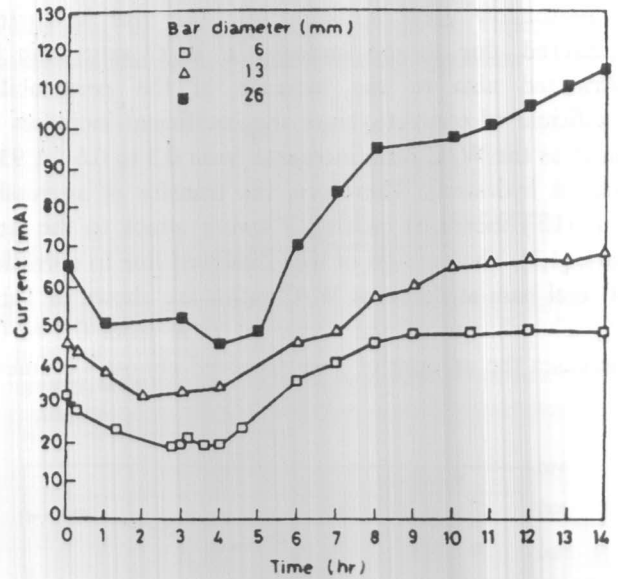


Figure 6. The effect of bar diameter on current-time relationship.

In addition, large bar diameter means large anode area subjected to the corrosion process, resulting in an increase in the current values measured. The photographic picture obtained at the end of the test run for specimens with variable bar diameter is shown in Figure (7). The picture shows clearly the change in crack width as the bar diameter increases. There are large brown areas around the cracks formed for larger bar diameter specimens. These areas are due to iron loss resulted from corrosion of steel in concrete. The changes in iron loss with bar diameter and with cover/bar diameter ratio [c/d] are listed in Table (3). The weight of iron loss increases with decreasing the c/d values. Therefore, c/d parameter can be used as a good measure for corrosion intensity, only at fixed specimen size.

Table 3. Relationship between c/d ratio and iron loss at different steel bar diameters and at 75 mm specimen size.

Bar Diameter mm-(d)	Cover (mm) (c)	c/d ratio	Iron loss (gm)
6	34.5	2.64	13.07
13	31	2.38	117.83
22	26.5	1.18	24.50
26	24.5	0.94	27.46

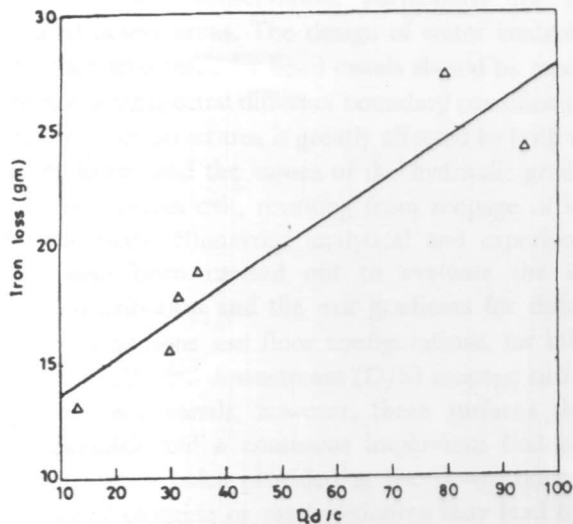
Table (4) shows the change in weight loss obtained due to corrosion for samples with variable specimen sizes and bar diameters. The iron loss data are correlated with the parameter  $D.d/C$  as shown in Figure (8) and presented by the following equation:

$$\text{Iron loss} = 10.46 + 0.2 [D.d/c]$$

where, "D" specimen size in mm; "d" bar diameter in mm and "c" cover thickness in mm. The equation above provides a satisfactory correlation for the experimental data, where R and  $R^2$  are 0.93 and 0.86, respectively. As the correlation coefficients approach 1.0 the correlation fitness increases.

**Table (4).** Corrosion intensity of steel bars of different sizes and cover thickness.

Bar (d)	Specimen (D)	Cover (mm) (c)	Iron loss (gm)	(D.d/c) mm
13	50	18.5	18.88	35.13
13	75	31.0	17.83	31.45
13	100	43.0	15.50	29.88
32	100	34.0	24.22	94.00
26	75	24.0	27.46	79.5
6	75	34.5	13.07	13.04



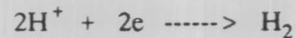
**Figure 8.** Blot of iron loss versus diameter of specimen, D; bar, d; cover, c.

In general, the results obtained in most current time curves show considerable fluctuations in current values with time. These fluctuations can be divided into three stages;

The first stage is characterized by an initial decrease in current values with time. This can be explained by formation of iron oxide layer which protects steel temporarily. In addition, the formation of chlorine gas on the surface area of anode - due to electrolysis of NaCl electrolyte - may form a barrier on the surface area of steel bar resulting in resistivity increase, consequently, current values decrease. The formation of chlorine gas on anode surface area can be described by the following equation:



Since electrolysis process is divided into anodic and cathodic reactions, the cathodic reaction in this process is hydrogen gas evolution. This is noticed by the formation of gas bubbles on the Cathode surface area. The reaction is presented by the following equation:



The second stage is characterized by a sharp increase in current due to the initiation of a microcrack resulted from steel corrosion which is accompanied by a volume expansion [2]. In this stage resistivity decreases and chloride ions penetrate fast into the concrete.

The third stage is characterized by relatively small current variations, since resistivity reached almost constant value. In this stage a clear longitudinal crack can be observed visually. As time increases the crack width increases and additional small cracks are developed according to intensity of corrosion process. Finally, Figure (9) is a photographic picture of a section inside a corroded specimen obtained at the end of the test run. There is a large dark area present in the picture and oriented towards the cover surface. The dark spot formed is due to leaching of the famous brown colour of iron rust. The formation of this colour on the cover thickness even in small intensity means that the corrosion process is active and continue to progress, depends upon factors such as discussed in this study.

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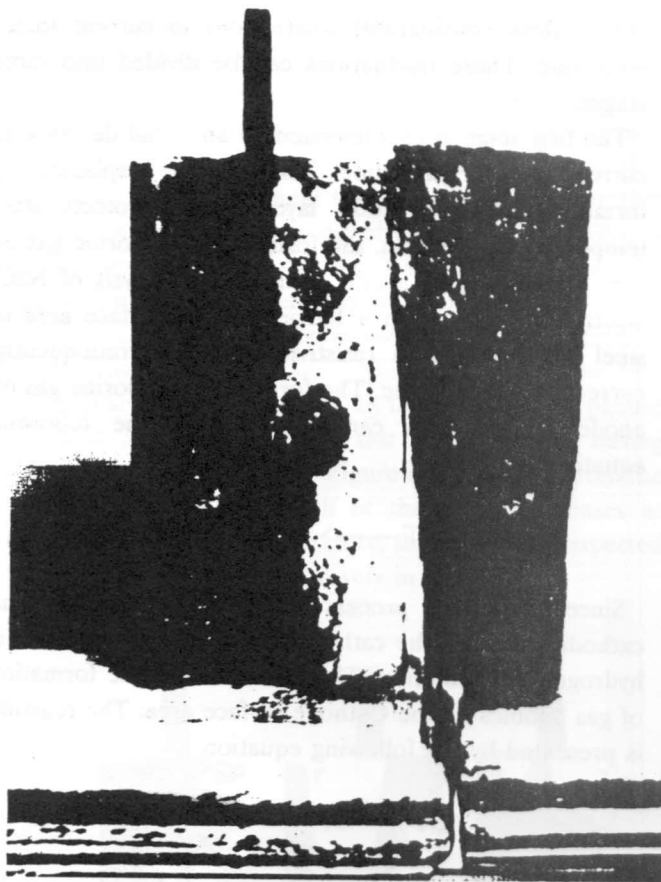


Figure 9. Photographic picture for a section inside a specimen obtained at the end of the test run.

CONCLUSIONS

The corrosion of steel bars in concrete increases with increasing water/cement ratio, and decreasing curing time. The intensity of corrosion of reinforcing steel in concrete increases with increasing bar diameter. For the same diameter bar the corrosion of steel is increased with decreasing the cover thickness. The ratio between cover diameter and steel bar diameter is a useful guide to estimate the corrosion resistance of steel in concrete.