

IMPACT OF SOIL-BORNE CHLORIDE ON REBARS CORROSION IN REINFORCED CONCRETE MEMBERS

ALI A. AL-TAMEEMI¹, MOHAMMED SH. MAHMOOD^{1,*}, NABEEL A.
ALBAHADLI¹, HAYDER H. ALKHUDERY¹, RAFAH M. ALTURAIHEE²

¹Faculty of Engineering, University of Kufa, Najaf, Iraq

²Najaf Construction Laboratory, Najaf, Iraq

*Corresponding Author: mohammedsh.alshakarchi@uokufa.edu.iq

Abstract

This study presents the impact of chloride ion present in the soil in contact with reinforced concrete in the initiation of corrosion of steel reinforcement. The factors affecting the corrosion process due to the penetration of chloride ion from chloride bearing soils in contact with concrete specimens, representing different reinforced concrete members, were studied. The results proved that there exists a threshold limit for the concentration of soil-borne chloride ion, to initiate the corrosion. The value of this limit was related to the thickness of the concrete cover, concrete grade, besides the type of exposure (number of sides exposed to chloride attack). It was shown that the safe percentage of chloride ion in the groundwater and soil in contact with concrete was 2% in aqueous extract (0.4% in soil) when the thickness of the concrete cover was not less than 50 mm. This proportion could reach 6% in aqueous extract (1.2% in soil), when the cover thickness was not less than 75 mm, or when the concrete possessed a 35 MPa compressive strength as well as exposed on one side only. Consequently, special limitations for the permissible proportions of chloride ion in soils in contact with reinforced concrete members should be established by design codes.

Keywords: Chloride, Concrete, Corrosion, Reinforcement, Threshold.

1. Introduction

The corrosion of reinforcing steel is the most important source of deterioration of reinforced concrete (RC), as corrosion causes concrete cracking, separation of the concrete cover and loss of bond between concrete and reinforcement. Furthermore, corrosion leads to a sharp decrease in the cross-sectional area of the reinforcing steel which consequently will impair the structural carrying capacity of RC members and may lead to complete structural failure [1-3].

Despite the fact that the basic environment of the concrete (pH greater than 12) provides stability for the oxide layer that protects the reinforcing steel from exposure to corrosion initiation factors, the rebars may corrode due to the loss of stability of the protective layer caused by the occurrence of carbonation or chloride attack to concrete. Corrosion reaction resulting from chloride attack is very dangerous because it is associated with the creation of localizing pits as a result of the availability of large, protected areas in rebars (cathode) compared to the small, corroded area (anode) [4, 5].

Many methods are used to increase the resistance of concrete to corrosion; for example, use of inhibitors [6], metal painting of rebars [7], cathodic protection of reinforcing steel [8] and using high-performance concrete [9].

The presence of chloride salts inside concrete is a result of two sources; the first is, contamination of concrete constituents (cement, aggregates, water, additives) with chlorides. The second source is the external source when concrete is exposed to chloride-bearing soil, groundwater, seawater, brackish water, or spray from these sources [10, 11]. This exposure results in chloride penetration into the concrete due to the diffusion phenomenon as well as the capillary action. The rate of salts penetration depends on the concrete permeability and the thickness of the concrete cover. Many researchers indicated that chloride would penetrate the concrete sooner or later within its service life when concrete is exposed to chloride in service [5, 12].

There exists a threshold for chloride amount inside concrete related to the initiation of rebars corrosion. This threshold depends upon several factors such as; a-cement fineness and C3A content, b-concrete porosity and moisture content, c-availability of oxygen and the corrosion potential, besides other factors related to the characteristics of reinforcing steel [12, 13].

The determination of a threshold limit for chloride ion in concrete may depend on the source of chloride contamination. Uniformity of distribution and the chemical combination of chloride ions with the hydration products will differ when the mixture ingredients are contaminated with chlorides, from the case of permeation of ions from the surface of concrete [13, 14]. However, most national building codes specify limits for the maximum allowable total chlorides in concrete.

The Unified Arabic Code for reinforced concrete [15] recommends a maximum content of chloride ion of 0.15 percent by weight of cement, in RC exposed to chlorides. For other structural concrete members, the permissible content of chloride ion is increased to 0.3 percent by cement weight. ACI 318-19 building code [16] limits the maximum allowable water-soluble chloride ions to 0.15 percent by weight of cementitious materials for RC exposed to chloride in service, while the limits are 0.06, 1.00, and 0.3 for pre-stressed, dry protected,

and other RC construction, respectively. There exists a wide variation in these limits proposed by different codes. Lower and higher values for maximum allowable chloride content are reported in many other design codes [13, 17]. Also, many codes specify a maximum limit for chloride ion in the aggregates used in the concrete mixes, while other codes follow another method to assess the chloride content of concrete ingredients.

The Unified Arabic Code for reinforced concrete [15] limits the permissible percentage of ion chlorides in coarse and fine aggregates by not more than 0.06% and 0.04% of aggregate weight, respectively. For total aggregates, the maximum ratio of chloride ion is limited to 0.05% of the weight of aggregates used in RC and 0.015% when using aggregates in steam cured or precast concrete. ACI 318-19 [16] allows the evaluation of the total chloride ion content of the concrete mixture by combining the total chloride ion content of the concrete ingredients based on the mix proportions.

Despite the clear and significant effect of chloride salts on the initiation of corrosion and the subsequent deterioration of RC, all design codes do not state any limits for the concentration of these salts in the soil in contact with the RC, while those codes include certain requirements for the severity and the acceptable limits of sulfate ions concentrations in soils and groundwater in contact with concrete. Therefore, researchers are required to determine the permissible concentrations of chloride ion in the soil and groundwater that will be in contact with concrete members to encounter these limits within the related codes.

It is well known that the soil deposits in many regions in different countries had been formed after the recession of the marine environment. Consequently, the soil in these regions is contaminated with gypsum and chloride soluble salts [18-21]. Thus, RC structures constructed in these regions will suffer from reinforcement corrosion problems. Strict limitations are needed to be developed and applied in such regions to overcome the chloride ion impact on rebars corrosion.

The recent research tries to highlight the need to avoid some problems related to steel reinforcement corrosion caused by external chloride attack from chloride bearing soil. The research aims to determine the acceptable limits of the concentration of the chloride ion in soils in contact with RC, so as to assign a threshold for this ion that when being exceeded, may result in significant damage and deterioration in concrete due to the corrosion of the reinforcement.

The research was intended to verify the hypothesis of the dependence of soil borne chloride ion threshold on several factors. These factors included concrete quality, the thickness of concrete cover, and the type of exposure (number of sides exposed to chloride attack). Studying these factors were related to certain cases, which represent as closely as possible the actual situations encountered in normal strength reinforced concrete constructions. Chloride free materials were used in this research to study the effect of external chloride attack *per se* on corrosion of rebars, while the experimental conditions were selected to simulate actual exposure cases, but at an accelerated rate.

The result of this study supported by further researches can be utilized to set suitable limitations certified by building codes for chloride ion content in soils that are expected to be in contact with reinforced concrete.

2. Methodology

2.1. Materials

A. Cement

Ordinary Portland cement produced by the Tasluja plant and sulphate resisting cement from the Bazian plant were used for concrete mixtures. The results of physical and chemical tests of the two types of cement conformed to Iraqi specifications IQS No. 5- 2019 [22] for class 42.5 N cement,

B. Coarse aggregates

River gravel with 5-19 mm grading conforming to Iraqi specifications IQS 45-84 reapproved 2016 [23].

C. Fine aggregate

Sand from Annajaf quarry (gradation area no. 2) conforming to Iraqi specifications IQS 45 reapproved 2016, was used in all concrete mixes.

D. Reinforcing steel

cold drawn mild steel with 420 MPa tensile strength was used in all specimens.

E. Chloride salt

Table salt was used to produce saline water.

All concrete materials were selected to be within the limits of the allowable specifications with respect to chloride content, as the research was focused to deal with external chloride attacking only. Two concrete mixes were designed according to ACI standard practice ACI 211.1.91 reapproved 2002 [24] to produce two grades of concrete with mean 28 days compressive strengths of 21, and 35 MPa. These two strengths were chosen to represent concrete usually employed in conventional construction. The design slump for all mixes was 100-180 mm. Mix proportions (cement : sand : gravel) for the first mix were 1:2.4:3.38, w/c ratio was 0.65, while the proportions of the second mix were 1:1.62:3.01, w/c ratio was 0,55. The water content used in the two mixes was 210 kg/m³. This quantity of water was needed to attain the designed slump.

2.2. Research program

The research included studying many variables affecting the process of steel bars corrosion due to exposing RC to chloride bearing soils. These factors included the type of concrete member, compressive strength of concrete, cover thickness, and the exposure conditions. Based on previous author's study, the state of exposure to soil borne chloride was substituted by exposing the specimens to water containing chloride content equivalent to the chloride percentages in the contaminated soils. Two grades of concrete, 21 and 35 MPa were used in this research to elucidate the effect of the compressive strength on the threshold of chloride ion in soil. Forty-eight RC specimens were cast to cover the investigated variables. The details of those variables are illustrated in Table 1.

The research involved two parts, in the first part, the RC specimens after had been cured in water for 28 days, were put in water basins exposed to water containing different amounts of chloride salt. The permeation of chloride ion into concrete was accelerated, then electrochemical tests were done in the second part

of the research to detect the role of each one of the studied variables on steel reinforcement corrosion.

Table 1. The investigated variables.

Member	Symbol	No. of exposed sides	Cement type	Cube concrete strength (MPa)	Amount of chloride ion, in aqueous solution (%)			
Foundation	F	Two	Sulphate-resistant	21	0	0.6	2	6
				35	0	0.6	2	6
Column+ Beam	C B	Two ¹	Sulphate-resistant	21	0	0.6	2	6
				35	0	0.6	2	6
Slab	S	One ²	Ordinary	21	0	0.6	2	6
				35	0	0.6	2	6

¹in case of columns in contact with the soil, and tie beams

² for soils used for levelling roofs and thermal insulation purposes.

2.3. Details of specimens

RC specimens were designed to simulate the exposure of various types of RC members (slabs, columns, and footings) to external chloride attack. Steel moulds were used for casting the specimens representing each type, Specimens dimensions were chosen depending on the thickness of the concrete cover specified for each member type. Table 2 includes the types, dimensions, and reinforcement of the studied specimens.

Table 2. Dimensions and reinforcement details of specimens representing the studied RC members.

Member represented	Specimen dimensions (L×W×H) (mm)	Concrete cover thickness (mm)	Reinforcement details
foundations	300×180×180	75	16 mm Dia.in the Longitudinal direction*
			10 mm Dia.in the Transverse direction**
Columns+ Beams	300×150×10	50	16 mm Dia.in the Longitudinal direction*
			10 mm Dia.in the Transverse direction**
Slabs	300×10×10	25	10 mm Dia.in the Longitudinal and Transverse directions*

* Main reinforcement protruded 3 cm above specimen surface.

**Shear reinforcement.

The place of the rebars (main and shear reinforcement) used as reinforcement for the tested specimens was fitted in the positions of the most severe case of exposure

expected to exist at a construction site. In the case of reinforced concrete beams, columns, and foundations, these particular positions are noticed at member corners, where two orthogonal sides are exposed to chloride bearing circumstance at the same time. However, the most severe case of exposure for slabs is seen to be located at places where the concrete is in contact with the levelling soil course, probably contaminated with chloride salts. The positions of severe exposure in different members are shown in Fig. 1. Details of specimens and reinforcing bars are shown in Fig. 2. The columns and the beams were represented by the same specimens due to similar exposure conditions and thickness of the concrete cover. Plate 1 shows one of the steel moulds with reinforcement before casting in a tested specimen while Plate 2 shows different RC specimens after being removed from the moulds.

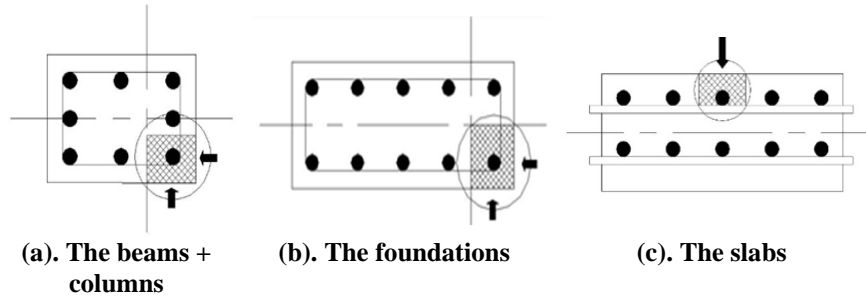


Fig. 1. Positions of the most severe exposure in the studied members.

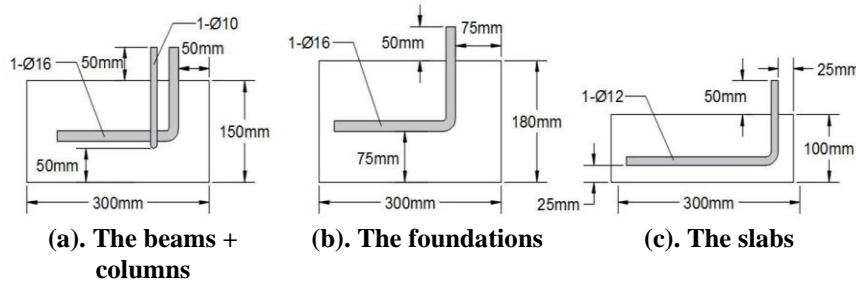


Fig. 2. Dimensions of concrete specimens and details of reinforcement.

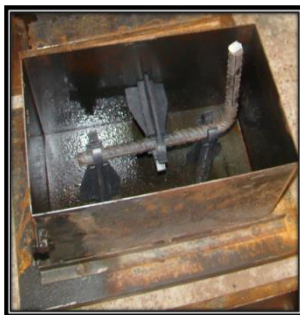


Plate 1. Mold and reinforcement of one of the specimens.



Plate 2. Different RC specimens removed from the moulds.

Identification of specimens

The tested forty-eight RC specimens were identified according to the studied variables. The specimens that represented the foundations were given the first symbol F and those specimens representing the columns and beams were given the first symbol C and B while the symbol S was used for the specimens representing the slabs. The second symbol was related to the grade of concrete, it was 21 for concrete possessing 21MPa compressive strength, and 35 for 35 MPa strength. The exposure conditions were identified by the third symbol, either 0.6, 2 or 6 to represent the concentration percentage of chloride salt in the aqueous solution to which the specimens were exposed. The symbol 0 was given to the non-exposed (reference) specimens.

2.4. Tools and equipment

2.4.1. Assembly of specimens

In order to monitor the corrosion reaction caused by chloride attack in rebars which is an electrochemical process, reinforcing steel bars in the tested specimen were protruded above the surface of the concrete. This was done to provide an electrical point of contact to facilitate the measurement of half-cell potential (HCP) and corrosion current (I_{corr}) in the reinforcing steel.

The protruding rebars were electrically insulated by a plastic insulator which was removed only during HCP measurement (see Plate 2). Moreover, the basins in which the specimens were stored were made of electrically insulating materials to eliminate any electrical disturbance to the corrosion process.

To achieve this purpose a system modified from a similar one used by the authors in previous work for accelerating the migration of soil-borne chloride ion into concrete, was employed. The modified system included glass water basins fabricated with suitable dimensions to accommodate the tested RC specimens. Each basin was divided into two parts separated from each other by the concrete specimens.

The first part was partially filled with water containing chloride salt representing the salt laden soil to which the concrete was exposed in service. In this part, the specimens were let to be exposed on the selected positions to the water-borne chloride. The exposure was on one or two sides, to the intended depths according to the research program.

To expose a specimen on one side, its' unexposed side was laid on the base of the glass basin, while for making the exposure on two sides, the specimen was lifted using a perforated glass spacer that allowed saline water to reach and contact with the desired area of the specimen. The second part of the basin was filled with distilled water.

These two parts were isolated from each other by silicon material applied at contact places between the specimens and the glass, and between the contacted pieces of glass, or between the concrete pieces themselves.

Figures 3(a) to 3(c) illustrate the system of putting the different types of specimens inside the basins, and Plates 3 shows many RC specimens put inside the glass basins.

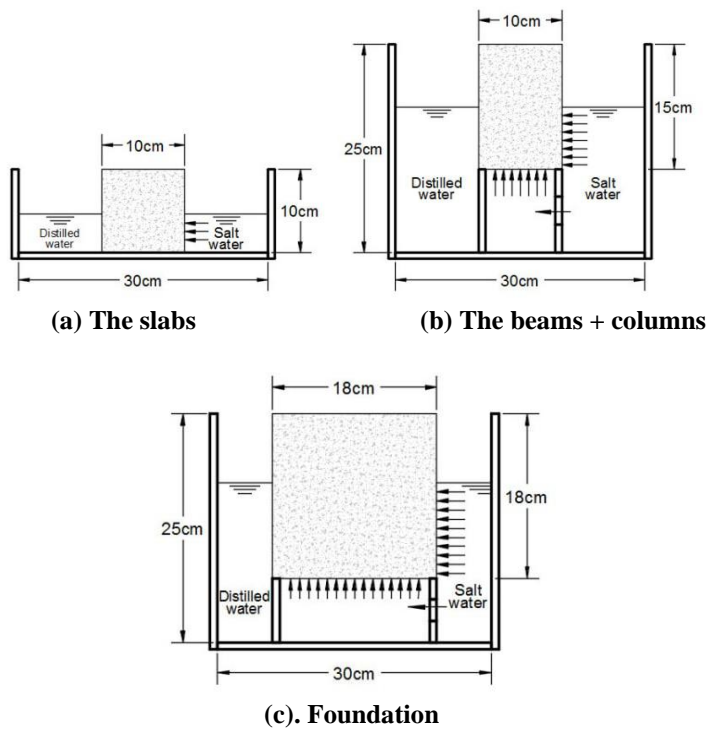


Fig. 3. Exposure types of RC specimens representing different members inside the basins.



Plate 3. The specimens inside the exposure basins.

2.4.2. Exposure to chloride ion.

The role of soil borne chloride ion on the corrosion of reinforcing bars was detected by studying three different percentages of chloride ion in the soil, low (0.12%), moderate (0.4%), and high (1.2%). The chloride percentages by weight in the water surrounding the specimens (Cl^- in water) were calculated to represent the amount of salt in the soil that would be dissolved in the water filling the voids of the soil. According to the void ratio, unit weights of the soil and unit weight of water, chloride % in water could be calculated as in Eq. (1)

$$Cl_{\% \text{ in Water}}^- = Cl_{\% \text{ in Soil}}^- \times \frac{\rho_s}{\rho_w} \times \frac{(1+e)}{e} \quad (1)$$

where ρ_s and ρ_w represent the unit weight of soil and water respectively, and e represents the void ratio in the soil

Cl in water became 0.6%, 2%, and 6% respectively for angular-grained silty sand soils studied by this research. Also, the total weight of chloride salt added to the basin water for each specimen was the required quantity to ascertain a state of equilibrium between the external ion concentrations (in the basin water) and the interior ion concentration (in the void water inside concrete). Two void ratios (0.25, and 0.15) were employed for concretes with compressive strength of 21, and 35 MPa respectively [25]. Table 3 shows the amounts of table salt necessary to be added to the basin water for each specimen. The percentage of chloride in the basin water was monitored periodically to compensate for the consumed salt until the depletion of the estimated chloride amount, then the process of accelerating the penetration of chloride ion would be ended. It is worth noting that the term "chloride concentration," wherever indicated in this research will refer to the concentration of the ion in aqueous solution, unless put between brackets or it is expressly indicated to the amount of chloride in soil.

Table 3. Weight of table salt needed for each chloride concentration to be added to basin water (gm) for all specimens.

Chloride concentration in the aqueous solution, %	Specimen type					
	Slabs with:		Beams + Columns with:		Foundations with:	
	Fc= 35 MPa	Fc= 21 MPa	Fc= 35 MPa	Fc= 21 MPa	Fc= 35 MPa	Fc= 21 MPa
0.6	9	15	13.5	22.5	28.5	47.5
2	30	50	45	75	95	158.33
6	90	150	135	225	285	475

2.4.3. Acceleration of chloride ion permeation

This work benefitted from the system that had been adopted previously to accelerate the process of penetration of soil borne chloride ion into the RC specimens depending on "The electrical migration technique" [26]. Constant current, 30V, 5A DC power supply device (model LW –DS305D) was used to apply a potential difference of up to 30 volts between the sides of the concrete specimen. This amount of potential was selected according to the test conditions to prevent the significant increase in the temperature of the RC concrete specimens. Corrosion of rebars was accelerated while the specimens were at atmospheric pressure Two specimens were examined for each case to take care of the probable variation in the results [27]. Stainless steel sheets were used as electrodes. The negative electrode was placed in the saline water, while the positive electrode was placed in the distilled salt-free water as shown in the electrical circuit presented in Fig. 4.

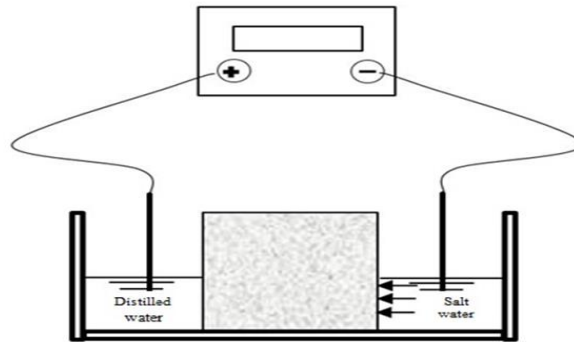


Fig. 4. The electrical circuit to accelerate the penetration of chloride ion.

It is important to note that the protruding rebars were insured to be completely electrically insulated throughout the acceleration process. The current passing through the accelerating cell for each specimen was periodically measured using 3A DC ammeter during the duration of the test. The completion of accelerating the permeation chloride ion inside the RC specimens was ensured when no more current could be monitored.

2.4.4. Electrochemical tests

At end of the acceleration period of chloride permeation inside the tested specimens, electrochemical tests were conducted utilizing the protruding steel bars for each specimen. these tests included HCP, and corrosion current measurements.

2.4.4.1. HCP measurement

The potential of the reinforcing steel protruding from the RC specimens was measured relative to the Standard Cu-CuSO₄ electrode according to the requirements of the American Standard ASTM C876 [28] using a high - resistance voltmeter type MCM model LC-4. The end of the standard electrode was fixed on the concrete surface near the rebar to determine the probability of corrosion in the rebar following the limits mentioned in that specification.

2.4.4.2. Corrosion current measurement

Corrosion current (I_{corr}) in the reinforcing bars in each specimen was measured utilizing programmed polarizing device type Mlab 200 to polarize the potential of rebars then drawing "Tafel" plots to detect the I_{corr} in each rebar [13], then the value of the current was divided by the rebar surface area to get the value of corrosion current density (i_{corr}).

$$i_{corr} = \frac{I_{corr}}{\pi \cdot D \cdot l} \quad (2)$$

where D and l represent rebar's diameter and rebar's length, respectively.

3. Results

3.1. Results of the HCP test

It can be observed from the results shown in Fig. 5 that a "high" probability of corrosion, depending on the limits stated in ASTM C 876 [28], was confirmed in

all specimens except F35 specimens where the probability of corrosion was "low". When noticing the HCP values in the specimens exposed to a similar concentration of chloride ion (0.6%, 2%, or 6%), it seems that the thickness of the concrete cover not exceeding 50 mm in the specimens exposed on both sides did not have a clear effect on the results, so it did not prevent the possibility of "high" rebar corrosion.

The results showed that the impact of increasing compressive strength on reducing the HCP was more pronounced in the specimens representing the foundations (F35) where the thickness of the concrete cover was 75 mm, as well as in the specimens representing the RC slabs having 25 mm cover thickness. This finding declares two facts; the first is the role of increasing the thickness of the cover accompanied with increasing compressive strength in inhibiting the movement of chloride ion inside the concrete, and the second fact is that the small thickness of the concrete cover shows up that the most influential factor on lowering the HCP is mainly related to the quality of the concrete. The internal microstructure of concrete affects the extent of inhibiting the permeation of chloride ion inside the concrete through the gel pores since the unconnected pores (in case of good quality concrete) act as an effective impedance of the movement of chloride ion that causes corrosion of reinforcing steel [25]. This fact is clearly manifested when comparing the HCP values of S21 and S35 specimens presented in Fig. 5. These findings confirm the validity of measuring the HCP in detecting the influence of each one of the studied variables on probability of occurrence of rebars corrosion.

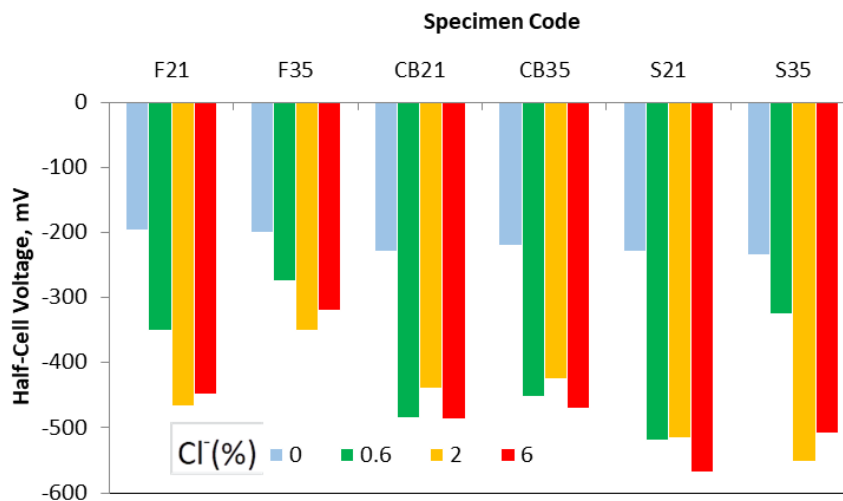


Fig. 5. The tested half-cell potentials of different RC specimens.

3.2. Results of the corrosion current density tests.

Figure 6 illustrates the polarization test "Tafel curves" of some specimens. Corrosion current density (i_{corr}) for each specimen was detected from those curves as discussed in 2.4.4.2. The results of the i_{corr} values for all RC specimens are listed in Tables 4, 5, and 6. Any single result represents the results of two companion specimens. The tables also include the ratio between the i_{corr} resulted due to

exposing the specimens to a chloride ion concentration in the aqueous solution of 2%, to the i_{corr} resulting due to exposure to 0.6% chloride concentration. Also, the ratios between i_{corr} resulting due to exposure to a chloride ion concentration of 6%, and 2% are recorded in those tables.

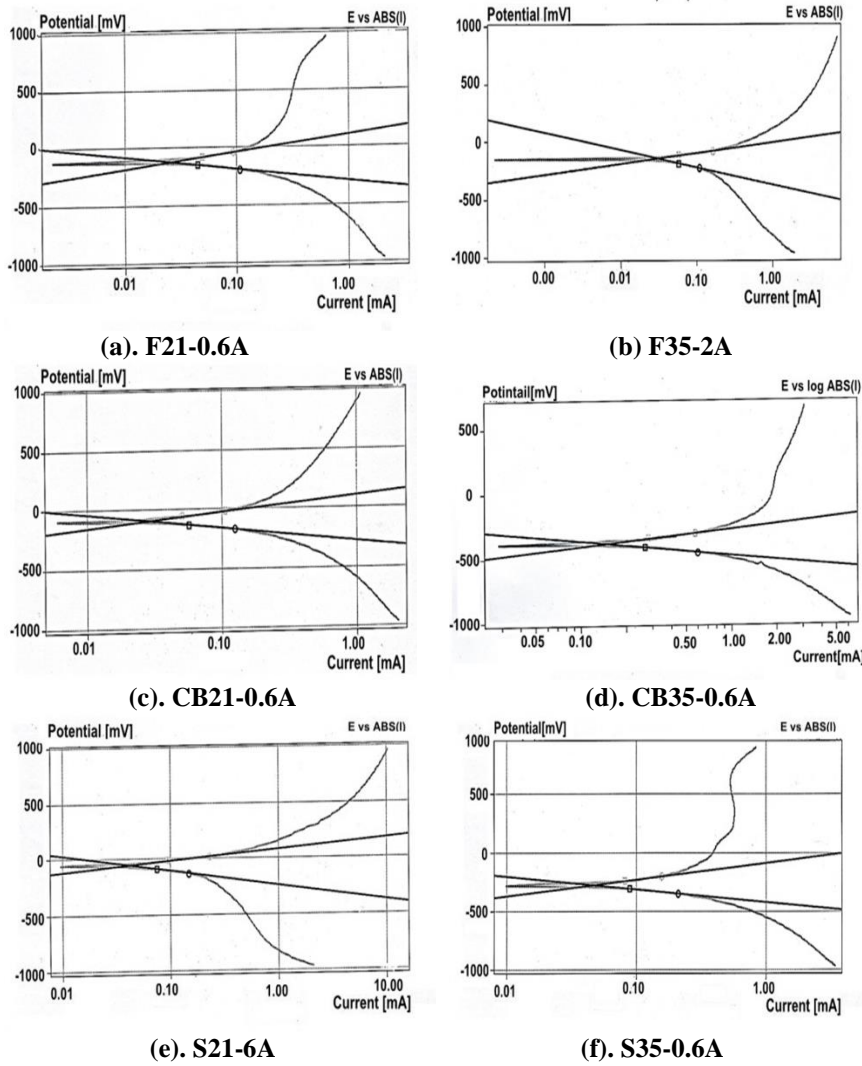


Fig. 6. Polarization curves of some specimens.

Table 4. Results of corrosion current density in the slab specimens.

Specimen type	S21/0.6	S21/2.0	S21/6.0	S35/0.6	S35/2.0	S35/6.0
Corrosion current density, $\mu\text{A}/\text{cm}^2$	0.45	0.47	0.95	0.17	0.27	0.49
Ratio of current density for (0.6% Cl / 2% Cl)	1.04	-	-	1.59	-	-
Ratio of current density for (2% Cl / 6% Cl)	-	2.02	-	-	1.81	-

Table 5. Results of corrosion current density in the column + beam specimens.

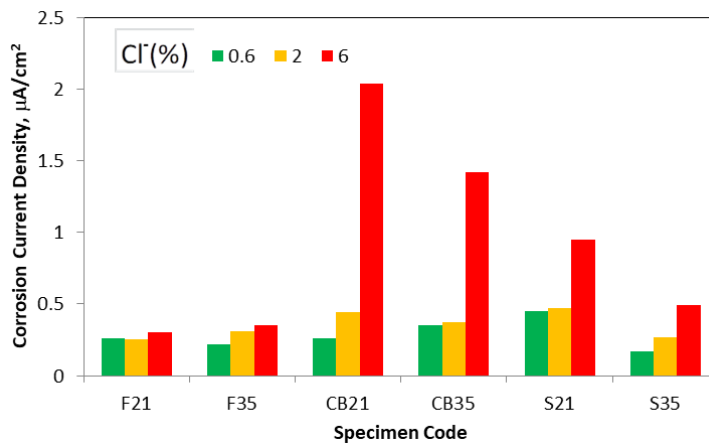
Specimen type	CB21/0.6	CB21/2.0	CB21/6.0	CB35/0.6	CB35/2.0	CB35/6.0
Corrosion current density $\mu\text{A}/\text{cm}^2$	0.26	0.44	2.04	0.35	0.37	1.42
Ratio of current density for (0.6% Cl/2% Cl)	1.69	-	-	1.06	-	-
Ratio of current density for (2% Cl / 6% Cl)	-	4.64	-	-	-	3.84

Table 6. Results of corrosion current density in the foundation specimens.

Specimen type	F21/0.6	F21/2.0	F21/6.0	F35/0.6	F35/2.0	F35/6.0
Corrosion current density $\mu\text{A}/\text{cm}^2$	0.26	0.25	0.3	0.22	0.31	0.35
Ratio of current density for (0.6% Cl/2% Cl)	0.96	-	-	1.41	-	-
Ratio of current density for (2% Cl / 6% Cl)	-	1.2	-	-	-	1.13

The importance of executing polarization tests to detect the level of corrosion in steel reinforcement comes from the fact that HCP data just indicate the probability of corrosion, which will take place when an appropriate circumstance are available. In fact, the actual initiation of corrosion reactions can only be confirmed by measuring the corrosion rate. The rate of corrosion could be estimated reasonably by measuring the current density at the test site as stated by ACI 222 Committee [29]. Accordingly, the corrosion level, is classified into four categories, (high) when the i_{corr} value is greater than $1 \mu\text{A}/\text{cm}^2$, (moderate) when the values are between $1 - 0.5 \mu\text{A}/\text{cm}^2$, and (low) when the values range between $0.5 - 0.1 \mu\text{A}/\text{cm}^2$. The level is classified as (negligible) when the i_{corr} is less than $0.1 \mu\text{A}/\text{cm}^2$.

The results of i_{corr} for all the tested specimens are illustrated in Fig. 7. These results show the effect of several interrelated factors on the rate of the corrosion reaction represented by the (i_{corr}). The following articles outline the role of many factors in affecting the rate of the corrosion process, so as to get beneficial information to detect a threshold for the chloride ion concentration in the soil surrounding concrete.

**Fig. 7. The tested corrosion current density in different RC specimens.**

4. Discussion

4.1. Effect of concrete cover thickness and quality of concrete

To study the role of cover thickness, as well as concrete quality on corrosion process, the present work was intended to detect the corrosion rate for specimens possessing different concrete compressive strengths, each had a different thickness of the concrete cover, but was exposed to similar circumstances. The results shown in Fig. 7 shows that the thickness of the concrete cover has a significant effect on the amount of corrosion rate. The i_{corr} value in the specimens that represent the two types of foundations F35 and F21 with a concrete cover of 75 mm thickness did not exceed $0.5 \mu\text{A}/\text{cm}^2$, which is less than the i_{corr} values in other specimens in which the thickness of the concrete cover was less than 75 mm (50 mm, 2 mm).

The corrosion rate in the foundations representative specimens can be classified as “negligible” in the case of exposure to 0.6% chloride concentration in the aqueous solution, while the corrosion rate was “low” when the specimens were exposed to chloride concentration of 2% and 6%. On the other hand, in the case of specimens representing the columns and beams (CB21 and CB35), which were exposed to chloride concentration of 0.6% and 2%, the i_{corr} reached 0.29, 0.45 $\mu\text{A}/\text{cm}^2$ respectively, i.e., the corrosion rate could be classified as “low”, while the i_{corr} values of similar specimens exposed to 6% Chloride were 2.04, and 1.42 $\mu\text{A}/\text{cm}^2$ for specimens with concrete compressive strength of 21 and 35 MPa respectively. Consequently, the i_{corr} of the specimens with 50 mm concrete cover which were exposed to a high concentration of chloride ion can be classified as “high”.

These results can be explained by referring to the fact that enhanced quality of concrete, is usually accompanied by a dense gel structure beside a low permeability. It can be concluded that the microstructure of the concrete can inhibit the movement of chloride ions if sufficient thickness is available to lengthen the ion movement path between the anode and the cathode required to complete the oxidation reaction [30, 31]. This phenomenon is valid for all exposure conditions including the severe exposure where the chloride concentration in the aqueous solution was 6%. On the other hand, the quality of the concrete has an effect on slowing the corrosion reactions when the chloride content is not more than 2%, but the quality alone could not prevent the rate of the reaction in the severe conditions of exposure to exceed the threshold between the “medium”, and the “high” limits.

4.2. Effect of exposure type

Different cases of exposing the tested specimens to the chloride contaminated soil were employed in the present study to detect the influence of type of exposure on corrosion rate. The foundation, and beams representing specimens were exposed on two sides to simulate actual conditions in the site, while, for the same reason slabs specimens were exposed on one side only. The relationship between the i_{corr} and exposure type could be manifested easily when comparing the i_{corr} values presented in Tables 4, 5 and 6 for RC specimens representing slabs (S35 and S21) that were exposed to chloride attack on one side, with the results of the other specimens (F35, F21, CB35 and CB21), which were exposed to chloride ion on two orthogonal sides.

The thickness of the concrete cover in the slab representative specimens (25mm) was lower than the thickness of the cover in other specimens. Nevertheless, in the case of the specimens possessing high compressive strength which were exposed to 0.6, and 2% chloride concentrations, the i_{corr} value was between 0.17 and 0.27 $\mu\text{A}/\text{cm}^2$, respectively. The corrosion rate so did not exceed the "low" limit. Moreover, the i_{corr} value in those specimens exposed to a 6% concentration of chloride ion did not exceed 0.49 $\mu\text{A}/\text{cm}^2$ "moderate rate".

In spite of the high chloride ion binding ability of C_3A compound in ordinary Portland cement, used in specimens representing slabs, it can be clearly concluded from the previous results that the attack of chlorides to concrete on more than one side leads to a significant increase in the rate of corrosion reactions compared to the case of exposure on one side only. This increase can be justified due to the increased probability of existence of paths of interconnected pores in the concrete matrix that enhances the permeation of chloride ions inside concrete towards steel reinforcement [25].

The effect of casting direction on the distribution of microscopic pores and their orientation may have an effect on the movement of chloride ions within the concrete and so on corrosion reaction. However, these subject needs further research.

4.3. Effect of degree of exposure

The present study is focused to study the effect of exposing the tested specimens to different percentages to soil-born chloride so as to clarify their influence on the initiation of reinforcement corrosion. The program followed proved to be efficient to reveal the intended results. When comparing the i_{corr} results listed in Tables 4, 5 and 6 for the specimens exposed to 0.6% and 2% chloride ion concentration with the results of the specimens exposed to 6% concentration, it can be noticed that the differences were not significant.

The results of the first group showed that the ratio between the i_{corr} in the case of exposure to 2% and 0.6% chloride concentration ranged between 0.96-1.69 $\mu\text{A}/\text{cm}^2$. On the other hand, the results clarify that the exposure of specimens to 6% chloride concentrations significantly increased the rate of corrosion of reinforcement. The i_{corr} value was increased in some cases to more than four times the value when exposed to a 2% concentration of chloride.

It can be concluded that the calculated concentrations of dissolved chloride ion in the basin water used in this study were appropriate to reach a state of equilibrium with the ion concentration in the void water inside concrete. Also, the results gave clear evidence of the validity of the "threshold" phenomenon for chloride content to initiate corrosion of rebars.

4.4. Determination of permissible limits for chloride ion

The results of this research show that there exists a threshold for the chloride ion concentration in the soil in contact with the concrete. When this threshold is exceeded significant corrosion in reinforcing steel will take place. This chloride concentration limit is similar to the corresponding threshold of chloride ion content in the concrete constituents (aggregates, cement, water, etc.) mentioned in the codes and specifications related to the internal chloride attack. The results indicate that this threshold of chloride ions is correlated with the compressive strength of

concrete, concrete cover thickness and type of exposure, as shown in Table 7. This table includes the percentages of chloride ion, at which the corrosion rate does not exceed the "low" limit,

Table 7. The permissible limit of chloride ion in groundwater and soil in contact with concrete.

Type of exposure	Permissible chloride ion concentration % in aqueous extract (in soil) for concrete with :					
	F _c = 21 MPa and thickness of concrete cover of:			F _c =35 MPa and thickness of concrete cover of		
	2.5 cm	5 cm	7.5 cm	2.5 cm	5 cm	7.5 cm
On one side	2(0.4)	-	-	6(1.2)	-	-
On two sides	-	2(0.4)	6(1.2)	-	2(0.4)	6(1.2)

It is shown that the corrosion of rebars could not take place in concrete with 50 mm cover thickness, if the presence of chloride is limited to not more than 2% in the water extract (0.4% in the soil in contact with concrete), regardless of concrete quality and exposure type. This chloride concentration could be increased to 6% in the water extract (1.2 % in the soil) by increasing the thickness of concrete cover to 75 mm or using concrete having 35MPa compressive strength besides limiting the exposure to be on one side only.

These findings proved the validity of the hypothesis adopted in this research that the studied variables have a significant role in influencing the threshold limit of the chloride ion content in soils in contact with reinforced concrete members. Therefore, it is very important for building codes to set special requirements for soil- born chloride ion content

5. Conclusions

Based on the circumstances of the research including the type of materials, concrete grades, experimental conditions, as well as the circumstances of the studied cases, the following remarks can be concluded:

- The results prove the research hypothesis that the threshold limit of chloride ion content in soils is strongly dependent on intrinsic characteristics of reinforced concrete, namely concrete quality, and thickness of the concrete cover. Also, the threshold depends upon the type of exposure (number of sides exposed to chloride attack).
- The research results indicated that it is possible to avoid the detrimental effect of external chloride attack on reinforced concrete members from chloride bearing soils by strictly restricting the chloride ion content in the soil to a certain threshold limit.
- It was shown that the role of the concrete quality on corrosion probability was more pronounced in the specimens where the concrete cover thickness was (75 mm) or (25 mm).
- It was found that increasing the thickness of the concrete cover did reduce the rate of corrosion (i_{corr}) significantly especially when the chloride content in soil was low to moderate.

- the results indicated that exposing concrete to the attack of chlorides on more than one side greatly increases the rate of corrosion in the reinforcing steel, especially, when the concrete cover thickness did not exceed 50 mm.
- The present research findings imply that the design codes should set special requirements for the threshold limit of chloride ion content in soils in contact with reinforced concrete members.
- Further research related to the threshold limits of chloride ion in the soil in contact with reinforced concrete, is suggested for the following purposes:
 - a) Detecting the threshold limits for chloride ion content between 0.4 to 1.2%.
 - b) Studying the effect of cement type on the threshold limit.
 - c) Studying the effect of contamination of soil with sulphate ions (SO_3^-) on the threshold limit.
 - d) Investigating the effect of using additives to cement on the threshold limit.
 - e) Detecting the impact of the direction of casting on the corrosion of reinforcing steel.

Nomenclatures

Cl	Chloride ion
e	Void ratio of soil
F_c	Compressive strength of concrete, MPa
I_{corr}	Corrosion current, μA
i_{corr}	Corrosion current intensity ($I_{corr}/2\pi l$), $\mu\text{A}/\text{cm}^2$

Greek Symbols

ρ_s	Unit weight of soil g/cm^3
ρ_w	Unit weight of water, g/cm^3

Abbreviations

HCP	Half-Cell Potential, mV
RC	Reinforced Concrete
Rebars	Reinforcing bars

References

1. ACI committee 222, (2001). *Corrosion of Metals in concrete*. American Concrete Institute. Manual of Concrete Practice, R1-222 R 30. Farmington Hill, MI.
2. Hawkins, C.; and Weale, C. (2006). Options for repair and durability of concrete structures. *11th Middle East Corrosion Conference Proceeding*, Bahrain.
3. Al-Tameemi, A.A. (2006). *Behavior of reinforced concrete members subjected to corrosion of reinforcement enhanced by internal chlorides and sulphate attack*. Ph.D. Thesis, University of Baghdad, Iraq.
4. Pruckner, F. (2001). *Corrosion and protection of reinforcement in concrete measurements and interpretations*. Ph.D Dissertation, Department of National Sciences and Mathematics, University of Vienna, Austria, 2001.

5. NEA, CSNI (2003). Electrochemical technique to detect corrosion in concrete structures in nuclear installations. *Technical Note Report*, R 21.OECD, France.
6. Yousif, H.A. (1997). *Corrosion of reinforcement in concrete containing high range water reducing agent and rice husk ash*. Ph.D. Thesis, University of Technology, Baghdad, Iraq.
7. Al-Moatasim, F.A. (2002). *Effect of using different metal paintings on the resisting of concrete reinforcement corrosion*. M.Sc. Thesis (in Arabic), University of Baghdad, Iraq.
8. Al-Sofi, G.A. (2002). *Cathodic protection of reinforcing steel in concrete*. Ph.D. Thesis, University of Baghdad, Iraq.
9. Hubboubi, S.K. (2010). *Assessment of corrosion-resistance characteristics of furfural concrete*. Ph.D. Thesis, University of Baghdad, Iraq.
10. Al-jalawi, N.; Altameemi, A.A.; and Al-Jarrah, S.H. (2016). Effect of age and cover thickness on steel reinforcement corrosion at splash zone in reinforced concrete hydraulic structures. *International Journal of Scientific & Technology Research*, 5(9), 129-133.
11. Al-Tameemi, A.A.; and Al-Jarrah, S.H. (2017). Studying the effect of addition of silica fume and concrete compressive strength on rebars corrosion in reinforced concrete marine structures. *Scientific The annual scientific conference of Iraqi Ministry of Housing and Municipalities*, Baghdad, Iraq.
12. Katwan, M.J. (2001). Corrosion of steel reinforcement in hot countries, an acute case study. *Material and Structures*, 34, 360-366.
13. American Concrete Institute, (2010). *Protection of metals against corrosion. ACI 222R-01* (Reapproved 2010), Farmington Hill, MI.
14. Obla, K.; Lobo, C.; Hong, R.; and Berke, N. (2017). Evaluation of Chloride Limits for Reinforced Concrete Phase A. *Final Report*. the RMC Research & Education Foundation (Project 14-01), and Concrete Research Council, ACI Concrete Foundation.
15. Arab Housing and Construction Ministers Council (1997). Unified Arabic code for designing and implementation of reinforced concrete structures. (In Arabic). The Arab League, Cairo, Egypt.
16. American Concrete Institute (2019). Building code requirements for structural concrete and commentary. *ACI 318M-19*, Farmington Hill, MI
17. Vermani, P.Y.; and Ghasemi, H. (2012). Literature review of chloride threshold values for grouted post-tensioned tendons. *Report No. FHWA-HRT-12-067*. Federal Highway Administration, McLean, VA.
18. Al-Saoudi, Namir K.S.; and Al-Shakerchy, M .Sh. M. (2010) *Statistical analysis of some geotechnical properties of Najaf city*. Proceedings of International Geotechnical Conference, 3, Moscow, Russia, 1173-1180.
19. Mahmood, M.Sh.; Aziz, L.; and Al-Gharrawi, A.M.B. (2018). Settlement behavior of sand soil upon soaking process. *International Journal of Civil Engineering and Technology*, 9 (11), 860-869.
20. Abdalhusein, M.M.; Akhtarpour, A.; and Mahmood, M.Sh. (2019). Effect of wetting process with presence of matric suction on unsaturated gypseous sand soils. *Journal of Southwest Jiaotong University*, 54(5), 1-11.

21. Mahmood, M.Sh.; Akhtarpour, A.; Almahmodi, R.; and Abdalhusein, M.M. (2019). *Settlement assessment of gypseous sand after time-based soaking*. *IOP Conference Series: Materials Science and Engineering*, 737 012080
22. Iraqi Specifications (2019). The Portland cement. *IQS 5-19*, COSQC, Baghdad, Iraq.
23. Iraqi Specifications (2016). Aggregates from natural sources for concrete and building construction. *IQS 45-84* (Reapproved 2016), COSQC, Baghdad, Iraq.
24. American Concrete Institute (2002). Standard practice for selecting proportions for normal, heavyweight, and mass concrete. *ACI Committee 211.1-91* (Reapproved 2002), Farmington Hill, MI, 38.
25. Neville, A.M. (1995). *Properties of concrete*. (6th ed.). Longman Group Ltd., 841.
26. Stanish, K.D.; Hooton, D.; and Thomas, M.D.A. (1997). Testing the chloride penetration resistance of concrete : A literature review. *FHWA Contract DTFH61-97-R-00022*, University of Toronto, Canada.
27. ASTM (2005). *Standard test method for electrical indication of concrete's ability to resist chloride ion penetration*. ASTM C1202-05. Annual Book of ASTM Standards V 04.02, 62.
28. ASTM (1999). *Standard test method for half-cell potentials of uncoated reinforcing steel in concrete*. ASTM C 876. Annual Book of ASTM Standards, Vol. 03.02, 1-5
29. ACI Committee 222 (2001). *Corrosion of prestressing steels*, ACI 222.2R-01.
30. Al-Khaiat, H.; Jones, B.; And Haque, M.N. (2007). *Designing durable concrete structures in the Arabian Gulf: A draft code*. *32nd Conference on Our World in Concrete and Structures*, Singapore, 1-8.
31. California Department of Transportation (2012). *Corrosion guidelines*. Version 2. California, US.