

Influence of Sacrificial Cathodic Protection on the Chloride Profile in Concrete

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The durability of reinforced concrete structures significantly depends on the condition of the steel embedded in them. Structures exposed to chloride containing environment have reduced durability due to corrosion of the reinforcement steel. Several diffusion models have been proposed for chloride penetration. They mainly aim at predicting the initiation of corrosion of the reinforcement. They are based on diffusion conditions influenced by parameters such as relative humidity, temperature, rains etc. This work presents the influence of sacrificial cathodic protection on the chloride profile in concrete. Cathodic protection to the embedded steel in concrete was established by plugging-in a sacrificial magnesium alloy anode at the center of the slab and providing an electrical link between them. The current flowing between the magnesium anode and the embedded steel was regularly measured. The water soluble chloride content at different distances from the anode and at different times was determined after implementation of cathodic protection. The chloride content decreased at different distances from the anode, with increase in time. The diffusion of chloride occurred at a more accelerated rate due to the flow of cathodic protection current.

Keywords: Reinforcement Steel, concrete, corrosion, sacrificial cathodic protection, chloride profile

1. INTRODUCTION

The low cost and durability of reinforced concrete favours its use as the most preferred construction material. The durability of the structure is highly dependant on the condition of the steel rods used as reinforcements. The film formed on the steel surface due to the high alkalinity existing in concrete, pH close to 13, protects the steel from corrosion [1, 2]. However, the chloride ions that enter the concrete from the environment break the protective film and promote corrosion of the embedded steel. This in turn reduces the durability of the structures.

The primary cause for corrosion of the embedded steel has been reported to be chloride ions [3, 4 & 5]. Corrosion of steel in concrete occurs when the chloride content in concrete exceeds 0.6 Kg/m^3 or $\sim 0.2 \%$ [6, 7 & 8]. The source of chloride could be from deicing salts used or the environment (such as marine). The corrosion of steel embedded in concrete is controlled by the diffusion of chloride in concrete [9, 10].

The chloride profiles obtained were related to the environment surrounding the concrete [11, 12]. Diffusion coefficient and remaining service life are obtained from mathematical models generated using the chloride concentration profiles [13, 14]. Hence studying the chloride profiles in concrete will be extremely useful.

The corrosion of the embedded steel reinforcement is reported to be due to the free chloride since it can only diffuse into the concrete and cause corrosion [15, 16 & 17]. Hence in the present study the concrete core samples obtained were analysed for their free chloride content. The chloride content obtained was related to the cathodic protection functioning in the concrete slab to understand its effect.

2. EXPERIMENTAL PART

2.1. Concrete slab

In the present work, concrete slabs (of size $1.2 \text{ m} \times 1.2 \text{ m} \times 0.1 \text{ m}$) were cast using ordinary Portland cement. Coarse aggregates of size in the range 0.018 to 0.025 m were used. The water / cement ratio used was 0.45 . $1:2:4$ mix ratio (cement: coarse aggregate: fine aggregate) was employed. The aggregates were thoroughly washed with triple distilled water several times to remove any soluble ionic species present in them, prior to casting. Sodium chloride (AR grade) was added during the casting process itself, equal to 3.5% by weight of cement. The salt was dissolved in the water used for casting the slab.

0.01 m diameter and 1.0 m long plain steel rods were used for reinforcing the slab. Two mats of assembly were used, joined by welding at diagonally opposite corners, with a spacing of 0.03 m between them. A cover thickness of 0.025 m was provided for the reinforcements.

A 0.2 m diameter and 0.08 m deep hole was provided at the center of the slab for the sacrificial magnesium alloy anode to be plugged.

2.2. Cathodic protection

A high purity magnesium alloy anode containing 0.18% manganese, with a steel core for electrical contact was used for cathodically protecting the steel reinforcement. The anode was designed for a life of three years. It was packed in a conventional backfill and plugged in the site provided at the center of the slab, 23.5 hours after casting the slab. The cathodic protection was established by connecting the rods from the reinforcement assembly (at diagonal ends) to the anode, through a switching circuit unit and monitored. The current flowing between the magnesium anode and

the steel reinforcement was periodically measured, plotted against time of measurement and analyzed. Figure 1 illustrates the reinforced concrete slab with the sacrificial anode embedded at the center.

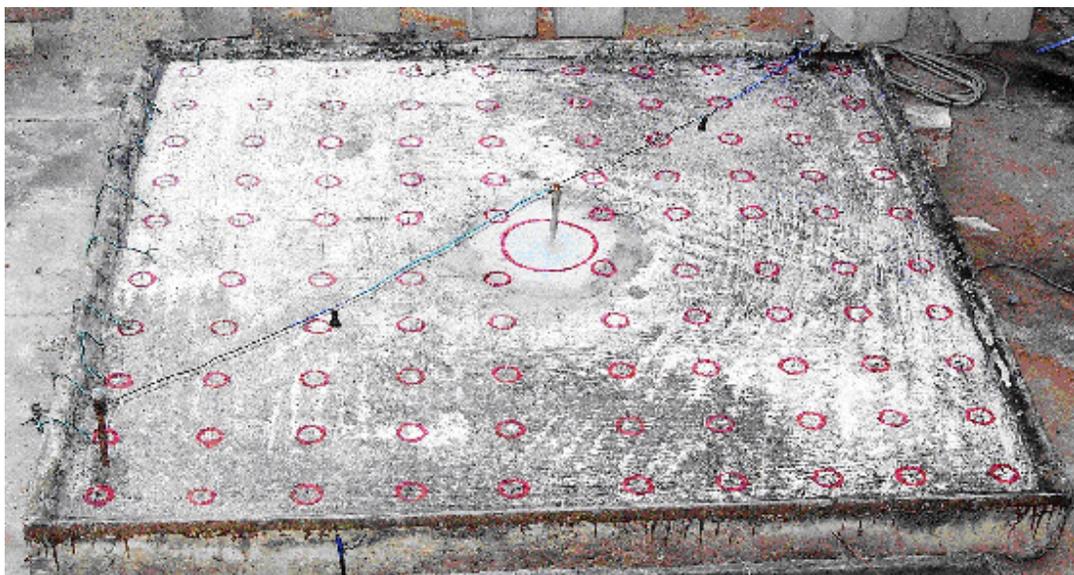


Figure 1. Concrete slab with cathodic protection

2.3. Chloride content determination

Core drills of 0.01 m diameter were obtained at different durations after cathodic protection was applied, at different distances from the anode (0.23 m, 0.52 m and 0.95 m), close to the reinforcement assembly. The core was ground into fine powder to pass 300 micrometer sieve. The powder mass was weighed and digested with specific volume of deionized water for 24 hours and filtered using vacuum filter unit. A standard volume of the filtrate was titrated against 0.01 N silver nitrate. The chloride content was calculated and presented in terms of Kg/m^3 of concrete.

The results were plotted against time of measurement for the different distances at which the measurement was made.

The diffusion rates were also calculated at different timings using solution to Fick's Second law [10]. These were analyzed and compared with those reported

3. RESULTS AND DISCUSSION

The variation in concentration of chloride with respect to time at a distance of 0.23 m from anode is shown in figure 2. The profile indicates that as the duration of cathodic protection increases, the concentration of chloride decreases. The decrease is relatively rapid during the initial three months. During this period, the chloride concentration decreases from 12 Kg/m^3 to $\sim 0.36 \text{ Kg/m}^3$. However,

later, the decrease in concentration becomes very slow, with increase in time. The decrease in concentration from $\sim 0.36 \text{ Kg/m}^3$ to $\sim 0.05 \text{ Kg/m}^3$ occurs during a period of nearly 20.4 months.

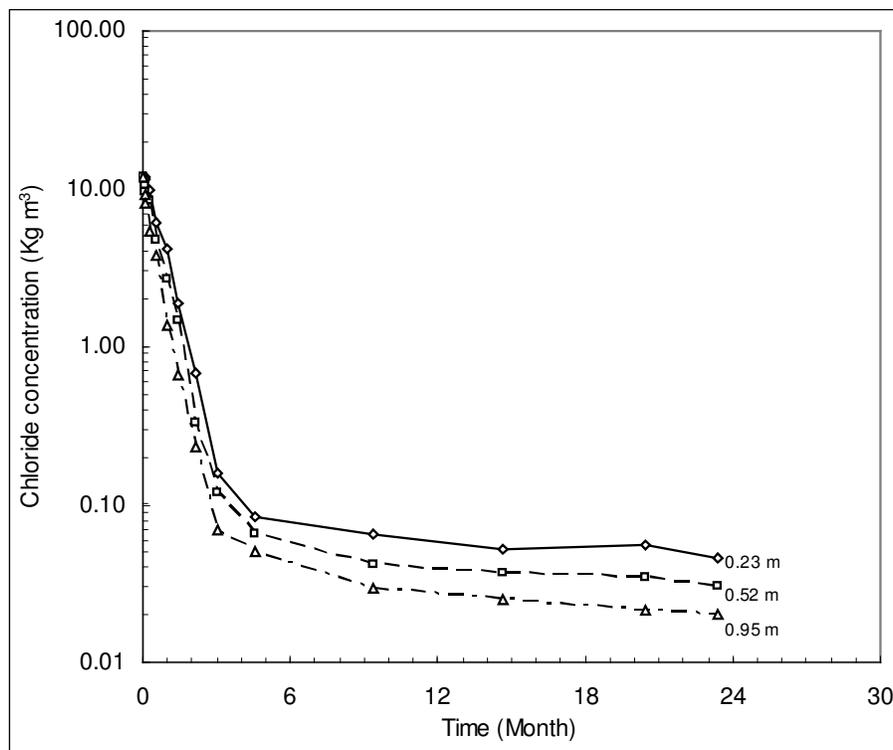


Figure 2. Variation of chloride concentration with time at different distances from anode

At a distance of 0.52 m from the anode, the chloride concentration decreases from 12 Kg/m^3 to 0.15 Kg/m^3 initially, over a duration of three months. During this period, the decrease is observed to be relatively rapid, which is also illustrated in figure 2. Subsequently this decrease in chloride concentration slows down to a significant extent, reaching 0.023 Kg/m^3 after a period of 20.4 months. Beyond this duration, the decrease in chloride concentration is observed to be very slow.

The decrease from 12 Kg/m^3 to 0.061 Kg/m^3 occurred at 0.95 m from the anode within a period of three months. Here again, very slow decrease in chloride concentration was observed beyond this period. The chloride ion concentration decreased from 0.061 Kg/m^3 to 0.009 Kg/m^3 over a period of twenty months. This is also shown in figure 2.

At all the three distances from the anode, the chloride concentration was observed to decrease rapidly during the initial stages. This decrease slowed down to a considerable extent later. The initial rapid decrease in chloride content can be attributed to the relatively higher conductivity existing in the concrete at the initial stages as the concrete cures. It is reported that the internal zone where chloride is present in concrete is able to retain more moisture compared to other areas [18]. Hence, conductivity of concrete in this zone would be relatively high. This observation is reinforced by the fact that the current flowing in the slab during this initial stage is of the order of mA, as shown in figure 3. This

figure indicates that the current density between the magnesium alloy (anode) and the reinforcement steel (cathode) is decreasing from 40.68 mA to 26.2 mA during the initial stages when the chloride concentration rapidly decreases. As time increases, the current flow in the concrete decreases. The decrease in current with increase in time could be primarily due to drying of concrete (curing) which reduces its conductivity. Further, the reduction in chloride concentration with time also contributes to the reduction in conductivity of concrete.

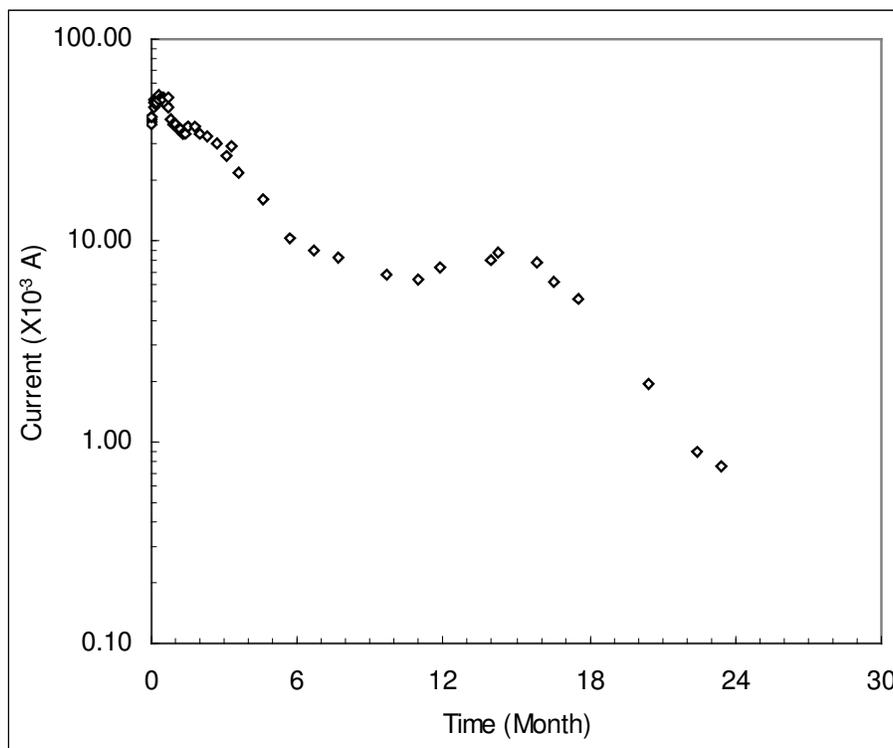


Figure 3. Variation in current flowing in concrete with time, on application of cathodic protection

The diffusion coefficients for chloride were evaluated for the three distances at different times. They are of the order of 10^{-7} m²/S during the period when concentration rapidly decreased, as compared to 10^{-11} to 10^{-13} m²/S, reported in the absence of external current flowing in the concrete [19, 20]. After the initial rapid decrease zone, the diffusion rate decreased to an order of 10^{-12} m²/S. The values determined are reported in table I. It can be seen that the current flowing in the concrete due to sacrificial cathodic protection is able to increase the diffusivity of chloride ions in concrete by about four orders of magnitude during the initial stages.

The time dependant variation in the diffusion rate of chloride ions in concrete is reported by several researchers [17, 21]. At all the three distances from anode, the diffusion rate decreases as time increases. This is due to the drying of concrete which results in reduction of diffusion path for the chloride ions. The diffusion rate also decreases when the distance from the anode increases at any

measurement time. This is probably due to the increase in distance through which the diffusion has to occur in addition to the changes in concentration gradient of chloride ions.

Table 1. Chloride diffusion coefficient at different distances from anode

| Time (Month) | Diffusion coefficient (m ² /S) | | |
|-----------------|---|---------------------------|---------------------------|
| | 0.23 m | 0.52 m | 0.95 m |
| 0.12 | 1.021 x 10 ⁻⁷ | 9.984 x 10 ⁻⁸ | 8.131 x 10 ⁻⁸ |
| 0.27 | 3.947 x 10 ⁻⁸ | 3.620 x 10 ⁻⁸ | 3.514 x 10 ⁻⁸ |
| 0.56 | 1.139 x 10 ⁻⁸ | 1.042 x 10 ⁻⁸ | 1.010 x 10 ⁻⁸ |
| 1.01 | 9.163 x 10 ⁻⁹ | 6.766 x 10 ⁻⁹ | 4.638 x 10 ⁻⁹ |
| 1.47 | 2.485 x 10 ⁻⁹ | 1.068 x 10 ⁻⁹ | 1.001 x 10 ⁻⁹ |
| 2.16 | 1.057 x 10 ⁻⁹ | 7.569 x 10 ⁻¹⁰ | 6.769 x 10 ⁻¹⁰ |
| 3.02 | 8.296 x 10 ⁻¹⁰ | 5.283 x 10 ⁻¹⁰ | 4.134 x 10 ⁻¹⁰ |
| 4.53 | 6.511 x 10 ⁻¹⁰ | 2.313 x 10 ⁻¹⁰ | 1.457 x 10 ⁻¹⁰ |
| 6.87 | 2.496 x 10 ⁻¹⁰ | 9.710 x 10 ⁻¹¹ | 8.064 x 10 ⁻¹¹ |
| 9.40 | 7.845 x 10 ⁻¹¹ | 3.655 x 10 ⁻¹¹ | 1.494 x 10 ⁻¹¹ |
| 12.32 | 8.991 x 10 ⁻¹² | 5.043 x 10 ⁻¹² | 4.167 x 10 ⁻¹² |

Since the diffusion of the chloride ions is towards the anode, as the increase in concentration of chloride with decrease in distance from the anode suggests, the embedded steel rebar is exposed to lesser and lesser chloride concentration of chloride ions. Further, since the embedded steel is rendered as the cathode, it repels the chloride ions that might diffuse towards the steel. These factors favour the protection offered to the embedded steel by the sacrificial cathodic protection technique.

The chloride diffusion towards the anode was analyzed to understand where the chloride was removed to. At the end of the test duration, the backfill samples were obtained from the region adjacent to the anode (anode/backfill interface). These were also analyzed for their chloride content in order to determine where the chloride has been removed.

The analysis of the backfill samples obtained closest to the anode exhibited a chloride content of 0.27 Kg/m³, after the test duration. During the entire test period, the slabs were exposed to open atmosphere. The water from the rains that occurred during this period used to be collected in the pond provided on top of the slab (for wetting the slab periodically) and overflowed. Hence during the rainy seasons, the slabs were thoroughly wetted. The chloride reacts with the anode to form magnesium chloride. Magnesium chloride is ionic and highly soluble in water. Moreover, this compound is inherently hygroscopic. This could result in the chloride ions migrating to the liquid zone and getting washed away from the concrete. This may probably be the reason for the reduction in chloride content in the backfill as well. Similar instances are reported in field conditions where the reduction in chloride concentration in concrete reduces due to washing away by rains [18].

4. CONCLUSIONS

- a. The chloride ion concentration in concrete at the three distances from the magnesium alloy anode decreased with increase in time.
- b. Also, as the distance from the anode increased, the chloride ion concentration decreased.
- c. The chloride diffusion rate in concrete is significantly increased by the current flowing in the concrete due to cathodic protection.
- d. The diffusion rate is dependant on the duration of cathodic protection and
- e. The diffusion rate is also dependant on the variations in chloride concentration at different distances from the anode.

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