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Experimental Investigation of the Behaviour of Reinforced Concrete Structures Exposed to the Escravos River of Nigeria

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Article Info	Abstract
 	This study investigated the behaviour of reinforced concrete structures exposed to the Escravos River of Nigeria. Reinforced concrete samples were prepared in the laboratory with various sizes of steel reinforcement – 10mm, 12mm and 16mm diameter steel bars. After curing, these samples were immersed into water samples extracted from the Escravos River. The corrosion process was accelerated by means of application of an external impressed current of 0.4A. The impressed current was applied via a 12 volts DC power source. The circuit was connected in such a way that the protruding steel reinforcement served as the anode, while a 6mm stainless steel rod that was placed in the solution/electrolyte served as the cathode. Various tests were carried out to determine the corrosion current, corrosion resistance and the chloride diffusion coefficient of the concrete. The results obtained showed that the size of the embedded steel reinforcement influences the corrosion behaviour of the structure. As the size of the steel reinforcement increased, the corrosion current increased while the corrosion resistance decreased. This was attributed to the larger surface area of the larger diameter steel reinforcements. On the other hand, varying the size of the steel reinforcement did not have any impact on the rate of chloride diffusion into the concrete samples.

1. Introduction

Chloride-induced corrosion of steel reinforcement has been identified as the primary cause of untimely deterioration of marine concrete structures [1, 2]. These chlorides usually permeate into the hardened concrete through diffusion or they may be introduced into the fresh concrete when chloride-contaminated water is used in preparing the concrete mix [3, 4]. The presence of chloride in the concrete decreases the pH of the concrete's pore solution [5] and this in turn weakens the protective passive layer surrounding the steel reinforcement, thereby making it easy for corrosive elements to gain access to the steel reinforcement to induce corrosion.

Once corrosion is induced in the steel reinforcement, there is the risk of reduction in the cross sectional area of the steel reinforcement and spalling of the concrete, both of which will have negative impact on the serviceability and safety of the structure [2]. According to [6], this form of concrete deterioration has been reported to be responsible for the billions of dollars being spent yearly for the repair and rehabilitation of marine concrete structures. As a result of this, numerous studies e.g. [7, 8] have been carried out in the past to understudy the causes and mechanisms governing steel reinforcement corrosion, and ways to reduce it. However, most of these studies have

been conducted in temperate marine environments, with very few conducted in tropical marine environments.

Nigeria is a tropical environment and has a coastline that stretches over 1,000 km, where many marine structures are housed. Hence, it is imperative to conduct studies to determine how concrete structures located in this area will be affected by chloride induced steel reinforcement corrosion. Such studies will be of extreme importance as it will help in providing guidelines for the design and construction of structures in this environment. In this study, water samples were obtained from the Escravos River, which is located in the Niger Delta region of Nigeria – a region that is largely enclosed by brackish water. Reinforced concrete samples prepared in the laboratory were then exposed to these water samples, so as to determine the rate of chloride diffusion into the samples.

2. Methodology

2.1 Materials
The constituent materials used for the experiments consisted of Portland limestone cement, fine aggregate, coarse aggregate (maximum size of 19mm) and potable water. The mineralogical compositions of the Portland limestone cement is shown in Table 1.

Table 1: Mineralogical composition of Portland limestone cement

Mineral	Content (%)
C_3S (Tricalcium silicate)	68.12
C_2S (Dicalcium silicate)	6.08
C_3A (Tricalcium aluminate)	7.89
C_4AF (Tetra calcium alumina ferrite)	10.72

High yield deformed steel reinforcing bars of grade 460, were used for the experimental work. Three different bar sizes of diameter 10mm, 12mm and 16mm were used for the study. The steel bars were cleaned and weighed before placement into the concrete samples.

2.2 Preparation of Concrete Samples
The concrete samples were prepared in two stages. In the first stage, formworks of size – 100 x 200 x 300mm, were constructed using plywood. Holes were drilled in the formworks to provide room for the placement of the steel reinforcing bars. The holes were drilled in such a way that a minimum cover of 20mm will be provided between the steel reinforcing bars and the concrete. After this, the formworks were oiled, and the steel bars were placed in their positions in the forms. Just before casting, the protruding section of the steel reinforcing bars at the concrete surfaces and the top 20mm of the bars in the concrete were sealed with plastic tape to minimize corrosion in these areas, leaving only 160mm length of bars exposed to concrete.

The second stage involved the casting of the concrete. A concrete mix ratio of 1:1.5:3:0.55 (cement: fine aggregate: coarse aggregate: water) was adopted for the study. The mixed concrete was poured into the formworks containing the steel bars (see Figure 1). After casting, the samples were covered with polythene sheets for a minimum of 24 hours and then de-moulded. Thereafter, the samples were cured for 28 days under air before the commencement of the accelerated corrosion test. On completion of the 28 days curing, all the concrete samples were kept partially immersed in water for 3 days to obtain uniform moisture distribution in the immersed part/section of the specimen. After this, the samples were then subjected to accelerated corrosion for another 35 days before testing in line with BS EN 12390-11 [9].

Three sets of samples (namely A-10, A-12 and A-16), were prepared, to understudy the effect of bar diameter on corrosion. For the A-10 samples, 10mm diameter steel reinforcements were used, while 12mm and 16mm diameter steel reinforcements were used for the A-12 and A-16 samples respectively.

Figure 1: Cast concrete samples with protruding steel reinforcing bars

Table 2: Details of concrete samples used for the experimental study

Code	Bar Size (mm)	Conc. cover C_1 (mm)	Conc. Cover C_2 (mm)
A-10	10	20	44
A-12	12	20	44
A-16	16	20	44

2.3 Setup for Accelerated Corrosion Process

The seawater used for the accelerated corrosion test was obtained from the test location, which is Escravos. Chemical analysis conducted on the seawater as reported in a previous study by the authors [10] showed that chloride ions were the predominant ions contained in the seawater. The seawater was seen to have an average chloride content of about 17,000 mg/l. The seawater was poured into drums and the cured concrete samples with the protruding steel reinforcement were placed in the drums containing the seawater for a period of 35 days. The concrete samples were placed in such a manner that the level of the seawater was maintained at the same level of the top of the concrete samples.

The corrosion process was accelerated by means of application of an external impressed current of 0.4A. The impressed current was applied via a 12 volts DC power source. The circuit was connected in such a way that the protruding steel reinforcement served as the anode, while a 6mm stainless steel rod that was placed in the solution/electrolyte served as the cathode. Each setup was covered by means of a local sack that was wetted daily to ensure a controlled humidity environment throughout the exposure period. A photographic representation of the test setup is shown in Figure 2.

Figure 2: Picture showing setup for accelerated corrosion experiment

2.4 Test Methods

2.4.1 Corrosion current density
The corrosion current density was measured using a linear polarisation device with a sensorised guard ring (see Figure 3). This system employs two potential sensors between the auxiliary electrode and the guard-ring to control and confine the applied guard-ring current to the prescribed area. The equipment consists of a potentiostat fitted with an *IR* (where *I* is the current passing through the concrete and *R* is the solution resistance of the concrete) compensation facility and a multimeter.

Figure 3: LPR system for determining corrosion current density

2.4.2 Determination of total chloride content/diffusion coefficient

To obtain the diffusion coefficient, concrete powder were obtained by drilling cores at various depths of the concrete samples in accordance with the modified NordTest NT Build 443 [11]. The total chloride content at each core was then obtained by the use of the potentiometer titration method in accordance with BS EN 12390-11 [9]. Chloride diffusion profiles were developed using the total chloride contents, which was expressed as a percentage ratio to weight of concrete. Thereafter, the chloride diffusion coefficient (D_c) was obtained by performing non-linear regression on the chloride profiles, using Fick's second law of diffusion [12]:

$$C_x = C_s \left(1 - erf \left[\frac{x}{2\sqrt{D_c t}} \right] \right)$$
(1)

where:

C_x Chloride content measured at average depth x and exposure time t, % by mass of sample

C_s Calculated chloride content at the exposed surface, % by mass of sample

x Depth below the exposed surface to the mid-point of the ground layer, in metres

D_c Calculated non-steady state chloride diffusion coefficient, in square metres per second (m^2/s)

t Exposure time, in seconds (s)

erf   Error function.

3. Results and Discussion

3.1 Corrosion Current and Resistance

Table 3 shows the corrosion current and resistance obtained for all the concrete samples after 7, 16, 28 and 35 days of exposure to the accelerated corrosion test setup. After 7 days of exposure the A-10 samples had a corrosion current and resistance of 20.5mA and 238Ω respectively; but after 16 days, the corrosion current had increased by about 46% to 30mA, while the corrosion resistance had decreased by about 48% to 160.5Ω. Between 16 and 28 days, the corrosion current recorded an increase of about 40%, while the corrosion resistance recorded a decrease of about 31%. This same trend was observed for all the other concrete samples and seems to suggest that the longer the concrete samples were exposed to the accelerated corrosion test setup, the more the corrosion current increased and the more the corrosion resistance decreased. Similar findings were also reported by [13, 14] and can be attributed to the increase in the rate of ingress of chlorides into the concrete, which would have been caused by the accelerated effect of the impressed current [15].

In terms of the effect of the size of the steel reinforcing bars, it was observed that after 7 days of exposure to the accelerated corrosion test setup, as the diameter of the steel bar was increased from 10mm to 12mm, the corrosion current increased by about 7% while the corrosion resistance decreased by about 29%. Similar trends were observed at 16, 28 and 35 days, and seem to suggest that larger bar diameters are more prone to corrosion than smaller diameter bars due to their larger surface areas.

Table 3: Corrosion current and resistance measured for all specimens after 7, 16, 28 and 35 days of exposure to the accelerated corrosion test setup

Sample	Number of days under accelerated corrosion							
	7 days		16 days		28 days		35days	
	Current (mA)	Resistance (Ω)	Current (mA)	Resistance (Ω)	Current (mA)	Resistance (Ω)	Current (mA)	Resistance (Ω)
A-10	20.5	238	30	160.5	42.00	122.5	48	95
A-12	22.0	185	44.5	110	55.00	75.5	59	55
A-16	24.0	170	49.5	98.5	65.00	74	68	50

3.2 Total Chloride Content/Diffusion Coefficient

Figure 4 to 6 shows the chloride profile developed from the measured total chloride content obtained at different depths from the concrete samples after 35 days of exposure to the accelerated corrosion test setup. From the figures, it can be seen that the total chloride content measured for all the samples decreased with depth. Similar trends have been reported by several authors [16 – 19]. At a distance of 44mm from the surface of the concrete (which is equivalent to the concrete cover used in the casting of the concrete samples), the chloride content for the A10, A12 and A16 samples was about 0.076%, 0.072% and 0.063% respectively. It has been shown from literature [20] that the critical chloride content at which corrosion can be initiated is 0.1% by weight of concrete (approximately 0.4% by weight of cement). Comparing this value to that recorded for the concrete samples, it can be seen that the difference between them is very small, thus implying that corrosion of the embedded steel reinforcement must have commenced. This explains the high corrosion current and low corrosion resistance recorded for the concrete samples after 35 days of exposure to the accelerated corrosion test setup as seen in Table 3.
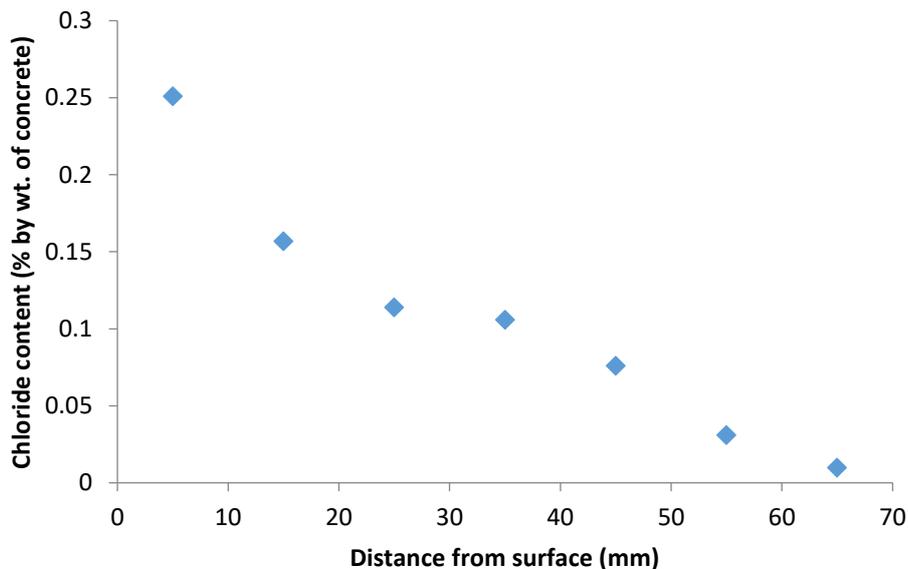
Figure 4: Chloride profile A-10 concrete sample after 35 days of exposure to accelerated corrosion test setup
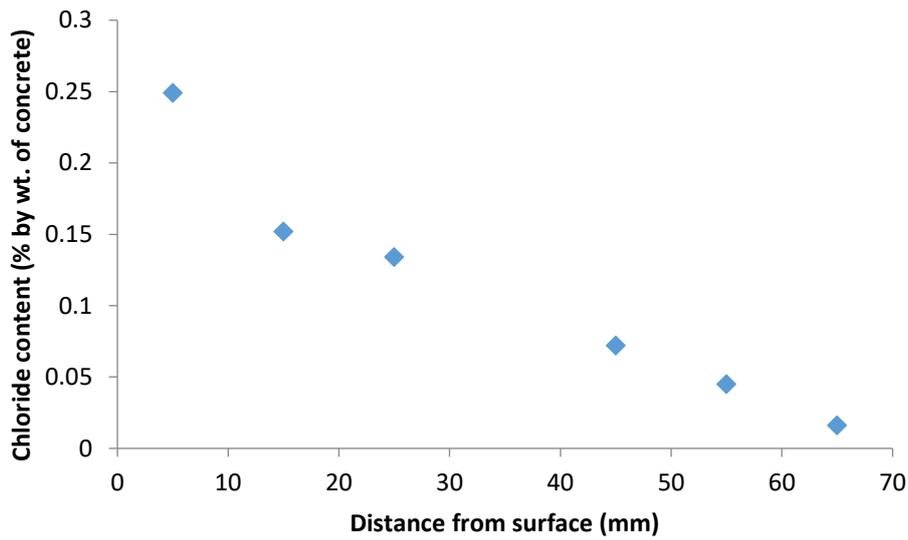
Figure 5: Chloride profile A-12 concrete sample after 35 days of exposure to accelerated corrosion test setup
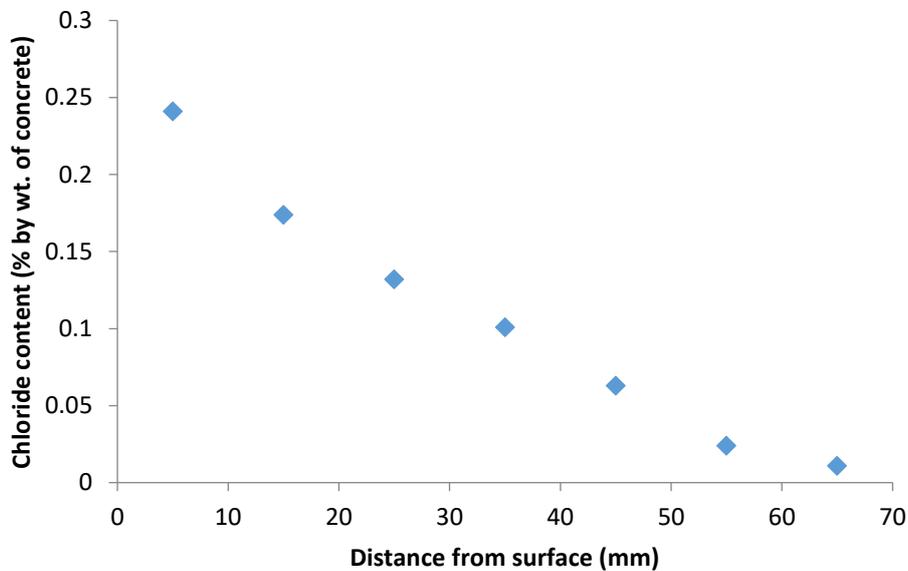
Figure 6: Chloride profile A-16 concrete sample after 35 days of exposure to accelerated corrosion test setup

Using Equation 1, non-linear regression was performed on the chloride profiles shown in Figures 4 to 6 to obtain the chloride diffusion coefficient (D_c) and the chloride concentration at the concrete's surface (C_s). The results obtained are summarized in Table 4.

Table 4: Chloride diffusion coefficient (D_c) and surface chloride concentration (C_s) of concrete samples

Sample	Diffusion coefficient (D_c) x10^{-11} m^2/s	Surface chloride concentration (C_s) %	Adj. R^2
A-10	8.65	0.26	0.9551
A-12	9.31	0.26	0.9653
A-16	8.41	0.27	0.9903

From the table, it can be seen that there is no significant difference between the D_c and C_s values of the various concrete samples, despite the different sizes of steel reinforcement in the samples. This implies that the ingress of chloride into concrete structures is not dependent on the size of the embedded steel reinforcement, but on the properties of the concrete.

4.0 Conclusion

In this study, experiments were carried out to understudy the corrosion behaviour of concrete samples that were exposed to an accelerated corrosion setup using water samples extracted from the Escravos River in Nigeria. Three different sizes of steel reinforcement were inserted into the concrete samples, and the concrete samples were exposed to the accelerated corrosion setup for a period of 35 days. Various tests were conducted to measure the corrosion current, corrosion resistance and the chloride diffusion coefficient of the concrete. From the results obtained, it was seen that as the size of the steel reinforcement increased, the corrosion current increased while the corrosion resistance decreased. This was attributed to the larger surface area of the larger diameter steel reinforcements. It was also observed that increasing the size of the steel reinforcement did not have any significant impact on the rate of chloride diffusion into the concrete samples. This seems to suggest that the main factor influencing the rate of chloride diffusion into concrete structures is the properties of the concrete and not the size, number or spacing of the embedded steel reinforcement.

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