EFFECT OF CHLORIDE SALT ON REINFORCED CONCRETE STRUCTURES IN LAGOS COASTAL ENVIRONMENT

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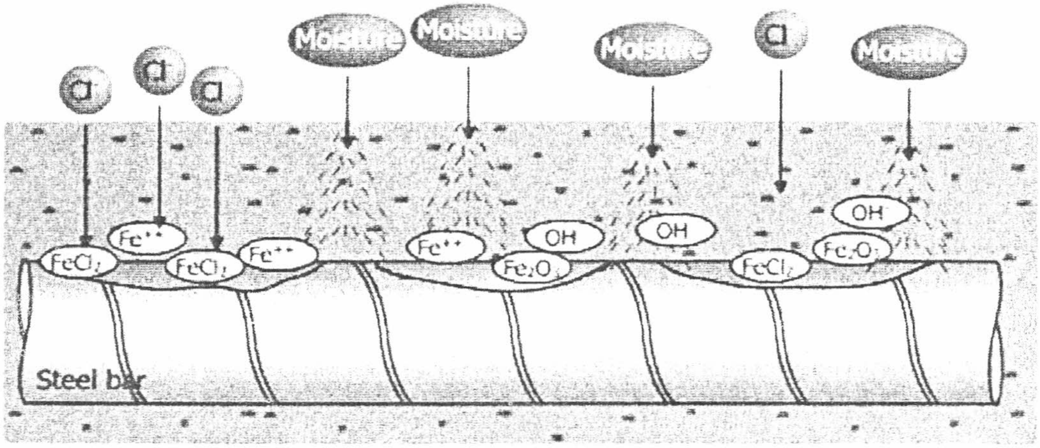
ABSTRACT

This paper identified and documented the deterioration pattern of concrete structures in Lagos coastal environment. It also determined the concentrations of chloride ions and their effects on reinforcements in concrete structures. Water samples were collected from Lagos coastal environment (Tin Can Island and Bar Beach) for the purpose of the experiment. Laboratory analyses of the water samples were carried out to determine their chloride contents. Values obtained for the chloride concentrations were used to prepare different concentrations of chloride solutions used as aggressive curing environments with an increment of 5 g/L equivalent analytical sodium chloride. Concrete cubes numbering ninety were cast and cured in the different aggressive environments. 7nos. concrete blocks measuring 100 x 100 x 300 mm embedded with 12 mm diameter high yield bars were cast and cured in the prepared aggressive media. The test blocks were connected in parallel to a D.C rectifier set at 10 volt to accentuate the rate of corrosion. A Half-Cell potential apparatus was used to determine the corrosion potential at intervals of 4 days for a period of 28 days after the initial 28 days of curing. Compressive test values obtained show that chloride does not have much of adverse effect on concrete. The results of the Half-Cell potential readings showed that rebars in 24878.80 mg/L curing tank was the most affected by corrosion with peak average potential reading recorded for rebar as 466.50 mV, this is also confirmed by the tensile test conducted.

Keywords: *Reinforcing bars, chloride concentration, corrosion potential, tensile stress, coastal environment.*

1.0 INTRODUCTION

Concrete is a material of choice for construction of structures exposed to extreme conditions whether it is offshore oil platforms in icy water or hazardous waste containment vessels buried in the earth. As demand for construction in harsh environments increases, so is the desired service life of these structures (Kurtis *et al.*, 1994). The need to design structure for durability has taken the centre stage of design now because of degradation problems. Structures are designed for a specified life-time, finding an optimum solution between erection and maintenance costs. There is an upcoming need for a steady control of the quality of important structures during their life time by monitoring. However, to develop optimum monitoring systems for structures both knowledge of material degradation processes and their effect on structural behaviour is necessary. Durability of concrete is both a matter of a correct treatment of the material and a correct structural design. Changing the composition of a concrete will change its porosity and as such its behaviour under the influence of different environmental conditions (Walraven, 1999). According to Biddah and Nazmy (2003), durability of concrete is its ability to resist deterioration caused by external or internal causes, and perform in a satisfactory manner throughout its intended service life. The strength and the durability of concrete are influenced mainly by the extent the hydration process is allowed to proceed and the effectiveness of the hydrates in producing a dense and low permeability concrete. Akindahunsi (2008) noted that, unlike strength which is a bulk property, the durability is a function of its porosity. A permeable surface will allow the ingress of harmful substances which can cause durability problems. Drying of the concrete at early ages due to inadequate curing relative to the concrete natural exposure environment results in restricted hydration in the surface layers and thus to higher porosity and permeability. According to Jensen *et al.* (1999) chloride ingress is a common cause of deterioration of reinforced concrete structures. Concrete may be exposed to chloride by seawater or deicing salts; chloride initiates corrosion of reinforcement, which through expansion disrupts concrete and noted that composition of paste and exposure conditions have a strong influence on chloride ingress. Chlorides can enter concrete and ultimately induce reinforcement corrosion leading to the degradation of the concrete itself and eventually affecting the structures' ability to carry its design load. Diffusion is the main process governing the transportation of chloride ions through semi-permeable materials (Jones *et al.* 1995). Figure 1.0 shows a mode of corrosion due to chloride salt.



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

$$Fe^{2+} + 2Cl \rightarrow FeCl_2$$

$$FeCl_2 + 2OH \rightarrow Fe(OH)_2 + 2Cl$$

$$\frac{1}{2}O_2 + H_2 + 2e \rightarrow 2OH$$

$$2Fe(OH)_2 + \frac{1}{2}O_2 \rightarrow Fe_2O_3 + 2H_2O$$

Figure1: Mode of Corrosion due to Chloride Salt

As far as the verification of the performance of a structure with respect to chloride penetration is concerned, a condition that chloride induced corrosion of the reinforcement should not occur during the service life of the structure, is relatively easy to understand and on the safe side. It may be sufficient to carry out chloride ion concentration using equation (1.0), to ensure during verification that the chloride ion concentration at the location of the reinforcement is below the critical concentration that could initiate corrosion in the reinforcement, Takewaka and Sakai (2006). Therefore, the verification of a structure for reinforcement corrosion due to the ingress of chloride ions is conducted by ensuring that

$$\gamma_i = \frac{C_d}{C_{\lim}} \leq 1.0 \quad \text{......} (1)$$

where,

γ_i : Factor representing the importance of the structure. In general, it may be taken as 1, but should be increased to 1.1 for important structures

$C_{\lim}$: Critical chloride concentration for initiation of steel corrosion.

C_d : Design value of chloride ion concentration at the depth of reinforcement.

Mathematical formulations based on the diffusion theory are most commonly used to model chloride penetration in concrete. When using the equations such as Equation (2.0) based on the Fick's second law of diffusion to model, the design value of chloride ion concentration at the depth of reinforcement C_d is considered satisfactory.

$$C_d = \gamma_{cl} C_0 (1 - erf(\frac{c}{\sqrt{D_d t}})) \quad \text{......} (2)$$

where,

C_0 = Assumed chloride ion concentration at concrete surface (kg/m^3).

c = Expected value of concrete cover thickness (mm). In general, the designed cover thickness may be selected.

t = Design service life of the structure (year).

γ_{cl} = Safety factor, to account for the variation in the design value of the chloride ion concentration at the depth of reinforcement C_d. Normally, it may be set at 1.3, but in the case of high fluidity concrete, a value of 1.1 may be selected.

D_d = Design value of diffusion coefficient of chloride ions into concrete (cm^2/year)

$erf(x)$ = Error function, defined as $erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$.

This study examined the effects of Lagos marine environment on reinforced concrete structures. Water samples were collected for analyses and the result was used to synthesize different curing environments for concrete cubes and reinforced concrete blocks in the laboratory to monitor the effect of this aggressive environment.

2.0 MATERIALS AND METHODS

Lagos coastal environment was visited and pictorial documentations of structures in this environment were carried out to examine the severity of effect of chloride on structures in this environment. Water samples from Lagos coastal environment (Tin Can Island and Bar Beach) were collected for laboratory analyses to determine their chloride concentrations. Cement used as the binding agent was Ordinary Portland Cement (OPC). Sharp sand and granite chippings used as fine and coarse aggregates for concrete materials were obtained from a nearby quarry in Ile-Ife, Osun - State. Potable water was used for mixing concrete. High yield steel 12 mm in diameter, used for the experiment was sourced from a local store. Analytical sodium chloride (NaCl) and sodium sulphate (Na_2SO_4) utilized for the experiment were obtained from a chemical store, distilled water used to prepare different concentrations of salts solutions was obtained from the Environmental laboratory of Civil Engineering Department of Obafemi Awolowo University, Ile Ife, Osun State. A rectifier set at 10 volts was used so also are four numbers of 10 amps ammeters to measure current drawn by each aggressive curing environment. Copper plates used for the experiment were prepared from the Electronic and Electrical Engineering Department of the University. Copper sulphate ($CuSO_4$) solution, porous pot and a multimeter were also used.

Chloride analysis was carried out using standard method for the examination of water and waste water (APHA, 1998). The results obtained from the analyses of water samples collected from Lagos coastal environment were used as the basis for dosing the four curing tanks in different concentrations of chloride while the fifth curing tank served as the control. Distilled water was used for control in order to eliminate the effect of chloride on reinforcement in this tank. The four curing tanks consist of the following chloride concentrations: 15776.80, 18618.05, 21844.80 and 24878.80 mg/L. This is because the chloride analysis carried out for sea water was found to contain equivalent 31g/L of sodium chloride and interval of 5g/L was chosen with a step below the obtained chloride concentration value and two steps above the obtained value. This was used to prepare a synthetic environment in the laboratory to monitor the effect of these concentrations on reinforcements. Cement, sand and granite chippings used for preparation of the concrete was in 1:2:4 mix ratio. Trial mixes were made to determine optimum water/cement ratio, taking into consideration the moisture content of the aggregates. 37 mm slump in height was recorded for the test carried out to determine workability of the concrete mix. Five sets of 18 nos. 100 x 100 x100 mm concrete cubes were cast and a set placed inside the different chloride concentration curing tanks and the last set placed inside distilled water to act as control. Compressive strength tests were carried out on the cubes after 7, 14, 21, 28, 56 and 90 days of curing using ELE compression machine.

5 nos. of the reinforced concrete blocks were cast using 100 x 100 x 300 mm moulds with four of them placed in four different curing tanks containing different concentrations of chloride. One concrete specimen was each placed in the curing tanks containing different concentrations of chloride and the last one placed inside control curing tank. The arrangement was from the lowest concentration to the highest. The set-up was connected in parallel to a rectifier regulated to 10 volts to accentuate the rate of corrosion. Corrosion potential was measured using half cell apparatus, the reference electrode (Cu-$CuSO_4$) was made to have good electrical contact with the concrete. The porous pot containing $CuSO_4$ was left for 15 minutes on the reinforced concrete block in order to allow the $CuSO_4$ solution to permeate into the concrete. A high input impedance multimeter capable of reading 1 mV was used in this study. Concrete specimens were initially cured in the different aggressive environments for 28 days and Half – Cell potential readings were taken afterwards at intervals of four days for another 28 days. The use of electrochemical potential to determine the areas of corrosion in reinforcing steels is described in ASTM C876-91. The positive terminal of the digital multimeter is connected to the porous pot placed on the concrete containing $CuSO_4$ and the negative terminal is connected to the protruded reinforcement from the concrete, and the millivolts reading taken, the schematic arrangement of how the electrochemical potential is measured is shown in Figure 2 and typical set up for the experiment is shown in Plate 1. Tensile tests using 120 kN Avery – Denison machine were conducted on the corroded reinforcing bars removed from concrete blocks in the different curing environment at the expiration of 28th day curing period after the last potential reading was taken.

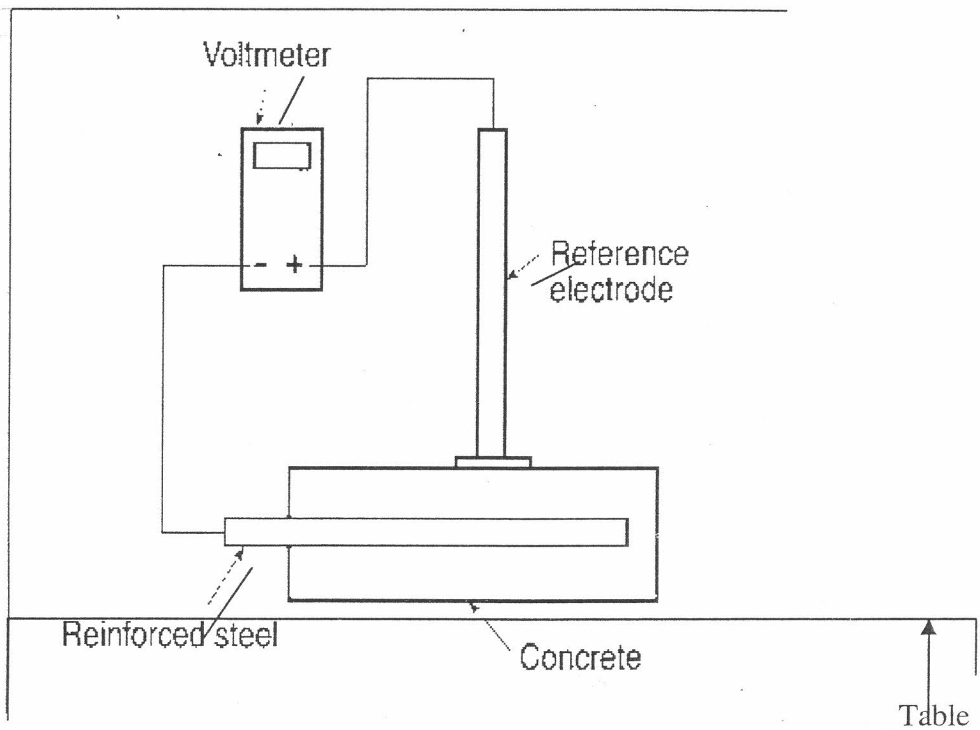


Figure 2: Schematic showing basics of the half-cell potential measurement technique

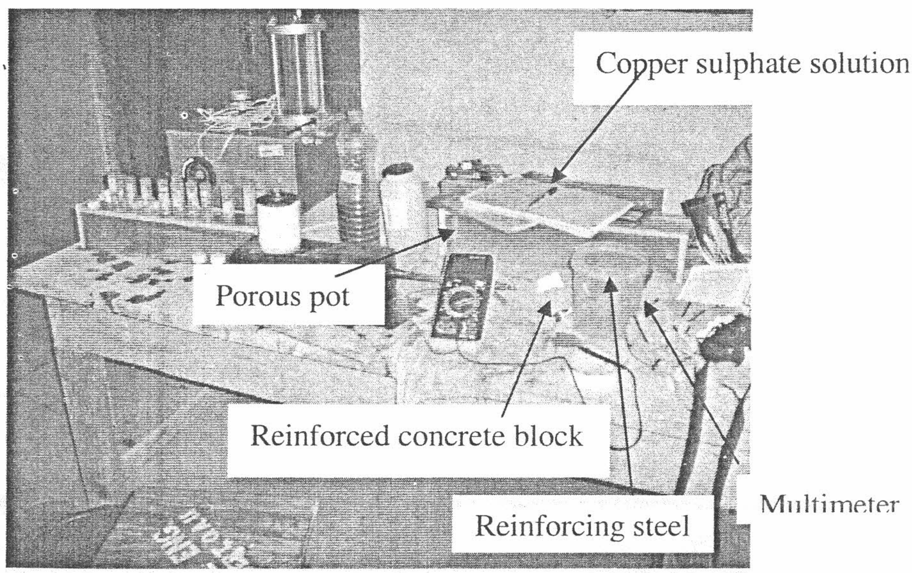


Plate 1: Half Cell Potential measurement test on a reinforced concrete block using multimeter and Porous pot

3.0 RESULTS AND DISCUSSION

Some pictorial documentation of corrosion of reinforcements in structures and sheet piles from Lagos coastal environment are presented in Plates 2 to 5. Plate 2 shows exposed and corroding reinforcements which was an indication that the concrete section was becoming weak and was peeling off, while the steel section was also undergoing serious corrosion. Corroding sheet piles that are serving as protection against wave front for embankment along a road section is shown in Plate 3, this poses a great risk to the life span of the road. Plate 4 is a picture of an embankment protection undergoing deterioration with sheet piles giving way as a result of corrosion. Steel barriers shown in Plate 5 were undergoing serious corrosion problems which resulted in the collapse of a section of the barrier.

Analyses results of water samples collected from Bar Beach (Ocean water) and Tin Can Island (Lagoon water) areas of Lagos and two different streams at Ile-Ife, Nigeria, for comparison are presented in Table 1. It is observed from Table 1 that water sample from the Ocean has the highest concentration of chloride of 18618.05 mg/L, followed by that of Lagoon with 14026.77 mg/L, Ede road and market road streams are 1133.97 and 954.78 mg/L respectively. It is seen that ocean water has the highest concentration of chloride followed by Lagoon water and the streams in the upland areas of the country like Ile-Ife contain relatively low amount of chloride concentration. This gives an indication of the effect of coastal environment on steel and reinforced concrete structures.

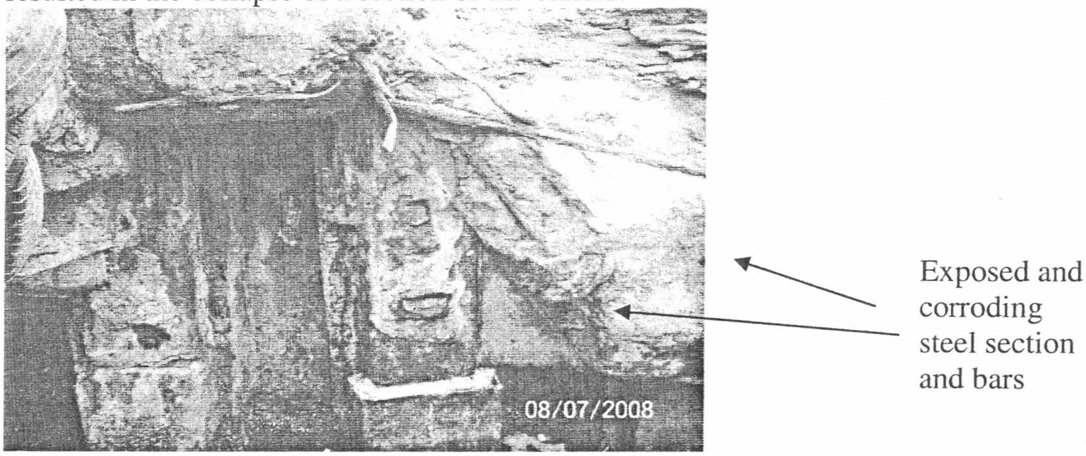


Plate 2: Corroded and exposed reinforcements at Flour Mills area, Apapa, Lagos, Nigeria

(Sheet piles undergoing corrosion)

Plate 3: Corroded sheet piles at C.M.S Lagos

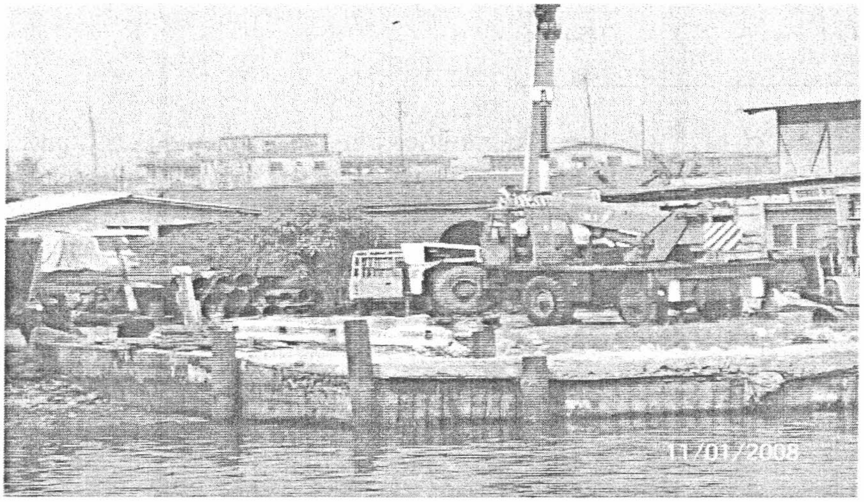


Plate 4: Concrete structure and sheet piles undergoing deterioration

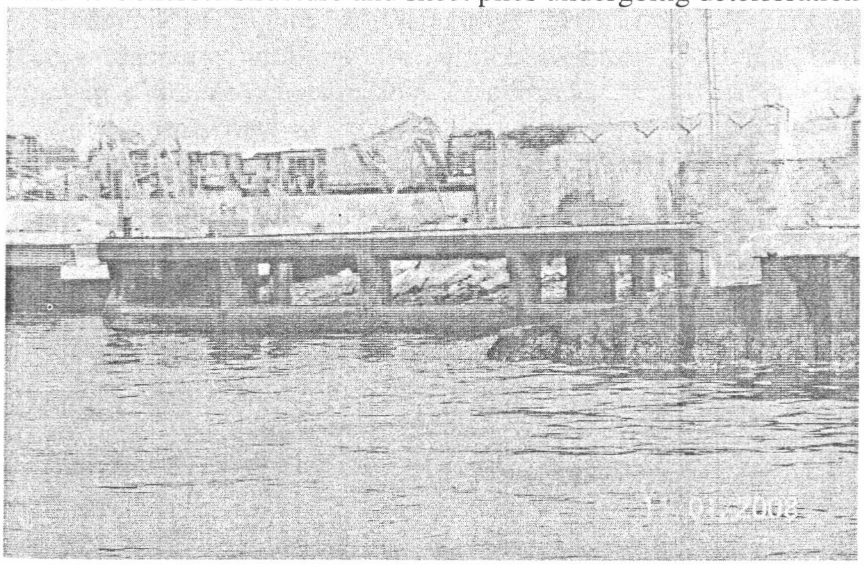


Plate 5: Corroded steel barrier

Table 1.0: Results of analysis of chloride salt in water samples

Source	Coordinates Northing (m)	Easting (m)	Altitude (m)	Chloride concentration (mg/L)
Bar beach V. I., Lagos (Ocean water)	0547460	0709775	10	18618.05
Tin Can Island area, Lagos (Lagoon water)	0539133	0711331	11	14026.77
Ede road stream, Ile-Ife	0668566	0828598	248	1133.97
Market area stream, Ile - Ife	0671428	0828066	272	954.78

To establish firmly the characteristics of the concrete used for the experiment, sieve analyses of the aggregates (fine and Coarse) used for the experiment were carried out and the results are presented in Figure 3.0. The uniformity coefficient of particle distribution for curve for sand gave a value of 4.7 which is an indication of a well graded soil. The maximum nominal size of coarse aggregate used is 20 mm; the values of specific gravities obtained for sand (2.62) and granite (2.77) are in conformity with normal aggregates (Shetty 2002, Neville and Brooks 1990). Moisture content value for sand was found to be 3.23 % while that of granite while that of granite was 0.22 %, moisture content values obtained were taken into account in the determination of water/cement ratio of 0.5 used for casting of concrete.

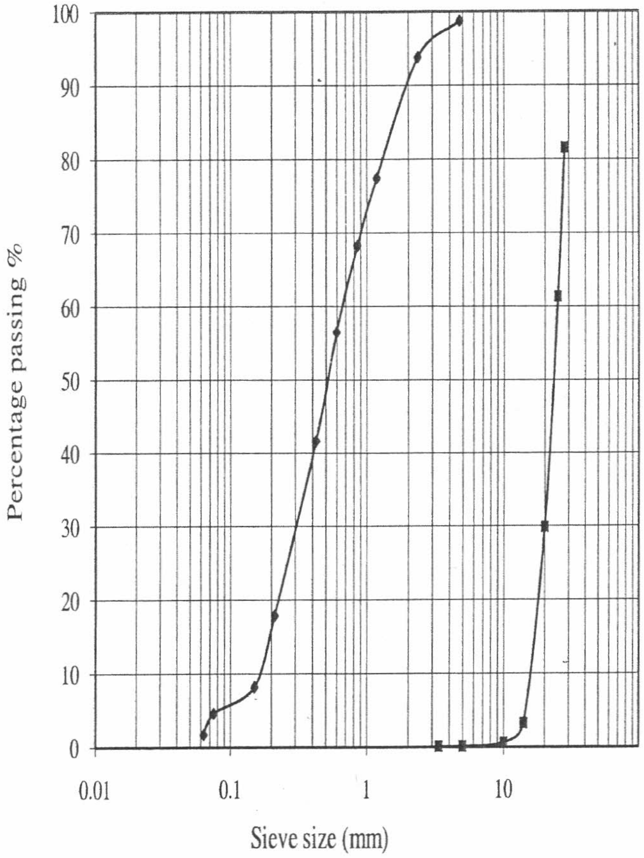


Figure 3: Particle size distribution curve for sand and granite

The results of the average compressive test values after 7, 14, 21, 28, 56 and 90 days of curing is presented in Figure 4. Generally, there is strength increase with age for all the concrete cubes in different concentrations of chloride. At the end of ninety days of curing the average value of the compressive strength of cubes in the control curing tank is 28.13 N/mm^2 while the values in 15776.80, 18618.05, 21844.80 and 24878.80 mg/L chloride concentrations curing tanks are 26.17, 26.20, 26.10 and 25.83 N/mm^2 respectively. It is observed that there are no significant differences between the highest and the lowest compressive strengths. This shows that chloride may not have any serious adverse effect on concrete. This agrees with the views of Bucea and Sirivivatnanon (2003) and Prasad *et al.* (2006) that chloride reacts with the hydrates of cement to form salt that does not have any harmful effects on concrete. However, Sadiq *et al.* (1996) reported substantial drop in strength though the aggressive medium used was hydrochloric acid environment.

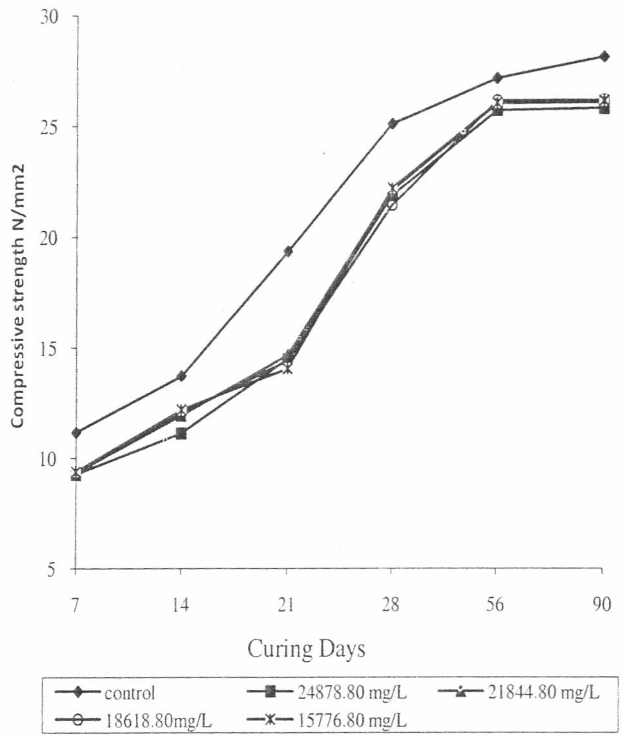


Figure 4: Compressive strengths of concrete cubes in different concentrations of chloride solutions

The potential readings for reinforcing bars (rebars) in different concentrations of chloride solution curing tanks are presented in Figure 5. The average potential readings show that corrosion problem was prominent in all the rebars in the different concentration curing tanks. According to ASTM C876 (1999), for an indication of 90% corrosion activity in reinforcements, the Half-cell potential reading should be more than 350 mV. In Figure 5, average values of potential readings indicating corrosion, is highest in rebar of 24878.80 mg/L curing tank followed by that of 15776.80, 21844.80 and 18618.05 mg/L curing tanks respectively.

Values obtained for rebars in water curing tank were much lower and rebar of concrete block cured in ambient air has the least set of values. This shows that concentration of chloride ions has the greatest effect on corrosion of reinforcing bars. However, the reason for the higher average potential readings of rebar in 15776.80 mg/L chloride curing tank when compared to either rebar in 21844.80 mg/L or 18618.05 mg/L chloride curing tanks is due to the fact that the direct current (D.C) rectifier used to set up the experiment was first connected to this curing tank from where connections were made to the other tanks. The use of direct current rectifier is to accentuate the rate of corrosion; this gives the chloride ions more freedom for mobility within the curing environment to attack reinforcement. This is why the rebar in 15776.80 mg/L chloride curing tank suffered more corrosion effects than the one in 18618.05 mg/L or 21844.80 mg/L chloride curing tanks. Table 2 shows the results of tensile tests conducted on the rebars removed from the concrete blocks and weights of corroded bars. Tensile test could not be carried out on rebar in 24878.80 mg/L curing tank because it had been seriously affected by corrosion to the effect that the tensile machine could not grip firmly on the corroded bar. Rebar in 15776.80 mg/L chloride curing tank has the least tensile stress which is an indication that lot of corrosion activity had taken place on it and this was due majority to the amount of current drawn during the experiment. Rebar in 21844.80 mg/L curing tank seemed to have a bigger diameter than the one in 18618.05 mg/L curing tank but the tensile stress result showed that the rebar was much weaker when compared to the one in the 18618.05 mg/L curing tank. The results of tensile tests on rebars showed higher values when compared to those in the aggressive environment and the one under ambient air had the highest value which was an indication that reinforcement in this environment would have longer service life.

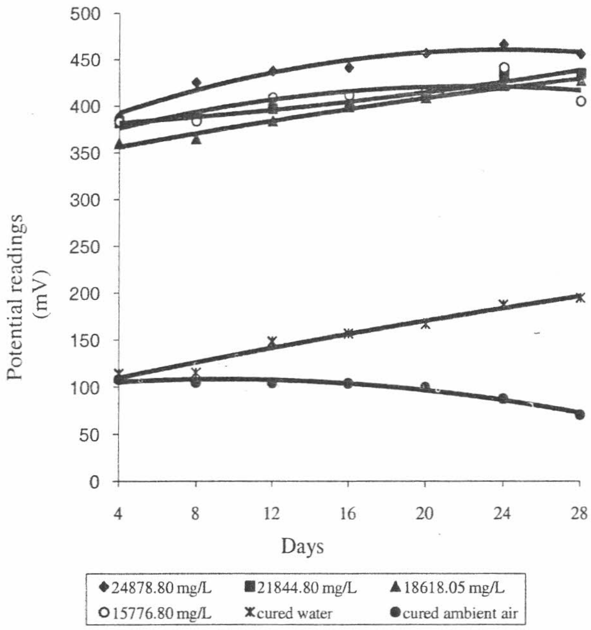


Figure 5: Half Cell Potential readings for concrete blocks in chloride solutions

Table 2: Results of tensile test and weight of corroded bars

Rebar removed from different curing environment.	Av. dia. of steel (mm)	Weight of corroded rebar (kg)	Ultimate tensile load (N)	Tensile stress (N/mm^2)
Rebar in concrete of 15776.80 mg/L	9.20	0.270	25600	3542.47
Rebar in concrete of 18618.05 mg/L	10.13	0.340	48200	6055.48
Rebar in concrete of 21844.80 mg/L	10.63	0.309	43400	5196.06
Rebar in concrete of 24878.80 mg/L	8.67	0.252		
Rebar in concrete cured in water	12.60	0.411	57600	5819.77
Rebar in concrete cured under ambient condition	12.83	0.410	58800	5833.00

4.0 CONCLUSION

This paper has established Lagos coastal environment to be an aggressive environment and a documentation of severity of effects of the environment contained in it. Chloride salt contained in Lagos ocean environment is in the range of 18618.05 mg/L. Laboratory simulation of the environment was carried out with reinforced concrete blocks cured under different chloride concentrations as aggressive environments with the aid of a D. C. rectifier to accentuate the rate of corrosion. The results showed that reinforcements under these conditions corroded seriously with concentrations of chloride having more adverse effect on reinforcement followed by accentuation of rate of corrosion. Tensile test conducted also confirm the fact that chloride concentration affects corrosion the most and followed by any means that accentuates rate of corrosion.

REFERENCES

(1) Akindahunsi A. A. (2008). "A study of Concrete Degradation in the Coastal Environment Lagos, Nigeria". An unpublished M.Phil. thesis submitted to the Postgraduate College of Obafemi Awolowo University Ile-Ife, Nigeria

(2) APHA, (1998) Standard Method for the Examination of Water and Wastewater, 20^{th} ed. America Water Works Association and Water Pollution Control federation, Washington DC.

(3) ASTM C876 (1999). "Obtaining Effective Half-Cell Potential Measurements in Reinforced Concrete". irc.nrc-cnrc.gc.ca/pubs/ctus/18_e.html - 31k Date accessed June 2^{nd} 2007

(4) Biddah, A, and Nazmy, A, (2003). "Environmental and Mix-design Effects on Reinforced Concrete Performance in

UAE". *The Seventh Annual U.A.E. University Research Conference*

(5) Bucea, L and Sirivivatnanon, V. (2003). "Salinity Hazard and Deterioration Mechanisms in the Built Environment". CSIRO Manufacturing and Infrastructure Technology PO Box 310, North Ryde,NSW1670. http://www.cmit.csiro.au/research/special /urban-salinity/ Date accessed 22nd May 2008

(6) Gu, P., and Beaudoin, J. (2006). "Obtaining Effective Half-Cell Potential Measurements in Reinforced Concrete Structures". Retrieved June 16, 2007, from National http://irc.nrc-cnrc.gc.ca/pubs/ctus/18_e.html

(7) Jensen, O. M, Hansen, P. F, Coats, A. M and Glasser, F. P (1999) "Chloride ingress in cement paste and mortar". *Cement and Concrete Research* 29: 1497-1504

(8) Jones, M.R, Dhir, R. K and Gill, J P (1995). "Concrete Surface Treatment: Effect of Exposure Temperature on Chloride Diffusion Resistance". *Cement and Concrete Research.* 25 (1): 197-208.

(9) Kurtis, K.E., Monteiro, P.J.M, Brown J.T. and Meyer-Ilse, W. (1994). "Mechanisms of Concrete Damage Caused by Sulphate Attack Examined through Transmission X-ray Microscopy". www-als.lbl.gov/als/compendium/. Date accessed January 13, 2008

(10) Neville, A. M and Brooks, J. J (1990). Concrete Technology. Longman Scientific and Technical, Longman Group Uk Ltd, Longman House, Burnt Mill, Harlow, Essex CM20 2JE

(11) Prasad, J, Jain, D.K and Ahuja, A. K., (2006). "Factors Influencing the Sulphate Resistance of Cement Concrete and Mortar". *Asian Journal of Civil Engineering (Building and Housing)* 7 (3): 259-268

(12) Sadiq, O. M., Akpan, A. J. and Musa, O. A (1996). "Strength Evaluation of Concrete in Chemically Aggressive Environment". *Nigerian Society of Engineers Technical Transactions* 31 (2): 80-86.

(13) Shetty, M. S (2002) Concrete Technology Theory and Practice. S. Chand and company Lt. Ram Nagar, New Delhi 110 055

(14) Takewaka, K and Sakai, K (2006). "Evaluation Method of Durability in Concrete Structures". www.jsce.or.jp/committee/concrete/e/newsletter/newsletter02/. Date accessed 4th April 2008

(15) Walraven, J., (1999) "How can we Shorten the bridge between Design and Material Engineers". www.itn.is/ncr/publications/doc-23-1.pdf. Date accessed 10th April 2008

(16) Zaki, A. (2006). "Principles of Corrosion Engineering and Corrosion Control". Elsevier Science & Technology Books