- Technical Paper -

EFFECT OF OXYGEN ON CORRODING RC STRUCTURES UNDER VARIABLE MOISTURE CONDITIONS

Raja Rizwan HUSSAIN[*1] and Tetsuya ISHIDA[*2]

ABSTRACT

This research aims at investigation of the influence of coupled effect of limited oxygen and moisture diffusion on the corrosion process of RC structures under various defined conditions quantitatively for which the previous research data is limited. About 100 RC corrosion cells with different compositions and moisture exposures have been used in laboratory tests. The experiment results (half-cell potential and gravimetric mass loss) show that the diffusion of oxygen is a vital limiting factor for corrosion only when the concrete is either submerged under water or is in high relative humidity environment.
Keywords: oxygen, relative humidity, corrosion, reinforced concrete

1. INTRODUCTION

The corroding reinforced concrete structures have always been an issue of great concern for professional civil engineers and researchers all over the world. Reinforced concrete structures are corroded under the effect of various environmental actions such as chloride, carbonation, temperature etc. However, these severe environments can cause corrosion only if enough amounts of oxygen and moisture are available in the vicinity of corroding reinforcement bar in concrete. Therefore, it is necessary to understand the coupled effect of oxygen and moisture on corrosion of RC structures. In this research, qualitative as well as quantitative (for which the previous research data is limited) deep investigations have been carried out in order to clarify the involved mechanisms of corrosion under variable oxygen and moisture conditions. Thus, the objective of this research is experimental determination and clarification of the influence of the coupled effects of oxygen and moisture diffusion through the concrete cover on the corrosion process of reinforcement in concrete structures under various defined conditions.

2. TEST PROGRAMS

2.1 Materials
(1) Reinforcing material

Deformed round carbon steel bars 13 mm in diameter were used as reinforcing material in the experiment specimens. The surfaces of steel bars were polished by sand paper No.200. Finally, steel bars were degreased by acetone just prior to being placed in the mould in order to ensure accurate experiment results as much as possible.
(2) Concrete

Ordinary Portland cement (OPC) as per JIS R5210 specifications was used. Natural river sand passed through JIS A1102 sieve No. 4 (4.75-mm openings), was used as fine aggregate for all concrete mixes. Its density and water absorption were 2.65 g/cm^3 and 2.21%, respectively. Crushed sandstone with a maximum size of 20 mm was used as coarse aggregate with density of 2.70 g/cm^3 and water absorption 0.59%. It was retained on the sieve No.4 (4.75mm-openings) and cleaned before being used. The air content was kept around 3.5±1 %. Mix proportions of various corrosion cells with different compositions are shown in the following Table 1. Different cases in Table 1 will be explained in the coming pages of this paper.

Table 1 Mix proportions

Case #	W/C	Binder (kg/m^3)	Water (kg/m^3)	Fine agg. (kg/m^3)	Coarse agg. (kg/m^3)
1,2,3,5,10	0.3	555	167	654	980
9	0.45	371	167	756	1031
4,6,7,8	0.55	303	167	801	1043

2.2 Specimen preparation and experiment scheme

The corrosion cell specimens are derived from the previous research survey [1,2] with necessary modifications as explained below in order to satisfy the present research requirements and to take care of the factors that have been overlooked in the past research works and thus making this research work original. Schematic diagram and original picture of the corrosion specimen (200x140x150mm) with two 13mm diameter deformed mild steel bars with appropriate spacers to hold the bars in required position firmly (one bar completely embedded and other coming out from both faces) cast in plastic molds in order to guarantee no oxygen penetration into the concrete except the top surface exposed to the environment (Fig. 1). The reason for using two steel bars is to make it possible to measure corrosion potential and corrosion mass loss using the same specimen.

*1   PhD Candidate, Dept. of Civil Engineering, The University of Tokyo, JCI Member
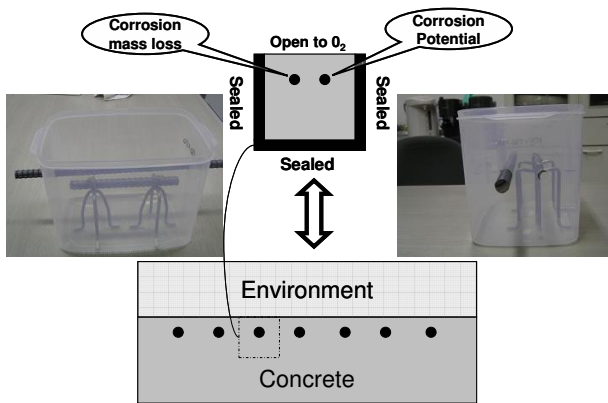*2   Associate Prof., Dept. of Civil Engineering, The University of Tokyo, JCI Member

Fig.1 Schematic diagram of the specimen

The bar emerging out from the two sides is used for the corrosion potential measurement only since the two edges are not embedded into the concrete and are not under chloride attack. Therefore, in order to find the mass loss using the same specimen a separate steel bar was embedded completely into the concrete. This was done to obtain more reliable and accurate results. Uniform chloride content has been used as corrosion initiator considering the corrosion cell as a fused anode cathode micro-cell system. The oxygen concentration available for corrosion at the surface of rebar embedded in concrete was limited by varying water to cement ratios, cover depths and chloride concentrations as shown in Table 2.

Table 2 Relevant parameters of the corrosion cells for investigations performed on the influence of oxygen on corrosion

Case #	Concrete cover (mm)	W/C ratio	Total Chloride (% mass of binder)
1	25	0.3	5
2	40	0.3	5
3	70	0.3	5
4	25	0.55	1
5	25	0.3	1
6	25	0.55	5
7	40	0.55	5
8	70	0.55	10
9	40	0.45	5
10	70	0.3	10

The test consists of eighty specimens. Eight specimens were made for each case and two specimens were placed in each of the four environmental exposure conditions in duplicate for six months and one year duration. The temperature was kept at $20\,^{\circ}C$ throughout the test duration. This paper comprises of only six months results and one year experiment results will be published soon elsewhere. The four environmental exposure conditions are shown in Fig. 2. Exposure I represent the normal benchmark condition, while exposure II and III are intended to clarify the role played by moisture and oxygen in constant stable environments. Exposure IV represents the changing cyclic environmental conditions. The wetting cycle was kept one month based on the calculations obtained from the past research results [3,4] that all the oxygen present in the specimen will be consumed by the corroding reinforcement bar in one month for the given conditions and afterwards there will be no oxygen left for corrosion causing the corrosion reaction to halt completely.
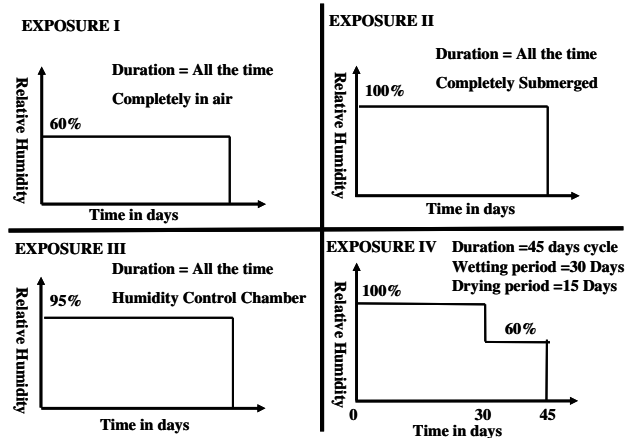

Fig.2 Environmental exposure conditions

All the specimens were allowed to set and harden in mold for 1 day before being de-molded and then cured for the next 28 days in the environment control chamber in sealed condition at 20ºC. After that the specimens were epoxy coated on the top face edges of plastic containers in order to avoid any possible oxygen penetration and given the already described four environment exposures for six months (Fig. 3).
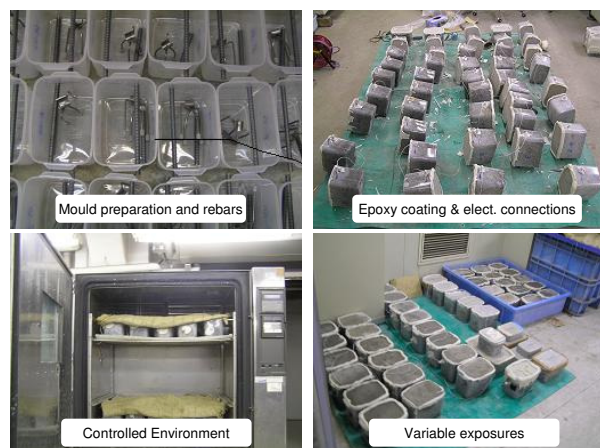

Fig.3 Experimental program

Half-cell potentials were measured with two days interval for all specimens using copper-copper sulfate reference electrode (CSE) in accordance with standard specifications which can be found elsewhere [5]. For further illustration of the measurement procedure adopted in this research consider the Fig. 4. A standard Voltmeter with 0.0001V accuracy is connected with the R.C specimens and the standard electrode through the specified wire in order to make a half-cell potential measuring circuit.
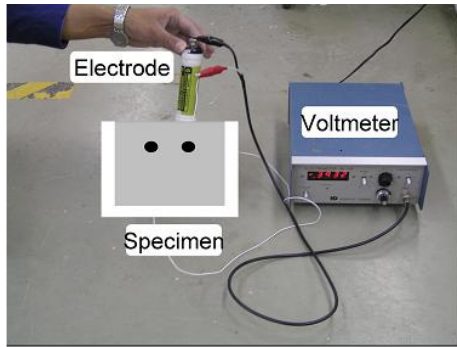
Fig.4 Half-cell potential measurement assembly

After an exposure of six months, the specimens were split along the position of steel in concrete and steel bars completely embedded (Fig. 5) in the concrete for gravimetric mass loss analysis were removed. Then the mass loss was determined by chemical cleaning [6] of corrosion products using standard systematic step by step method (Fig. 6). Finally, corrosion rates were calculated from experimentally obtained gravimetric mass losses using Faraday's Law.
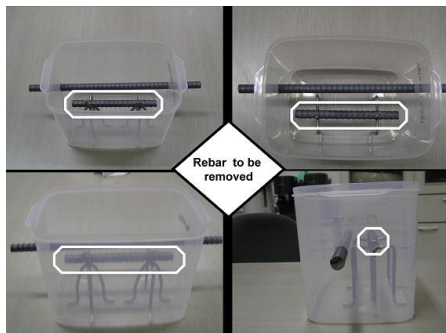

Fig.5 Steel bar completely embedded in concrete for gravimetric mass loss measurement

Fig.6 Gravimetric mass loss determination

3. EXPERIMENT RESULTS AND DISCUSSIONS

From the experiment results shown in Fig. 7 and Fig. 8, following facts and findings are discovered:

(1) Concrete cover does not effect the penetration of oxygen in normal dry air conditions (60% R.H 20°C). Because it was found from the experiment results (Fig. 8, Case 1–3 & Case 6-7) that the corrosion of specimens with different concrete covers do not show any variation in corrosion rate when the specimens are placed in normal air dry conditions.

(2) The experiment results for specimens submerged in water or placed in high relative humidity conditions show much reduced corrosion rates with increasing cover depth (Fig. 8, Case 1-3 & Case 6-8).

a) In case of high relative humidity conditions (95% R.H in this experiment: Exposure III) the concrete cover is almost in-effective if the cover depth is low (25 mm in this experiment) and does not show appreciable difference from the normal dry air conditions (Fig. 8 Case 1 & 6). This means supply of oxygen to corroding steel bar is not stopped even at very high humidity conditions if the cover is thin. But as the concrete cover starts increasing, the oxygen penetration is inhibited and the corrosion rate falls as compared to normal dry air conditions (Fig. 8, Case 2,3,7,8 & 10). Thus increased cover depth is very effective to stop penetration of oxygen and reduce corrosion damage for structures under heavy rainfall areas and splash zones in seawater where humidity is very high.

b) In case of submerged specimens, the corrosion rates are very low for all the cases (Fig. 8, Case 1-10). Further increase in cover depth makes the dissolved oxygen penetration into the concrete even lower and corrosion rates becomes much less. But, since the corrosion rate at relatively thin concrete covers is also very low, so practically speaking there is no need to keep thick concrete covers for submerged structures for economical reasons. One more interesting point is that the corrosion rate of Case 8 in Fig. 8(h) (10%Cl & 70mm cover) is lower than that of corrosion rate in Case 6 in Fig.8(f) (5%Cl and 25mm cover) in spite of double chloride concentration. It means that if the structure is submerged and the cover is thick, corrosion cannot occur even in extreme saline conditions.

(3) In case of Wetting/Drying cyclic exposure conditions, the results are complex. Experiment results (Fig. 8, Case 1-10) are variable and depend on the relative relation between the concrete cover and wetting drying cycle duration. For the specific conditions in this experiment, it was found that the corrosion rates of specimens with thick cover (Fig. 8, Case 3,8,9 & 10) were higher as compared to air dry specimens in contrast to thin covers specimens (Fig. 8, Case 1 & 4-6) , which is opposite to what was expected. The reason is sorted in the fact that in case of specimens with thin concrete covers (Fig. 8, Case 1 & 4-6), the water reached the steel bar faster than the specimens with thick concrete covers (Fig. 8, Case 3,8, 9 & 10), resulting in depriving the steel bars from oxygen in less time since the wetting cycle was long (30 days). It can be inferred that if the cycle was short for example one day or two days wetting cycle then no doubt the specimens with thin concrete cover will corrode more than the specimens with thick concrete cover.
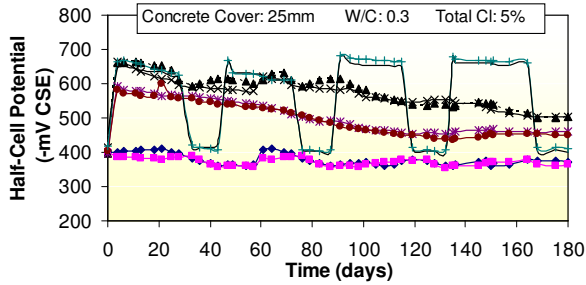
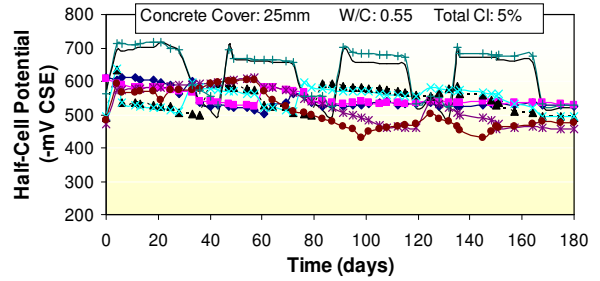Series1   Series2   Series3   Series4
Series5   Series6   Series7   Series8

Series 1 & 2: Exposure I   Series 3 & 4: Exposure II
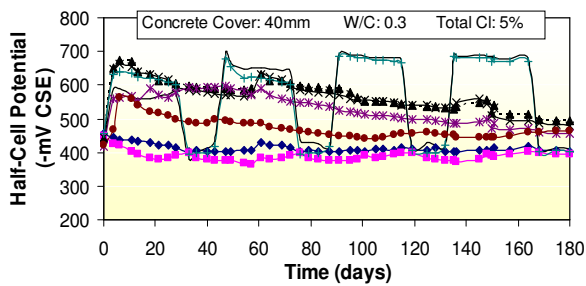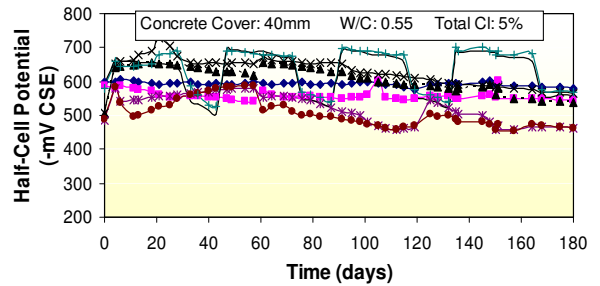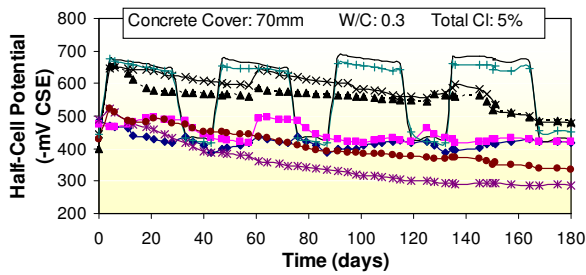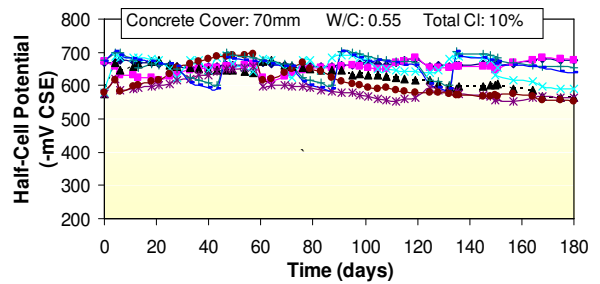Series 5 & 6: Exposure III   Series 7 & 8: Exposure IV
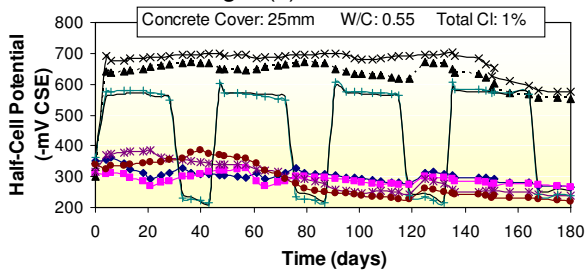
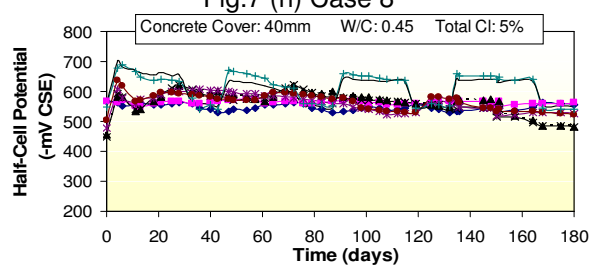Fig.7 (a) Case I

Fig.7 (b) Case 2
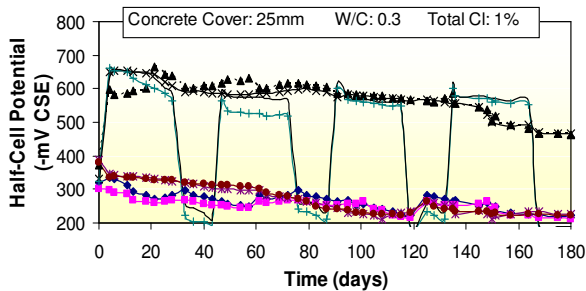
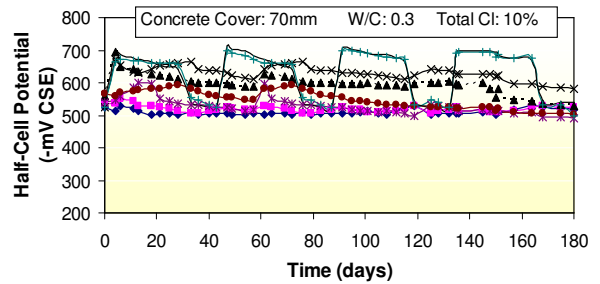Fig.7 (c) Case 3

Fig.7 (d) Case 4

Fig.7 (e) Case 5

Fig.7 (f) Case 6

Fig.7 (g) Case 7

Fig.7 (h) Case 8

Fig.7 (i) Case 9

Fig.7 (j) Case 10

Fig.7 (a)-(j) Half-cell potential variations during six months exposure

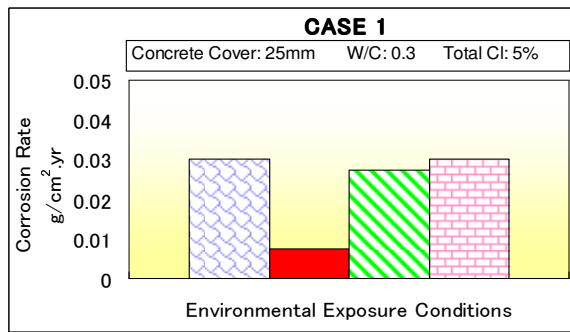☐ Air ■ Submerged ▨ 95%R.H ▨ Wet/Dry Cycle

(Right: High Corrosion Range)

CASE 1
Concrete Cover: 25mm　W/C: 0.3　Total Cl: 5%

Corrosion Rate g/cm²·yr

Environmental Exposure Conditions

Fig.8 (a)

CASE 6
Concrete Cover: 25mm　W/C: 0.55　Total Cl: 5%

Corrosion Rate g/cm²·yr

Environmental Exposure Conditions

Fig.8 (f)

CASE 2
Concrete Cover: 40mm　W/C: 0.3　Total Cl: 5%

Corrosion Rate g/cm²·yr

Environmental Exposure Conditions

Fig.8 (b)

CASE 7
Concrete Cover: 40mm　W/C: 0.55　Total Cl: 5%

Corrosion Rate g/cm²·yr

Environmental Exposure Conditions

Fig.8 (g)

CASE 3
Concrete Cover: 70mm　W/C: 0.3　Total Cl: 5%

Corrosion Rate g/cm²·yr

Environmental Exposure Conditions

Fig.8 (c)

CASE 8
Concrete Cover: 70mm　W/C: 0.55　Total Cl: 10%

Corrosion Rate g/cm²·yr

Environmental Exposure Conditions

Fig.8 (h)

CASE 4
Concrete Cover: 25mm　W/C: 0.55　Total Cl: 1%

Corrosion Rate g/cm²·yr

Environmental Exposure Conditions

Fig.8 (d)

CASE 9
Concrete Cover: 40mm　W/C: 0.45　Total Cl: 5%

Corrosion Rate g/cm²·yr

Environmental Exposure Conditions

Fig.8 (i)

CASE 5
Concrete Cover: 25mm　W/C: 0.3　Total Cl: 1%

Corrosion Rate g/cm²·yr

Environmental Exposure Conditions

Fig.8 (e)

CASE 10
Concrete Cover: 70mm　W/C: 0.3　Total Cl: 10%

Corrosion Rate g/cm²·yr

Environmental Exposure Conditions

Fig.8 (j)

Fig.8 (a)-(j) Corrosion rate variations

This answers more corrosion of structures with small cover under tidal rise and fall of sea water.
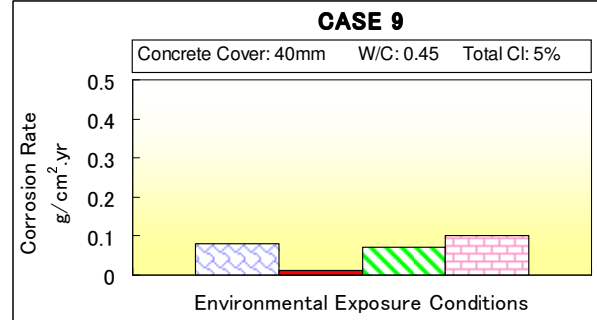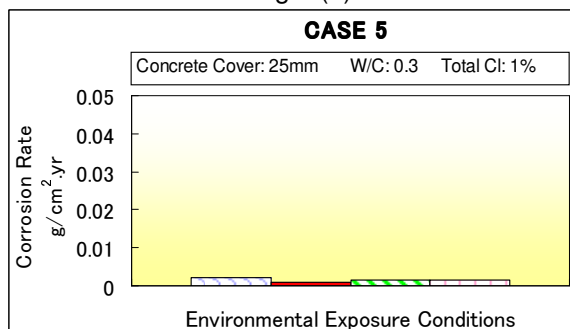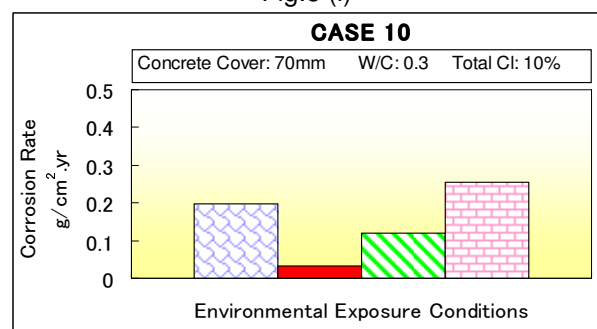
(4) Comparing the over all results for all the cases Fig. 8(a)-(j), it is seen that the reduction in W/C is very effective for protection against corrosion in all the exposures (dry, wet, high R.H and submerged). For example Case 10 (0.3W/C) of Fig. 8 shows much lower corrosion rate as compared to Case 8 (0.55 W/C) of Fig. 8. But the mechanisms are different for different exposure conditions.

a) For air dry conditions, the lowering of W/C does not effect the O_2 penetration but results in lowering of moisture necessary for corrosion.

b) In case of submerged and high humidity cases, low W/C reduces the penetration of oxygen due to fine concrete porous media.

c) In cyclic wetting drying exposure, W/C has a dual effect; it reduces the oxygen penetration during wetting cycle and provides less moisture during drying cycle. Overall resulting in reduced levels of corrosion.

(5) Chloride concentration has an indirect effect on the oxygen diffusion control criteria. When the specimen is in air, chloride concentration is in-effective in regards to the effect of oxygen. But for the submerged, 95%R.H and cyclic wetting/drying cases, chloride concentration is directly proportional to the O_2 diffusion. The reason is that the oxygen consumption rate is related to the rate of corrosion reaction which is initiated by chloride. Increase in chloride concentration increases the corrosion rate resulting in the increase of oxygen consumption rate. This produces for more flux of oxygen to diffuse into the concrete and vice versa.

(6) The half-cell potential values for specimens submerged under water and having low to medium chloride concentration (1-5% in this experiment) rise suddenly on the negative side after the specimens are submerged (refer to Fig. 7, Case 1-7 & 9) and then falls gradually until it gets constant but still remains much higher than the air dry true value. Therefore, it can be said that the under water potential measurements are not the true representative values of corrosion and need to be re-calibrated for under water measurement.

(7) But, it should be noted here that the half-cell potential values do not rise linearly for higher chloride concentrations (10% total Cl in this experiment) and remain below the upper limiting value on the negative side (Fig. 7(h) and (j)). This limiting value has been determined as -700mV from this experimentation and should be utilized while recalibrating the standards.

(8) Half-cell potential measurements for cyclic wetting drying exposure show sudden increase and decrease in potential on the –ve side at the time of start of wetting and drying cycle and during the cycle the change is gradual. (Fig. 7(a) to (j)). This change is more prominent in low chloride cases (Fig. 7, Case 1-7 & 9) and less prominent in high chloride cases (Fig. 7, Case 8 & 10) due to air dry increased potential.

(9) Another interesting aspect found in the experiment results is that at the start of each wetting cycle (after about 5 days in 30 days wetting cycle), except the first wetting cycle there is sudden rise in potential and then the remaining rise is gradual.

Especially this effect was observed in cases of thin concrete cover (Fig. 7, Case 1 & 4-6). It is inferred that water level reaches the steel bar depth faster in these specimens due to low concrete cover and deprives the bar from oxygen suddenly causing a sharp drop (Fig. 7, Case 1 & 4-6).

(10) The corrosion potentials obtained in submerged case are more negative as compared to the high humidity case (95%R.H in this experiment). This shows further limitation of oxygen availability and reduced concrete resistivity under water.

(11) Overall, the most peaked potential is found in the cyclic exposure specimens, followed by the submerged case, high R.H case and at the bottom remains the air dry exposure condition specimens (Fig. 7(a)-(j)). In each case there are small variations due to the non-uniform corrosion behaviour as a result of non-uniform chloride pitting attack on various parts of steel bars. This attitude is very much justified.

4. CONCLUSIONS

Qualitative as well as quantitative effect of oxygen on the corrosion of RC structures under various environments and compositions has been successfully obtained through extensive laboratory experimentation in this research for which the previous research data is limited. It can be concluded from the experiment results that the diffusion of oxygen is a vital limiting factor for corrosion reaction only when the concrete is either submerged or is in high relative humidity environment with dense concrete cover and low W/C ratio. It was also found that the under water half-cell potential measurements are not the true representative values of corrosion progress showing extremely negative half-cell potentials due to reduced concrete resistively and need to be re-calibrated in the light of experiment results obtained in this research.

REFERENCES

[1] M.Raupach: Investigations on the influence of oxygen on corrosion of steel in concrete-Part I, Materials and Structures, Vol. 29, pp.174-184, April. 1996

[2] M.Raupach: Investigations on the influence of oxygen on corrosion of steel in concrete-Part 2, Materials and Structures, Vol. 29, pp.226-232, May. 1996

[3] K. Maekawa, T. Ishida and T. Kishi: Multiscale modeling of concrete performance, Journal of advanced concrete technology, Vol. 1, No. 2, pp.91-126, July 2003.

[4] Hussain Raja Rizwan and Tetsuya Ishida: Electrochemical modeling of corrosion in reinforced concrete and the effect of chloride and temperature, Proceedings of the Japan Concrete Institute, Japan. Vol.29, No.1,pp.1389-1394, 2007.

[5] ASTM C 876-91: Standard test method for half-cell potentials of uncoated reinforcing steel in concrete, ASTM, U.S.A, 1999

[6] ASTM G1-03: Standard test practice for evaluating corrosion test, ASTM, U.S.A, 2002.