Experimental Investigation of Re-Corrosion Phenomenon in Simulated Repaired Steel Reinforced Self Consolidating Concrete Structures

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This paper aims at investigating the phenomenon of macro-cell corrosion in the reinforcing steel of repaired chloride-contaminated self compacting concrete (SCC) patches. Self consolidating concrete because of its workability and stability is now a centre of focus among researchers and engineers working in the field of construction and repairs. Few researchers found SCC as a good repair material then ordinary concrete. But the literature and research relating to the repair of SCC concrete structures patches is limited. Therefore, thorough research has been carried in this paper to investigate the above said phenomenon. In this research, four prismatic specimens with two sets of 5% and 3% chloride contaminated SCC at the two ends were prepared respectively and the middle portion of these specimens was cast after 24 hours with uncontaminated SCC simulating the actual patch repair in the field; repaired due to chloride induced corrosion . From the six months experiment results of corrosion potentials and corrosion rates, it was found that the specimen having no chloride content at the middle portion showed high cathodic reactions and both chloride contaminated sides of the specimens showed even more corrosion than before being repaired due to the separation of anode and cathode and development of a macro-cell. This research has practical implications that need to be considered for an effective and durable repair of SCC structures.

1. INTRODUCTION

Self-Compacting Concrete (SCC) is an innovative concrete that does not require vibration for placing and compaction. It is able to flow under its own weight, completely filling formwork and

achieving full compaction, even in the presence of congested reinforcement. It greatly improves concrete placement and eliminate the problem of honeycomb without the need for additional mechanical compaction resulting in higher quality and speed of construction, and more durable structures. While in normal concrete, the problem of casting concrete in congested reinforced sections has been a serious problem that requires proper and adequate compaction by internal or external mechanical vibrators operated by skilled workers. Several researchers have investigated the uniformity of in situ SCC mixtures in relatively small and large specimens and compared the results with that of normal concrete [1–4].

Structural degradation due to the corrosion of steel reinforcement in normal concrete is a major aspect affecting concrete durability. When concrete is attacked by the chloride-rich environment, the liberated chloride ions from such environment reach the steel bars by diffusing through the concrete and cause corrosion. Concrete having low permeability and dense microstructure is believed to provide hindrance in chloride diffusion through the concrete body, which helps reduce the rate of corrosion of embedded reinforcing steel. SCC is expected to have a dense and less permeable microstructure because of its resistance to bleeding and segregation and the production of SCC usually involves the use of high range water reducer, super-plasticizer and/or supplementary cementing materials. These supplementary cementitious materials have been proven to increase the concrete corrosion resistance [5–7], while high range water reducers help in dispersing cement particles and reduce overall concrete permeability [8,9]. Due to these said reasons SCC is highly considered by some researchers as good repair material for chloride attacked corroded reinforced concrete structures patches [10].

Structural retrofitting and repairs of normal reinforced concrete due to corrosion has been a centre of focus for researchers all around the globe. Many researchers and engineers are delving into find the best suited repair techniques and materials which can provide economy and durability of the repaired structures. Many researchers have investigated the compatibility between old concrete and repair material [11-13]. Hussain et. al., [14] and Wasim and Hussain [15] investigated the macro-cell corrosion phenomenon in the repaired concrete patches of the chloride contaminated normal reinforced concrete under normal and various environmental conditions. However, the research relating to the repairs of SCC structures is very limited. This formulated the objectives of this research in which specimens were prepared with chloride contaminated reinforced SCC and then repaired with uncontaminated reinforced SCC simulating the actual patch repair in the field.

2. EXPERIMENTATION

2.1. Materials and Mix proportion

Type I ordinary Portland cement in compliance with the requirements of ASTM C150 has been used. 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%.For fine aggregate locally available Natural river sand passing through 4.75mm sieve was used. Its density and water absorption were 2.65 g/cm^{3}and 2.21%, respectively. Structuro 100 having main component polycarboxylic ether was used as super plasticizer

(SP) having specific gravity 1.01 and PH was 6.3; to achieve the desire workable conditions for SCC. The water to cement ratio (w/c) was kept 0.45 and the available tap water was used for experimentation. The normal SCC mix proportions used in this investigation are shown in Table 1. Sodium chloride (NaCl) of 99.9% purity was used as a source for chloride ions. Deformed round carbon steel bars 10 mm in diameter were used as reinforcing steel. The surface of steel bar was polished by sand paper No.200.

Table1. Mix proportions.

Materials	Proportions (kg/m3)
Cement content	450
Coarse aggregates	781
Fine aggregates	659
SP	1.6

2.2. SCC Mixing, Specimen preparation and Curing

The mixing was done in an electrically-powered horizontal mixer, the procedure laid out in accordance with ASTM C 192[16]. At the start of mixing, the drum of the mixer was cleaned and washed and all the water drained off. This wetted drum mixer was loaded with the aggregates and then absorption water was added.

Slump flow procedure

J Ring flow assembly

V funnel flow assembly

L box assembly

Figure 1. SCC tests procedure.

After this, cement, SP and then water with dissolved NaCl were added so that all the materials were properly mixed together to form chloride contaminated SCC. Immediately after completion of mixing; concrete temperature and slump flow were determined. The slump flow of this SCC mix was found 700mm with Visibility Index 1.Since in this research study; the main objective was corrosion study that's why the other SCC workability tests like J-Ring Flow, V funnel test and L- box test were not taken into consideration during experimentation, but just to give an idea about these tests, consider fig 1. The same above mix procedure and proportion was adopted to make normal SCC but in this case water without NaCl was used during mixing along with other mix ingredients.

The experimental specimens for this research were derived from previous research [14] and [15] with necessary modifications to take care of the factors that have been overlooked in the past research works and thus making the present research work original. In the previous research an artificial macro-cell was created resembling the one developed originally in case of repair works in the actual field for ordinary concrete due to the separation of anode and cathode and development of macro-cell as shown in fig. 2[15].
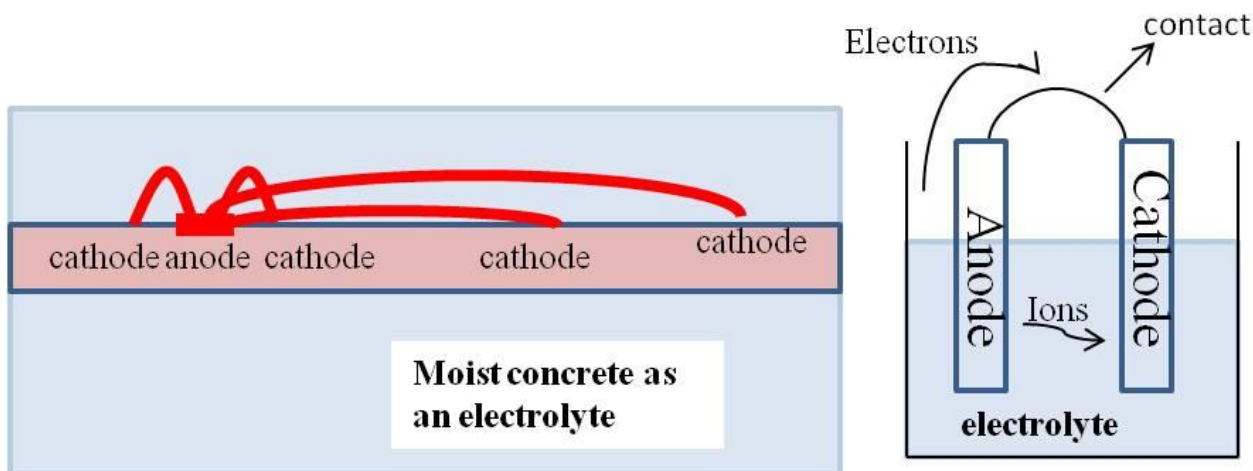

Figure 2. Separation of anode and cathode.

Filling the end portions with 5 % chloride contaminated SCC

After finishing the end portions with 5 % chloride contaminated SCC and allowed to set for 24 hours

Filling and finishing the middle portions with normal SCC after 24 hours setting of end chloride contaminate portions

Figure 3. SCC macro-cell specimen preparation.

The two sides of these specimens were cast first containing chloride 5% and 3 % chloride content respectively at the extreme ends. The middle portion of these specimens was cast after 24 hours with no chloride content presuming to be the repaired portion in the actual construction repairs to stop or minimize the chloride movement from contaminated to non contaminated portion of these specimens.The specimen preparation methodology is represented in fig 3 and the specimens' designation and the chloride content are mentioned in table 2. For placing reinforcing steel bars in specimens' molds; the clear cover was kept 15 mm because measured half-cell potential values for normal concrete at specimen surface could be considered as actual value at steel surface, if cover depth is within 20 mm [17].Specimens dimension and chloride content at different portions are shown in fig 4.

Table 2. Specimens and chloride content

Specimen designation	Total chloride content at the two ends (%)	Total chloride content at the middle (%)
Specimen 1	5	0
Specimen 2	5	0
Specimen 3	3	0
Specimen 4	3	0
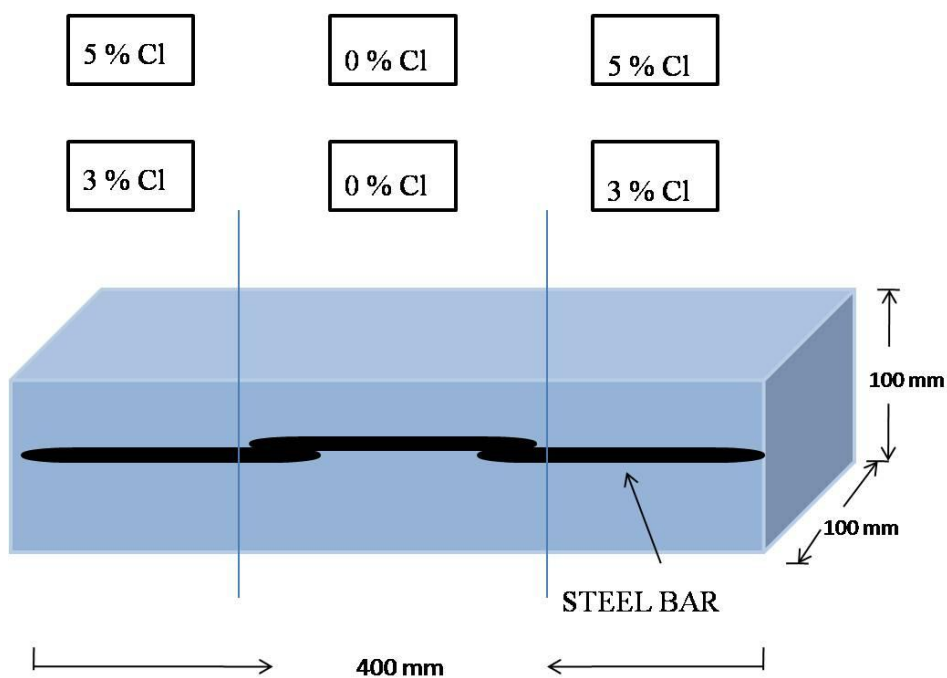
Figure 4. Specimens dimension and chloride content

Precautions were observed to avoid the formation of crevice corrosion. Crevice corrosion is a type of localized corrosion that can be developed within crevices or at shielded surfaces at concrete-steel interface where a stagnant pore solution is present. It is one of the most frequently encountered forms of localized corrosion and at the same time one of the most harmful ones. Crevices make a chemical environment in reinforced concrete which is different from that of freely exposed surfaces and therefore accelerate corrosion. This environment keeps moisture, traps pollutants, concentrates corrosion products and meanwhile excludes oxygen at the steel–concrete interface. It was prevented by reducing crevices in the concrete-rebar interface. Where it was not possible to get rid of crevices, precaution was taken to improve drainage and seal edges keeping crevices as open as possible and therefore preventing encapsulation of moisture.

A comprehensive experimental measurement methodology was conducted to clearly understand the role of steel reinforcement bars in the acceleration of the corrosion rate. The steel rebar corrosion current (Icorr) and corrosion potential (Ecorr) were measured for all specimens using a GECOR device [18] and ASTM C-876 [19]. The GECOR measures the corrosion rate as reflected by the corrosion current density and the half-cell corrosion potential. A true measure of the corrosion rate is possible by the polarization resistance technique. It has been well established by Stern and Geary that the corrosion current is linearly related to the polarization resistance, which gives a direct quantitative measurement of the amount of steel turning into oxide at the time of measurement. By Faraday's equation, this can be extrapolated to direct metal sectional loss. The corrosion current values in GECOR are calculated from the polarization resistance Rp using the relation Icorr = B/Rp, where Icorr is given in $\mu A/cm^2$ when Rp is given in $k.ohms/cm^2$ and B = 26 mV. The Icorr is directly proportional to corrosion rate through the relation, corrosion rate ($\mu m/year$) = 11.6 x Icorr. This gives a tool for quantifying the average reduction of rebar diameter over time. The measurement of corrosion rate usually involves applying electrical signal through a connection to the steel bar. In GECOR, this signal is confined to the steel rebar in a circle with a diameter of 110 mm. There is evidence that this technique gives a more accurate measurement of the corrosion rate [20]. The GECOR device is quite valuable and versatile for the corrosion measurement of steel in concrete. Consider fig. 5 as a schematic representation of taking measurement from GECOR for further illustration.
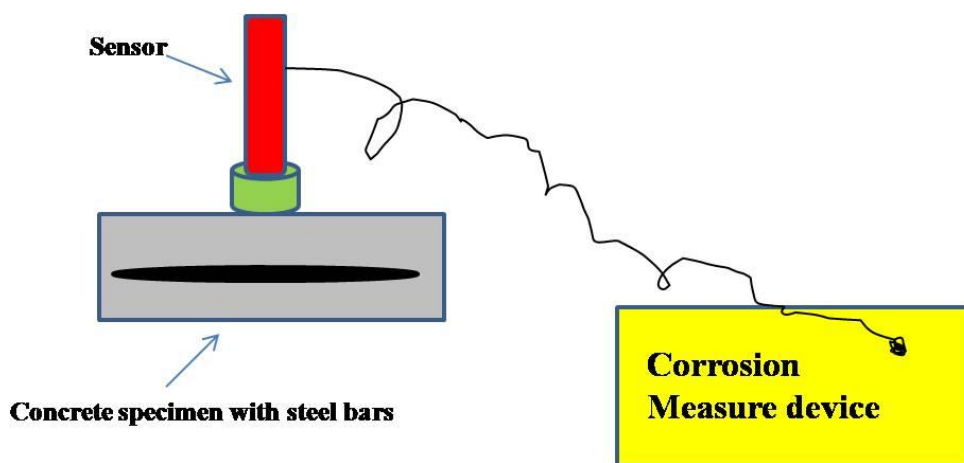
Figure 5. Corrosion rate and corrosion potential measurement assembly.

3. EXPERIMENT RESULTS AND DISCUSSIONS

3.1. Corrosion rates

Corrosion rate is considered as one of the most reliable corrosion measures for corroding steel and it has been used by many researchers in the world. Therefore in this research the corrosion rate measurements were taken in accordance with standard specifications [18-20]. After six months of corrosion rates observations; the following results were obtained;

1)   In specimens 1 and 2 which were 5% chloride contaminated at the end portion, the highest corrosion rate of $4.99\mu A/cm^2$ after 60days was obtained while on day1, it was $2.78\mu A/cm^2$ in this contaminated end portion as shown in fig 6. This result indicates that there is an incremental increase in corrosion rate with the time till 60days, which can be due to the formation of macro-cell (anodic in nature) between contaminated and uncontaminated normal SCC portion simulating the actual patch repaired in the field. After reaching the max corr. rate $4.99\mu A/cm^2$, the rate started to decrease slowly and it reached $3.81\mu A/cm^2$ after 180 days.

2)   In specimens 1 and 2, the middle 0% Chloride portion simulating the actual patch repair was showing the same incremental increase in corrosion rate as in the case of contaminated portion. The highest corrosion rate of $2.046\mu A/cm^2$ was obtained on 60th day while on day1 it was $0.28\mu A/cm^2$ in this uncontaminated middle portion indicating the incremental increase in corrosion rate as shown in fig 6. This result at first shows that even though there was no chloride in this middle portion but still there was high corrosion rate which was increasing by time ascertaining the chloride transfer from contaminated portion to uncontaminated middle portion. Secondly it is also suggesting that the high corrosion rate $4.99\mu A/cm^2$ at the two extreme ends of this high chloride contaminated specimen induced a macro-cell (cathodic in nature) in the middle no chloride portion.
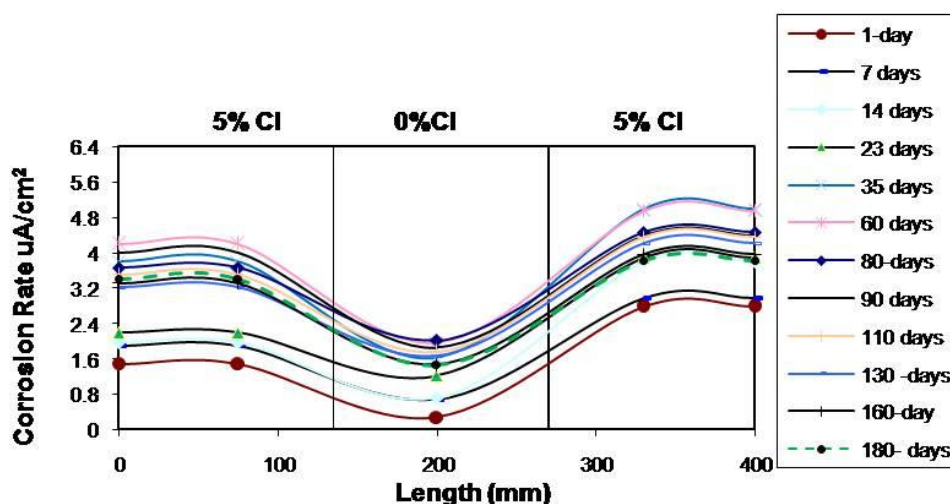

Figure 6. Corrosion rates of 5 % chloride contaminated specimen at the two ends.

3)   In specimens 3 and 4 which were 3% contaminated at the extreme end portion, after six months the highest corrosion rate of $2.93\mu A/cm^2$ was obtained while on day1, it was $1.29\mu A/cm^2$ in

this contaminated end portion indicating the incremental increase in corrosion rate as shown in fig 7. This result is the same as obtained above in the high chloride contaminated specimen, authenticating the experimental work and confirming the formation of macro-cell.

4) In specimen 3 and 4, the middle 0% Chloride portion simulating the actual patch repair the highest corrosion rate of $1.313\mu A/cm^2$ was obtained while on day1 it was $0.18\mu A/cm^2$ in this uncontaminated middle portion indicating the incremental increase in corrosion rate as shown in fig 6. This result is in conformity with obtained results in the specimen 1 and 2 corroborating the formation of macro cell and authenticating the experimental work.
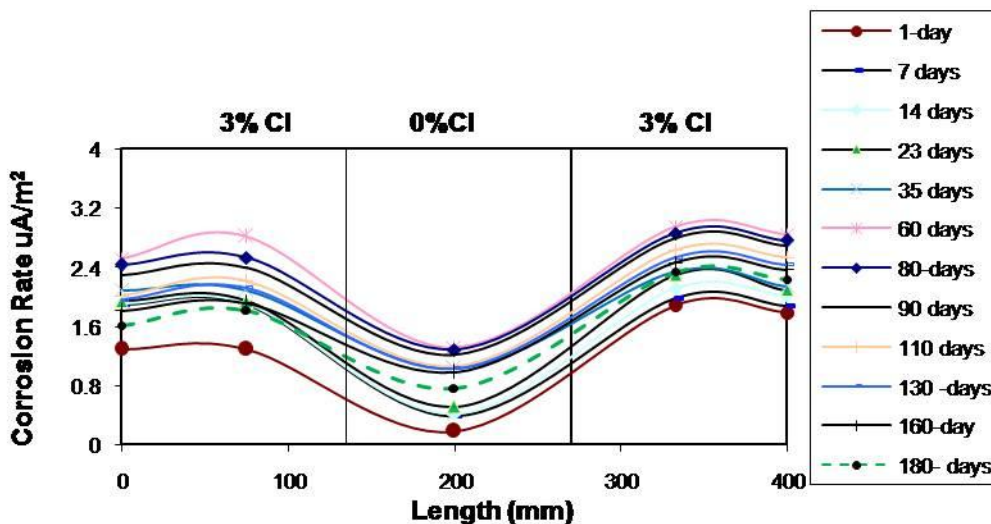

Figure 7. Corrosion rates of 3 % chloride contaminated specimen at the two ends.

3.2. Half Cell-Corrosion Potentials

Half-cell potential measurement is probably the most common method used for measuring the risk of reinforcement corrosion. There are many researchers who have done research on chloride induce corrosion of reinforced concrete using corrosion potential for measurements [21-23]. The corrosion potentials readings of the specimen were also taken for six months using copper-copper sulfate reference electrode (CSE) in accordance with standard specifications ASTM C 876-09[19] to experimentally corroborate the objectives of this research.

After six months of corrosion potential readings of specimens 1 and 2, the very high chloride induced corrosion potential of -0.598 Volts at the two extreme ends was found however in the middle 0% chloride portion simulating the actual patch repair,-0.505 Volts corrosion potential was observed as shown in fig 8. The reason behind this high -0.505 Volts potential at the middle 0% Cl portion was actually due to the macro-cell formation (anodic in nature) at the extreme contaminated portion which also induced a macro-cell corrosion potential (cathodic in nature) in the middle no chloride portion.
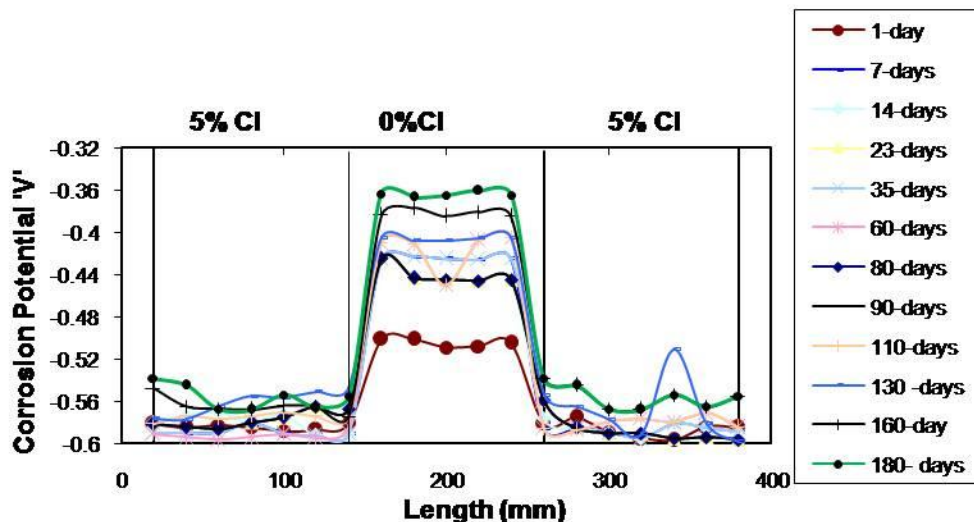
Figure 8. Corrosion potentials of 5 % chloride contaminated specimen at the two ends.

In 3 % chloride contaminated specimens (3 and 4) at the end, the corrosion potential was -0.396V and -0.286 Volt at the middle as shown in fig 9. This again shows and confirms the macro-cell formation due to above mentioned reason. These above corrosion potential results are in compliance with the corrosion rate results showing the authentication of research and investigation.
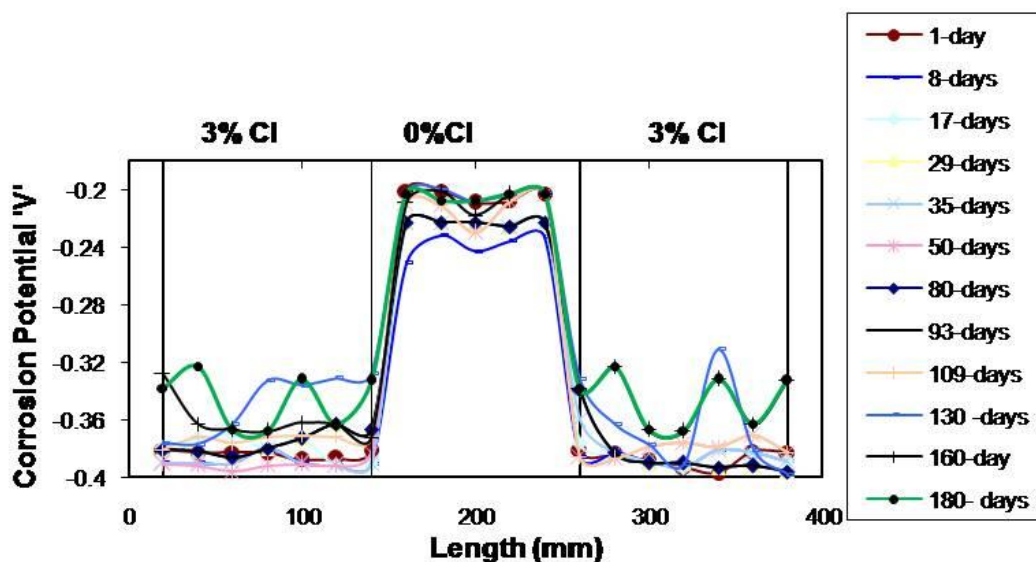

Figure 9. Corrosion potentials of 3 % chloride contaminated specimen at the two ends.

*3.3. Salt Content Measurements in the Repaired Patch*

After six months of corrosion rate and half cell potential observations; the experiment specimens were split into two along the longitudinal direction to view the actual behavior of corrosion

in the specimen at the ends and at the middle portion. From the visual observation of the steel bar taken from the middle portion of the specimen 1 having no chloride content as shown in fig 10, it is quite clear that it remained nearly un-corroded. For more deep investigations; the salt content of all specimens having different chloride contents at the end was measured to investigate the movement of the chloride from the contaminated portion to the uncontaminated middle portion of these specimens as shown in figure 11(a) and 11(b). It is also interesting to note that the salt content of the broken specimen containing 5% total chloride at the ends was found 0.10%, 0.06% and 0.09% total chloride content at three different intervals as shown in figure 11a. The average of these intervals is 0.083% total chloride which is not significant to cause corrosion in normal reinforced concrete [24-25] etc. But, from the experimental results of corrosion rates and potential values as shown in fig 5 and 7 and ; re-corrosion of the repaired reinforced SCC patch although containing no chloride content can be assumed. The average salt content of specimens having 3% total chloride contamination at the end was found 0.05%, 0.03% and 0.04% total chloride content at three different intervals as shown in figure 11b.
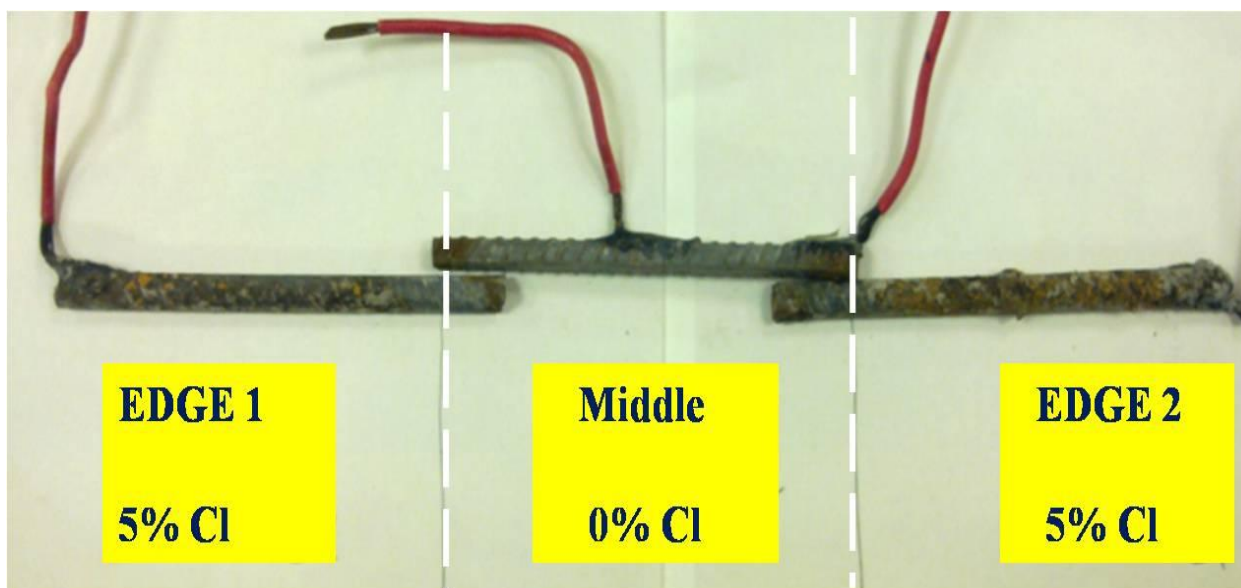

Figure 10. Visual observation of end and middle portion's steel bars of 5% contaminated specimen.

The experiment results of this paper confirm the formation of cathode in the repaired no chloride contaminated middle portion and active anode in the two chloride contaminated ends of the experiment specimen. This results in forming of macro-cell and causing even higher corrosion around the repaired no chloride reinforced SCC section in the chloride contaminated SCC. It has practical implications that need to be considered for an effective and durable repair of corroding reinforced concrete structures. This research emphasizes on the evaluation of new corrosion mechanism to effectuate the successful patch repair specially in corroding reinforced SCC structures by new and innovative methodologies.
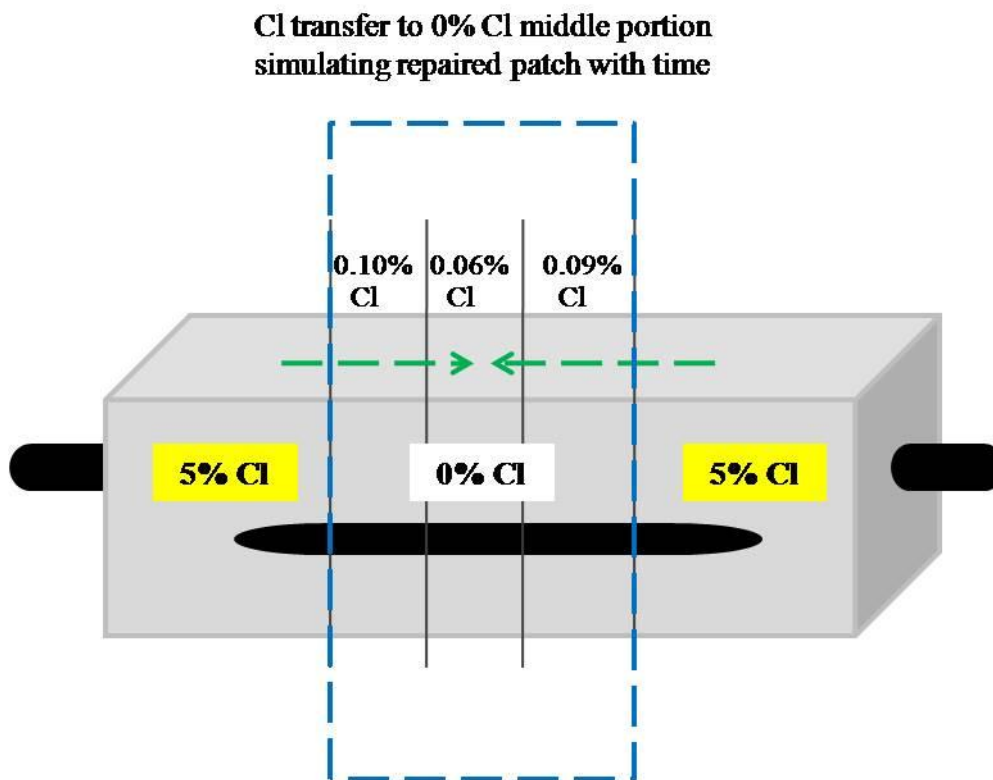
Figure 11. a) The chloride transfer from 5 % Cl contaminated portion to the 0% Cl portion.
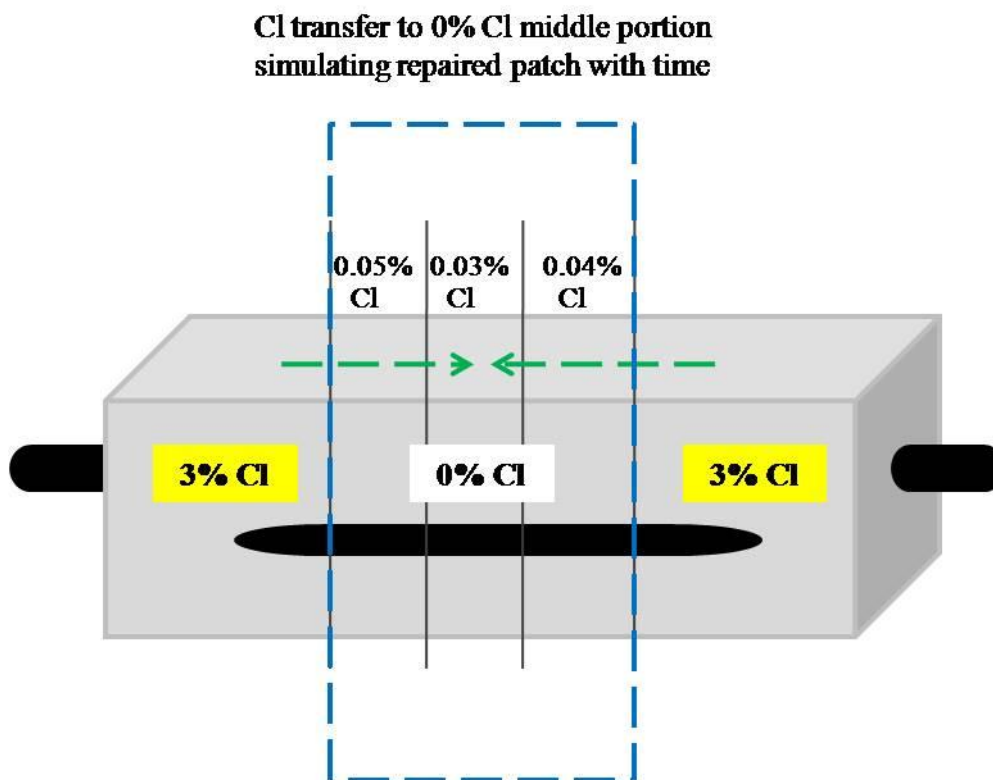
Figure 11. b) The chloride transfer from 3 % Cl contaminated portion to the 0% Cl portion.

4. CONCLUSION

SCC is considered by some researchers as good repair material for corroded normal concrete structures because of its dense, less permeable microstructure, strong resistance to bleeding and segregation and presence of water reducers/ super plasticizers. Through this research, the actual behaviour of re-corrosion in and around patches of already repaired corroded reinforced SCC due to chloride attack is successfully investigated for which very limited research is available in the past. From experiment results of corrosion rate; it is found that the highest chloride induced anodic corrosion rate of $4.99 \mu A/cm^2$ at the contaminated ends of chloride content 5 % caused macro-cell cathodic rate of $2.046 \mu A/cm^2$ in the middle no chloride portion. Similar behavior and results were obtained from corrosion potential observations; the corrosion potential of -0.598 Volts at the two extreme ends of the same specimen caused a macro-cell cathodic potential of -0.505 Volts in the middle no chloride portion. This shows that even those patches of the reinforced SCC which are repaired and considered as safe against corrosion in the construction field, can get more corrosion in the form of macro-cell induced in the surrounding chloride contaminated areas of reinforced SCC. In case of 3 % chloride contaminated specimens, the highest corrosion rate of $2.93 \mu A/cm^2$ at the two ends and a macro-cell cathodic rate of $1.29 \mu A/cm^2$ in the middle portion were obtained. The potential was -0.396V at the two ends and -0.286 Volt at the middle which again shows the corrosion macro-cell formation due to the above mentioned reasons. The results of 3 % specimens show the same macro cell corrosion phenomenon similar to the 5% chloride contaminated specimen, which confirms the experimental authenticity and reproducibility of this research. This paper triggers about an alarming condition which can prevail in SCC structures, resulting in severe degradation of structural elements surrounding the corrosion repaired patches. Therefore, the authors believe that this research is novel and will bring substantial impetus in the field of repair and maintenance of corroded reinforced SCC structures.The significant consequence of this research will be the emergence of new research studies and techniques especially relating to corrosion in SCC.

References

1. KH. Khayat, K. Manai, A. Trudel, *ACI Mater. J*. (1997) 491–500.
2. KH. Khayat, S. Tremblay, P. Paultre, *RILEM Publications S.A.R.L* (1999) 291–306.
3. M. Sonebi, AK. Tamimi, PJM. Bartos, *ACI Mater. J.* (2003) 492–500.
4. Zhu W, Gibbs JC, Bartos PJM, *Cem. Concr. Compos.* (2001) 57–64.
5. S. Hussain, Rasheeduzzafar, *ACI Mater. J*. (1994) 264–72.
6. O. Al-Amoudi, Rasheeduzzafar, M. Maslehuddin, A. Al-Mana, *ACI Mater. J*. (1993) 564–70.
7. SS. Rasheeduzzafar, SS. Al-Saadoun, AS. Al-Gahtani, *ACI Mater. J.* (1992) 37–44.
8. MN. Haque, OA. Kayyali, *ACI Mater. J.* (1995) 532–41.
9. LH. McCurrich, *Concrete* (1986) 9–10.
10. A.A.A. Hassan, K.M.A. Hossain, *Cem.Concr. Compos.* (2009) 29–38.
11. PH. Emmons, AM. Vaysburd, JE. McDonald, *Concrete Int*. (1993) 40–45.

12. DR. Morgan, *Construct Build Mater.* (1996) 57–67**.**
13. NP. Mailvaganam, *Indian Concr. J. (2001*) 759–764.
14. Hussain Raja Rizwan, M. Wasim and Ishida Tetsuya, *Australian Journal of Civil Eng*. (2010) 53-60, Australia.
15. M. Wasim and Hussain Raja Rizwan, *Int. J. Electrochem. Sci.,* 7 (2012) 1412 – 1423.
16. ASTM C192 / C192M-07 , *American Society for Testing Materials,* (2007), USA.
17. T. Uomoto, (2000) 671–8.
18. GECOR-8, http://www.ndtjames.com/Gecor-8-p/c-cs-8.htm, May 4, 2012.
19. ASTM C 876-09, *American Society for Testing and Materials*, (2009), U.S.A.
20. C. Andrade, C. Alonso and J. Sarra, *Cem. & Concr. Compos.*, 24 (2002) 55–64.
21. B.H. Oh, S.Y. Jang and Y.S. Shin, *Magazine of Concrete Research* (2003) 117–124.
22. P.B. Bamforth, *Magazine of Concrete Research* (1999) 87–96.
23. S.E. Hussain and S. Rasheeduzafar, *ACI Material J.* (1994) 264–273.
24. Hussain Raja Rizwan and Ishida Tetsuya, *Construction and Building Mater. J*. 25 (2011) 1305-1315.
25. Ki Yong Ann, Ha-Won Song, *Corrosion Sci.* (2007) 4113-4133