International Journal of Civil Engineering

Structure-Concrete

Investigation of long term coupled effect of high temperature and constant high humidity on corrosion rehabilitated patches of reinforced concrete structures

M. Wasim[1], Raja Rizwan Hussain[2,*], M. A. Baloch[3]

Received: August 2013, Accepted: December 2013

Abstract

This paper aims at finding the long term coupled effect of high temperature and constant high relative humidity on the corrosion rehabilitated patches of chloride contaminated steel reinforced concrete. This paper is an extension of previous research in which the authors experimentally corroborated re-corrosion in the repaired reinforced concrete (RC) patches in the form of macro-cells. In previous research, the coupled effect was investigated by laboratory controlled experimentation at varying temperature of 30, 40 and 50°C and a high ambient relative humidity of 85% in environmental control chambers for duration of one year. The specimens were prepared having total chloride concentration in mixing water 3% and 5 % by mass of binder. In this present research paper, the two year results of the same specimens are presented to get a deep insight of the long term phenomenon of macro-cell corrosion under the coupled effect of high temperature and humidity on repaired RC patches.

Keywords: *Macro-cell corrosion, Electrochemistry, High temperature, High relative humidity reinforced concrete, Long term experimentation.*

1. Introduction

One of the most durability concerns for the structural safety and serviceability of reinforced concrete structures is corrosion. The associated cost of rehabilitation of corroded reinforced structures is very significant therefore the complete understanding of the cause of deterioration and application of adequate rehabilitation techniques are needed to facilitate durable repair. Several researchers have investigated and reported the deterioration of reinforced concrete (RC) structures due to the corrosion of steel in the past [1-4]. It has been investigated that the corrosion induced deterioration of reinforced concrete due to chloride attack is significant [5, 6]. Moreover, the chloride induced corrosion is investigated to be contingent on temperature [6, 7] and humidity [8]. Furthermore, the chloride induced corrosion of reinforcing bar in concrete is featured by a termed called macro-cell. The interpretation of the experimental corrosion measurements (corrosion potential and galvanic current) of concrete specimens becomes difficult due to the existence of this macro-cell.

Rehabilitation of corroded reinforced concrete (RC) structures is an issue of prime importance for engineers and researchers working in modern construction repair industry. Generally, patch repair is considered to be the most applicable and suitable technique for rectifying localized damage in concrete due to corrosion. This patch repair of structural member involves the removal of loose concrete that has cracked and delaminated; surface treatment of the affected corroded steel of the patch area and application of the fresh patching materials, which normally re-gains the original profile of the member.

The authors of this research paper, previously investigated and established the phenomenon of macro-cell formation in the repaired reinforced concrete patches due to the separation of anode and cathode [9], which is illustrated in Fig. 1. They also corroborated that the presence of high chloride content aided by the severe environmental conditions i.e. varying temperature and high constant humidity, not only break the passive film which protects steel from further corrosion but also accelerate the corrosion of reinforcement steel bars even in repaired reinforced concrete patches [10]. However, what would be the effect of long term coupled effect of varying temperature and constant high humidity on macro-cell corrosion of such repaired RC patches remained a question and leads to the objectives of this research paper.

** Corresponding author: raja386@hotmail.com*
1 College of Engineering, King Saud University, Riyadh, 11421, Saudi Arabia
2 Associate Professor, CoE-CRT, Civil Engineering Department, College of Engineering, King Saud University, Riyadh, 11421, Saudi Arabia
3 CEREM, Mechanical Engineering Department, King Saud University, Riyadh, 11421, Saudi Arabia

[Downloaded from ijce.iust.ac.ir on 2026-09-06]

[DOI: 10.22068/IJCE.13.1.69]

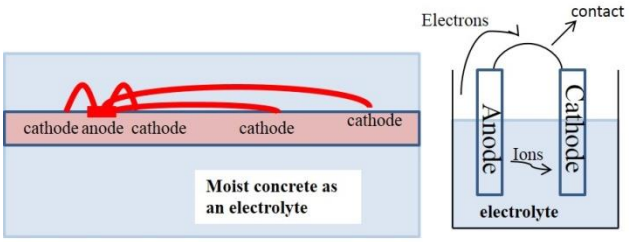


Figure 1 Separation of cathode and anode

2. Experimentation

Deformed round carbon steel bars 13 mm in diameter were used as reinforcing material in the experiment specimens. Type I cement in compliance with the requirements of ASTM C150 has been used. Coarse aggregates were a blend of 20 mm and 10 mm crushed limestone and the fine aggregates were a blend of natural red sand and manufactured sand obtained from the crushed limestone satisfying the ASTM limits and criteria. The water to cement ratio was kept 0.45 for all the mixes. Table 1 will illustrate the mix proportion of the specimens.

Table 1 Mix proportions

Specimens	Total Chloride (% mass of binder)	W/C	OPC Kg/m^3	Fine aggregate Kg/m^3	Coarse aggregate Kg/m^3
#1, #2 at 50°C #3, #4 at 40°C #5, #6 at 30°C	5% at the ends	0.45	371	756	1031
#7, #8 at 50°C #9, #10 at 40°C #11, #12 at 30°C	3% at the ends	0.45	371	756	1031

2.1. Specimen preparation and experiment scheme

This experimental investigation is an extension of the previous research finding [10] in which specimens were prepared for finding the effect of varying temperature and constant high humidity on the repaired corroded patches of reinforced concrete structures. The details of experimentation methodology including preparation of concrete specimens and curing conditions can be found elsewhere [10]. The schematic diagram of these specimens is shown in Fig. 2 and the complete mixing procedure is shown in Fig. 3. Since the objective of this research is to find the long term coupled effect of varying temperature and high humidity on macro-cell corrosion phenomenon, these specimens were kept at 50°C, 40°C and 30°C temperature conditions and 85% relative humidity in environment control chambers for 2 years.

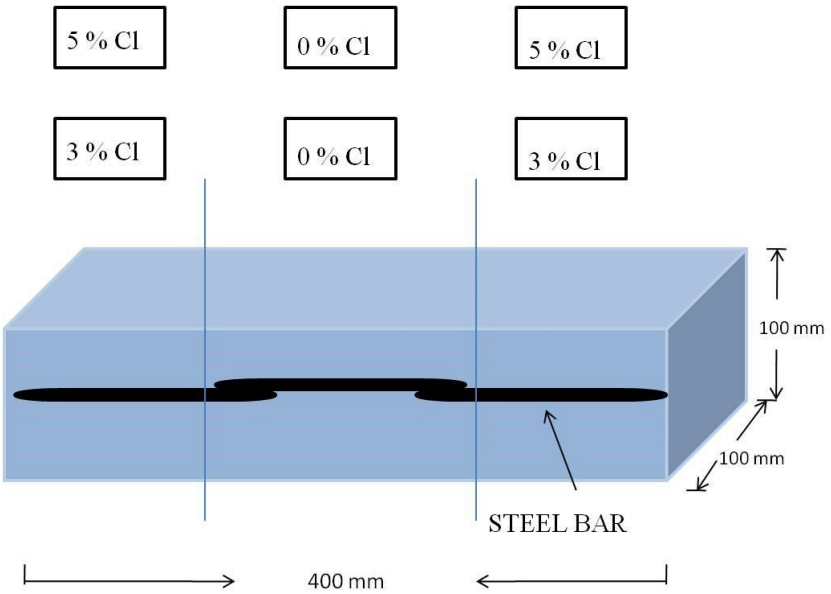


Fig. 2 Schematic representation of the identical test specimen

[Downloaded from ijce.iust.ac.ir on 2026-09-06]

[DOI: 10.22068/IJCE.13.1.69]

Figure 3 Specimens preparation

The steel rebar corrosion current (Icorr) and corrosion potential (Ecorr) were measured for all specimens using a GECOR device [11] and ASTM C-876 [12]. 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 (GECOR-8, 2012) 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 $k\Omega/cm^2$ and B = 26 mV. The Icorr is directly proportional to corrosion rate through the relation, corrosion rate (μm/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 [13]. The GECOR device is quite valuable and versatile for the corrosion measurement of steel in concrete. See Fig. 4 for further illustration.

Special care was given in wetting the concrete surface of the specimens before taking half-cell potential measurements because it is one of the most important points in the measurement of half-cell potential so that the resistivity of the concrete is reduced to such an extent which does not affect experiment measurement results. If the measured value of half-cell potential does not stop fluctuating during the measurement, it means that surface of the concrete is not wet enough and the resistivity of concrete is hindering the formation of proper contact between the electrode and the concrete electrolyte.

Figure 4 GECORE -8 (Corrosion Measurement device)

3. Experiment Results

3.1. Corrosion potential measurements

Corrosion potentials were measured for 2 years of all the specimens kept at varying temperature under constant. The following results were obtained;

1) At the middle non contaminated portion of the specimen having 5% chloride at the end portions and kept at 50°C (#1 and #2), the maximum corrosion of **-0.235** Volts was found after 2 years as compared to **-0.285** Volts at 30°C in the middle zero chloride portion of the same specimens (#5 and #6). However previously, much higher readings of these specimens were obtained on completion of one year observations [10]. The reason of this phenomenon could be the long term coupled effect of temperature and constant high humidity due to which the decline in corrosion potential after two years was significant. The results are shown in Figs. 5 and 6.

2) The maximum corrosion potential reading of the specimens #1 and #2 was found **-0.363** Volts as compared to high chloride induced potentials of **-0.432** Volts (figure 5) of the same specimens #5 and #6 at 30°C (figure 4)

[Downloaded from ijce.iust.ac.ir on 2026-09-06]

[DOI: 10.22068/IJCE.13.1.69]

after completion of two years. These results were incompliance with the above result at the middle portion that showed the decline in corrosion at elevated temperature.

3) At the middle non contaminated portion of the specimen #3 and #4 which were put at 40 °C maximum corrosion potential of **-0.399** Volts was found, being higher than the other specimens at 30 and 50 °C.

4) The highest corrosion potential of **-0.497** Volts was found in specimens #3 and #4 as compared to **-0.363** Volts at the two extreme ends of the specimen #1 and #2. After 365 days of observations, significant decline was observed that potential dropped from -.702 to -0.497 after one more year of observations.

5) In the 3 % chloride contaminated specimens (#7 and #8) at the end, the corrosion potential of -0.255 Volts was obtained as compared to high -0.311 Volts of same specimens (#11 and #12) which were kept at 30 C^{o}.

6) In specimen #7 and #8, the corrosion potential of **-0.205** volts at the middle non contaminated portion was obtained as compared to **-0.215** Volt at 30^{o}C.

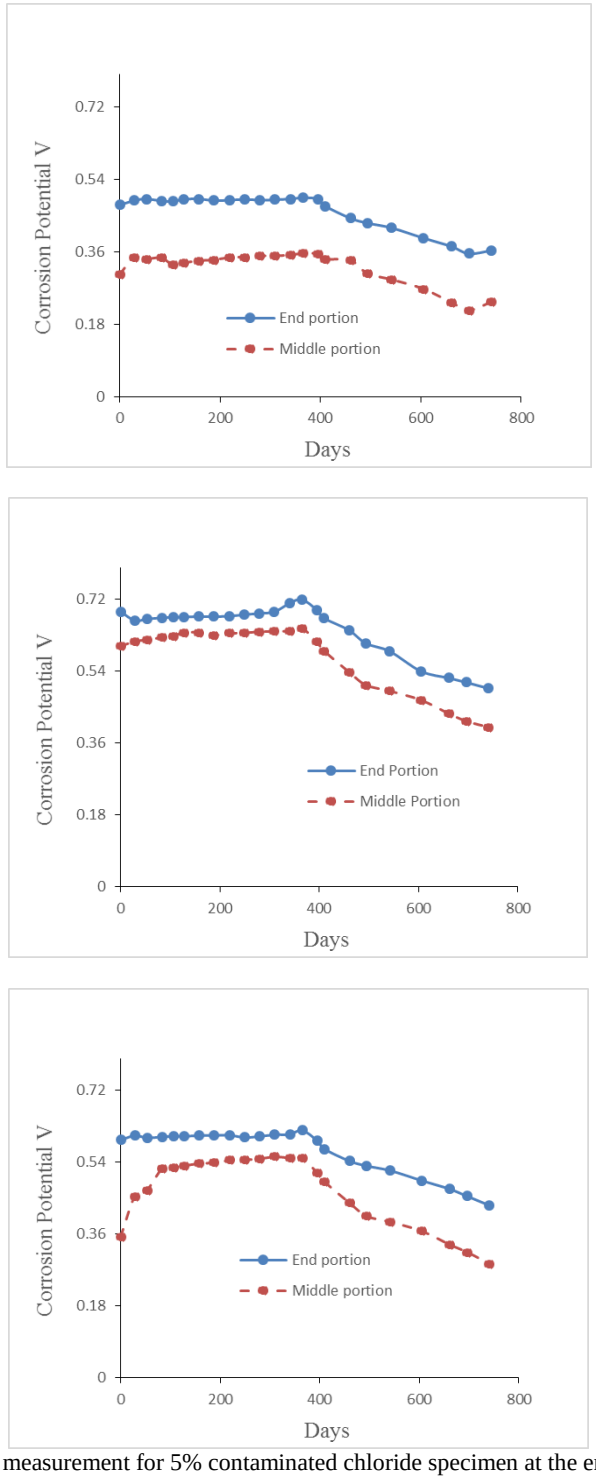
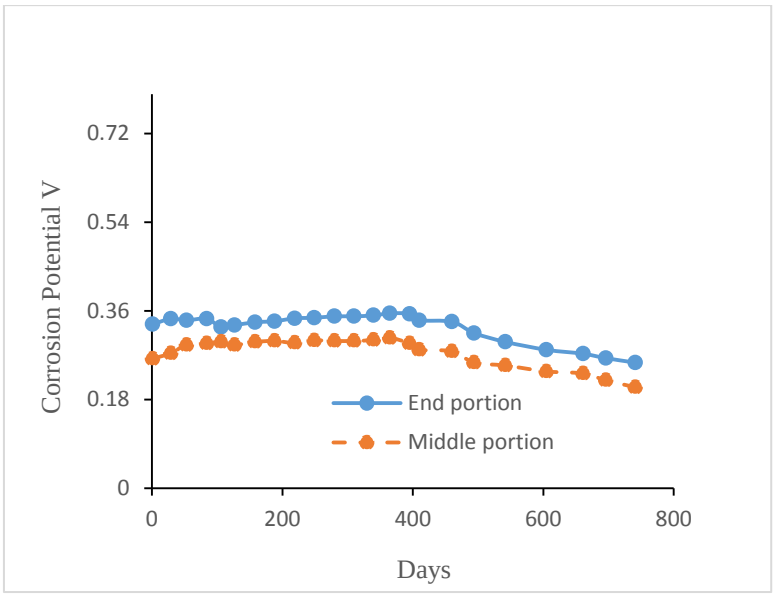
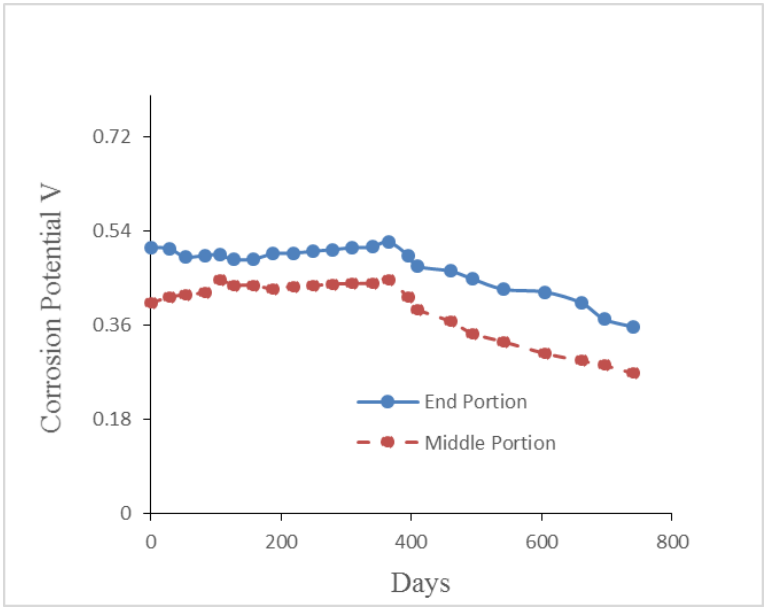


Fig. 5 (a-c) Corrosion potential measurement for 5% contaminated chloride specimen at the end kept at 30^{o}C, 40^{o}C and 50^{o}C

[Downloaded from ijce.iust.ac.ir on 2026-09-06]

[DOI: 10.22068/IJCE.13.1.69]





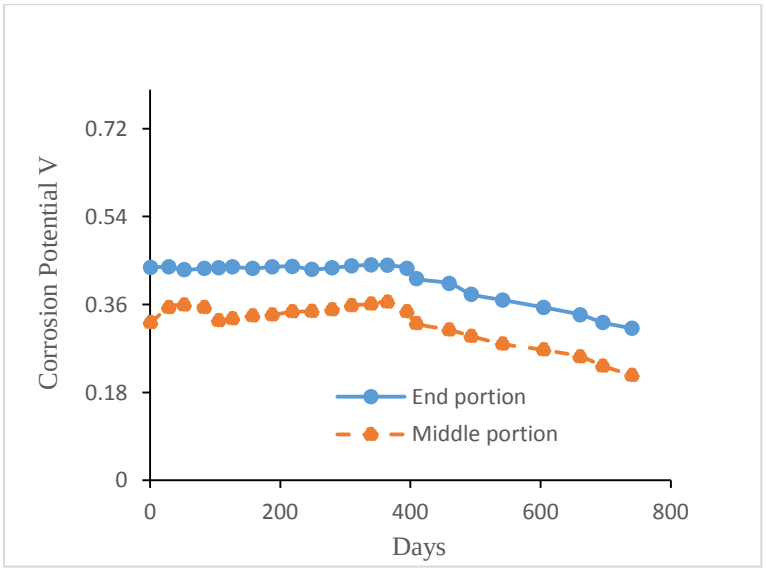


Fig. 6 (a-c) Corrosion potential measurement for 3% chloride contaminated specimen at the end kept at 30°C, 40°C and 50°C

[Downloaded from ijce.iust.ac.ir on 2026-09-06]

[DOI: 10.22068/IJCE.13.1.69]

3.2. Gravimetric mass loss

Finally after two years of observations, the specimens were broken for gravimetric mass loss to calculate the corrosion rates of steel in these specimens. The following results were obtained:

1) The steel bar from the end portion of 5% chloride contaminated concrete gave the highest % mass loss of 3.73 at 40ºC while the steel bar from its middle portion gave 2.81 % mass loss. When the steel taken from the end portion of the same specimen kept at 30ºC gave the highest % mass loss of 3.11 and 2.09 % obtained from its middle steel. However interestingly even after exposure of two years observation, the steel of the end portion of the same specimen kept at 50ºC gave the highest % mass loss of 3.31 and middle steel gave 2.27 % mass losses which was lower than the mass losses at 40ºC. The results are shown in Fig. 7.

2) The steel from the end portions of 3 % chloride contaminated concrete specimens kept at 30ºC, 40ºC and 50ºC gave 2.65, 3.11 and 2.75 % mass loss respectively. While the middle steels from the uncontaminated portion of these specimens gave 1.75, 2.19 and 1.88 % mass losses respectively as shown in figure 7. Similarly in the 3% chloride contaminated specimens reduced % mass losses at 50ºC obtained as compared to the mass loss at 40ºC, confirming the authenticity of the results of this research.

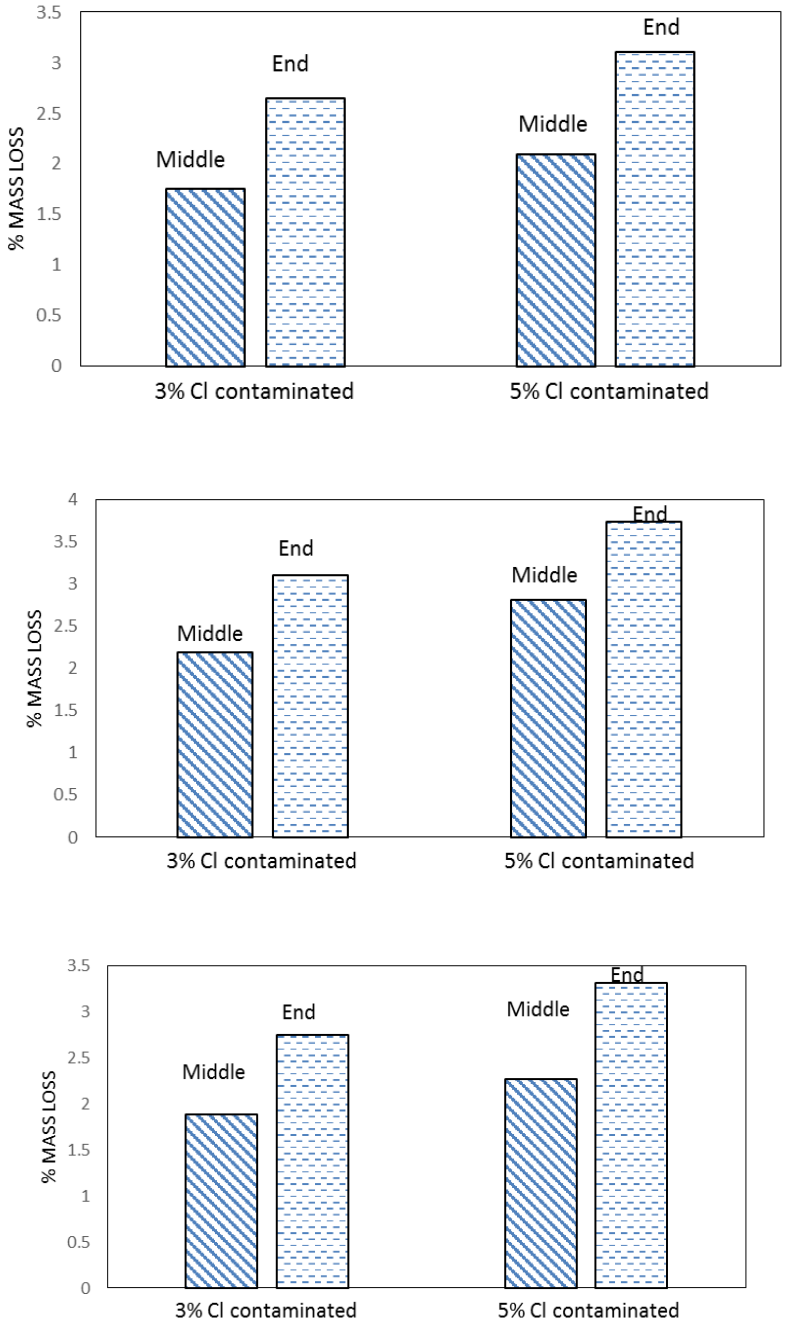


Fig. 7 % Mass loss for 3% and 5% chloride contaminated specimen at the end kept at 30°C, 40°C and 50°C

[Downloaded from ijce.iust.ac.ir on 2026-09-06]

[DOI: 10.22068/IJCE.13.1.69]

4. Discussions

It can be seen from the obtained results of all the specimens at varying temperature that corrosion potential is decreasing with the passage of time. The obtained results further authenticating the previous research results [10]. From the previous research, it was inferred that in the case of the specimens having the highest concentration of Cl and highest temperature showed an interesting falling trend and reduction in the corrosion potential values with the increase in temperature. The reason of this phenomenon explained in that research [10], was due to the reduction of oxygen solubility in the pore solution at high temperature and the blockage of concrete pores at high relative humidity and high temperature which resulted in discontinuity of interconnected concrete pores.

In this long term research, the same trend as obtained from previous one year observations was observed. But, interestingly the corrosion potential were further decreased owning to the same reason as explained above. The obtained results presented in this paper, trigger towards the alarming situation that could exit in the repaired portion of the chloride contaminated concrete due to macro-cell formation and could cause further destruction due to formation of anodic ring around the repaired patches. Moreover, the long term serviceability and durability of the whole structure becomes a question mark even though its corroded patches being repaired with the common repair techniques assuming it to be safe. Therefore by considering the obtained long term results, it is expected that this data would be used as a bench mark for patch repairs of the reinforced concrete structures and the necessary mitigation techniques will be applied in accordance to this research data for successful repairs.

As it can be seen from gravimetric mass loss results of various specimens put in varying temperatures, shown in figure 7(a-c), the steels from the middle portion of all the specimens simulating the actual patch repair in field, were corroded and gave approximately 70% of the mass loss obtained in their respective contaminated end portions, indicating the chloride transfer and vulnerability of repaired portion against corrosion.

The corrosion mass loss usually increases with the increase in chloride concentration justified with the sample having 3% and 5% chloride. However, interestingly even after the long term exposure of two years, the similar decline of corrosion potential and mass loss was observed at 50 ºC as it was obtained in previous one year results [10]. The steel bars were corroded less at 50ºC than at 40ºC as indicated from the corrosion potential and mass loss results as shown in figures and . One of the reasons could be the unavailability of oxygen at such a high temperature and R.H which are must for corrosion process to occur. The increased temperature resulted in decreased solubility of oxygen in the pore solution of concrete at the ITZ and high R.H created disconnection in the concrete pores providing obstacles in the oxygen path from the exposed surface up to the embedded steel bar corroding surface [1, 2, 8].

It can be inferred from these observations that under limiting oxygen controlled corrosion reaction conditions at higher chloride induced corrosion rate, a stable iron oxide layer could have been developed on steel bar which prevents further corrosion of steel until the oxygen limiting corrosion reaction conditions are maintained. This is a novel and useful finding which can lead to the development of a new technique to passivate steel bar embedded in chloride contaminated concrete.

5. Conclusions

It is corroborated from the experimental findings of this long term research that the corrosion develops in RC structures repaired patches in a form of macro-cell corrosion and its severity varies with temperature in a non-uniform way. It is observed that temperature escalated the corrosion process in repaired patches from 30°C to 40°C. However, it was interesting to observe the decrease in corrosion potential and corrosion mass loss at 50°C in comparison to 40°C temperature condition at the contaminated portions, and non-contaminated simulating the actual patch repairs portions of the experimental specimens. One reason of this decline in corrosion at 50°C can be the reduction of oxygen solubility in the pore solution at high temperature resulting in oxygen controlled corrosion reaction at high chloride concentration. Another reason can be the blockage of concrete pores at high relative humidity and high temperature resulting in discontinuity of interconnected concrete pores and finally resulting in the shortage of oxygen at such a high R.H and high temperature condition. It can be concluded from this observation that under limiting oxygen controlled corrosion reaction conditions at higher chloride induced corrosion rate, a stable iron oxide layer is developed on steel bar which prevents further corrosion of steel until the oxygen limiting corrosion reaction conditions are maintained.

Furthermore the results presented in this paper, trigger towards the alarming situation that could exit in the repaired portion of the chloride contaminated concrete due to macro-cell formation and could cause further destruction due to formation of anodic ring around the repaired patches at longer stages. Therefore by considering the obtained long term results, it is expected that this data would be used as a bench mark for patch repairs of the reinforced concrete structures and the necessary mitigation techniques will be applied in accordance to this research data for successful repairs.

Acknowledgement: This project was supported by King Saud University, Deanship of Scientific Research, College of Engineering Research Center.

References

[1] Hussain RR, Tetsuya I. Influence of connectivity of concrete pores and associated diffusion of oxygen on corrosion of steel under high humidity, Construction and Building Materials Journal, 2010, No. 6, Vol. 24, pp.1014-1019.

[Downloaded from ijce.iust.ac.ir on 2026-09-06]

[DOI: 10.22068/IJCE.13.1.69]

[2] Hussain RR, Tetsuya I. Development of numerical model for fem computation of oxygen transport through porous media coupled with micro-cell corrosion model of steel in concrete structures, Computers and Structures Journal, 2010, Nos. 9-10, Vol. 88, pp.639-647.

[3] Hussain RR, Tetsuya I. Experimental investigation of time dependent non linear 3d relationship between critical carbonation depth and corrosion of steel in carbonated concrete, Journal of Corrosion Engineering, Science and Technology, 2010, No. 5, Vol. 46, pp. 657-660 (4), U.K.

[4] Hussain RR, Tetsuya I. Investigation of volumetric effect of coarse aggregate on corroding steel reinforcement at the interfacial transition zone of concrete, submitted to KSCE Journal of Civil Engineering, 2010, No. 1, Vol. 15, pp. 153-160.

[5] Hussain RR, Tetsuya I. Enhanced electro-chemical corrosion model for reinforced concrete under severe coupled environmental action of chloride and temperature, Construction and Building Materials Journal, 2010, No. 3, Vol. 25, pp. 1305-1315.

[6] Hussain RR. Enhanced classical tafel diagram model for corrosion of steel in chloride contaminated concrete and the non linear experimental effect of temperature, International Journal of Concrete Structures and Materials, 2010, No. 2, Vol. 4, pp.71-75.

[7] Hussain RR, Tetsuya I. Novel approach towards calculation of averaged activation energy based on arrhenius plot for modeling of the effect of temperature on chloride induced corrosion of steel in concrete, Journal of ASTM International, 2010, No. 5, Vol. 7, pp. 1-8, doi: 10.1520/JAI102667.

[8] Hussain RR. Effect of moisture variation on oxygen consumption rate of corroding steel in chloride contaminated concrete, Cement and Concrete Composites, 2011, No. 1, Vol. 33, pp. 154-161.

[9] Hussain RR, Wasim M. Tetsuya Ishida. Induced macro-cell corrosion phenomenon in the simulated repaired reinforced concrete patch, Australian Journal of Civil Engineering, 2010, No. 1, Vol. 8, pp. 53-60.

[10] Wasim M, Hussain RR. Unique declining electrochemical trend of macro-cell half-cell potential with increase in temperature at constant high humidity for corroding steel bars in repaired concrete patches, International Journal of Electrochemical Science, Vol. 7, pp. 1412-1423.

[11] GECOR-8. http://www.ndtjames.com/Gecor-8-p/c-cs-8.htm, cited on June 11, 2013.

[12] ASTM C 876-09. Standard test method for corrosion potentials of uncoated reinforcing steel in concrete, American Society for Testing and Materials, USA, 2009.

[13] Andrade C, Alonso C, Sarra J. Corrosion rate evolution in concrete structures exposed to the atmosphere, Cement & Concrete Composites, 2002, Vol. 24, pp. 55-64.

[Downloaded from ijce.iust.ac.ir on 2026-09-06]

[DOI: 10.22068/IJCE.13.1.69]