International Journal of ChemTech Research
CODEN (USA): IJCRGG, ISSN: 0974-4290, ISSN(Online):2455-9555
Vol.10 No.3, pp 749-757, 2017

Corrosion of Reinforcement in Reinforced Cement Concrete: A Review Paper

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Abstract : This paper reviews various aspects of corrosion of the reinforcement embedded in concrete by various factors like moisture, permeability pH and temperature etc and also their corrosion controlling methods. As reinforcement used for many reinforced concrete structures exposed to moisture in the air causing slight corrosion even before casting of concrete. Alternative methods and materials are also taken into the paper along with numerical modelling for predicting the corrosion rates. The electrochemical method of evaluating the corrosion rates are reviewed in which four different water cement ratios are taken by various researcher. Epoxy materials compared to conventional cementite materials shows very small shrinkage defect. For damage prediction rate of corrosion is very crucial input parameters. Corrosion influencing factors such as cover cracking, resistivity, concrete quality and cover depth should be incorporated in corrosion rate prediction models. For accurately predicting the corrosion rates both laboratory and field data should be considered during model development.
Keywords : Corrosion, concrete, steel, oxidation.

Introduction

Corrosion is the deterioration of materials by chemical interaction with their environment. The term corrosion is sometimes also allied to the degradation of plastics, concrete and wood, but generally refers to metals. The corrosion cells generated by electrochemical potentials in two methods:

1. When two unlike metals are mixed in concrete, like steel and aluminium conduit pipes, or there exists substantial in surface characteristics variation of the steel.
2. Cells can be made because of the concentration difference in the vicinity of reinforcing steel of dissolved ions, such as alkalise and chlorides.

The change of iron or steel into rust is electrochemical in nature, viz, the electrochemical responses – as recognized from concoction responses – include the passage of electrical charge. Electrons are discharged in the oxidation reaction, and consumed in the reduction response. As a result, one of the two metals becomes anodic and the other

cathodic. The chemical reactions take places at the anodic and cathodic areas are as follows:

Anode: Oxidation reaction (dissolution of iron):
$Fe \rightarrow Fe^{2+} + 2e^-$ (1)
Cathode: Lessening response (oxygen reduction):
$H_2O + (1/2)\ O_2 + 2e^- \rightarrow 2OH^-$ (2)

For these two half-cell responses to happen, the vicinity of water and also oxygen – the last broken down – is required. As collection of charge is outlandish, the two responses must happen at the same rate. The general response can be composed as takes after:

$Fe + H_2O + (1/2)\ O_2 \rightarrow Fe\ (OH)_2$ (3)

Under regular states of fortification steel installed in cement, the erosion item Fe $(OH)_2$ will be further oxidized to Fe_3O_4 or Fe_2O_3. The general mechanism of corrosion is shown in the below figure 1.

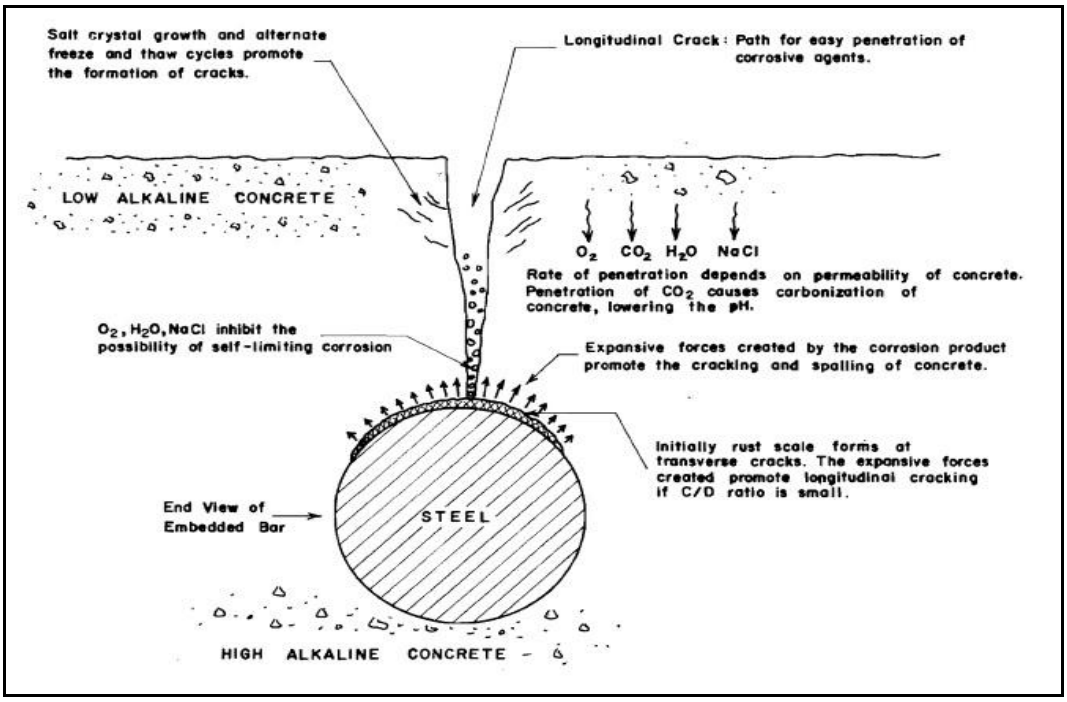

Figure 1. General mechanism for the corrosion of reinforcing steel in concrete

Reinforcement steel is a compound that basically comprises of iron and a nearly little quantity of carbon. In nature, the vast majority of the iron exists in a stable state as iron metal, oxides for example, magnetite (Fe_3O_4) and hematite (Fe_2O_3). For steel production, energy is required at the steel plant to change iron mineral into steel. The procedure of metallic corrosion can be viewed as the tendency of changing over the fabricated developed material back to the original state. The items that in this way produced are iron oxides or hydroxides and are generally alluded to as rust. Metallic erosion is ordinarily viewed as an undesirable procedure of deterioration.

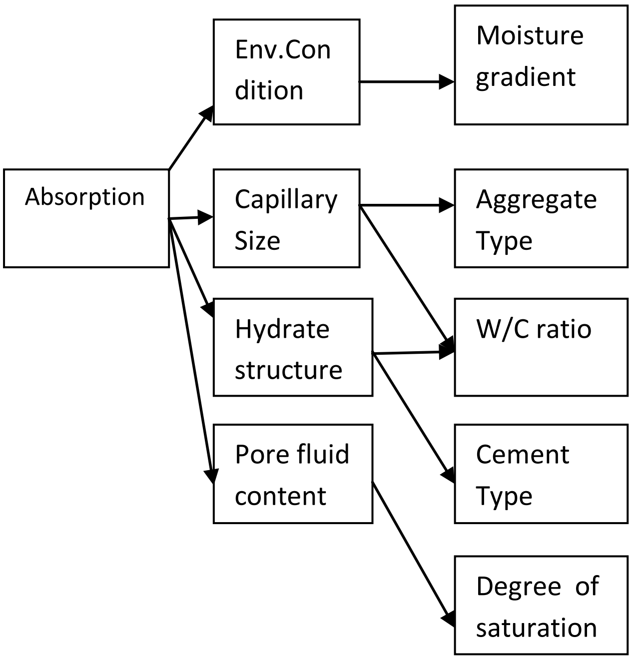

Figure2. Factors affecting absorption of concrete

Verma et al. [1] have conducted their study on monitoring of corrosion of steel bars in reinforced concrete structure. In their study they focused on concrete structure failures because of the corrosion of embedded re-bars. The concluded several parameters which govern the corrosion are temperature, moisture, absorption and oxygen availability as shown in given below figure2.

Castel et al. [2] they proposed a new correction factor for calculating the reinforced concrete structure development length. To relate the strength of bond to corrosion a scalar bond damage parameter has been introduced, this parameter has been utilized by them for AS3600 provisions modification in RC structures. Their model shows conservative results up to maximum bond damage threshold. Their model well validate with the experimental results.

Cleland et al. [3] studied the corrosion of reinforcement in concrete repair. They experimentally studied the performance of five repair materials to provide comparative data so that the prevention of corrosion for both uncoated and coated reinforcing bars. In their study they considered two different environments one exposed to de-icing salt and another to normal British Isles. They concluded that epoxy materials compared to conventional cementite materials shows very small shrinkage defect. They found that half-cell potential of steel are less negative and that of bars are less negative with deeper cover compared to lower cover. They measure high permeability at the surrounding and cementitious mortars interface but epoxy surrounding concrete shows less permeability. They noticed significant half-cell potential for specimen repaired with SBR and acrylic modified mortar and unmodified OPC/sand mortar.

Ohtsu and Yosimura [4] studied the analysis of crack propagation and crack initiation due to corrosion of reinforcement. They conducted stress analysis because of the corrosion of reinforcement in the concrete utilizing boundary element method (BEM) and linear elastic fracture mechanics (LEFM). A wide study during initiation and propagation of cracks because of the reinforcement has been conducted. For simulating the expansion behaviour of corrosion they considered vertical pressure and hydrostatic pressure. They focused on the five cracks propagated due to reinforcement. One is surface crack propagated vertically while other are spalling crack. They also concluded the following parameters.

1. Under hydrostatic pressure spalling crack or a diagonal crack could follow surface crack which propagated towards the stress-free surface. When initiation of surface crack starts they observed peak pressure.
2. They observed where the surface crack detained by aggregates internal crack propagates towards inside.
3. They concluded under hydrostatic pressure spalling crack can be initiated either by internal crack or surface crack.

4. When pressure increased a new high stress zone created which results in that surface crack could follow internal crack unless it is arrested by aggregates.
5. They also noticed that stress distribution suggest a vertical crack initiation, after arrest of surface crack.

Hussain et al. [5] studied chloride threshold for corrosion of reinforcement in concrete. They prepared a specimen of cement mortar utilizing three different tri-calcium aluminate cements with steel bar. It has been immersed in 5% NaCl solution. They examined pore solution for Cl^- (chlorine) and OH^- (hydroxide) concentration, they computed Cl^-/OH^- threshold solution. They noticed that pH value of pore solution affect the Cl^-/OH^- threshold ratio. They found for pH values of 13.26 and 13.36 threshold Cl^-/OH^- values as 1.28 and 2.0. They noticed that free chloride threshold value is independent of tri calcium aluminates (C_3A) content in cement.

Hillerborg et al. [6] proposed a model for fracture mechanism for studying crack growth and crack formation by finite elements. Figure 3 illustrates the model proposed by them. The model comprises three parts. First part represents the true crack which consist an area where no stress get transmit. The second part is micro-cracking area where fracture process zone (FPZ) starts. The last part is full material or undamaged area. In the first part stress discontinuity and displacement occurs. Due to aggregate bridging and interlocking stress may be transferred in the second part. In the third part the crack to propagate when stress at FPZ tip becomes f'_t.

Valenza and Scherer [7] studied the salt scaling durability issue for concrete. They summarize that damage of internal crystallization is not because of the hydrostatic pressure. Internal crystallization and relaxation of hydrodynamics consider all characteristics of experimental results conducted on air-entrained cement paste or vycor glass. If ice creation arises in the voids of air and compress the surrounding matrix, internal frost action will immune the air-entrained concrete. Crystallization pressure destructs the dilation in the absence of adequate entertainment air. Salt scaling may be prevented, if the body is sufficiently air-entrained which imposed suction, by ice in the air voids.

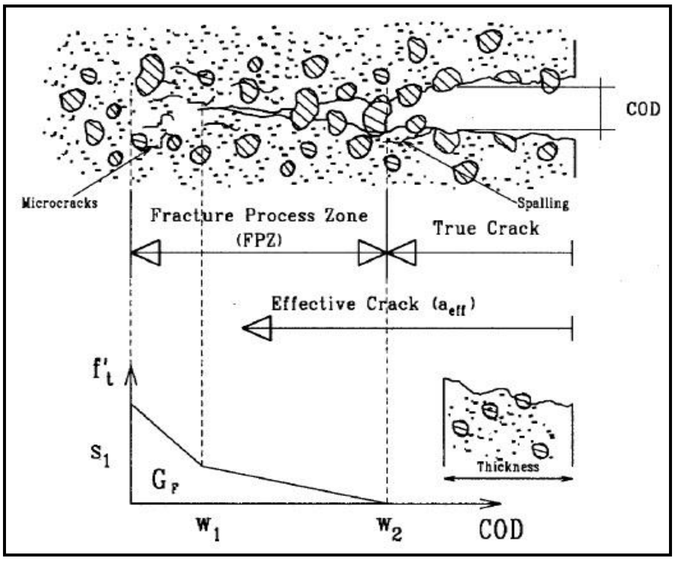

Figure 3. Hillerborg's fictitious crack model

They studied various mechanisms like thermal shock, precipitation and growth of salt, reduction in vapour pressure and osmotic pressure for salt scaling. They concluded no mechanism accounts for all characteristics of salt scaling. They concluded when salt allied to layers of ice developed thermal stresses are not too large to result in destructive stresses. When the critical degree of saturation surpassed damage takes place in presence of salt in the ore solution. Moderate salt concentration results in severe damage. In the end they proposed a mechanism named glue spalling as the cause of salt scaling which accounts for all the characteristics of damages.

Raupach and Schieß [8] reinforcement corrosion has been built up as the transcendent variable bringing on boundless untimely decay of concrete development around the world, particularly of the structures situated in the coastal marine environment. The most essential reasons for corrosion start of reinforcing steel are the entrance of chloride particles and carbon dioxide to the steel surface. After start of the corrosion process, the corrosion items (iron oxides and hydroxides) are generally stored in the limited space in the concrete around the steel. Their development inside of this confined space sets up extensive stresses, which break and spall the concrete cover. This thus brings about deterioration of the concrete. Thus, the repair costs these days constitute a noteworthy piece of the present spending on infrastructure. Quality control and anticipating the reclamation of these structures need non-destructive investigations and checking strategies that identify the corrosion at an early stage.

Elsener et al. [9], Montemor et al. [10] and Saremi and Mahallati [11] studied, Loss of corrosion which devours significant financial backing of the nation by method for either reclamation measures or recreation. There have been an expansive number of examinations on the issues of deterioration of concrete and the subsequent corrosion of steel in concrete. Appropriately checking the structures for corrosion execution and taking suitable measures at the proper time could impact large savings. In addition, the repair operation themselves are entirely mind boggling and require unique treatments of the crake zone, and in many examples the future of the repair is restricted. Appropriately, corrosion observing can give more finish data of changing state of a structure in time.

Nassar and Soroushian[12] experimentally studied milled glass as a replacement of cement. They used milled glass for production of recycled aggregate concrete because it possesses high strength durability. They conducted the experiments on milled glass and concluded that milled glass can partially replace the cement on the basis of following results obtained.

1. Fine size of milled glass around 13 micrometre in concrete undergoes pozzolanic reaction and results in better micro-structure quality.
2. They found a less permeable microstructure of recycled aggregate concrete because sub-micron size filling results in better and denser packing.
3. They noticed that recycled aggregate concrete after using milled glass possess improved durability characteristics like permeability, sorption, freeze-thaw resistance.
4. The main key in improvement of pozzolanic reaction is the waste glass milling in the sub-micron size.

Chung [13] studied corrosion control of steel-reinforcement concrete. They reviewed all the materials and methods for corrosion control of steel-reinforcement concrete. The methods they studied are steel surface treatment, concrete surface coating, and utilization of admixtures in concrete, cathodic protection. In steel surface treatment the widely utilized methods are galvanizing and epoxy coating. Surface coating improves the impermeability, they concluded acrylic rubber can be utilized but these methods suffer from coating with reduced durability. In the methods utilizing admixtures the utmost used admixture are latex, calcium nitrite and silica fume.

Otieno et al.[14] studied prediction of corrosion rate in RC Structures. They studied that the most important parameter for predicting damage in corrosion for reinforced concrete is the corrosion rate. They concluded the followings,

1. For predicting the damage, instantaneous or constant values have been used by the researchers.
2. Time variant behaviour or other issues like cover cracking concrete quality have not been considered during the model development.
3. Inherent variability of corrosion rate and features affecting it should be considered during model prediction.
4. Validation of model using natural resources is very important stage during development of model particularly for numerical models.
5. For accurately predicting the corrosion rates both laboratory and field data should be considered during model development.

Hansen and Saouma [15] simulated the reinforced concrete deterioration of steel corrosion and concrete cracking. They studied that corrosion can be easily modelled using diffusion model, but nonlinear programme is needed to model cracking. To predict the deterioration in concrete bridge the interaction between the concrete-fracture/steel-corrosion has been utilized by. They used ABAQUS to model the corrosion of reinforcing bar in concrete. They included the polarization effect at the interface of reinforcing bar and concrete. The calculated the corrosion rate using this model. They concluded that reinforcing bar corrosion fracture can be investigated using linear fracture mechanism. They also found that propagation of crack starts from vertical, horizontal and diagonal directions and it also depends on the bar spacing cover of concrete. They also concluded that crack opening a tensile effect results in propagation of crack in vertical and horizontal direction while crack-sliding a shear effect results in diagonal crack propagation.

RC structure corrosion rate is get affected by many parameters like chlorides concentration and penetrability of concrete that also get varied with time. Yuan et al. [16] studied time variation nature of corrosion rate. They proposed three different phases for time variation. First is descent phase second is steady phase and last one is ascent phase as shown in the figure 4. But this type of variation cannot be used to predict the corrosion rate in RC structures.

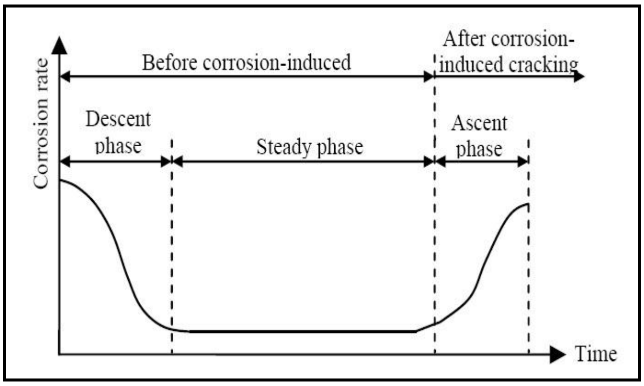

Figure 4. Phases of time variant corrosion rate

Raupach [17], Redaelli et al. [18] and Warkus et al. [19] developed models for corrosion propagation. In the light of the paradigm shift to incorporate the corrosion propagation phase in the service life of corrosion-affected reinforced concrete (RC) structures. Zhang et al. [20], Torresacosta et al. [21], Liu Y. and Weyers [22] and Maaddawy and Soudki [23] developed several models to predict times to different corrosion-induced damages (limit states) such as cover cracking, loss of steel cross-section area, loss of stiffness. Even though these prediction models usually have several input parameters, it is clear that the rate of corrosion governs their outcome either in terms of the time to attainment of a pre-defined limit state or its severity at a given time.

Li [24] developed a sensitivity analysis that showed corrosion rate is one of the most important input parameters in the corrosion-induced damage models. Isgor &Razaqpur [25] and Liu &Weyers [26] developed a dynamic model for corrosion prediction in steel concrete structures. Isgor developed corrosion prediction model using electrochemical principles while Liu has conducted experimental and developed a model for corrosion prediction of chloride contaminated concrete structures.

Masadeh[27] studied the performance of galvanized steel reinforcement in concrete in sea and Dead Sea water. In their study they used an 8mm diameter and 24 cm length of material reinforced from steel. They have used hot dipping method for galvanization of steel reinforcement. They found good corrosion resistance in sea water after galvanization of steel reinforcement.

Masadeh [28] studied the effect on corrosion of steel reinforcement by addition of carbon black on steel has been conducted. They have studied four different mixture ratios 0.1, 0.2, 0.3, 0.4 of carbon black in the steel. Before studying them they have immersed the mixture in chloride (3.5%) for half year (six months). They found decrement in corrosion rate with increment in carbon black content they also noticed decrement in chloride ions penetration.

Liang and Yang [29] focussed on theoretical elucidation on site measurements of corrosion rate of reinforcements by three techniques i.e. by electrical charge, corrosion current and electrical resistivity of concrete and came to conclusion given in below table1.

Table1: Levels of concrete resistivity regarding

S.No.	Resistivity(KΩcm)	Corrosion risk
1	≥100-200	Negligible corrosion, concrete too dry
2	50-100	Low corrosion rate
3	10-50	Moderate to high corrosion when steel is active
4	Less than 10	Resistivity is not the controlling parameter of the corrosion rate

Risk of Corrosion

Saraswathy and Song [30] presented their study on electrochemical and non-destructive techniques on corrosion monitoring and assessment of reinforced concrete structure and their application to bridges, buildings and other civil engineering structure. For measurement of the corrosion rate in steel embedded in concrete can be assessed by different methods such as:

1. Open circuit potential measurement
2. Surface potential measurement
3. Concrete resistivity measurement
4. Linear polarisation resistance measurement
5. Tafel exploration
6. Galvanostatic pulse transient method
7. Visual inspection
8. Noise analysis
9. Electrochemical impedance spectroscopy
10. Ultrasonic pulse velocity technique
11. Cover thickness measurement
12. Infrared thermograph electrochemical

Bazant P. Edenek [31] developed a complete mathematical model of the corrosion process as a basis for calculations of the finite element method by formulating the transport of oxygen and chloride ions through the concrete cover, the mass sinks and source of oxygen and concluded on many factors especially rust production rate and the polarisation of electrode due to changes in concentration of oxygen and ferrous hydroxide.

Melchers and Petersen [32] studied on long term corrosion of cast iron cement lined pipes which are prone to corrosion on the external surface that are in contact with soil and developed a realistic model for the prediction of pitting pipe corrosion in soil and its calibration to field and historical data.

Conclusion

1. The methods for controlling the corrosion of steel reinforcement required steel surface treatment, concrete surface coating, and utilization of admixtures in concrete, cathodic protection.
2. In steel surface treatment the widely utilized methods are galvanizing and epoxy coating.
3. Surface coating improves the impermeability, they concluded acrylic rubber can be utilized but these methods suffer from coating with reduced durability.
4. In the methods utilizing admixtures the utmost used admixture are latex, calcium nitrite and silica fume.
5. Epoxy materials compared to conventional cementite materials shows very small shrinkage defect
6. For damage prediction rate of corrosion is very crucial input parameters and should therefore receive sufficient attention with respect to its assessment and prediction.
7. Corrosion-influencing factors such as cover cracking, resistivity, concrete quality and cover depth should be (explicitly) incorporated in corrosion rate prediction models.
8. For accurately predicting the corrosion rates both laboratory and field data should be considered during model development.
9. Milled glass and concluded that milled glass can partially replace the cement, fine size of milled glass around 13 micrometre in concrete undergoes pozzolanic reaction and results in better micro-structure quality.

10. It is evident that the quality of the concrete plays a major role in the behaviour of any type of reinforcement because the concrete is the first defence against corrosion
11. ECR, probably the most-used alternative reinforcement material, is particularly susceptible to defects
12. Salt scaling may be prevented, if the body is sufficiently air-entrained which imposed suction, by ice in the air voids.

Objective and expected outcome of the study

The review presented in this paper was motivated to develop a prediction model. The impetus for the study emanates from the need to quantify the corrosion propagation phase of the service life of corrosion affected reinforced concrete structure. Corrosion is one of the most important input parameter in corrosion induced damage prediction and should therefore require sufficient attention.

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