Development of Effective Prediction Technique for Condition Assessment of Concrete Structures: Corrosion Monitoring
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Abstract:
Corrosion is a chemical process of destruction of material because of its reaction with the environmental conditions. Corrosion occurs when the relative humidity of air becomes more than 65%. Corrosion in concrete is the leading cause for the deterioration of structures. Reinforced concrete structures show a very good durability as it is capable of withstanding the different kind of environmental exposure. However, the main limitation of concrete, even of good quality, is that the penetration of chlorides, carbon dioxide (CO₂), moisture, etc., can cause the corrosion of reinforcement bars (rebars). Corrosion of structure can be reduced by proper monitoring and taking suitable control measures at the proper time interval. Detailed review of corrosion of reinforced steel in concrete and its control has been studied and are presented in this paper.

Key words: Corrosion; Concrete; Reinforce; Chloride; Cement.

I. INTRODUCTION

Concrete is the most widely used construction material in the world. Many kinds of materials, elements and structures are fabricated with cement-based mixes. Reinforced concrete was industrially developed at the beginning of the 20th century, and it has stimulated tremendous developments in housing and infrastructures. Reinforced and prestressed concrete represents a very successful combination of materials, not only from a mechanical point of view but also from a chemical perspective, because the hydrated cement is able to provide to the steel an excellent protection against corrosion. This chemical compatibility allows for the composite behavior of reinforced concrete and is the basis of its high durability. The composite action occurring in the steel–concrete bond may be unlimited in time while steel remains passive. The study of the conditions leading to reinforcement. Corrosion is then of high importance because corrosion may significantly affect the load-bearing capacity of reinforced or prestressed concrete. The natural state of metals is their oxidized state. Metals can be found in nature in the form of oxides, carbonates, sulphates, etc. (minerals). In a pure state only the so-called ‘noble’ metals can persist in contact with the environment without undergoing oxidation. For the practical use of a metal, certain energy is invested in its reduction from the natural mineral state. The metal then presents the tendency to liberate this energy to attain its lower energy state. The process by which a metal returns to its mineral state is known as ‘corrosion’. Corrosion is therefore the process by which the metal passes from its metallic state at ‘zero’ valence to its oxidized state liberating electrons. For iron it can be simply written as:

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\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-
\]

Deterioration of concrete structures due to harsh environmental conditions leads to performance degradation of RC structures, and premature deterioration of structures before completing expected service life is major concern for engineers and researchers. Deterioration rate of structures depends on the exposure conditions and extent of maintenance. Corrosion, a result of chemical or electrochemical actions, is the most common mechanism responsible for deterioration of RC structures which is mainly governed by chloride ingress and carbonation depth of RC structures. Usually, there are two major factors which cause corrosion of rebars in concrete structures, carbonation and ingress of chloride ions. When chloride ions penetrate in concrete more than the threshold value or when carbonation depth exceeds concrete cover, then it initiates the corrosion of RC structures. If the corrosion is initiated in concrete structures, it progresses and reduces service life of the structures and rate of corrosion affects the remaining service life of RC structures. However, these severe environments can cause corrosion of reinforcement only if required amounts of oxygen and moisture are available at the rebar level in concrete structures. Corrosion of steel bars is the major cause of failure of concrete structures and about two tons of concrete is used. Due to the high alkalinity of concrete pore fluid, steel in concrete initially and, in most cases, for sustained long periods of time, remains in a passive state. Initiation of corrosion occurs either due to reduction in alkalinity arising from carbonation or the breakdown of the passive layer by the attack of chloride ions.

The time to initiation of corrosion is determined largely by the thickness and the quality of concrete cover as well as the permeability of concrete. High quality and durable concrete is required to reduce the rapid deterioration of concrete under severe environmental conditions. In this context, the beneficial effects of alternative cementing materials should be considered. When alternative cementations materials such as fly ash is used in concrete, not only reduced the porosity but also the pores become finer and the change in mineralogy of the cement hydrates leads to a reduction in the mobility of chloride ions.
Construct and use concrete structures with reinforcement of steel namely multi-storey buildings, bridges, dams, railway sleepers, tunnels, nuclear power plants, turbo generator foundations, reservoirs etc. Reinforced steel corrosion of the pre-stressed concrete structure is a trouble worldwide and has restored scientific attentiveness in the last few decades. If humidity and oxygen are present there International Journal of Engineering Science and Computing, Occurs corrosion in the reinforcement because of the entry of carbon dioxide which causes loss of alkalinity. Many progresses regarding to physical properties of entrained metal and the concrete have come up. However, it’s a very complicated task to regularly monitor the health of concrete structure because of the intricate and sophisticated design of structures and use of complicated instruments; this requires specialized knowledge for interpretation of data. Common materials which are easily available have been utilized to see their functioning on the potential growth at the metallic solution interface-Polystyrene, aluminum paint, red oxide and black Japan paint have been tested. When paint is utilized as an anti corrosive substance the key thing to be kept in the mind is the bond strength in between the reinforcement and concrete. Chemicals like CaCl2 and sodium Hexa-meta phosphate (HMP) were examined for their positive and negative performance of the maintenance/worsening of stable potential.

II. LITERATURE REVIEW

Naik et al, (1994) evaluated the effect of adding of a class C fly ash on the permeability of concrete by replacing cement with fly ash in the range of 0-70% by weight in the concrete composites. For the test results of air permeability, they have concluded that at lower ages upto 28 days, the concrete having high volume of fly ash showed higher levels of ingress of air relative to the normal Portland cement concrete. On water permeability test results, they have reported that concrete water permeability decreased with age. All three of the concrete mixes indicated fair resistance to water permeability upto the ages of 14-40 days. At 91-day age, the high volume (50%) fly ash concrete showed lower water penetrability to that of normal Portland cement concrete. They observed that chloride penetrability reduced with age. The 50% fly ash concrete showed the lowest permeability to chloride ions amongst all the mixture tested. The concrete composites with 50 and 70% replacements of cement with fly ash were better compared to the no fly ash concrete at 91 days with respect to chloride-ion permeability.

V. Saraswathyetal, (2002) studied numerous activation methods to improve the resistance to corrosion and also strength of concrete by speeding up the hydration of fly ash blended cement. The compressive strength of the concrete specimens after 7, 14, 28 and 90 days were evaluated which were prepared by replacement levels 10%, 20%, 30% and 40% of the activated fly ash and after that the results were compared with ordinary Portland cement concrete (without fly ash).

The activated fly ash cement showed better resistance to corrosion and strength of concrete when the replacement levels were 20–30% of activated fly ash cement. The better results were obtained when the fly ash was chemically activated as compared to the other activation investigated.

Haetal, (2005) investigated the influence of fly ash on the rusting performance of steel in concrete and mortar by some accelerated short-term techniques in NaCl solutions. The various techniques adopted for determination of durability enhancements were weight loss method, OCP (Open Circuit Potential) measurements, impressed voltage and anodic polarization technique. Apart from this macro cell corrosion studies, pH measurements and approximation of free chloride content were also performed. The replacement of fly ash up to 30% level helped in improving corrosion resistance properties of the steel in concrete, improved the permeability characteristics, delayed initiation time of corrosion and decreased.

H.A.F. Dehwah, (2012) evaluated the corrosion resistance of SCC (Self-Compacting Concrete) which was prepared using QDP (quarry dust powder), SF (silica fume) plus quarry dust powder or fly ash . SCC specimens were prepared and tested for corrosion resistance, chloride penetrability and diffusion. The permeability was moderate for chloride in SCC specimens including QDP or fly ash and the permeability was low in the specimen including QDP plus SF. M. Criado et al, (2012) examined the inhibitive consequence of two mixes of organic composites, disodium β-glycerol phosphate or GPH with sodium 3-aminobenzoate (3AMB) and glycerol phosphate with sodium N-phenylantranilate (PhAMB), on the rusting of carbon steel reinforced bars implanted in carbonated chloride-polluted OPC and alkali-activated FA (fly ash) mortars. At room temperature and at 65% relative humidity.

M. Kishore Kumar etal, (2012) studied the reinforced concrete durability w.r.t rusting of reinforcement. The initiation time and the time for cracking are determined by change in the slope of the specimens for different grades of concrete. For 30% replacement of cement with fly ash the initiation time of M25 grade was around 54 days as compared to other % of replacements. For 30% replacement of cement with fly ash the initiation time of M30 grade was around 63 days as compared to other % of replacements. For 30% replacement of cement with fly ash the initiation time was maximum in both grades of the concrete. The compressive strength of the concrete specimens is higher in both grades of the concrete at 90 days of curing. Rob B.

Ana Maria Aguirre-Guerrero etal, (2016) tested the performance of 2 hybrid kind geopolymer mortars made of alkaline-activated FA and MK (Metakaolin) as defensive coatings against the chloride-induced rusting in reinforced cement concrete. In both cases, the coated, Portland cement (OPC)-based concretes (substrates) were subjected to accelerated techniques such as impressed voltage and wetting/drying cycles in the company of 3.5% NaCl solution. International Journal of Engineering Science and Computing, August 2017 14400 http://ijesc.org/ The open circuit potential and linear polarization involving techniques were used to monitor the corrosion. To protect the structures that are open to marine locations, the geopolymer type mortars can be used.

Causes of corrosion in concrete

Durability issues associated with concrete structures are some of the biggest problems the civil engineering community is facing today around the world. One of the most significant
durability issues is the corrosion of steel reinforcement, which leads to rust formation, cracking, spalling, delamination and degradation of structures. This is considered to be the main factor causing damage in bridges and other infrastructure. Atmospheric corrosion, galvanic corrosion and stress corrosion cracking can impact the performance and appearance of concrete structures. Therefore, to deal with these issues, research around the globe is oriented towards developing methods or materials to prevent this corrosion of steel in concrete. This paper presents a review of reinforcement corrosion, its mechanisms, and prevention.

I: Corrosion of Steel in Concrete
In general, when metals and alloys interact with their environment chemically, biochemically or electrochemically, surface loss occurs, and they convert to their oxides, hydroxides, or carbonates which are more thermodynamically stable. This process is termed as corrosion. Along the surface of an embedded steel bar, when there is a difference in electrical potential, the concrete acts as an electrochemical cell which consists of anodic and cathodic regions on the steel, with the pore water in the hardened cement paste acting as an electrolyte. This generates a flow of current through the system, causing an attack on the metal with the more negative electrode potential i.e. the anode while the cathode remains undamaged. Thus, corrosion of rebar is initiated.

II: Chloride Induced Corrosion
Steel remains in passive state, i.e. free from corrosion, when it is embedded in a sound concrete layer; but it converts to an active state (corrosion initiates) when the concrete around it deteriorates. Chloride ions may penetrate from the environment or be mixed internally and reach the reinforcement. When chloride penetrates into concrete, the alkalinity near the reinforcement increases, to maintain electro-neutrality, Cl- and OH- ions diffuse to the interface. Because of their greater movement, the chloride ion concentration will build up close to the surface, saturating the interface with (Fe2+) and (Cl-). This will reduce the formation of Fe(OH)+ shifting the potential in a more cathodic direction. The chloride content required for steel depassivation and corrosion initiation is known as critical chloride content. If the chloride ion concentration goes beyond this threshold value, the passive layer gets locally destroyed and it leads to localized pitting corrosion.

III: Carbonation
The porosity of concrete ranges from the micrometre to the nanometre level. The porosity of concrete ranges from the micrometre to the nanometre level. In concrete’s pores, apart from liquid water, adsorbed water and structural water are present, which affects different structural and mechanical concrete properties. This porous structure and the natural reactivity of concrete make it prone to a natural degradation, called as carbonation. Penetration of CO2 into the concrete layer and subsequent neutralization of alkalis in the pore fluid is called carbonation. It reduces the pH of concrete to around 9 where the passive layer is not stable and corrosion may occur.

IV: Stress Corrosion Cracking (SCC)
SCC is defined as the process in which a crack grows on a metal due to simultaneous action of both tensile stresses and a corrosive environment, leading to failure without warning. Certain conditions lead to crack propagation due to the anodic part of the corrosion process; this is called anodic stress corrosion cracking. The conditions required for this type of SCC can only rarely be reached in concrete structures. Another form of SCC is caused by absorption in the metal of hydrogen gas produced by a cathodic reaction and is called hydrogen induced stress corrosion cracking.

IV: Stray Current Induced Corrosion
In concrete, electrolytic corrosion occurs when a current from an external source enters and leaves the reinforcing steel. This is referred to as stray-current corrosion. The currents can be generated from nearby cathodic protection systems, railways, high voltage power supplies etc. and travel through electrical paths other than their intended path.

V: Prevention of corrosion in concrete
The prevention of corrosion is primarily achieved in the design phase by using high quality concrete and adequate cover. This is very important, because the majority of the corrosion damages are related to wrong design or bad execution (placing, compaction and curing of concrete). Concerning the concrete quality, the beneficial effects of a low water-binder ratio on concrete permeability are well-known. The cement type is also important: blast furnace slag and pozzolanic cement greatly reduce chlorides transport in concrete, provided the concrete is properly cured. For more recent alternative binders (sulfoaluminate cements, activated alkaline binders, geopolymers), the research has not yet fully established which are the improvements and limitations related to the prevention of corrosion and for this reason these binders will not be taken into consideration in this paper. An increase in the thickness of the cover increases the barrier to aggressive species, delaying corrosion initiation, but very high cover depth, more than 70-80 mm, is not realistic. In relatively few but very important cases it may be necessary to increase the durability of the structure with appropriate preventative measures, often referred to as additional protection system. This happens in particular in the presence of very aggressive environment, mainly related to the presence of high concentrations of chlorides: marine structures, bridge decks, parking garages. These methods can also be used when it is impossible to obtain adequate cover thickness, as with very slender elements, when the structure is inaccessible for maintenance, or when the direct or indirect costs of future maintenance are extremely high.

VI: Cathodic prevention:
The application of cathodic protection (CP) to rebar in concrete dates back to the years ’70 and was initially referred to already corroding structures. In the early 90s, Pietro Pedeperri proposed a special type of cathodic protection: it consists to polarize cathodically the passive rebars before corrosion initiation. This technique was named cathodic prevention (CPrev), to distinguish its peculiarities from those of cathodic protection. The principle of cathodic prevention is based on the definition of localised corrosion initiation and repassivation, given by M Pourbaix. Pitting (corrosion initiation) and repassivation potential of steel reinforcements in chloride containing concrete are firstly proposed by Pietro Pedeperri and later introduced in the EN ISO standard for CP in concrete. Protection current density in the order of 1-3 mA/m2, lower than the values applied to corroding rebars, produces a cathodic polarisation.
(potential reduction) of 100-200 mV, then enabling an increase in critical chloride content of one order of magnitude, i.e., more than 4% by cement weight.

VII: Corrosion inhibitors:
Corrosion inhibitors seem to offer a simple and cost-effective prevention technique. They may be used both as a preventative technique, if added to fresh concrete, and as a repair system, if applied on hardened concrete. Only the first approach is considered here. Nitrite based inhibitors were studied since the early 50s. While organic inhibitors, based on blends of alkanolamines, amines or amino-acids, have been proposed in 80s. In proper concentration, some inhibitors can delay the initiation of corrosion, due to the higher critical chloride content: 1-1.5% by cement mass for organic corrosion inhibitors and variable, proportional to the dosage, for nitrite-based inhibitors: with the highest dosage the critical chloride content can be 2% or more.

III. METHODS OF CORROSION MONITORING

The different techniques have been reported in previous literature that can be used for monitoring and evaluating the corrosion of rebars in concrete structures for diagnosing the cause and effect of corrosion. Such studies were performed by different researchers and have been presented in Below Table.

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Method</th>
<th>Advantages</th>
<th>Limitations</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Galvanostatic pulse method</td>
<td>Measures half-cell potential and electrical resistance simultaneously</td>
<td>Unstabilized readings</td>
<td>Based on the polarization of rebar by means of small constant current</td>
</tr>
<tr>
<td>2</td>
<td>Linear polarization resistance (LPR)</td>
<td>Rapid and requires only localized damage, more detailed information</td>
<td>Measurements are affected by temperature and humidity</td>
<td>Electrical conductivity of fluid can be related to its corrosiveness</td>
</tr>
<tr>
<td>3</td>
<td>Half-cell potential</td>
<td>Simple, portable, results in the form of equi-potential contours</td>
<td>Needs preparation, saturation required, not very accurate, and time consuming</td>
<td>Electric potential of rebars is measured relative to half-cell and indicates probability of corrosion</td>
</tr>
<tr>
<td>4</td>
<td>Time domain reflectometry (TDR)</td>
<td>More robust, easy, and locates corrosion and identifies extent of damage</td>
<td>Less sensitive</td>
<td>By applying a sensor wire alongside of the reinforcement a transmission line is created. Physical defects of the reinforcement will change the electromagnetic properties of the line</td>
</tr>
<tr>
<td>5</td>
<td>Ultrasonic guided waves</td>
<td>Identify location and magnitude of corrosion</td>
<td>Not very reliable</td>
<td>Based on propagation of ultrasonic waves</td>
</tr>
<tr>
<td>6</td>
<td>X-ray diffraction and atomic absorption</td>
<td>Simple and reliable</td>
<td>Hazardous</td>
<td>Intensity of X-ray beams reduces while passing through a material</td>
</tr>
</tbody>
</table>

Methods to Protect Structures from Corrosion
To increase the service life of RC structures, it is required to protect reinforcing steel completely from being corroded. Several chemical and mechanical methods are developed to prevent concrete structures from corrosion by retarding the corrosion rate and by controlling corrosion through reducing permeability of concrete and reducing the ingress of harmful ions such as oxygen and moisture, and some protective systems have been used in the form of coating. Different corrosion inhibitors and protecting systems have been discussed below.

- Fly ash increased the corrosion resistance of concrete by reducing porosity of concrete porosity which decreases penetration rate of harmful ions.
- Penetrating amino alcohol corrosion inhibitor reduces the steel corrosion.
- Calcium nitrite based corrosion inhibitor reduces the carbonation depth.
Failure of concrete structures due to corrosion of embedded rebars is a major problem causing significant loss of money and time. Hence, there is a need to fully understand the root causes of failure before the repairing for effective remediation. An effective method to measure corrosion is a fundamental requirement for planning maintenance, repairing, and removal for reinforced concrete structures. Information regarding corrosion state required three parameters: half-cell potential, concrete resistivity, and corrosion current density. Corrosion rate in a concrete structure is governed by several parameters such as moisture content, availability of oxygen, and temperature. So, for better results it is necessary to repeat corrosion rate measurement in regular time interval. Half-cell potential measurement is the most widely used technique for the evaluation of corrosion of steel in concrete. However, in interpreting the data, environmental factors should be taken into account. For interpretation of half-cell potential readings, it requires precise understanding of corrosion protection mechanisms and good knowledge and experience in half-cell potential mapping. In present research it has been observed that half-cell potential measurements are useful.

V. REFERENCES


