

Corrosion of Steel Reinforcement Bars and its Protection by Geopolymer Coating

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Abstract

Embedded reinforcement bars in concrete structures, are prone to corrosion and it decreases the durability of concrete structures. Corrosion of rebars causes extensive spalling and cracking of concrete structures, finally our valuable structures will collapse within 15 to 20 years. Hence it is very much essential to prolong the service life of concrete structures by some means. There are many ways to prevent corrosion in concrete structures. Certain protective measures such as addition of inhibitors in concrete, coating to reinforcement bars and concrete surfaces, cathodic protection etc are widely used to prevent corrosion. Among these methods, coating to rebars is easiest and economical method of protection. Many coating systems such as galvanizing, cement based coating, epoxy coating, cement polymer coating, etc are now available for rebar protection. However, each coating is having its own merits and demerits. In this present study, the possibility of using geopolymer coating with industrial waste product fly ash has been attempted for rebar protection in order to extend the service life of concrete structures. In addition, several corrosion monitoring techniques have been adopted to evaluate its corrosion performance. Based on this preliminary study, it has been found that geopolymer coating improves the level of protection and extends the durability of reinforcement bars even in the presence of chloride.

Keywords: Corrosion, Mechanism, Rebars, Concrete, Protection, Geopolymer coating, Electrochemical techniques, Corrosion monitoring, Durability factor.

Introduction

Corrosion is defined as “the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties [1]. Generally, corrosion is a spontaneous process. It is thermodynamically unavoidable reaction of metals, which can be viewed simplistically as the tendency for a metal to revert to its natural, lower energy state, i. e., iron

ore. This tendency to decrease in energy is the main driving force behind corrosion of steel structures. Fig 1 illustrate th corrosion cycle of steel.

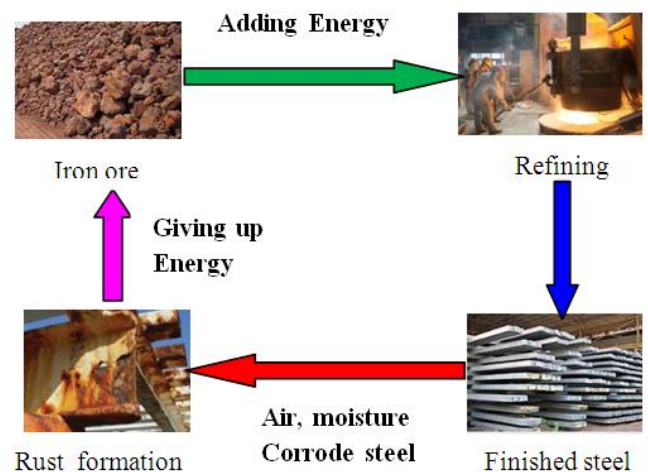
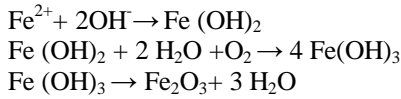


Fig. 1. Corrosion cycle of steel

A recent report determined that the direct cost of corrosion in the United States to be 3. 1% of the Gross Domestic product (GDP). [2]. Reinforced Cement Concrete [RCC] is the most commonly used construction material all over the world. Corrosion of steel rebars represents the major cause of degradation of reinforced concrete structures. The two main causes of electrochemical corrosion of rebars are carbonation and the presence of chlorides [3]. Carbonation usually induces a generalized corrosion while chloride will lead into pitting or localized attack. Basic Corrosion processes of steel in concrete are (1) depolarization reagent arrives at the surface of metal through the medium surrounding it, (2) Electrochemical reactions occur at the interface between the metal and surrounding medium.



and (3) Reaction products are accumulated at the surface of metal or removed away from the surface of metal into solution.



When the moving ferrous ions and hydroxide ions meet, they react to form ferrous hydroxide $\text{Fe}(\text{OH})_2$. If moisture and oxygen are present, the ferrous hydroxide is then further oxidized to form ferric oxide or rust. As a result of these effects, longitudinal cracking of concrete cover has been formed due to expansive corrosion products and degradation of steel concrete bond as shown in Fig. 2.

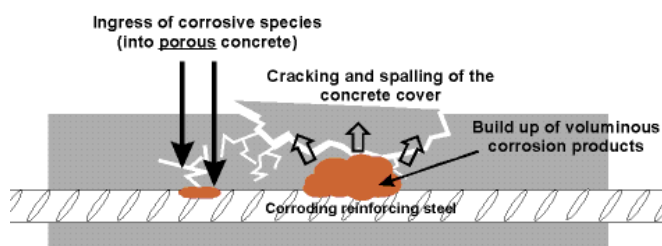


Fig. 2. Corrosion of rebars in concrete

As a result of these effects, the service life and the load-bearing capacity of reinforced concrete elements are considerably reduced. Table 1 shows the causes and effects of corrosion of rebars.

TABLE. 1. Causes and effects of corrosion of rebars

Causes	Effects
Expansion stress by rust	Longitudinal cracking
Dissolved Fe^{2+} in pore solution and ooze out along cracks	Steel cross section reduction and rust stain on the surface of concrete structure
Reduction in steel cross section	Degradation of steel-concrete bond and breakdown of reinforcement
Degradation of steel-concrete bond and reinforcement	Spalling of concrete and degradation of structures

In order to prevent corrosion, certain protective measures have to be adopted in RCC structures such as addition of inhibitors in concrete, coating to reinforcement bars, coating on concrete surfaces, cathodic protection etc, [4]. Among the above techniques, application of coatings over rebars is an effective and economical way of protection. Rebar coatings such as metallic coating like Galvanizing [GAL], Fusion Bonded Epoxy coating [FBE], Interpenetrating Polymer Network coating [IPN], Cement Slurry Coating [CSC], Conducting Polymer Coating [CPC], Cement Polymer Composite Coating

[CPCC] are widely adopted all over the world. However, each system is having its own merits and demerits.

In this present study, the possibility of using geopolymer coating with industrial waste product fly ash for rebar protection against corrosion. The corrosion performance of geopolymer coating [GPC] system has been evaluated in simulated concrete environment i. e. cement extract [CE] even in the presence of chloride i. e., CECl.

Literature review on geopolymer coating

Z. F. Farhana et al carried out a study on corrosion behaviour of rebars embedded in geopolymer paste by potential method and conclude that the passive layer formed on the rebar embedded in the paste protect them against corrosion [5]. P. N. Balaguru et al evaluated the effectiveness and durability of geopolymer surface coating using strength test of flexural concrete prisms reinforced with carbon steel [6]. HuiCong Hao et al examined the characteristics of geopolymer made with solar panel waste glass and concluded that it has the potential to serve as the partial replacement of Metakaolinite and exhibits favourable mechanic characteristics[7]. M. S. Sity Salwa et al reported the potential of geopolymer coating for better future with a reduced carbon foot print [8].

M. Irfan Khan et al carried out studies on class F fly ash based sodium silicate free geopolymer coating and declared that it can be used as a green coating for material protection [9]. Y. Zarina et al examined the geopolymer coatings made with metakaolin, fly ash and granulated blast furnace slag and concluded that it has several advantages like prevention of corrosion, high bonding strength and suitability in high temperature exposure [10]. Abdullaj Mohd Mustafa Al Bakri et al investigated a method for geopolymer coating on material for high fire and erosion resistance and high mechanical strength [11].

Jadambaa Temuujin et al examined the feasibility of using fly ash for the manufacture of fire resistance coating on metal substrates and declared that the optimised coating formulation exhibit a very promising fire resistant characteristics [12]. Mohd Mustafa Al Bakri Abdullah et al carried out studies on fly ash based geopolymer protective coating material and their effective applications. It has reported that geopolymeric mix design has superior use as cementitious coatings with high thermal applications [13]. Zuhua Zhang et al investigated the interfaces between the geopolymer and cement paste and cement mortar and the pore structure of geopolymer by various characterization methods and concluded that the amorphous alumina silicate geopolymeric gels, which were chemically fit in seawater, to provide a suitable protection for marine concrete structures [14].

From the literature, it is clear that geopolymer has been used as either coating for concrete surfaces or concrete as fire resistance material etc. No literature is available on geopolymer coating for corrosion protection rebars. Hence it is proposed to study the corrosion resistance behaviour of geopolymer coated specimens exposed in CECl.

Experimental

Various electrochemical studies have been performed on

uncoated and geopolymer coated specimens exposed in CECl environment.

Preparation of cement extract

Initially, cement extract (CE) has been prepared with Portland Pozzalona Cement (PPC) for electrochemical studies. Known amount of PPC has been accurately measured using a digital balance and transferred to conical flasks. Then distilled water with a water-cement ratio 2:1 is added to the cement and mixed thoroughly. Conical flasks containing cement and water mixture are rigidly fixed in the spring mounted clamps of the electronic shaker (Fig. 3). This shaker is run for one hour. Finally, the mixture containing cement and water is filtered through No. 1 Wattman filter paper. Then the filtrate is collected and stored in air tight container. Thus the obtained filtrate is known as cement extract (CE). pH of CE has been measured using Digital pH meter and a value of 12. 21 has been obtained.



Fig. 3 Preparation of cement extract

Preparation of geopolymer coating system

Geopolymer is prepared by fly ash with sodium hydroxide and sodium silicate activators. Initially, binder solution has been prepared with a mixture of sodium hydroxide sodium silicate solutions and they were kept for 24 hours for complete polymerisation reaction.

In the next day, siliceous and inhibitive pigments like fly ash [F], titanium-di-oxide [T], iron oxide [F], aluminium oxide [A] have been thoroughly mixed with binder solution. Then this binder pigment mixture has been applied on the rebar surface by brushing. Later, these specimens have been kept in the oven at specific temperature to form uniform coating and it is known as "geopolymer coating [GPC] system.

Electrochemical studies

The corrosion behaviour of uncoated and geopolymer coated specimens have been studied by various electrochemical techniques such as electrochemical impedance spectroscopy (EIS), linear polarization (LPR), potentio-dynamic polarization (Tafel), anodic polarization and potential time behaviour. The geopolymer coated specimen has been used as working electrode. Saturated calomel electrode (SCE) and

platinum foil are used as reference and auxiliary electrodes respectively.

Three electrode system has been adopted in all electrochemical studies except potential time behaviour. Digital voltmeter with an accuracy of ± 10 mV is used for measuring potential of working electrode. EIS, LPR and Tafel techniques have been carried out using an electrochemical measurement unit Princeton Applied Research, model PARSTAT 2273. and interpretation has been done by the respective softwares provided in this instrument. Anodic polarization has been performed in CE with 1000 ppm of chloride condition and the remaining electrochemical techniques are carried out in CE with 5000 ppm chloride condition. The results obtained by the above three techniques are presented in Table 2.

Electrochemical Impedance Spectroscopy(EIS) technique

The corrosion performance of geopolymer coated rebars has been studied by electrochemical In EIS study, frequencies ranging from 100 Kilo hertz to 10 milli hertz with 6 points per decade and AC amplitude of 10 mV have been impressed and the response in terms of charge transfer resistance [R_{ct}] has been obtained. The impedance plot has been fitted with ZSimpwin software (version 3. 21).

Linear polarization technique

To study the instantaneous corrosion rate of geopolymer coated specimens in cement extract using Linear Polarization Technique (LPR). The geopolymer coated rebars has been immersed in PPC extract with 5000 ppm of chloride and the open circuit potential; (OCP) has been measured initially. In this method, the potential current behaviour has been studied in the potential region of ± 20 V at the vicinity of OCP. Later the polarization resistance (R_p) has been predicted from the slope of the polarization curve. The curve fitting for linear polarization has been done by PowerCORR software.

Potentiodynamic Polarization Study

The corrosion behaviour of geopolymer coated specimens exposed in PPC extract with 5000 ppm of chloride has been evaluated by Potentiodynamic polarization technique i. e., Tafel extrapolation method. The potential range of ± 200 mV at the vicinity of OCP has been applied on the geopolymer coated rebars exposed in PPC extract. From the polarization curves, the corrosion current (I_{corr}) values had been determined. Later corrosion rate (mmpy) has been calculated.. The curve fitting for this test has been done by PowerCORR software.

Anodic polarization test

In order to study the tolerable limit for chloride of geopolymer coated rebars, an accelerated electrochemical technique known as anodic polarization technique has been carried out. Initially, the open-circuit potential of geopolymer coated specimens is measured against Saturated Calomel Electrode (SCE). Then it is anodically polarized by applying a current of $290 \mu\text{A}/\text{cm}^2$ through a platinum foil auxiliary electrode. The variation in potential with time is measured with a digital voltmeter. This experiment is carried out for two medium viz., CE and CE with 1000 ppm of chloride medium.

Potential time studies

The corrosion behaviour of the above two systems have been studied using open-circuit potential measurement with respect to a Saturated Calomel Electrode (SCE). A digital voltmeter has been employed for this study. This potential is measured on each specimen at an interval of 24 hours and the corresponding values are monitored for a period of 33 days..

Results and Discussion

The results obtained by the EIS, LPR and Tafel techniques on geopolymer coated and uncoated specimens exposed in CECl condition are presented in Table 2. The Bode plot of impedance measurement is shown in Fig. 4. The curves attained from potentiodynamic polarization for GPC and uncoated systems are given in Fig. 5.

TABLE. 2. Data on corrosion obtained from EIS, LPR and Tafel techniques

Sl. No	Systems Studied	Electrochemical Techniques		
		EIS	LPR	Tafel
		Rct (KΩ)	Rp (KΩ)	CR (mmpy)
1	GPC system	2.928	2.981	0.1530
2	Uncoated	1.346	1.300	0.5440
Durability Factor		2.180	2.290	3.560

The anodic polarisation behaviour of uncoated and GPC coated specimens is shown in Fig. 6. From the figure it can be seen that uncoated specimen shows OCP value of -562mV. After impressing current, it move towards anodic direction. But, except one value all the other potential values are in negative side. The visual inspection clearly indicates that severe rust spots found on the entire surface of the exposed portion.

In the case of geopolymer coated specimen the initial OCP was -194mV and a value of 337 mV has been observed after impressing current. Throughout the test period, the geopolymer coated system displays positive values and not even a single rust spot has been found on the exposed portion. This results clearly indicates that GPC system can tolerate 1000 ppm of chloride.

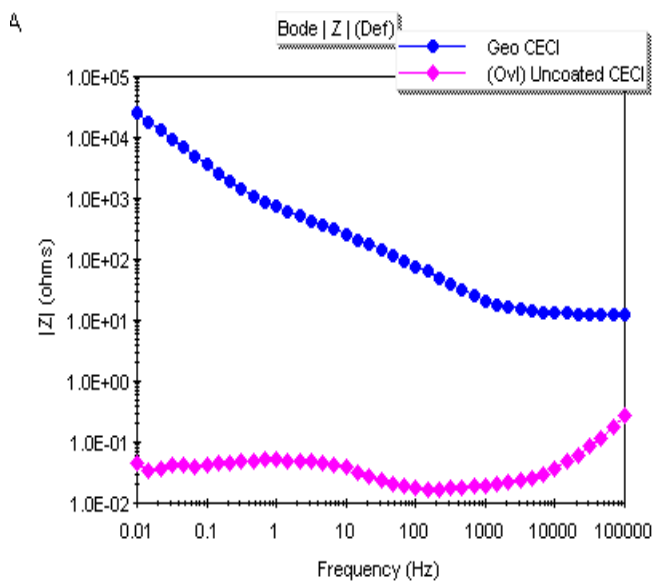


Fig. 4. Bode plot for GPC and uncoated systems

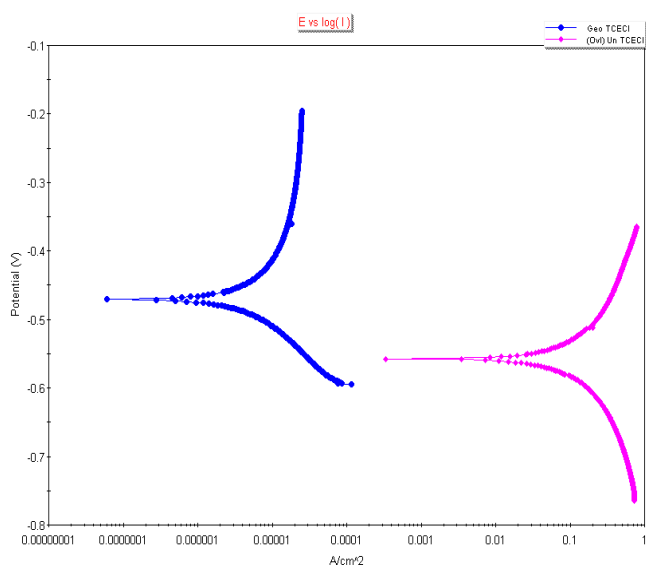


Fig. 5. Polarization curves for GPC and uncoated systems

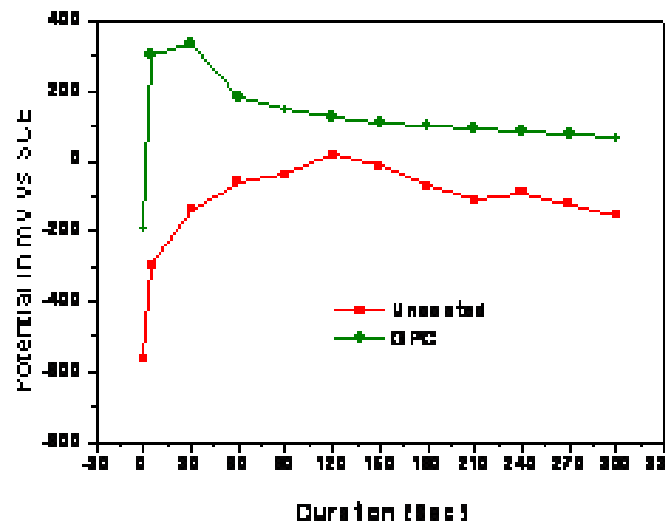


Fig. 6. Anodic polarization behaviour of GPC and uncoated systems

The potential time behaviour of GPC and uncoated systems is shown in Fig. 7. From the figure it can be observed that the uncoated specimen shows a maximum potential of -860mV within 4 days of exposure. Later on, it fluctuates with time. However, majority of values are more than -750mV indicating its active condition. In the case of GPC system, the potential fluctuate with time upto 16 days. Later on, almost steady state potential values were observed. In general, the potential values are far less than the potential of uncoated system. This indicates its protective ability even in the presence of chloride.

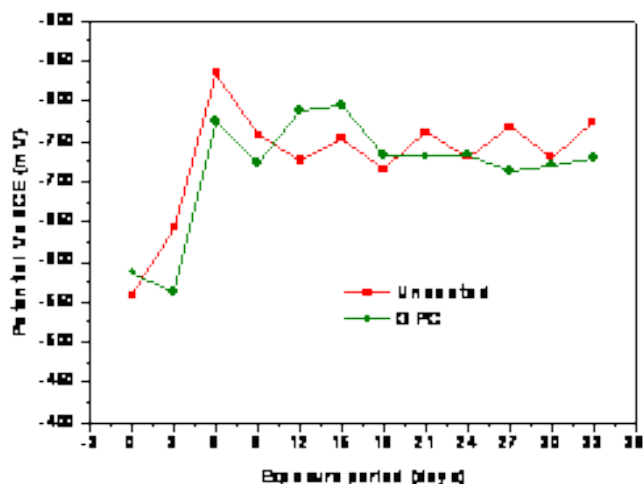


Fig. 7. Potential time behaviour of GPC and uncoated systems

Conclusions

The results of various electrochemical studies clearly indicate the corrosion resistant behaviour of GPC system even in the presence of 5000 ppm of chloride. A minimum durability factor of 2 has been obtained for GPC system. It can tolerate 1000 ppm of chloride even under accelerated test condition. The potential values of GPC system are less than the potential of uncoated system. From the above findings, it can be concluded that geopolymer coating has superior corrosion resistant property and enhance the service life of concrete structures even in the presence of chloride.

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