Model Based Corrosion Assessment in Rebars of Different Fly Ash Blended Concrete using Piezo Sensors

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ABSTRACT

With the increase in infrastructure developments and increasing emphasis on the use of green materials, the construction industry is in the need of constant innovation and improvisation in both materials and technology. The fly ash (FA) is most widely used in the construction field as a replacement of cement in concrete production. In this paper, model-based corrosion assessment in rebar of different FA blended concrete using non-dimensional stiffness parameter determined by piezo sensors is studied. The Accelerated corrosion tests are conducted on rebar of different blended concrete cylindrical specimens, before embedding the rebar in concrete piezo sensors are surface bonded. The measurements are made with the piezo sensor of size 10x10x0.2mm surface bonded on rebar using electro-mechanical impedance (EMI) technique. The non-dimensional stiffness parameter is acquired out from the conductance and susceptance signatures of the piezo sensor. The stiffness parameter is standardized against the corrosion level. Based on the level, a corrosion evaluation model is proposed. The experimental results based on the model-based corrosion assessment shows that it can be proved for normal concrete, blended and fly ash based geopolymer concrete.

1. Introduction

Steel embedded in concrete is protected against corrosion by both, chemical and physical barriers. Chemical protection is provided by the high pH (12.5±1) of the concrete interstitial solution, which causes passivation of the reinforcing steel. Physical protection can be achieved by hindering the access of aggressive agents. The development and use of blended cement is growing rapidly in the construction industry mainly due to considerations of environmental protection, energy saving, cost saving and conservation of resources[1]. Hence, the various replacements of cement with FA and Geopolymer (FA and geopolymer addition affects the physical and chemical properties of concrete) on the corrosion resistance are studied. Fly Ash (FA) is a fine residue from powdered coal combustion that acts as a pozzolanic material [2] i.e. the particles react with water and lime to produce cementitious products[3,4]. Reasons for FA replacements of cement in various proportions include economy and enhancement of certain properties of the fresh concrete (workability and pumpability) and of the hardened concrete[4]. The term ‘Geopolymer’ was acquainted by Joseph Davidoits in 1978 for a class of inorganic, amorphous to semi-crystalline, three-dimensional silico-aluminate materials[5]. The chemical reactions among various alumino-silicate oxides with silicates under highly alkaline conditions, yielding polymeric Si-O-Al-O bonds called as Geopolymerisation[6]. The two principle constituents of geopolymers are source material and alkaline liquids. The source materials on alumina silicate ought to be rich in silicon (Si) and aluminum (Al). Reasons for geopolymer replacement of cement in various proportions because it possess excellent mechanical properties and fire resistance[7].
The geopolymers are used as heat-resistant materials\cite{9-12}, refractory material\cite{13}, high-tech composites\cite{14-16}, thermal insulation\cite{17-21}, cements and concretes\cite{22-25}, and for medical application\cite{26} in research and development. The influence of a combination of FA and ground granulated blast-furnace slag (GGBS) on the properties of high strength concrete has been studied\cite{27}. Worked has been done on three types of mix first plain cement concrete (PCC), second high volume fly ash concrete (HFAC, containing 40% of FA) and ground granulated fly ash concrete (GGFAC, containing 25% of FA and 15% of GGBS) and observed their mechanical behaviour and acid resistance up to 50 weeks and present their microstructure at 7 days and 360 days and also their study by using SEM. And found that GGFAC achieved satisfactorily early strength while maintaining long-term strength than PCC and GGFAC is superior to PCC and HFAC in terms of acid resistance.

Nevertheless, attention should be focused on the role of FA and geopolymer in the corrosion mechanism, especially on chloride-induced corrosion. The influence of FA on chloride permeability of concrete has been studied\cite{28}. The threshold chloride level increased with increasing FA content has been reported\cite{29}. FA concrete was found to have increased resistance to chloride ion penetration and increased electrical resistance. Interestingly, some studies reported that FA can accelerate the corrosion of steel in concrete\cite{30,31}. Hence, FA and geopolymer can be used as a replacement material with cement for health monitoring and corrosion assessment in rebar. The other corrosion-related studies on FA and geopolymer include the following:

Talakokula et al., (2014)\cite{32} presented a diagnostic approach for the assessment of corrosion based on equivalent system parameters via EMI technique and found that the extracted equivalent structural parameters correlate well with the actual stiffness and mass. Also, identified the corrosion rate using lead zirconate titanate (PZT) identified mass loss and found that the PZT it correlates well with the actual mass loss. At last, they recommended that a value of Δk/k over 0.4 indicates alarming corrosion. Talakokula and Bhalla (2014)\cite{33} presented a comparative study of reinforcement corrosion assessment capability using surface bonded piezo sensor (SBPS) and embedded sensor (ES, in the form of CVS) for RC structures using equivalent structural parameters and they concluded that the embedded CVS is effective in monitoring the initial changes occurring during the ingress of chloride ions into the concrete and both the SBPS and CVS are complementary to each other and should be used together for more comprehensive monitoring. Talakokula et al., (2018)\cite{34} monitored the early hydration of RC structures using non-dimensional structural parameters identified by piezo sensors via EMI technique and they found that the non-dimensional structural parameters are effective in monitoring the early age hydration. Sam et al., (2012)\cite{35} proposed a reusable method for the EMI method using piezo sensors to evaluate the damage of the adhesive layer between fibre-reinforced plastic plates in a corrosive environment. Farhana, Z.F. et al. (2013)\cite{36} studied the corrosion performance of reinforcement bar in GPC and OPC and results shows that fly ash based geopolymer concrete has high alkalinity which provides the passivity of reinforcement bars, good corrosion performance and low corrosion rate as compared to reinforcement bar embedded in OPC because reinforcement bar in GPC coated with strong and adherent silicate membrane.

In this paper investigates a model-based rebar corrosion assessment in different fly ash blended concrete using a piezo sensor via electro-mechanical impedance (EMI) technique. The quantification of corrosion-induced damage is based on the non-dimensional stiffness parameter and the statistical index identified by the piezo sensor. The Paper first presents a brief description of the EMI technique and then the development of empirical equivalent models based on measured electro-mechanical data.

2. EMI Technique Using PZT Patches

In the EMI technique, both the direct and the converse effects of the piezo sensors are utilized. The bonded PZT patch is first excited using an impedance analyser such that it starts vibrating and thus interacts with the host structure (converse effect). The structural interactions are in turn reflected in the form of electrical admittance signature (sensor effect). The self-sensing properties of the PZT
patch allow it to measure the output current produced by the application of specified voltage signal at a specified frequency. Because the PZT patch is bonded directly to the surface and it has been shown that the mechanical impedance of the structure is directly correlated with the electrical impedance of the PZT patch. The various application of the piezo sensor in structural health monitoring, energy harvesting, and bio-mechanics can be found in the author’s recent publication. The definition of effective impedance by considering force transfer distribution along the entire boundary of the PZT patch is introduced, to propose a further modification and improvement in modelling. A modified expression for coupled admittance signature shown in equation (1)

\[
\tilde{Y} = G + Bj = 4\omega j
\left[ \frac{T_{33}}{\rho{\varepsilon}^2} - \frac{2d_{31}\varepsilon^E}{(1-v)} + \frac{2d_{31}\varepsilon^E}{(1-v)} \left( \frac{2Z_{a,eff}Z_{s,eff}}{Z_{a,eff}+Z_{s,eff}} \right) \right]
\]

where G is the conductance, B is susceptance, ω is the angular frequency, w, l and h are the dimensions of PZT patch, Z_{a,eff} and Z_{s,eff} are the effective impedance of the structure and the PZT patch respectively, Υ is the complex Young’s modulus of elasticity (at constant electric field), ε is the complex electrical permittivity, k is wave number, d_{31} is piezoelectric strain co-efficient and v is the poisons ratio. It may be noted that Complex tangent ratio \(\bar{T}\) was introduced in place of \(\frac{\tan k l}{k l}\) with correction factors C1 and C2 for more accurate results.

### 3. Experiment Details

In this study, M30 grade concrete mixes, designated as A, B and C were cast in accordance IS 456 (2000). Mix A consists of cylindrical samples with the normal mix, Mix B consist of cylindrical samples with blended mix and Mix C consists of cylindrical samples with the FA+geopolymer mix as detailed in Table 1, 2 and 3. The size of the cylindrical specimen was 150-mm length and 100-mm diameter. The rebar was high yield strength deformed (HYSD) steel of 16-mm diameter, grade Fe 415 conforming to IS 1786 (1985) was placed at the centre of each cylindrical sample at the time of casting. The rebar’s length was 150mm, allowing 50mm to project out at one end of the cylinder. Mix A,B and C consist of surface bonded piezo sensor in which a piezo sensor surface bonded to rebar before casting as shown in Figure 1(a).

#### Table 1. Mix Proportion of M30 grade normal Concrete

<table>
<thead>
<tr>
<th>w/c Ratio</th>
<th>Cement (kg/m³)</th>
<th>Fine Aggregate (kg/m³)</th>
<th>Coarse Aggregate (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Superplasticizer (% by weight of cement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.43</td>
<td>482.55</td>
<td>932.33</td>
<td>744.38</td>
<td>207.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

#### Table 2. Mix Proportion of M30 grade Blended Concrete

<table>
<thead>
<tr>
<th>w/c Ratio</th>
<th>Cement (kg/m³)</th>
<th>FlyAsh (kg/m³)</th>
<th>Fine Aggregate (kg/m³)</th>
<th>Coarse Aggregate (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Superplasticizer (% by weight of cement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.43</td>
<td>313.66</td>
<td>168.89</td>
<td>901.45</td>
<td>719.73</td>
<td>207.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

#### Table 3. Mix Proportion of M30 grade fly ash based Geopolymer Concrete

<table>
<thead>
<tr>
<th>Ratio of Na₂SiO₃/NaOH</th>
<th>FA+GGBS (kg/m³)</th>
<th>Fine Aggregate (kg/m³)</th>
<th>Coarse Aggregate (kg/m³)</th>
<th>Na₂SiO₃ (kg/m³)</th>
<th>NaOH (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>550</td>
<td>500.83</td>
<td>876.5</td>
<td>239.64</td>
<td>95.86</td>
</tr>
</tbody>
</table>
The baseline conductance signatures from the SBPS were acquired after the 28-day curing period as shown in Figure 2(a), 2(b) and 2(c). Under normal environmental conditions corrosion of a rebar is a relatively slow process, often taking several years to progress significantly. An accelerated corrosion (Figure 1(b)) through impressed current technique was adopted\(^\text{[4-41]}\) to obtain the results in a reasonable time frame. After the baseline signatures were acquired, the specimens were placed in a beaker containing a “brine” solution (of salinity 35 parts per thousand). To accelerate corrosion, an electrical loop was set up with the steel bar specimens forming the anode, and the negative terminal was connected to a copper bar dipped in the solution acting as a cathode. A constant voltage of 10V was applied to the specimens using voltage supply until the specimens cracked due to corrosion. During this accelerated corrosion exposure, the admittance signatures were acquired periodically from the PZT patches.

\[
\text{Figure 1. a) Cylindrical Specimen with attached SBPS, b) accelerated corrosion setup}
\]

\[
\text{Figure 2. Baseline conductance signature (a) Normal Concrete, (b) Blended Concrete, and c) Fly ash based Geopolymer Concrete}
\]
3.1 Effect of corrosion exposure

The conductance signature of normal, blended and Fly ash based geopolymer sample during accelerated corrosion until sample crack is shown in Figure 3(a), (b), (c), and (d). Due to the formation of corrosion products and cracks, the resonance peak shifts from the baseline position. When the properties of the host structure are changed, the mechanical impedance of the structure will be changed resulting in a deviation of signature.

![Graphs showing conductance signature during corrosion exposure](image)

**Figure 3.** Variation of conductance signature during accelerated corrosion exposure a) Normal, b) Blended and c) Fly ash based Geopolymer concrete

4. Root Mean Square Deviation

As seen from Figure 3, the peaks of conductance signature shifted due to corrosion process which shows that the changes in the specimens due to corrosion have been captured well by the PZT patches. For quantitative analysis, different methods are used like signature assurance criteria (SAC), wave chain code (WCC) and root mean square deviation (RMSD). Bhalla et al. (2001) compared all the above methods and found RMSD is the most suitable method to quantify structural damage as it gives a scalar value for the deviation as shown in equation (2)

$$\text{RMSD} = \sqrt{\frac{\sum_{i}^{N} (G_i - G_i^0)^2}{\sum_{i}^{N} (G_i^0)^2}}$$

where

$G_i$ = conductance of PZT patch at any stage during the test, $G_i^0$ = baseline value, $i$ representing the frequency index (30-300 kHz). Figure 5 illustrates the RMSD index of normal, blended and Fly ash based geopolymer sample. The RMSD value for normal concrete exhibits a linear trend with a large scatter as shown in Figure 4(a). For blended concrete, the RMSD value exhibits a polynomial trend as
shown in Figure 4(b). For Fly ash based geopolymer concrete, the RMSD value could not be able to provide a consistent variation and as shown in Figure 4(c). A similar trend with RMSD value has been observed for reinforced concrete structures[32] and for steel bolted specimens[44]. Hence, RMSD based damage index could not be able to provide a consistent variation. To further gain the corrosion progression, non-dimensional stiffness parameter were extracted from the mechanical impedance of the structure and analysed, as described in the next section.

![Graphs showing RMSD variation](image)

**Figure 4.** Variation of RMSD index during accelerated corrosion progression: (a) Normal, (b) Blended, (c) Fly ash based Geopolymer

### 5. Analysis Based on Non-Dimensional Stiffness Parameter

An impedance technique was used to understand the correlation between change in signatures and corresponding change in non-dimensional stiffness parameters. This technique is outlined by [32,33,43] to determine the mechanical impedance of the structure, \( z_{\text{eff}} = x + yj \), at a particular frequency, \( \omega \), from the conductance and susceptance signature. The identified mechanical system for the normal, blended and Fly ash based geopolymer sample consisted of parallel spring damper system (k-c), parallel spring mass damper system (k-m-c) and series spring mass damper system (k-c-m) when examined in the frequency range 220kHz to 280kHz, 210kHz to 250kHz and 220kHz to 280kHz respectively as shown in Figure 5(a), 7(a) and 9(a).

Figure 5(b, c), 7(b, c) and 9(b, c) shows the variation between the experimental system and identified equivalent system. From this, it is observed that both the system matched well. Hence, the structural system identified based on well-matched of the ‘x’ and ‘y’ analytical plots and experimental system counterparts. Figure 6 shows the variation of identified stiffness and variation in \( \Delta k/k \) with corrosion progress of normal concrete sample. Figure 8 shows the variation of identified stiffness and variation in \( \Delta k/k \) with corrosion progress of blended concrete sample. Figure 10 shows the variation of identified stiffness and variation in \( \Delta k/k \) with corrosion progress of fly ash based geopolymer concrete. After an exposure period of 30 days with corrosion progression, the stiffness can be reduced by about...
35%, on an average in normal and blended sample while in flyash based geopolymer it can be reduced by about 20%, on an average after an exposure period of 60 days. By visual inspection of the sample, it can be observed that after 20 days the accumulation of corrosion products has just started and by 30 days, it had reached an alarming level where the sample had cracked due to the large increase in the volume of these corrosion products at the concrete/steel interface. Hence chloride-induced corrosion process can be distinguished into three phases based on visual inspection and non-dimensional stiffness parameter. In the normal and blended sample, based on non-dimensional stiffness parameter (Figure 6, 8 and 10), the corrosion phases divided into three phases. Phase I, the corrosion initiation phase up to 10 days, during which the non-dimensional stiffness parameter ranges from 0 to 0.2; phase II, the corrosion propagation phase up to 20 days, during which it ranges from 0.2 to 0.4 and in phase III, the cracking of concrete had reached after an exposure of 20 days. Hence, $\Delta k/k = 0.4$ indicates the alarming level in which the concrete had cracked. In flyash based geopolymer concrete, the days become twice but the ranges in all the phases in same.

5.1 Normal Concrete

The ‘x’ and ‘y’ for the identified system was given by\(^{(44)}\) in equations (3) and system parameters can be determined by algebraic manipulations as shown in equations (4)

\[
\begin{align*}
\begin{cases}
x = c \\
y = -\frac{k}{\omega} \\
c = x \\
k = -\omega y
\end{cases}
\end{align*}
\]  

![Figure 5.](image)

(b) Experimental System  
(c) Equivalent System

**Figure 5.** Identified system and comparison of experimental and equivalent plots: a) identified system (parallel combination of spring-damper), b) variation of ‘x’ and c) variation of ‘y’
5.2 Blended Concrete

The ‘x’ and ‘y’ for the identified system was given by\(^{(44)}\) in equations (5), and system parameters can be determined by algebraic manipulations as shown in equations (6)

\[
\begin{align*}
x &= c \\
y &= m\omega - \frac{k}{\omega} \\
c &= x \\
k &= \frac{y\omega\omega_0^2}{\omega^2 - \omega_0^2}
\end{align*}
\]

where, y=0, then \(\omega = \omega_0\)

(a)
Figure 7. Identified system and comparison of experimental and equivalent plots: a) identified system (parallel combination of spring-mass-damper), b) variation of ‘x’ and c) variation of ‘y’

Figure 8. Variation of identified stiffness and Variation in $\frac{\Delta k}{k}$ with corrosion progress

5.3 Fly ash based Geopolymer Concrete

The ‘x’ and ‘y’ for the identified system was given by\textsuperscript{[44]} in equations (7) and system parameters can be determined by algebraic manipulations as shown in equations (8).

\[
x = \frac{c^{-1}}{c^{-2} + \left(\frac{\omega}{k} - \frac{1}{\omega m}\right)^2}
\]
\[
y = -\frac{\left(\frac{\omega}{k} - \frac{1}{\omega m}\right)}{c^{-2} + \left(\frac{\omega}{k} - \frac{1}{\omega m}\right)^2}
\]
\[
c = \frac{x^2 + y^2}{x}
\]
\[
k = \frac{(\omega_0^2 - \omega^2)(x^2 + y^2)}{y\omega}
\]

where, $y=0$, then $\omega = \omega_0$
Figure 9. Identified system and comparison of experimental and equivalent plots: a) identified system (series combination of spring-mass-damper), b) variation of ‘x’ and c) variation of ‘y’

Figure 10. Variation of identified stiffness and Variation in $\Delta k/k$ with corrosion progress

Conclusion

This article presented a model-based corrosion assessment in different fly ash concrete by means of EMI technique using admittance signatures to determine damage sensitive non-dimensional stiffness parameter. The experimental results based on the model-based corrosion assessment shows that it can be proved for normal concrete, blended and fly ash based geopolymer concrete. From the results and observations, it is recommended that $\Delta k/k = 0.4$ indicates alarming corrosion level. The fly ash based geopolymer concrete has good corrosion resistance as compared to normal and blended concrete.
References