Rebar Corrosion Assessment Comparison of Different Piezo Configurations in Blended Concrete

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ABSTRACT

An embedded piezo sensor has high sensitivity, higher longevity, low cost and special encapsulation to the sensing element such that it is protected against deterioration by water. Its application of self-sensing mechanism technology is aimed at achieving high performance, better and more reliability and uniform quality. In this study different blended concrete cylindrical specimens were prepared to investigate the rebar corrosion assessment comparison of two different piezo configurations (surface bonded and embedded) in blended concrete. Experiments are conducted on different blended concrete on which piezo sensors are surface bonded on rebar and embedded in the surrounding of the rebar inside the concrete to compare the sensing capability of the two configurations. A series of accelerated corrosion tests have been performed on reinforced cylindrical concrete specimens. The equivalent stiffness parameter and the statistical index are being compared for the two types of sensor configurations. The experimental results based on the qualitative and quantitative analysis shows that the surface bonded and embedded piezo sensor assessed corrosion and are complementary to each other.

1. Introduction

The worldwide estimated cost of corrosion to be US$2.5 billion, which is equivalent to roughly 3.4 percent of the global domestic product (GDP) [1]. In reinforced concrete structures corrosion of rebars is one of the main causes which induces an early deterioration, reducing their residual service life [2]. When the aggressive agent reaches the reinforcement, due to chloride attack, corrosion may start affecting the steel (due to the reduction of both the mechanical properties and the bar section), the concrete (due to cover cracking) and both concrete and steel (due to the bond deterioration). Consequently, the safety and serviceability of the reinforced concrete structures are affected. Because of the very large number of existing deteriorated structures, urgent measures are required to decide when and how to repair them. About this subject, many authors assessed the corrosion in reinforced concrete structures by electro-chemical techniques such as linear polarization resistance technique (LPR) [3], alternating current impedance spectroscopy technique [4] and potential measurement technique [5]. For corrosion analysis, in-line inspection method [6], optical-fibre based technologies [7] and alternating current interface [8] were used in the recent past. Although all these methods are successful in providing health monitoring data, but it fails in automation and time-bound detection. Nowadays, electro-mechanical impedance (EMI) based techniques are used for monitoring the corrosion but very few studies were found and were discussed in the next section.

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1.1 State-of-the-art on corrosion monitoring using piezo sensors

A new corrosion monitoring technique was developed on reinforcing concrete to detect the ultrasonic signals during corrosion using piezo sensors. The accumulation of corrosion products changed the wave transmission. Thus, the wave amplitude increased with the corrosion process and this method could detect the cracking of concrete around the steel bar[9]. A work was done on reinforced concrete cube specimen for the assessment of corrosion based on equivalent structural parameters (stiffness, mass and damping) using EMI technique and found that the extracted equivalent structural parameters correlate well with the actual stiffness and mass[10]. A comparative study was done on reinforced concrete structures to check on the sensing capability of the surface bonded piezo sensor (SBPS) and embedded sensor (in the form of CVS) using equivalent structural parameters. The study found 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[11]. Early hydration in RC structures was monitored using non-dimensional structural parameters identified by piezo sensors via EMI technique and found that the non-dimensional structural parameters are effective in monitoring the early age hydration[12]. To evaluate the damage of the adhesive layer between fibre-reinforced plastic plates in a corrosive environment, the reusable piezo sensors was used with EMI technique[13].

In this paper investigates a rebar corrosion assessment comparison of two different piezo configurations (surface bonded and embedded) in different blended concrete using the electro-mechanical impedance (EMI) technique. The quantification of corrosion-induced damage is based on the equivalent stiffness parameter identified by the two types of piezo configurations and statistical index (root mean square deviation). 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.

1.2 EMI Technique using Piezo Sensors

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 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[14]. A modified expression for coupled admittance signature shown in equation (1)

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

where G is the conductance, B is susceptance, ω is the angular frequency, w, l and h are the dimensions of PZT patch, Z_{s,eff} and Z_{a,eff} are the effective impedance of the structure and the PZT patch respectively. \( \tilde{Y}^R \) is the complex Young’s modulus of elasticity (at constant electric field), \( \tilde{\varepsilon} \) 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 \( \tilde{T} \) was introduced in place of \( \frac{\text{tank}d}{\text{kl}} \) with correction factors C1 and C2 for more accurate results.

2. Experimental Details

In this study, three series of M30 grade concrete mixes, designated as A, B and C were cast in accordance IS 456 (2000)[15]. Mix A consists of 3 cylindrical samples with the normal mix, Mix B consist of 3 cylindrical samples with blended mix and Mix C consists of 3 cylindrical samples with the fly ash based geo-polymer 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 were high yield strength deformed (HYSD) steel of 16-mm diameter, grade Fe 415 conforming to IS 1786 (1985)[16] 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 two piezo configurations (CVS and SBPS) in which CVS was embedded inside the concrete in one sample as shown in Figure 1(a) and SBPSs were instrumented, which surface bonded to rebar before casting in other two samples as shown in Figure 1(b). It should be noted that unlike SBPS, the CVS is not directly in contact with the corroding rebar but situated at a horizontal distance of 20mm from it.

### 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>

**Figure 1.** Schematic diagram of a) RC Cylinder with SBPS and b) RC cylinder with embedded CVS

The baseline conductance signatures from the SBPS and the embedded CVS were acquired after the 28-day curing period. The baseline conductance signature of the SBPS bonded to the rebar is compared with that of the embedded CVS inside the concrete in Figure 2(a), 2(b) and 2(c). It should be noted that both the magnitude and the frequency of the resonance peak of the SBPS are higher than those of the embedded CVS, which suggests that SBPS encounters an overall stiffness higher than that of the embedded CVS[^11]. Under normal environmental conditions, corrosion of a rebar is a relatively slow process, often taking several years to progress significantly. To obtain the results in a reasonable time frame for a laboratory-based study, accelerated corrosion through impressed current technique was adopted[^16-17]. After the baseline signatures were acquired, the specimens were placed in a beaker

[^11]: Reference number for the stiffness comparison.
[^16-17]: References for the accelerated corrosion technique.
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 current of 150 mA/cm² was applied to the specimens using the power supply device until the specimens cracked due to corrosion. During this accelerated corrosion exposure, the admittance signatures were acquired periodically from the PZT patches instrumented in all the nine samples.

![Baseline conductance signature comparison](image)

**Figure 2.** Baseline conductance signature Comparison of SBVS vs CVS in (a) Normal Concrete, (b) Blended Concrete, and c) Fly ash based Geopolymer Concrete

### 2.1 Effect of corrosion exposure

The conductance signature of normal, blended and fly ash based geopolymer sample during accelerated corrosion exposure of 30 days in SBPS and 115 days in CVS is shown in Figure 3(a), (b), (c), (d), (e), and (f). 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.

![Conductance vs Frequency](image)
3. Root Mean Square Deviation

As seen from Figure 4, 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). 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)

\[
\text{RMSD} = \sqrt{\frac{\sum_i^N (G_i - G_i^0)^2}{\sum_i^N (G_i^0)^2}}
\] (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. On comparing SBPS and CVS, the RMSD value for normal concrete exhibits a linear trend with a large scatter as shown in Figure 4(a) and 4(b). For SBPS blended concrete, the RMSD value exhibits a polynomial trend while in CVS exhibits a logarithmic trend with less scatter as shown in Figure 4(c) and 4(d). For SBPS fly ash based geopolymer concrete, the RMSD value could not be able to provide a consistent variation and trend while in CVS exhibits a logarithmic trend as shown in Figure 4(e) and 4(f). A similar trend with RMSD value has been observed for reinforced concrete structures and for steel bolted specimens. Hence, the RMSDBased damage index for SBPS and CVS could not be able to provide a consistent variation. To further gain the corrosion progression, equivalent stiffness parameter were extracted from the mechanical impedance of the structure and analysed, as described in the next section.

Figure 3. Variation of conductance signature during accelerated corrosion exposure (a) SBPS (Normal), (b) SBPS (Blended), (c) SBPS (fly ash based Geopolymer), (d) CVS (Normal), (e) CVS (Blended), and (f) CVS (fly ash based Geopolymer)

SBPS: Surface Bonded Piezo Sensor, CVS: Concrete Vibration Sensor
Figure 4. Variation of RMSD index during accelerated corrosion progression: (a) SBPS (Normal), (b) CVS (Normal), (c) SBPS (Blended), (d) CVS (Blended), (e) SBPS (Fly ash based Geopolymer), and (f) CVS (Fly ash based Geopolymer)

SBPS: Surface Bonded Piezo Sensor, CVS: Concrete Vibration Sensor

4. Analysis Based on Equivalent Stiffness parameter

The impedance-based technique is outlined by [20] to determine the mechanical impedance of the structure, \( z_{\text{eff}} = x + yj \), at a particular frequency, \( w \), from the conductance and susceptance signature. In the normal concrete sample, an identified mechanical system for SBPS and CVS were parallel spring damper system (k-c) and series spring mass damper system (k-c-m) respectively as shown in Figure 5. Using the computational procedure outlined by [21], using equation(1), the ‘x’ and ‘y’ (real and imaginary components) of the structural impedance were determined in the frequency range...
220kHz to 280kHz. The equation of \( x \) and \( y \) were identified and then \( m, c \) and \( k \) were calculated by algebraic manipulations for different mechanical system as shown in Table 4. Figure 6 and 7 shows the variation between the experimental system and identified an equivalent system of ‘\( x \)’ (CVS and SBPS) and ‘\( y \)’ (CVS and SBPS) respectively. From this, it can be observed that the value of ‘\( x \)’ and ‘\( y \)’ in the case of SBPS is more as compared to CVS. Figure 8 shows the comparison of variation of the identified equivalent stiffness parameter of SBPS and CVS. In CVS, the value of stiffness remains constant as compared to SBPS. In SBPS, can be observed that the value of stiffness decreasing monotonically. The equivalent stiffness parameter in initiation phase which is up to 10 days, in CVS, it can be observed to be more sensitive. However, in SBPS it can be observed to be more sensitive in corrosion propagation phase and breaking of concrete. Corrosion propagation phase starts when the alkaline passive layer break around the steel. That is the reason that CVS is more effective during the initial stage of corrosion.

In the blended concrete sample, an identified mechanical system for SBPS and CVS were a parallel spring-mass-damper system (k-c) and series spring mass damper system (k-c-m) respectively as shown in Figure 9. Using the computational procedure outlined by\(^{[21]}\), using equation (1), the ‘\( x \)’ and ‘\( y \)’ (real and imaginary components) of the structural impedance were determined in the frequency range 220kHz to 280kHz (CVS) and 210kHz to 250kHz (SBPS). Figure 10 and 11 shows the variation between the experimental system and identified the equivalent system of ‘\( x \)’ and ‘\( y \)’ respectively. Figure 12 shows the comparison of variation of the identified equivalent stiffness of SBPS and CVS respectively.

In the fly ash based geopolymer concrete sample, an identified mechanical system for SBPS and CVS were a series spring-mass-damper system (k-c-m) respectively as shown in Figure 13. Using the computational procedure outlined by\(^{[21]}\), using equation (1), the ‘\( x \)’ and ‘\( y \)’ (real and imaginary components) of the structural impedance were determined in the frequency range 220kHz to 280kHz. Figure 14 and 15 shows the variation between the experimental system and identified the equivalent system of ‘\( x \)’ and ‘\( y \)’ respectively. Figure 16 shows the comparison of variation of the identified stiffness of SBPS and CVS respectively.

Hence, on comparison of normal, blended and fly ash based geopolymer concrete, it can be observed that the fly ash based geopolymer concrete have more corrosion resistance capability.

<table>
<thead>
<tr>
<th>Parallel Combination of Spring-Damper System</th>
<th>Parallel Combination of Spring-Mass-Damper System</th>
<th>Series Combination of Spring-Mass-Damper System</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x = c )</td>
<td>( x = c )</td>
<td>( x = c )</td>
</tr>
<tr>
<td>( y = -\frac{k}{\omega} )</td>
<td>( y = m\omega - \frac{k}{\omega} )</td>
<td>( y = \frac{-\omega k}{\omega m} )</td>
</tr>
<tr>
<td>( c = x )</td>
<td>( k = \frac{y\omega \omega o^2}{\omega^2 - \omega^2 o^2} )</td>
<td>( c = x^2 + y^2 )</td>
</tr>
<tr>
<td>( k = -\omega y )</td>
<td>( m = \frac{y\omega}{\omega^2 - \omega^2 o^2} )</td>
<td>( k = \frac{y\omega}{\omega^2 - \omega^2 o^2} )</td>
</tr>
</tbody>
</table>

\( \omega \) and \( \omega_0 \) are angular frequency and angular natural frequency respectively.
**Figure 5.** Identified system: (a) SBPS (Parallel combination of spring and damper), and (b) CVS (Series combination of damper-spring-mass)

**Figure 6.** Comparison of variation of equivalent and experimental plots of ‘x’: (a) CVS, and (b) SBPS

**Figure 7.** Comparison of variation of equivalent and experimental plots of ‘y’: (a) CVS, and (b) SBPS

**Figure 8.** Comparison of variation of equivalent stiffness of SBPS and CVS
Figure 9. Identified system: (a) SBPS (Parallel combination of spring, mass and damper), and (b) CVS (Series combination of damper-spring-mass).

Figure 10. Comparison of variation of equivalent and experimental plots of ‘x’: (a) CVS and (b) SBPS.

Figure 11. Comparison of variation of equivalent and experimental plots of ‘y’: (a) CVS and (b) SBPS.

Figure 12. Comparison of variation of equivalent stiffness of SBPS and CVS.
Figure 13. Identified system (Series combination of damper-spring-mass) of SBPS and CVS

Figure 14. Comparison of variation of equivalent and experimental plots of ‘x’:(a) SBPS and (b) CVS

Figure 15. Comparison of variation of equivalent and experimental plots of ‘y’:(a) SBPS, and (b) CVS

Figure 16. Comparison of variation of equivalent stiffness of SBPS and CVS
Conclusion

This paper has presented a rebar corrosion assessment comparison of different piezo configurations in blended concrete. By comparing the baseline conductance signatures of SBPS and CVS, it can be concluded that the magnitude and frequency of resonance peak of SBPS are higher than CVS. CVS is more effective during the initiation of corrosion while SBPS is more effective in propagation and cracking of concrete phase. Hence, both the sensor CVS and SBPS assess the corrosion and are complementary to each other.

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