**Non-Destructive Piezo electric based monitoring of strength gain in concrete using smart aggregate**

Jothi Saravanan T 1,2,3, Balamonica K 1,2, Bharathi Priya C 1,2, Gopalakrishnan N 1,2, Murthy S.G.N 2

1 Academy of Scientific & Innovative Research (AcSIR), Chennai, India
2 CSIR- Structural Engineering Research Centre, Chennai, India
3 tjs.saravanan@gmail.com, balamonica03@gmail.com, bharupriya@gmail.com, gnramana68@gmail.com, sercmurthy@gmail.com

**Abstract**

The form work removal at suitable time plays an important role in strength gain for reinforced concrete structures and transfer of pre-stressing forces for pre-stressed concrete. In the present study, smart aggregates embedded in concrete cubes have been examined for their suitability in estimating the Electro-Mechanical Impedance (EMI) signatures and correlating them with the strength gain during the initial curing regime. EMI signatures have been recorded for these smart aggregate embedded specimens for progressive strength loss. Different statistical have been evaluated to quantify the variations between the reference and modified states. Both stiffness and mass gain occurs for the smart aggregate, resulting in increase and decrease of frequency and amplitude peaks due to the progressive C-S-H gel formation. A relation between RMSD and strength parameter is developed which could be potentially used for arriving at the characteristic strength gain for timely removal of form work. The major contribution also include, the proposed serial/parallel connected multi-sensor configuration with a cluster of PZT sensors to monitor early age characteristics and strength evolution under large scale sensor deployment scenario.

**Keywords:** Non Destructive Testing, EMI, Smart Aggregate, PZT, Statistical metrics, Multi-Sensing technique.

1. Introduction

Embeddable multi-functional, piezo ceramic based smart aggregates for concrete structures have been described in this interesting study to assess early age concrete strength monitoring, impact detection and structural health monitoring [1, 2]. Novel methodologies using embedded piezoelectric transducers have been used to monitor the hydration process of cement paste from the wave velocity and amplitude measurements [3]. An on-line strength gain monitoring of early age concrete using electro-mechanical impedance based smart piezoelectric materials have been developed and reported [4]. An interesting scheme for development of bond between the steel and concrete interface through evolution of hydration of the cement paste is investigated in a detailed and exhaustive manner through piezo patches using electro mechanical impedance (EMI) techniques [5]. Further studies on EMI based techniques for monitoring the strength development of concrete from day-3 to day-28 have been reported by the same authors [6]. In yet another study of current interest, PZT patches coated with waterproof asphalt lacquer have been embedded in the concrete to study the changes in the real part of admittance (conductance) as an indicator of change in the strength and modulus [7]. Metrics based on correlation coefficients have been further used by the same authors to study the effect of changes in the conductance signatures on the amount of damage inflicted on a concrete beam [8]. Effects of boundary conditions and low frequency loading (mass loading) have been investigated and quantified [9]. An interesting work on the application of seismic compression and shear stress monitoring is recently proposed for low frequency application as typical of seismic loading [10]. At any particular frequency, the patch actuates the structure and the structural response is simultaneously sensed and measured by the patch in terms of electromechanical admittance, consisting of conductance and susceptance [11-12]. It is generally observed that the changes happening in the EMI signatures during concrete cracking has been less dramatic as compared to the initial setting process [13].
Non-destructive evaluation of the rheological properties of concrete during initial stage of fluid phase and the intermediate stage of semi-solid phase are attempted in this study using specially packaged and hermetically sealed piezo patches. Also, a comparative evaluation of two different smart aggregates embedded inside concrete has been carried out. Their conductance signatures are periodically acquired and seven different statistical metrics are obtained during initial stages of strength development. These cubes are subjected to compression tests later, and evolution of conductance signatures during cracking of surrounding concrete is also studied. EMI or admittance based health monitoring can be carried out in the final stages of solid phase also, where the conventional ultra-sonic based non-destructive testing and evaluation is an alternative.

2. Quantification through various statistical metrics

(1) Root mean square deviation (RMSD)

\[ RMSD = \sqrt{\frac{\sum (x_i^0 - x_i^1)^2}{\sum x_i^0}} \]  (2)

where \( x_i^0 \), \( x_i^1 \) are the i-th value of reference series and compared series respectively. This is actually a simplified version of the RMS value of the reference function to the deviated function calculated from an assumed zero mean.

(2) Mean Absolute Percentage deviation (MAPD)

\[ MAPD = \frac{\sum |x_i^0 - x_i^1|}{\sum |x_i^0|} \]  (3)

(3) Correlation coefficient (CC)

\[ CC = \frac{1}{n-1} \sum_{i=1}^{n} \left( \frac{X_i - \overline{X}}{s_X} \right) \left( \frac{Y_i - \overline{Y}}{s_Y} \right) \]  (4)

\[ \overline{X} = \frac{1}{n} \sum_{i=1}^{n} X_i \]  (5)

\[ s_X = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (X_i - \overline{X})^2} \]  (6)

Based on the sample of the paired data \((X_i, Y_i)\), the correlation coefficient is given by the Equation (4), where sample mean and sample standard deviation is given in Equations (5) and (6) respectively.

3. Robust PZT Patch for Concrete Structures

The PZTs used for the current study have a dual mode of operation both as an actuator and a sensor. These PZT patches come under the category of Soft PZTs (PIC 151) [13] having high permittivity, large coupling factor and high piezoelectric charge coefficient. Two types of smart aggregates, which have been investigated in this study include Araldite based package and Smart clinker 2.0.

3.1 Design and Packaging of Adhesive Coated PZT Patch

Step 1: First, the soft PZT patch (PIC151) is soldered and then admittance signature is obtained under free-free condition (Figure 1). Then, a 40 mm X 40 mm chart paper is taken and a butter paper is placed over the chart paper. Then, coffee-day straws of 22 mm length are pinned to the butter paper using a stapler. Finally, a mould of 20 mm X 20 mm X 1.5 mm is obtained as shown in Figure 2 (a). The diameter of the coffee day straw is 1.5mm, measured using a screw gauge of least count of 0.01mm.

Step 2: In the second step, a thin layer of adhesive is applied to the butter paper sufficient enough to ensure water proofing and able to withstand the casting pressure. This thin layer
provides the bottom layer for the PZT to be coated. Then, pasted patch is cured for 5 minutes. Figure 2 (b) shows a thin layer of adhesive after curing for 5 minutes. Hence, a general procedure adopted for adhesive coating is described in this section.

Step 3: After curing the PZT patch for 5 minutes, the soldered PZT is stuck at the center of the mould over the first adhesive layer using very little adhesive, as shown in Figure 2 (c). Then, rest of the mould is filled with epoxy till the top surface of the mould. The adhesive coated PZT is left to be cured for 24 hours as per the specifications of the manufacturer.

Step 4: After the adhesive coated PZT is cured for 24 hours, the chart paper is removed by extricating the staples and butter paper. Butter paper is used to provide a non-sticky surface for the bottom of the adhesive. Finally the coffee day straw pieces are removed carefully ensuring no micro cracks are formed while removal. Then, conductance signature is measured to note the effect of adhesive coating. Final adhesive coated PZT is shown in Figure 2 (d).

![Conductance Signature](image)

**Figure 1.** EMI spectrum of a free PZT

![Chart paper mould](image)

**Figure 2.** (a) Chart paper mould with first layer of adhesive; (b) After sticking PZT to first layer of adhesive; (c) Epoxy coating PZT

### 3.2 Design and Packaging of Smart Clinker

The soft PZT patch (PIC151) is soldered and then admittance signature is obtained under free-free condition. Then, a 40 mm X 40 mm chart paper is cut in shape marked by the ash-color shaded region marked as shown in the Figure 3 (a). The shaded region of the chart paper is then folded to form a 20 mm X 20 mm X 10 mm chart paper mould as shown in Figure 3 (b). In the second step, first layer of ordinary Portland cement paste of 1:2, cement to sand ratio and with a water/cement ratio of 0.4 is laid. The cement paste is allowed to dry for 1 hour. The cement paste is cured every 10 minutes to avoid any shrinkage cracks in the cement paste.
4. Monitoring Concrete Strength development

M40 concrete mix is prepared following the “Design of normal concrete mixes” as tabulated in Table 1. The admittance signatures are recorded to check the functionality of the embedded PZT patch and to obtain the required pristine state (undamaged) signatures of the concrete specimens. This conductance sweep is taken as the base value for the RMSD method. A total of three cubes are cast for the current study consisting of one cube containing araldite coated smart aggregate, two cubes with RS-epoxy coated smart aggregate, two cubes with smart clinkers and one control cube.

Table 1. Compositional details of the concrete tested.

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity (weight in kg)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>400</td>
<td>Type I Portland cement</td>
</tr>
<tr>
<td>Water</td>
<td>160</td>
<td>Potable water</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>660</td>
<td>Standard sand</td>
</tr>
<tr>
<td>Coarse Aggregate (20 mm)</td>
<td>701</td>
<td>Angular aggregate</td>
</tr>
<tr>
<td>Coarse Aggregate (10 mm)</td>
<td>467</td>
<td>Angular aggregate</td>
</tr>
<tr>
<td>Admixture</td>
<td>2.4</td>
<td>0.6 % by weight of cement</td>
</tr>
</tbody>
</table>

4.1 Experimental results and analysis

The concrete cube of 150 mm X 150 mm X 150 mm has been cast with these embedded two smart aggregates. It has been decided to split the EMI variation in two time segments, 1-3 days and 3-28 days, as the rate of change of the mechanical and strength gain properties of concrete are fast in the first few days as compared to the final days. Change of conductance signature for Araldite package (Figure 4) is supplemented with change in the peak frequency as well as in amplitudes, from day-1 to day-2 and day-3. The trend for latter days seems to combine with each other and also an additional peak has developed on the latter day signatures. A small variation in the peak frequency, towards the right-ward direction for smart clinker 2.0 (Figure 5) is observed and it means that there is a small increase of added stiffness. This change is small as compared to the other.

Figures 6-7 show the change of conductance signature for Araldite package and Smart clinker 2.0 from day-3 to day-26. In the case of Araldite, the resonant amplitude tends to an asymptotic stationery value while in smart clinker 200 \% increase of amplitude levels with a very small increase of the peak frequency is observed. The performance of the smart aggregates as evaluated through statistical metrics are given in Figures 8-9, which show the variation of RMSD and CC for different aggregates for day-6 to day-26, day-3 being kept as the reference. It is seen that smart clinker 2.0 out-performs the other in reflecting the micro-structural properties of concrete during the latter stages of curing regime.
**Figure 4.** Araldite (Conductance Signature 1-3 days)

**Figure 5.** Smart Clinker 2.0 (Conductance Signature 1-3 days)

**Figure 6.** Conductance Signature 3-26 days (Araldite)
4.2 EMI signatures of smart aggregates under Damage Evolution (Compression tests)

The embedded PZT cube specimens are loaded in uniaxial compression in a hydraulic compression testing machine. All the cube specimens are monitored during the curing period and the RMSD variation of each model during the curing period is shown in Figure 10. It can be observed that the strength degradation during compression testing can be best visualized in
the case of smart clinker 2.0. The slope of the RMSD curve is increasing with the increase in the applied load, indicating the sudden failure of the cube specimen after 90% of failure load. Hence, smart clinker 2.0 bonded PZT performs better even under compression loading conditions compared to other model considered for experimentation.

![Graph showing RMSD variation during cube compression testing period](image)

**Figure 10.** RMSD variation during cube compression testing period

From a comparison with the strength gain from day 3 to 28, RMSD was found to be better correlated than MAPD and CC. Figure 11 shows that the value of RMSD metric seems to linearly increase with the strength gain, which suggests that it could also be a consistent indicator. [Coefficient of determination (R²) is a measure of the strength of linear relationship between the two variables].

![Graph showing relationship between RMSD metric and strength gain](image)

**Figure 11.** Relationship between RMSD metric and strength gain (day 3-28)

5. **A methodology on the serial-parallel electrical connectivity of EMI Piezo Electric Sensors**

The novel idea of electrically connecting different sets of piezo electric sensor is to reduce the interrogation time required in data retrieval and processing. In the case of large sensor arrays, different groups or clusters of piezo sensors can be formed and each individual group can be an electrically connected network of few sensors. A group or set may be made of two to four sensors, judiciously selected such that the EMI peaks from each sensor can be clearly identified on the composite EMI signature. A simple way of achieving this is to use different sizes and thicknesses of carrier plates over which the sensors are pasted, packaged, hermetically sealed and embedded inside the concrete.
5.1 Experimental Investigation

Six PZT patches (P2 to P7) bonded on plates of increasing thickness, are placed at equal intervals in a concrete beam of 1.5 m span with cross section dimension 150 mm x 100 mm. Initially, plate-embedded PZT patches are set and position fixed in a direction normal to axis of the beam, after which the final compacted layer of concrete mix is laid. The setup of concrete beam connected to an LCR meter and a computer is shown in Figure 12. P2 to P7 are placed in a non-sequential order so that peaks due to them can be differentiated easily from composite signature. Individual responses were collected from each patch during each of the measurement day. Later patches were joined together in serial or parallel connection and the responses were taken. Figures 12 (a-b) show the combined responses of the patch 2 and patch 6 (P2-P6) from the pristine state to day-28, with both serial and parallel electrical connectivity respectively. The changes in the conductance for serial/parallel connection is due to the change in the micro structural properties of concrete. This change is quantifies using statistical metrics. Variation for P2-P6 pairs of PZT is shown in the Figure 13 (a-b). The changes in the signature for one hour of concrete setting are calculated and plotted for different patches.

![Figure 12. Experimental setup on concrete beam](image)

(a) Combined responses from the pristine state to day-28 for Serial connectivity (P2-P6)
(b) Combined responses from the pristine state to day-28 for Parallel connectivity (P2-P6)

**Figure 12.** Composite responses of Patch 2 and Patch 6 for serial/parallel electrical connectivity

![Graph showing conductance variation](image)

(a) Patch 2

(b) Patch 6

**Figure 13.** Conductance variation for P2-P6 pairs (up to initial setting time)

**Discussion and Conclusion**

The paper highlights the use of packaged piezo patch as an ideal candidate for NDE of the rheological properties of concrete during initial stage of fluid phase and the intermediate stage of semi-solid phase. Two different piezo based smart aggregates are embedded in the concrete and their EMI signatures are studied. Interestingly, the curves showed a right wards shift of
peaks and upward shift of amplitudes during curing and strength gain. With a decrease in the
stiffness and increase in the damping reversal in behavior of the graphs that is left ward shift
and downward shift is observed. A relation between RMSD and strength parameter is
developed which could be potentially used for arriving at the characteristic strength gain for
timely removal of form work. The contribution of the paper is the development of a novel
methodology based on serial/parallel connection of sensors to enable faster individual
interrogation of sensors. Interconnecting the patches using series/ parallel connection results in
reduced data collection. But to understand the changes in each patch, knowledge of well
distinguished peaks corresponding to each patch is essential. The variation in the thickness of
the plates resulted in distinguished peaks.

Acknowledgments
The paper is published with the approval of Director, CSIR-SERC. The first and fourth authors
acknowledge the tacit guidance of Tapas Kamakshi, Guru Ramana and Maha Periyava.

References
2. Song F, Huang G L, Kim J H, and Haran S. ‘On the study of surface wave propagation in
concrete structures using a piezoelectric actuator/sensor system,’ Smart Mater Struct 2008;
17: 055024.
3. Qin L, and Li Z. ‘Monitoring of cement hydration using embedded piezoelectric
characterization monitoring using piezo-ceramic based smart aggregates,’ Smart Mater
5. Gu H, Song G, Dhonde H, Mo Y L, and Yan S. ‘Concrete early-age strength monitoring
for online monitoring of strength development in concrete using smart PZT patches.’
7. Tawie R, and Lee H K. ‘Piezoelectric-based non-destructive monitoring of hydration of
reinforced concrete as an indicator of bond development at the steel-concrete interface.’
8. Tawie R, and Lee H K. ‘Monitoring the strength development in concrete by EMI sensing
technique.’ Constr Build Mater. 2010; 24: 1746-1753.
of a concrete beam based on PZT admittances and correlation coefficient’. Constr Build
11. Youm K S, Jeong Y J, Han E S H and Yun T S. ‘Experimental investigation on annual
changes in mechanical properties of structural concretes with various types of lightweight
based on the impedance analysis of piezoelectric sensor’. Constr Build Mater. 2010; 24:
2522-2527.