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Monitoring of Strength Gain in Concrete Using Smart PZT Transducers

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Abstract This paper presents the feasibility of using electromechanical impedance based active sensing technique for nondestructive strength gain monitoring of early-age concrete by employing piezoelectric lead-zirconate-titanate (PZT) patches on concrete surface. The strength development of early age concrete is actively monitored by performing a series of experiments on concrete specimens under moist curing condition. The electrical admittance signatures are acquired for five different curing ages and compared with each other. The resonant frequency shifts of PZT patches with increasing days is observed which is on account of additional stiffening due to strength gain of concrete during curing and level of stiffening being related to strength obtained from compression tests on companion cylinder specimens. The proposed approach is found to be suitable for monitoring the development of compressive strength in early-age concrete. It is also observed in this study that root mean square deviation (RMSD) in admittance signatures of the PZT patches can also be used as an indicator of concrete strength development.

Keywords: Electro-Mechanical Impedance, PZT, Active Sensing, Strength Gain, Early-Age Concrete

1. Introduction

Compressive strength of concrete is commonly considered its valuable property, that is, it usually gives an overall picture of the quality of concrete because the strength is directly related to the structure of the hardened cement paste. The usual primary requirement of good concrete in its hardened state is a satisfactory compressive strength (Neville, 1981). In addition, the compressive strength is a key parameter used to estimate the strength of a concrete structure as well. Design codes often relate predicted member strengths to concrete compressive strength for a variety of structural actions, including compression, bending, shear, and torsion. To predict the strength of a concrete structure as well as to investigate the quality of concrete (either in service or under construction), it is therefore necessary to have information about the strength of the concrete. Especially, the in-place concrete compressive strength must be accurately estimated in order to facilitate staged construction or to determine proper time to remove shoring or apply post-tensioning forces. For example, it was shown by Gardner and Scanlon (Gardner and Scanlon, 1990) that high construction loads applied to immature concrete slabs lead to large non-recoverable creep deflections that have a significant impact on the long term deflections of the structure. By these reasons, nondestructive test methods that can be applied to monitor or determine early-age concrete properties can be useful tools to ensure safety during construction even in-service.

For early-age monitoring of the performance of concrete, the great variety of nondestructive methods have been explored and developed

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based on acoustical, electrical, magnetic, mechanical, optical, radiographic, and thermal properties of the tested materials. Those include the surface hardness method, the penetration technique, the pull-out test, the rebound hammer method, the resonant frequency method and the ultrasonic pulse velocity methods (Naik, Malhotra and Popovics, 2004; Bungey, 1982). These methods typically measure certain properties of concrete from which an estimate of its strength, durability and elastic constants can be derived. However, these strength prediction methods share many limitations. For example, the calibration charts of the surface hardness method, the rebound method and the penetration technique are valid for the particular type of the cement and aggregates used and the age and moisture content of the specimen. In addition, the results are not very reproducible. The penetration and the pullout techniques cause a small amount of damage to the concrete surface, which must be repaired. The resonant frequency method and the ultrasonic pulse velocity technique demand that the transducers must be placed on the opposite faces of the component for accurate results. Very often, this is not possible and thus limits the application of the two techniques.

The recent advent of smart materials, such as piezoelectric materials, shape-memory alloys, and optical fibers has added a new dimension to present NDE techniques. The key advantage of using these materials is that they can be placed every where, even in the remote and inaccessible locations to actively monitor the conditions of various type of structures. Impedance based technique which uses smart piezo-ceramic (PZT) material has emerged as a powerful technique for many applications in NDE (Inman et al., 2005; Park et al., 2003; Sun et al., 1995). This method utilizes high-frequency structural excitations, which are typically higher than 20 kHz through surface-bonded PZT patches to monitor changes in structural mechanical impedance. The main advantage using this type of technique is that there is no requirement for the two opposite surfaces as in the case of resonant frequency method and the ultrasonic pulse velocity method. Also it does not require expensive transducers and bulky equipment.

In this paper, the feasibility of electro-mechanical impedance (EMI) based technique which utilizes smart PZT transducers for monitoring concrete strength development at early age is investigated. An experimental study was carried out on concrete cylinder specimens for strength gain measurements under moist curing condition and is monitored for a period of 28 days. Then using the results obtained by the experimental studies, relationships are discussed between the resonant frequency and root-mean-square-deviation (RMSD) indices and the strength gain by the concrete at early age.

2. Electromechanical Impedance (EMI) Technique for Strength Gain Monitoring

The impedance based NDE technique uses the coupling effect (electro-mechanical property) between the PZT patch and the host structure. The electromechanical coupling property of piezoelectric materials couples the mechanical admittance to the electrical admittance, making the latter a metric sensitive to any structural change. The basic principle is to measure variation in the mechanical admittance (inverse of impedance) caused due to structural change The interaction model of PZT patch with host structure is shown in Fig. 1 in which the electrical aspect of PZT patch is described by its

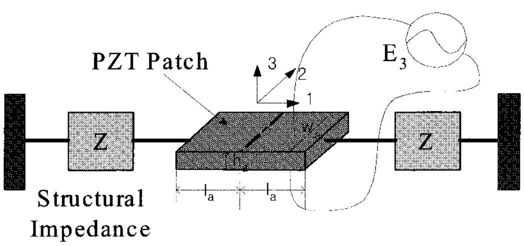


Fig. 1 Interaction model of PZT and host structure

short-circuited admittance and the host structure is represented by its driving point mechanical admittance.

The actuator (PZT patch) is powered by voltage, V or current, I. The entire electro-mechanical system may be electrically represented by an electro-mechanical admittance or impedance which is affected by the dynamics of the actuator and the host structure. The electrical admittance is defined as the ratio of the current to the voltage. The mechanical aspect of the actuator is described by its effective mechanical impedance, $Z_{a,eff}$. The mechanical impedance is defined as the ratio of the applied force to the resulting velocity. The host structure is generalized by its effective drive point mechanical impedance, $Z_{s,eff}$, which includes the effect of mass stiffness, damping, and boundary conditions (Inman et al., 2005). The electro-mechanical admittance of the PZT patch as coupled to host structure is then obtained as

$$\begin{aligned} \overline{Y} &= G + Bj \\ &= 4\omega j \frac{l^2}{h}\left[\overline{\varepsilon_{33}^{T}} - \frac{2d_{31}^{2}\overline{Y^{E}}}{(1-\nu)} + \frac{2d_{31}^{2}\overline{Y^{E}}}{(1-\nu)}\left(\frac{Z_{a,eff}}{Z_{s,eff}+Z_{a,eff}}\right)\overline{T}\right] \end{aligned} \quad (1)$$

where G is the conductance, B is the susceptance, j is $\sqrt{-1}$, l is the PZT length, h is the PZT thickness, d_{31} is a piezoelectric strain coefficient, $\overline{Y^E} = Y^E(1+\eta j)$ is the complex Young's modulus of the PZT patch (at constant electric field), $\overline{\varepsilon_{33}^T} = \varepsilon_{33}^T(1-\delta j)$ the complex electric permittivity of the PZT material (at constant stress), ω is the excitation frequency, ν is the Poisson's ratio, and $\overline{T}$ is the complex tangent ratio (Bahlla and Soh, 2004).

The electro-mechanical impedance technique measures any change in the mechanical impedance $Z_{s,eff}$ of the structure shown in (eqn. 1) which results in the deviation of the admittance signatures. In this study, this characteristic feature is used for strength gain monitoring. It is believed that the change in admittance signatures results from changing the mechanical properties of the host structure, which is due to strength development, i.e., additional stiffening, by concrete.

The experimental setup used for impedance based NDE consists of concrete test specimens, PZT patches, an impedance analyzer (HP4294A), a personal computer equipped with data acquisition software as shown in Fig. 2. The PZT patches are bonded on the concrete surface by using epoxy adhesive. PZT patches were connected to the impedance analyzer by wires connected to the electrodes of the patches for the acquisition of the admittance signatures. The personal computer equipped with software was used to record the admittance signature at each excitation frequency. The control of the experiment and the acquisition of data were achieved through a GPIB interface card by a personal computer.

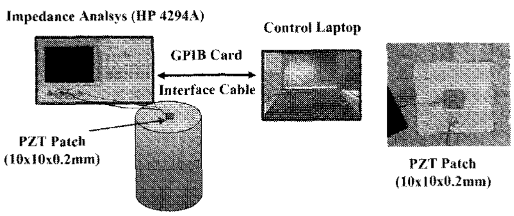


Fig. 2 Experimental setup for strength gain monitoring

3. Experimental Study

3.1 Preparations for Experiments

A series of experiments were conducted on concrete specimens to demonstrate the applicability of the proposed method for monitoring the strength gain in concrete. For that purpose in total of 16 concrete specimens were prepared (1 for EMI measurements and 15 for compression tests). All specimens are comprised of Type I Portland cement (C), water (W), well-graded washed sand (FA), and gravel coarse aggregate (CA). The proportions of the concrete by mass are 1:0.45:2.40:2.66 (C:W:FA:CA, respectively). All the cylindrical specimens are divided into 5 groups with same curing conditions, and within each group 3 cylinders with a diameter of 100 mm and a height of 200 mm are prepared for compressive strength tests at five different curing ages. Immediately after casting, the specimens were then placed in the outdoor for curing. The curing condition is a controlled air curing with plastic sheet cover to prevent water evaporation and temperature and moisture control (by providing additional water using water-spray during curing) to simulate a realistic field condition. Compressive strengths and admittance were acquired with concrete specimens at the ages of 3, 5, 7, 14 and 28 days.

In order to measure the strength gain of concrete, a PZT patch was instrumented on a concrete cylinder. The instrumentation was done three days after casting the cylinders. As concrete is a non-conductive material so a conductive paste was applied on the specimen before applying conductive epoxy adhesive for attaching the PZT with the host structure. The process of attaching the PZT with the concrete specimen is shown in Fig. 3.

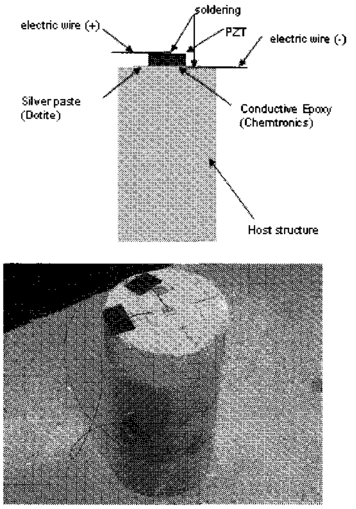


Fig. 3 PZT attachment procedure on the concrete surface

In order to correlate the change in admittance signatures along with increase in strength gain during curing process compression tests were conducted on companion specimens for each age and their average value is taken as standard strength at that particular age.

3.2 Frequency Ranges

It is very important to chose right frequency range as more information can be extracted from the structure having higher dynamic interaction at a given frequency range. In the impedance-based method, multiple frequency ranges containing 20-30 peaks are usually chosen (Park et al., 2004). The frequency ranges higher than 500 kHz have been found to be unfavorable, because the sensing region becomes extremely small and the PZT sensors shows adverse sensitivity to their bonding condition or PZT itself rather than the behavior of structure monitored. Therefore it is necessary to adjust the frequency range according to required sensing region. In the present case the range of 100-400 kHz was selected to be the favorable frequency range based on the preliminary examinations.

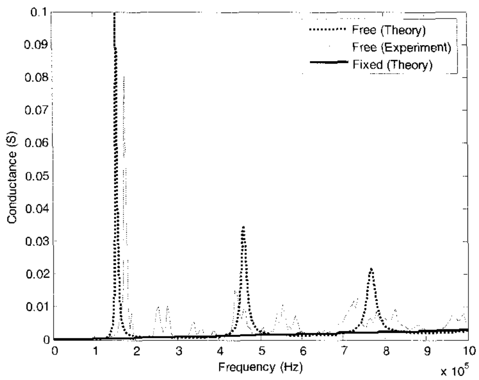
3.3 Strength Gain Measurements

The act of bonding a PZT patch on the surface of any structure tends to restrain the PZT patch and this degree of restrain depends upon the stiffness (or strength) of the component and bonding layer. Using admittance shown eqn.1 for a square PZT patch, admittance spectra can be derived for a "free" and "perfectly clamped" PZT patch, by substituting $Z_{s,eff}$ equal to 0 and ∞, respectively.

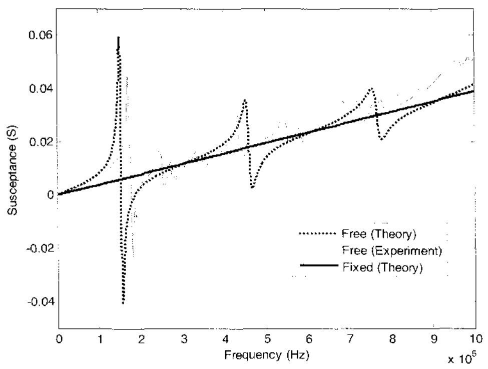
$$\overline{Y}_{free} = 4\omega j \frac{l^2}{h}\left[\overline{\varepsilon_{33}^T} + \frac{2d_{31}^2 \overline{Y}^E}{(1-\nu)}\left(\frac{\tan \kappa l}{\kappa l} - 1 \right) \right] \quad (3)$$

$$\overline{Y}_{fixed} = 4\omega j \frac{l^2}{h}\left[\overline{\varepsilon_{33}^T} - \frac{2d_{31}^2 \overline{Y}^E}{(1-\nu)} \right] \quad (4)$$

where K is the wave number. Fig. 4 displays the admittance spectra (0-1000 kHz) corresponding to these boundary conditions for a PZT patch $10 \times 10 \times 0.2(\text{mm}^3)$ in size, conforming to grade PIC 151 (PI Ceramic 2004 Lindenstrabe). It is observed from this figure that the three resonance peaks corresponding to planar vibrations vanish upon clamping the patch. However, the level of clamping is intermediate to these two extreme conditions, and therefore the admittance curves are likely to lie in between the two extreme curves depending on the stiffness (strength) of the component and the bonding layer (Soh and Bhalla, 2005). By using this principle the strength gain of concrete is monitored.



(a) real part (conductance)



(b) imaginary part (susceptance)

Fig. 4 Admittance spectra for free and fully clamped PZT patches (0-1000 kHz)

3.4 Results and Discussions

In order to minimize incoherent noise components, the signatures were acquired with 10 repeated measurements and averaged. Fig. 5 shows the averaged admittance signatures obtained from the PZT patches bonded to concrete specimens of 5 different curing ages. The plot of the curing at day 3 is selected to be a baseline signature to compare with other signatures. It is apparent from the figure that the first peak frequency gradually shifts to the right as the curing day increases. This shifting is on account of the additional stiffening action due to bonding with concrete. This trend is exactly opposite to the trend usually observed during failure tests, Soh and Bhalla (2005) observed that the peak frequency gradually shift towards the left as the applied load increases (and hence the damage accumulates). The shifting of the peak towards the right in this study indicates that the stiffness (and hence the strength) increases with time.

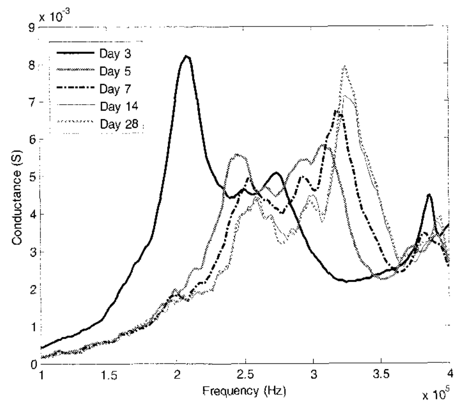
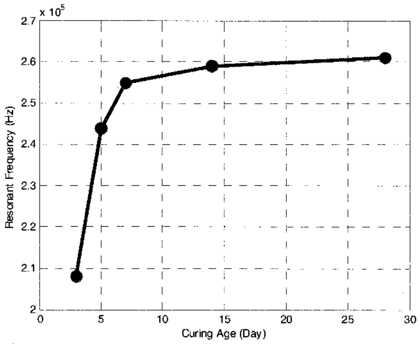


Fig. 5 Variations in admittance signatures for different curing ages

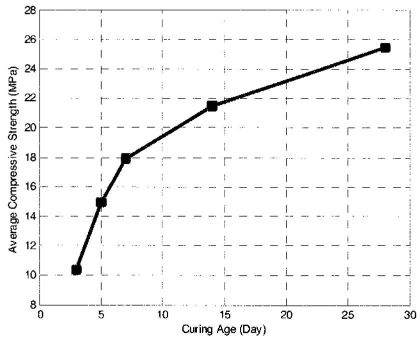
The quantitative amount of shifting for each curing day is listed in Table 1 and Fig. 6(a). Fig 6(a) shows the relationship between the resonant frequency shifts and compressive strength. Great amount of shifts are observed between day 3 and day 14, while the shift between day 14 and day 28 does not change too much. Fig 6(b)

Table 1 Resonant frequency shifts for different curing ages

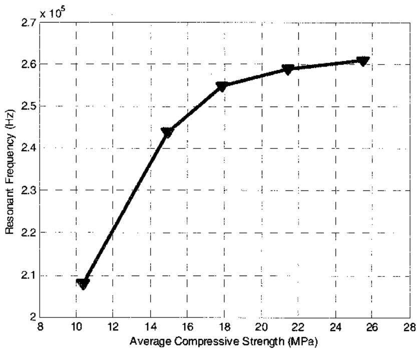
Days	Resonant Frequency (Hz)	Resonant Frequency Shifts (Hz)
Day 3 (Baseline)	208000	-
Day 5	244000	36000
Day 7	255000	11000
Day 14	259000	4000
Day 28	261000	2000



(a) resonant frequency vs. curing ages



(b) average compressive strength vs. curing ages



(c) resonant frequency vs. average compressive strength

Fig. 6 Plots for (a) resonant frequency vs. curing ages, (b) average compressive strength vs. curing ages, and (c) resonant frequency vs. average compressive strengths

shows the average compressive strength and curing days. A similar trend can be seen in the strength development with curing ages. In Fig. 6(c), it is observed that the resonant frequency shift and strength development has a strong correlation. The results indicate that the resonant frequency shift may be used as a reliable indicator for monitoring of the strength gain of early-age concrete. Shin et al. (2007) and Lee et al. (2003) have suggested that ultrasonic wave velocities (both body and surface waves) are good indicators for strength development monitoring. One advantage of the proposed method over the wave velocity methods is that online continuous monitoring may be possible with this active sensing technique. For example, in practice, inspection engineers equipped with velocity measurement instrumentation may periodically access to the test structure for monitoring of the strength gain using the wave velocity methods. However, once PZT and the controlling devices are initially installed into the structure, the active sensing methodology does not need any human intervention afterward and can acquire the signatures continuously. Moreover, if a wireless technology is combined with this methodology, the online monitoring can be achieved remotely.

In addition to the resonant frequency shift index, a RMSD (root mean square deviation) index is also used to quantify the strength development of concrete. The RMSD index is defined as

$$RMSD(\%) = \sqrt{\frac{\sum_{i=1}^{N}(G_i^1 - G_i^0)^2}{\sum_{i=1}^{N}(G_i^0)^2}} X100 \qquad (5)$$

where G_i^1 is the conductance of the cured state after day 3 at the i^{th} frequency point and G_i^0 is the conductance of the cured state on day 3 at the i^{th} frequency point. The RMSD plot is shown in Fig. 7.

It is seen that the RMSD values increase as curing days increase. This suggests that the

RMSD values can also be a good indicator for strength gain monitoring. One advantage of using RMSD approach, which is based on frequency-by-frequency comparisons, is that it does not need to consider of bonding conditions between a PZT and a host structure in strength gain monitoring. Xu and Liu (2002) studied that the effects of bonding layer on the dynamic interaction between the PZT and the structure. Their study reveals that the effects of bonding conditions are remarkable, which significantly affect resonant frequency estimation of the system. For example, the well-bonded sensor shows a smooth curve, while the dis-bonded sensor shows a very strong resonance as shown in Fig. 4. Therefore, in case with the well-bonded sensor, the resonant frequency shift may not be suitable as an indicator of the strength gain monitoring, while the RMSD may be useful.

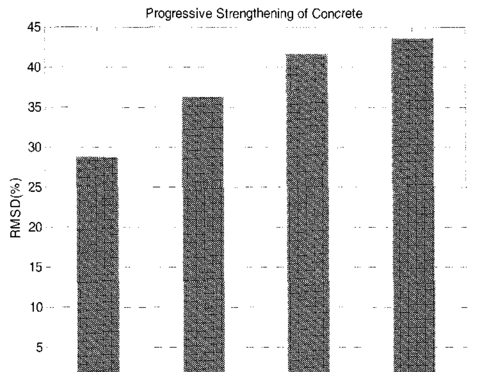


Fig. 7 RMSD values for different curing ages

4. Conclusions

This work is done to extend the applications of the conventional electro-mechanical impedance-based NDE technique for concrete strength gain monitoring at early-age. In this research work, the feasibility of employing smart piezoelectric (PZT) patches for monitoring of early age concrete has been presented through experimental results on laboratory sized concrete cylinder specimens. The strength gain measurement of early age concrete for different curing ages was done successfully using single PZT patch arrangement. It has been found during the experiments that the PZT sensors have very good capability for detecting the changes in the structures due to gain in strength. The striking advantage of this non-parametric technique for strength gain monitoring is that it gives direct condition of the structure as compared to many other techniques which uses indirect ways to estimate the strength of the concrete structures. Both the resonant frequency shift and RMSD of the admittance signatures of the PZT patch showed good indications of strength development.

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