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AN OPTIMIZED STRATEGY FOR ESTIMATING THE RATE OF HYDRATION OF CONCRETE USING PZT SENSORS

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Abstract. The piezoelectric patches paired with impedance-based signal diagnosis is one of the critical Structural Health Monitoring (SHM) techniques used for hydration monitoring concrete hydration. This investigation discusses the three different configuration PZT patches, instrumented on concrete cubes for assessing the hydration rate for concrete: (a) embedded in the concrete around the rebar, (b) affixed at the end of an aluminium foil embedded inside concrete. The hydration process was monitored considering statistical indices; root mean square deviation data (RMSD) were derived from sensor readings till 28 days of curing. Long-term (up to 28 days) hydration of concrete was assessed using the PZT sensors in these two configurations. Further, this study attempts to optimize the piezo-induced signal indices based on both sensor configuration. The magnitude of RMSD corresponding to the various frequency ranges obtained from PZT, and frequency based coupled parameters are derived to understand the hydration mechanism of the concrete.

Key words: PZT patches, Electro-mechanical impedance, Concrete, Hydration, Statistical indices, Frequency extracted parameters.

1 INTRODUCTION

Concrete is the backbone of the construction industry and is the most widely used building material due to its low cost, easy availability, and durability. Its unique properties make it an ideal choice for various applications in civil engineering. However, the behaviour of concrete is complex and depends on several factors such as the type of aggregates used, the water-cement ratio, curing conditions, and other environmental factors. The strength, durability, and performance of concrete are crucial parameters that need to be considered during the design and construction phase [1-3]. The microstructure of concrete, which is primarily determined by the hydration of cement paste, plays a significant role in determining its properties. Therefore, a thorough understanding of the physical and chemical processes involved in the hydration of cement paste is essential to enhance the performance and durability of concrete structures. Traditional methods for measuring the rate of hydration of concrete involve time-consuming and expensive laboratory tests, which may not accurately reflect real-world conditions [4,5]. Various Non-destructive evaluation (NDE) techniques have become an integral part of monitoring the hydration process in concrete structures [6]. These techniques, such as ultrasonic pulse velocity, rebound hammer, and acoustic emission, indirectly measure properties related

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to the strength of concrete [7]. Although these conventional techniques are widely used, they are limited to specific situations. As a result, there is a need for alternative NDE techniques that can overcome these limitations and provide accurate measurements of concrete strength during the hydration process.

In recent years, piezoelectric (PZT) sensors have emerged as a promising alternative for monitoring the civil engineering structures [8-10]. In the electro mechanical impedance (EMI) approach, piezoelectric patches are attached to a structure, and are used to send and receive ultrasonic waves through the structure. The waves interact with the structure and the piezoelectric patches, and the resulting changes in the electrical impedance of the patches can be measured and analyzed to detect any structural defects or damage. Bhalla and Soh [11] proposed a 2D approach to determine the effective impedance of the structure.

$$\bar{Y} = G + Bj = \frac{4jwl^2}{h}\left[\overline{\varepsilon_{33}^{T}} - \frac{2d_{31}^{2}\overline{Y^{E}}}{(1-\mu)} + \frac{2d_{31}^{2}\overline{Y^{E}}}{(1-\mu)}\left(\frac{Z_{a,eff}}{Z_{a,eff}+Z_{s,eff}}\right)\bar{T}\right] \tag{1}$$

PZT sensors are capable of detecting changes in the electrical properties of concrete that occur as a result of the hydration reaction, providing real-time feedback on the curing process [12]. Therefore, accurate monitoring of the hydration process is essential for ensuring the quality of concrete structures [13]. These sensors can detect changes in the mechanical properties of concrete during the hydration process and provide real-time information on the rate of hydration [14]. However, there are several challenges associated with using PZT sensors for monitoring the hydration process of concrete, such as the high sensitivity of the sensors to environmental factors and the need for an optimized data processing strategy [15]. Therefore, this study proposes an optimized strategy for estimating the rate of hydration of concrete using PZT sensors. The proposed strategy includes the use of multi attachment PZT sensors to overcome the environmental effects, a customized signal processing algorithm to enhance the signal-to-noise ratio of the sensor data, and a data fusion technique to integrate the information from multiple sensors. The effectiveness of the proposed strategy was demonstrated through experimental tests on concrete samples.

When assessing the propensity of dielectric materials to absorb and release some energy, the dissipation factor, which is used to calculate the phase angle in electric signals, is utilised. Therefore, any structural irregularities or bond deterioration modify the phase angle, which in turn affects the ability to store and sense charges. The results of the current study suggest that phase angle measurement may help to increase the statistical reliability and correctness of EMI-based results, therefore frequency-based changes should be taken into account for phase angle spectrum. This inspires the author to use the frequency indices PA and PARF obtained from the phase angle spectrum. According to earlier studies, phase angle spectra should be used to guide the choice of electrodes for electrical impedance measurements. It is advised to measure the phase angle repeatedly during the time-course investigations [16,17].

This paper presents a detailed investigations of sensor-based indices to represent the hydration behaviour for plain cement concrete. Two different configurations of PZT patches (both embedded, direct contact and other is metal wire based, indirect mode) were instrumented on concrete cubes, and the hydration process was monitored using statistical indices such as root mean square deviation data (RMSD) derived from sensor readings until 28 days of curing. The results of this investigation demonstrate the effectiveness of using PZT sensors in assessing the long-term hydration of concrete, with optimized piezo-induced signal indices based on sensor configuration and pattern. The authors also attempt to quantify the damage through extracted indices from phase angle spectrum i.e. first local phase angle peak (PARF), local phase angle peak value (PA), and the corresponding width of half-prominence (HPW). The findings of this study have significant implications for the field of concrete industry, as they offer a more accurate and reliable method for monitoring the hydration process of concrete. Overall, our findings suggest that PZT sensors, when used in conjunction with an optimized measurement strategy, have the potential to revolutionize the way in which the rate of hydration of concrete is monitored and controlled. This could lead to significant improvements in the quality and durability of concrete structures, ultimately benefiting the construction industry and society as a whole.

2 EXPERIMENTAL SETUP

2.1 Materials and Sample preparation

In this investigations, standard concrete cubes of size 150mm x 150mm x 150mm were cast using M30 concrete mix as per IS 10262: 2009. Two different configurations of Piezoelectric patches were used for monitoring the hydration of concrete. The concrete cubes were cast using a mix of Portland cement, water, coarse and fine aggregates in the ratio of 1:0.44:2.74:1.34 by weight. Three no's of cube samples were cleaned and oil was polished at the inner potion of the mould which enable easy removal during demoulding. The mix was prepared using a mechanical mixer and poured into standard cube moulds. The moulds were vibrated for compaction and allowed to cure for 24 hours in a moist environment. After 24 hours, the cubes were demoulded and allowed to cure in a water tank for 28 days.

2.2 PZT Patch Configuration

Two different configurations of PZT patches were used for monitoring the hydration of concrete. The first configuration involved concrete vibration sensor where the PZT patch embedded in the concrete around the rebar. The second configuration involved affixing the PZT patch at the end of an aluminium foil of size 508 ×10×1 mm^3 embedded inside the concrete. Then the non-bonded piezo configurations were connected to LCR meter with a frequency range of 30kHz-300kHz for data acquisition and analysis. The signal diagnosis system consisted of a data acquisition unit (DAQ) and a signal conditioning unit (SCU) connected to a computer for data storage and analysis. Figure 1 shows the proposed Schematic diagram for experimental setup hydration monitoring.

2.3 Hydration Monitoring

The hydration process was monitored using the PZT sensors for up to 28 days of curing. The signal data was acquired at regular intervals using the impedance-based signal diagnosis system. The root mean square deviation data (RMSD) was derived from the sensor readings to assess the hydration rate of the concrete. The magnitude of RMSD corresponding to the various frequency ranges obtained from PZT, and the configurations were combined using suitable weightages derived from genetic algorithm optimization technique to obtain a characteristic curve for hydration of the concrete. The optimized piezo-induced signal indices based on sensor configuration and its pattern were compared with the standard strength gain of generic cement mortars over time to validate the results.

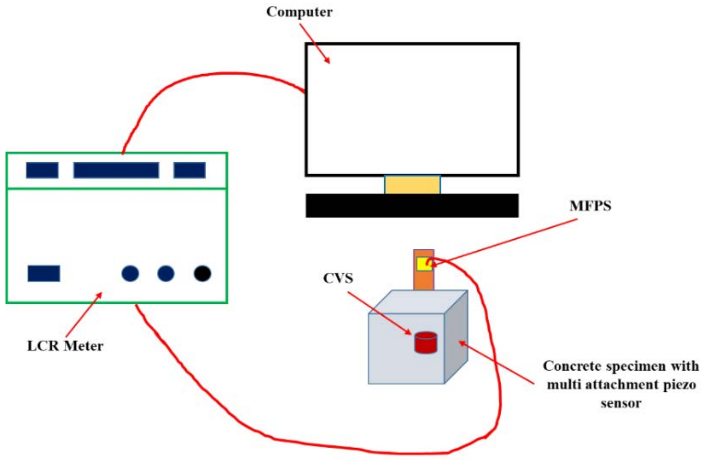

Figure 1. Schematic diagram for experimental setup

3 RESULTS

3.1 Statistical investigation of EMI signals

The present study aimed to highlight the need for statistical investigation in impedance-based hydration monitoring. This research also emphasizes the need for a more rigorous and systematic approach to impedance-based hydration monitoring that incorporates appropriate statistical techniques and considers individual differences in hydration response. The root-mean-square deviation (RMSD) was used as a preliminary method to understand the increase in strength during hydration trends in the structure. RMSD is a commonly used metric to measure the deviation between the coordinates of the original and modified structures. The calculated RMSD values indicated that the extent of compressive strength increased with increasing days of hydration. Figures 2 and 3 exhibit the conductance behaviour of metal foil and embedded configurations over various curing periods. The analysis of hydration progression and strain development is inferred by observing deviations in conductance signatures. The conductance peaks of both configurations shift towards the right with an increase in frequency and attain higher values at 28 days. In Figures 4 and 5, the RMSD behavior of metal foil and embedded configuration during long-term hydration is displayed. The trend of increasing RMSD values with curing days is indicative of the development of compressive strength. Notably, a lower RMSD value is observed at 28 days, suggesting that the concrete gains rapid strength up to 7 days, after which it gains strength at a slower rate. These results imply that RMSD can serve as a useful initial indicator for comprehending the strength gain of concrete specimens. Overall, the findings from this study demonstrate the potential of conductance and RMSD analyses in providing insights into the strength development of concrete over time. These methods can aid in optimizing the curing process and determining the optimal time for testing concrete strength.

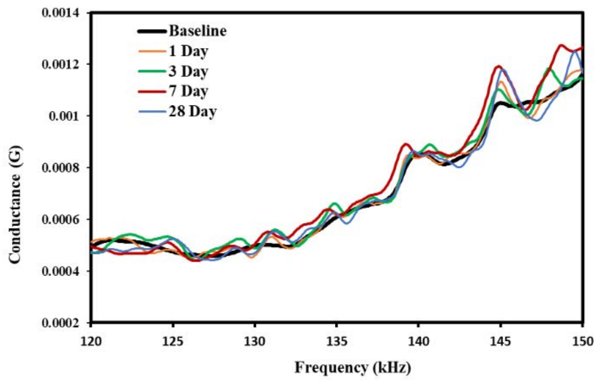

Figure 2. Conductance plot during long term hydration for metal foil based configuration

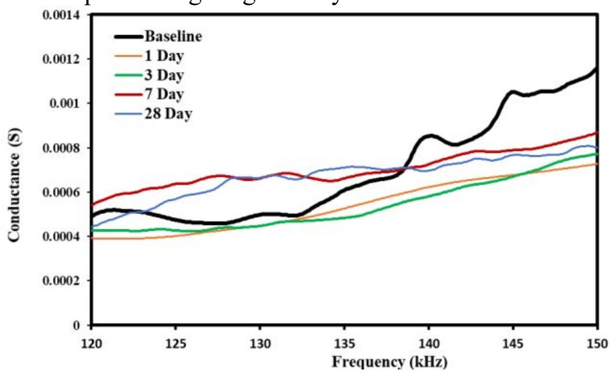

Figure 3. Conductance plot during long term hydration for embedded configuration

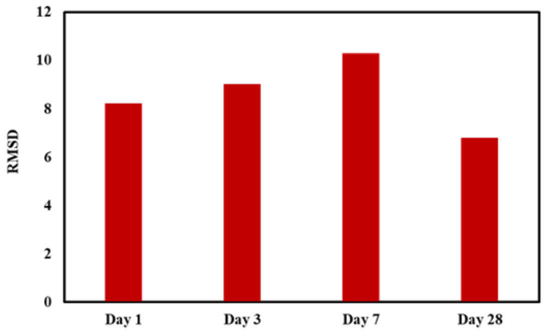

Figure 4. RMSD plot during long term hydration for metal foil configuration

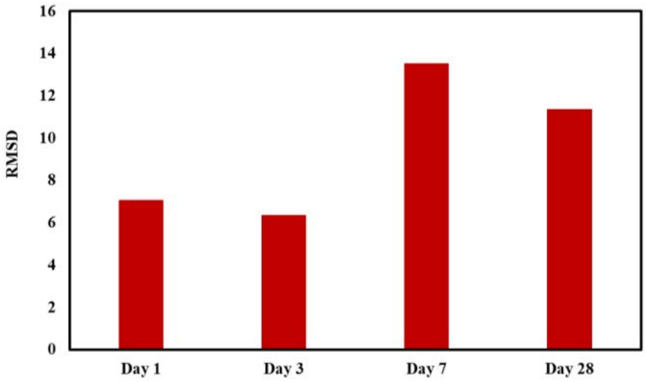

Figure 5. RMSD plot during long term hydration for embedded configuration

3.1 Frequency depended indices for hydration monitoring

The frequency-swept EMI measurement consists of the real part (Re(Y)) and imaginary part (Im(Y)) ranging from 30 to 300 kHz, where Y represents the electric admittance (reciprocal of impedance, Z). With prior information of the alternative current ($\bar{I}$) and applied sinusoidal voltage ($\bar{V}$), the expression Z, can be written as

$$Z = \frac{\bar{I}}{\bar{V}} \quad (2)$$

where $I = I_0 \, e^{(j\omega t+\varphi)}$ and $V = V_0 e^{j\omega t}$. I_0 and V_0 are the instantaneous peak value of current and voltage.

The impedance values were different for different stages of loading. For EMI signatures the phase angle (Φ) can be calculated as:

$$\tan\Phi = \frac{\text{Imaginary(Z)}}{\text{Real(Z)}} \quad (3)$$

For computations of the entire phase angle spectrum, the phase angle takes into account both conductance, the inverse of real (Z), and susceptance, the inverse of imaginary (Z), of EMI spectra (refer to Fig. 6). The first phase angle resonance peak is used to obtain additional indices, such as the phase angle peak value (PA), first phase angle peak (PARF), and half width of prominence (HPW), because the first mode for vibration-based structural inspection corresponds to the frequency at which damage occurs and reflects the relevant information of structural change.

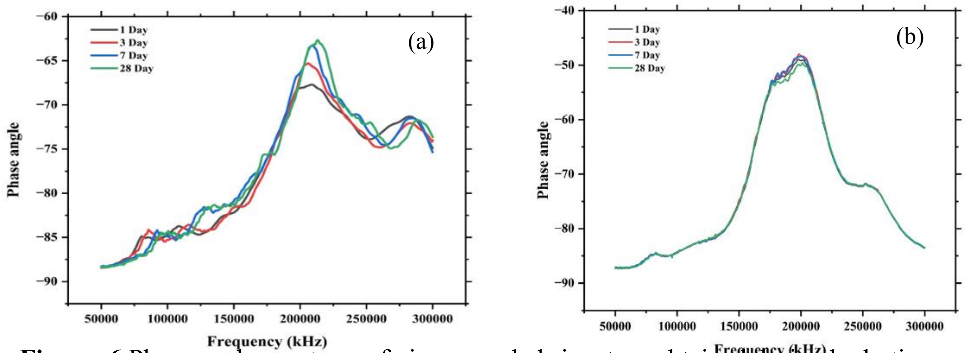

Figure. 6 Phase angle spectrum of piezo coupled signature obtained during hydration (a) Embedded (b) Metal wire

Fig. 7 (a)-(c), shows the variation of PARF index, PA and HPW for embedded and metal wire based PZT patch respectively. As hydration advances, the variance of PA and PARF rises in comparison to the baseline (see Fig. (b)). Peaks in the phase angle spectrum, including PA and PARF, will diminish as long as internal losses persist. The saddle point of transition of the peak and valley of the phase angle spectra for the prominence peak, on the other hand, is highly crucial for any structural change, making the HPW more appropriate to notify the strength increase by growing in value (see Fig. 7(c)).

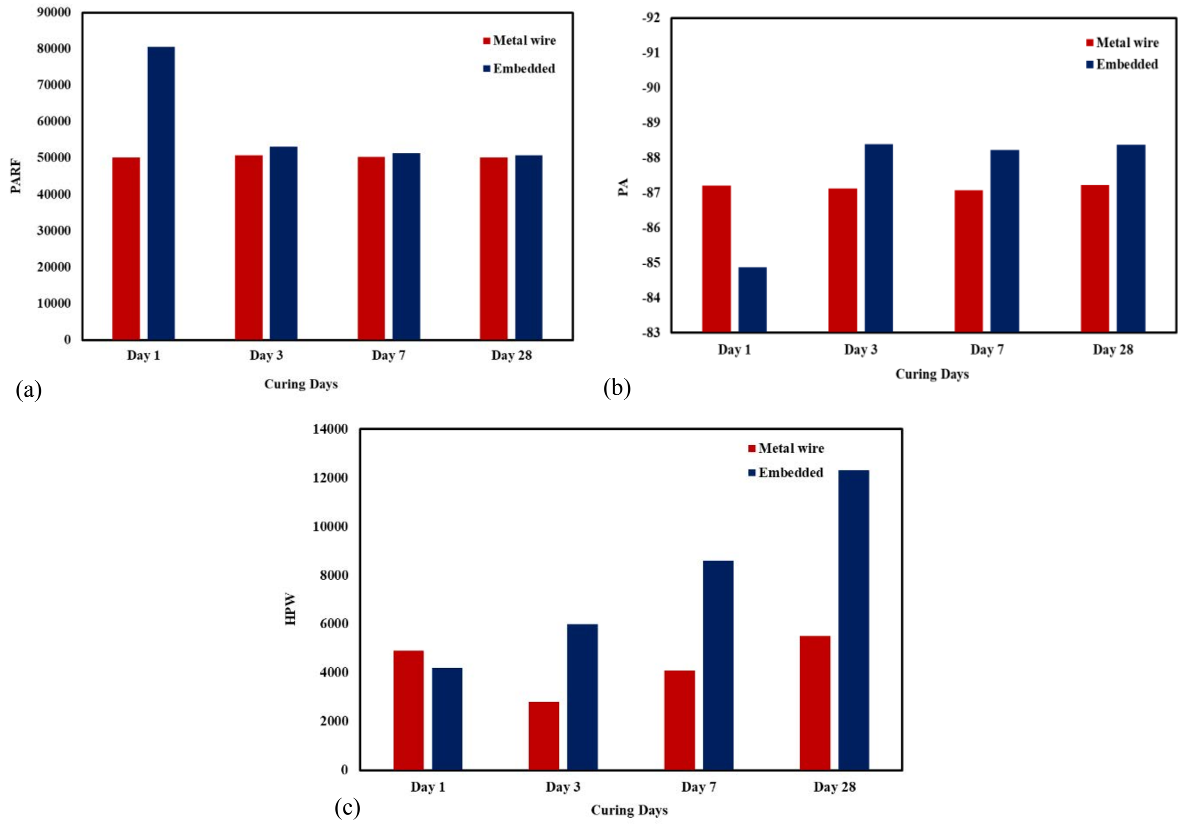

Figure. 7 Extraction of phase angle indices for surface bonded PZT patch for loading effect

(a) PARF index

(b) PA index

(c) HPW index

4 Conclusions

From the present study, the use of PZT sensors paired with impedance-based signal diagnosis is a crucial SHM technique for monitoring concrete hydration. This study investigated two different non-bonded configurations of PZT patches instrumented on concrete cubes to assess the hydration rate of concrete. The PZT sensors embedded in the concrete around the rebar were found to be more effective in monitoring the hydration of concrete than the PZT sensors affixed at the end of an aluminum foil embedded inside the concrete. This could be due to the fact that the PZT sensors embedded in the concrete around the rebar are closer to the hydration front and hence are more sensitive to changes in the electrical properties of the concrete. The evaluation of sensor based metrices (both statistical and frequency based) found satisfactory for hydration monitoring and strength of cement concrete.

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