

Integrated Monitoring of Early-Age Hydration and Structural Rehabilitation in RDF Ash-Modified Concrete Using Embedded Piezoelectric Sensors

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ABSTRACT

Verifying the performance of low-carbon binders while at the same time keeping watch over the members they form remains a practical barrier to wider use of sustainable concrete. This work tackles both problems together by applying an electromechanical impedance (EMI) framework, built on embedded lead zirconate titanate (PZT) sensors, to concrete in which refuse-derived fuel (RDF) ash replaces part of the cement. Cube specimens were prepared with ordinary Portland cement (control mix, CM) and with 30% RDF-ash replacement (RDF mix, RM) and were followed continuously over the first eight hours after casting to capture early-age hydration. Separately, reinforced concrete (RC) beams were taken through three progressive damage states and then repaired in three matching stages. Conductance signatures and resonance peaks were recorded throughout and condensed into a single root-mean-square-deviation (RMSD) index. Within eight hours the RMSD reached 14.35% for CM and 12.71% for RM, while the CM resonance peak migrated from 234.6 to 248.3 kHz. As the beams were damaged, conductance fell from 0.0135 S to 0.0089 S and RMSD climbed from 10.53% to 23.01%; staged repair reversed the trend, lifting conductance to 0.0145 S and RMSD to 30.86% as stiffer repair materials altered the sensor signature. The RDF mixture hydrated along a path close to the control and coupled reliably with the embedded sensors, and the EMI response tracked both deterioration and recovery without ambiguity. By placing fresh-state hydration tracking and long-term damage-repair diagnosis within one sensing scheme, the study extends earlier EMI work to waste-derived binders and points toward scalable, life-cycle monitoring that supports circular-economy goals in construction.

Keywords- Refuse-Derived Fuel Ash, Electromechanical Impedance, Piezoelectric Sensors, Structural Health Monitoring, Early-Age Hydration, Retrofitting.

I. INTRODUCTION

Pressure to build more sustainably, set against the rising environmental cost of rapid urbanisation, has forced civil engineers to reconsider both the materials they specify and the way finished structures are kept under observation. Cement manufacture accounts for close to 8% of global CO₂ emissions, while in fast-growing economies the disposal of municipal solid waste (MSW) is an equally stubborn problem; India alone generates upward of 62 million tonnes of MSW every year [1]. A large share of this material is never adequately treated, and the consequences—contaminated soil, polluted air, and tainted groundwater—are well documented [2]. Redirecting an incineration residue such as refuse-derived fuel (RDF) ash into concrete as a supplementary cementitious material (SCM) offers a way to ease both pressures at once [3]. In parallel, asset owners increasingly want structures that can report on their own condition. Periodic checks such as ultrasonic pulse velocity, the rebound hammer, and core extraction are intermittent by nature and tend to overlook the earliest signs of distress, particularly under slowly accumulating load or environmental attack [4]. That limitation has steered the discipline toward embedded sensing, in which piezoelectric transducers have become a robust means of registering material and structural change as it happens [5].

A considerable literature treats either the mechanical response of SCM concrete or the use of piezoelectric sensors for damage detection, but the two themes are seldom brought together. Studies of ash-based replacements have mostly examined strength, durability, and the reuse of combustion residues [3, 6], with far less said about how such residues react chemically during hydration or whether they interfere with sensor-based monitoring [7]. The structural-health-monitoring (SHM) literature, for its part, has shown that piezoelectric devices can flag cracking, corrosion, and strength development, yet most of that evidence rests on conventional concrete or metallic systems rather than waste-modified mixtures [8, 9, 10]. Among the available techniques, the electromechanical impedance (EMI) method—formed by bonding a lead zirconate titanate (PZT) patch to the host material—is especially suited to the problem: its high excitation frequency and tightly localised response make it sensitive both to the microstructural evolution of early hydration and to stiffness loss after damage [11, 8]. Its behaviour inside sustainable, waste-bearing concrete, however, has scarcely been examined, and it is precisely this gap that the present study sets out to close.

Two phases dominate the service life of any concrete element: the early hydration window, which governs setting and strength gain, and the later damage-repair cycle, which reflects how resilient and repairable the member proves to be. Monitoring hydration matters because faults in proportioning, curing, or placement during these first hours can quietly compromise long-term performance and invite early-age cracking [7]. Members exposed to seismic action, aggressive media, or sustained service load will, in turn, inevitably accumulate damage, and a corrosion- or load-induced loss of bond can be difficult to detect until it is advanced [12]. EMI sensing speaks to both situations without disturbing the member. Earlier studies have used the technique to follow microstructural development during cement hydration [13] and to locate damage in reinforced concrete under mechanical stress [14, 15]. Zhang et al. [13], for example, tracked early hydration of cement paste with PZT sensors and reported resonance and conductance shifts that mirrored stiffness gain; embedded transducers have likewise been used to follow strength development in blended binders [16] and to judge the effectiveness of strengthening interventions in RC members [17].

What distinguishes the present work is that it brings these two complementary concerns—hydration and damage recovery—under a single EMI-based scheme, rather than treating them in isolation as most earlier studies have done [13, 14]. Moreover, whereas RDF ash has usually been judged on its combustion and environmental merits, here it is examined as a pozzolanic additive, with its hydration characteristics and its compatibility with EMI sensing assessed together for the first time. Embedded PZT sensors record electromechanical impedance signatures during (a) the first eight hours after casting and (b) progressive damage followed by staged retrofitting of reinforced concrete beams. Root-mean-square-deviation (RMSD) indices and shifts in resonance peaks serve as the quantitative measures of material and structural change, giving a continuous account of how the system evolves over time.

The aim, then, is a solution that is at once technically sound and environmentally defensible. Substituting RDF ash for part of the cement lowers both the clinker demand and the embodied carbon of the mix, while the embedded EMI sensors furnish a real-time platform for quality assurance and condition assessment [18, 19]. Pairing hydration monitoring of cube specimens with damage-repair evaluation of RC beams shows how smart sensing can link green materials to intelligent infrastructure, and it opens the door to coupling EMI data with machine learning for longer-term performance prediction and preventive maintenance. The outcomes should carry weight for both researchers and practitioners, not least in resource-constrained settings where frugal material use and proactive monitoring matter most.

II. MATERIALS AND METHODS

A. Materials

Ordinary Portland cement of 43 grade, complying with IS 8112, served as the principal binder. The fine aggregate was natural river sand (specific gravity 2.64, fineness modulus 2.75), and the coarse aggregate was crushed granite of 20 mm nominal size and specific gravity 2.64. A polycarboxylate-ether superplasticiser was dosed at 0.3% by mass of binder to maintain workability. The RDF ash came from a brick-kiln unit that uses refuse-derived fuel for combustion; the fuel itself had been prepared from segregated municipal solid waste by removing inorganics and then burning the remainder at 850–1100 °C. Bottom ash recovered after combustion was oven-dried, ground, and passed through a 75 µm sieve before use. X-ray fluorescence and energy-dispersive analyses showed the ash to be rich in silica (49.7%) and alumina (10.5%) but low in calcium oxide (17.6%), a composition consistent with pozzolanic behaviour and well suited to partial replacement of cement [3].

B. Mix Design and Specimen Preparation

Two M30 mixtures were proportioned to IS 10262:2019: a control mix (CM) using 100% OPC, and an RDF mix (RM) in which ash replaced 30% of the cement. Both shared a fixed water-to-cement ratio of 0.43 and identical aggregate contents. CM contained 482.55 kg/m³ of OPC, whereas RM combined 337.78 kg/m³ of OPC with 144.76 kg/m³ of RDF ash; fine and coarse aggregates were held at 932.33 and 744.38 kg/m³, respectively, in both mixes. Two specimen types were cast. Cubes of 150 mm side, each with a centrally placed piezo sensor, were used to follow early-age hydration. Reinforced concrete beams measuring 700 mm × 150 mm × 150 mm reproduced damage and retrofitting; they carried two 16 mm bars

as bottom (tensile) reinforcement, two 10 mm bars at the top for compression, and 8 mm stirrups at 100 mm centres. In the beams the sensor was positioned close to the tensile reinforcement so that it would respond strongly to flexural distress.

C. Embedded Piezoelectric Sensor (EPS) Preparation

The active element was a lead zirconate titanate patch (PZT-5H, 10 mm × 10 mm × 0.2 mm). Each patch was sandwiched between thin mortar layers and sealed with epoxy to form an embedded piezo sensor (EPS), which shields the ceramic from the alkaline pore solution and improves durability. The encapsulation and calibration followed established piezo-impedance transducer practice [18]. Sensors were placed during casting so that the same device could report on hydration and, subsequently, on the damage-repair sequence.

D. Hydration Monitoring Setup

For the first eight hours after casting, EMI data were logged at one-hour intervals. Conductance signatures were captured with a precision LCR meter (Agilent 4284A) over the 30–500 kHz band at 100 Hz resolution. The signature taken immediately after casting served as the baseline, against which later changes in amplitude and resonance frequency were referenced. To compress each signature into a single number, the root-mean-square deviation (RMSD) was computed as in Eq. (1).

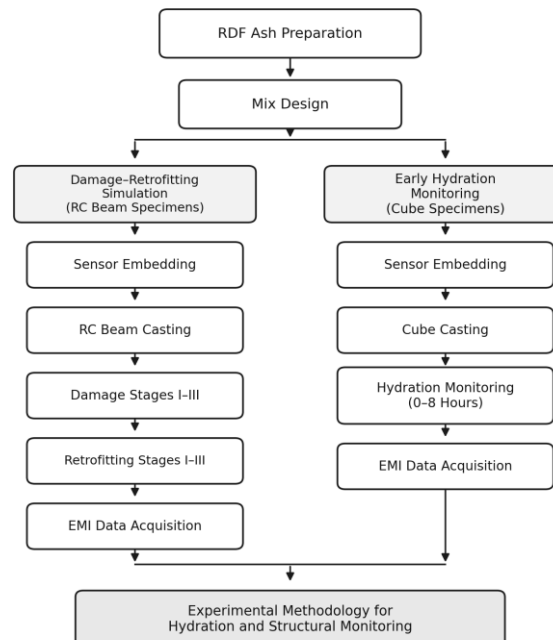
$$RMSD = \sqrt{\frac{1}{N} \sum_{i=1}^N (G_i - G_{bl})^2}$$

where G_i is the conductance at the i^{th} frequency point, G_{bl} is the corresponding baseline value, and N is the number of data points in the frequency range.

(1)

E. Damage and Retrofitting Simulation

To examine how damage develops and how well repair restores capacity, each beam passed through three damage stages and three matching retrofit stages. Damage I created a 150 mm × 150 mm × 75 mm notch at mid-span, mimicking spalling and loss of cover concrete. Damage II severed one of the 16 mm bottom bars, halving the tensile capacity. Damage III cut the second bar, removing the tensile reinforcement entirely and severely weakening the section. Repair then proceeded in three steps: Retrofit I re-welded the cut bars to re-establish tensile continuity; Retrofit II refilled the notch with fresh concrete to recover sectional integrity; and Retrofit III bonded an external composite overlay (GFRP or high-strength mortar) to raise stiffness and durability [17, 20]. EMI signatures were recorded at every stage with the same LCR setup, and the resulting resonance shifts, conductance amplitudes, and RMSD values were used to gauge the degree of degradation and recovery [14]. The overall procedure is summarised in Figure 1.



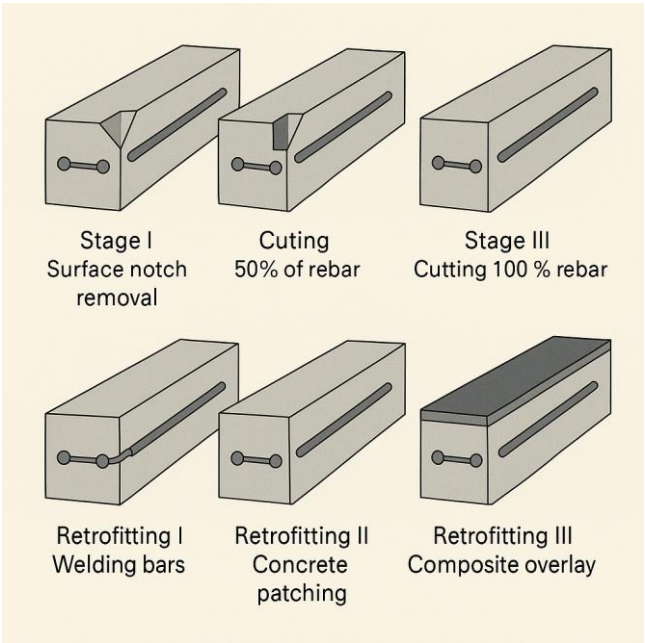


Figure 1. Experimental methodology: (a) overall workflow for hydration and structural monitoring; (b) the three damage and three retrofitting stages of the RC beam.

III. RESULTS AND DISCUSSION

A. Early-Age Hydration Tracked by EMI Signatures

Hydration is a time-dependent process that shapes setting, strength, and the developing microstructure. PZT-based signatures were recorded over the first eight hours for both the control mix (CM) and the RDF mix (RM). The real part of the impedance (conductance) showed its peak migrating steadily upward in frequency as the paste stiffened. In CM the peak moved from 234.6 kHz at one hour to 248.3 kHz at eight hours, with conductance falling from 0.0181 S to 0.0142 S; RM behaved similarly but more gently, shifting from 232.3 kHz to 242.1 kHz while conductance declined from 0.0172 S to 0.0147 S (Table 1). The slower migration in RM is the expected fingerprint of the ash’s more gradual pozzolanic reaction [13, 16].

Figure 2 traces the growth of RMSD, a proxy for stiffening. CM rose more sharply, reaching 14.35% by eight hours, while RM trailed at 12.71%. The conductance curves in Figure 3 tell the same story from the other side: RM declines more gradually than CM, consistent with its lower early stiffness gain.

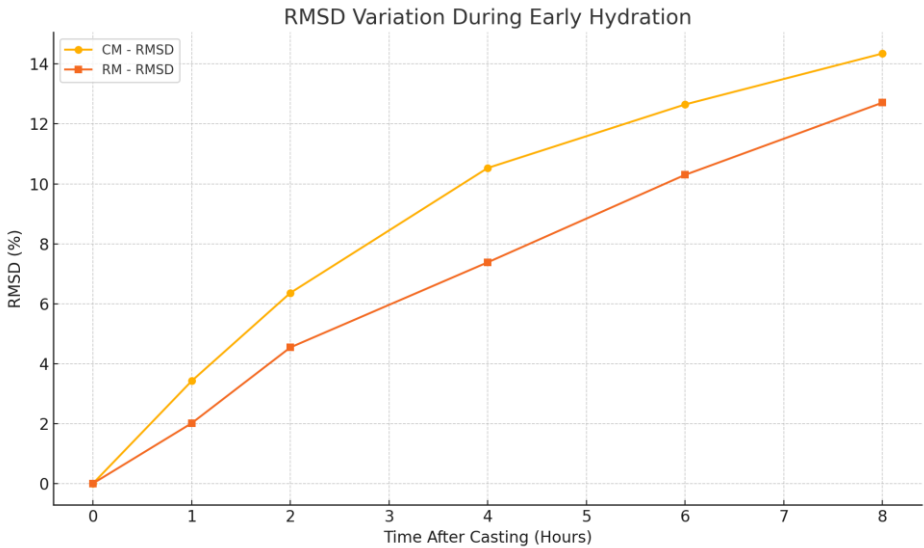


Figure 2. RMSD variation during early-age hydration.

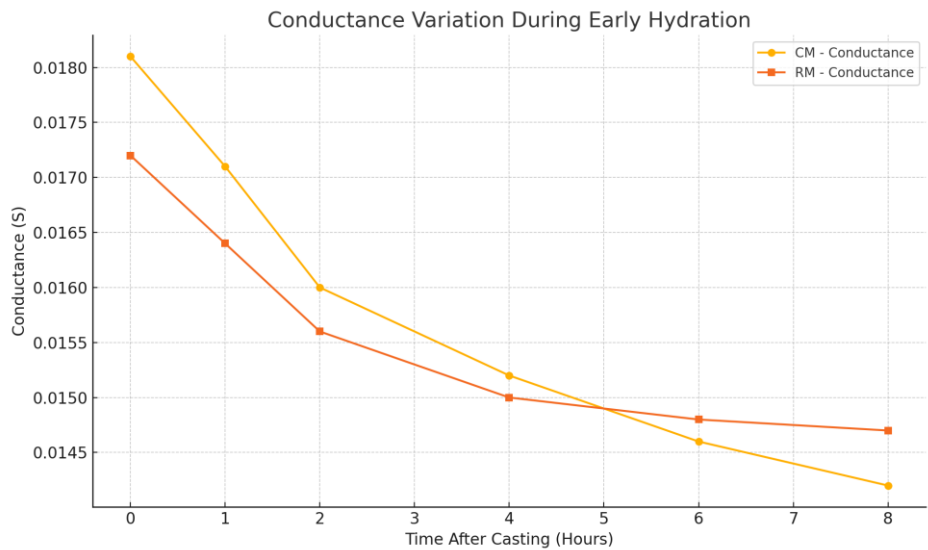


Figure 3. Conductance variation during early-age hydration.

B. Quantitative Assessment Using RMSD

Computed against the zero-hour baseline, RMSD increased monotonically for both mixes (Table 1), from 0% to 14.35% in CM and from 0% to 12.71% in RM. The faster climb in CM reflects the dominant, rapid hydration of Portland cement. Even so, RM attained about 88% of the CM value, which indicates that RDF ash remains a technically viable supplementary material even at this early age.

Table 1. RMSD (%) and conductance trends during early-age hydration monitoring (0–8 hours).

Time After Casting	CM RMSD (%)	CM Conductance (S)	CM Peak Freq. (kHz)	RM RMSD (%)	RM Conductance (S)	RM Peak Freq. (kHz)
0 h (Baseline)	0.00	0.0181	234.6	0.00	0.0172	232.3
1 h	3.42	0.0171	237.9	2.01	0.0164	233.8
2 h	6.36	0.0160	241.2	4.54	0.0156	235.5
4 h	10.53	0.0152	245.7	7.38	0.0150	238.4
6 h	12.65	0.0146	247.2	10.30	0.0148	240.7
8 h	14.35	0.0142	248.3	12.71	0.0147	242.1

Note: CM shows faster stiffness gain and resonance shift owing to rapid OPC hydration; RM hydrates more slowly but follows the same trend, supporting the use of RDF ash.

C. Damage Monitoring in Reinforced Concrete Beams

Embedded PZT sensors followed the beams through staged mechanical damage, beginning from the undamaged (pristine) state. EMI responses were collected after each damage stage and interpreted through conductance, peak frequency, and RMSD.

C.1. Conductance Response to Damage Stages

Figure 4 shows conductance falling as the beam moves from pristine toward fully damaged. The peak dropped from 0.0135 S (at 250.2 kHz) to 0.0089 S by Damage III, where both bars had been cut, while the peak frequency slid from 250.2 kHz to 221.8 kHz—an unambiguous mark of lost stiffness. These values are listed in Table 2.

C.2. RMSD Response to Damage Stages

RMSD captured the same degradation numerically (Table 2, Figure 5), rising from 10.53% at Damage I to 15.45% at Damage II and peaking at 23.01% at Damage III. The increase mirrors the conductance drop and the leftward frequency shift, and the step changes show that EMI can separate minor surface loss from serious internal failure. RMSD therefore serves not only as a measure of damage but as a threshold variable for automated decision-making within a monitoring system.

Table 2. Conductance and RMSD results during the damage and retrofitting phases of the RC beams.

Stage	Description	Conductance (S)	Peak Freq. (kHz)	RMSD (%)
Pristine (Baseline)	Before any damage	0.0135	250.2	0.00
Damage Stage I	Surface notch removal	0.0121	246.3	10.53
Damage Stage II	50% bottom reinforcement cut	0.0103	234.5	15.45
Damage Stage III	100% bottom reinforcement cut	0.0089	221.8	23.01
Retrofitting Stage I	Steel bar welding	0.0115	232.9	18.15
Retrofitting Stage II	Surface concrete patching	0.0128	240.6	25.00
Retrofitting Stage III	Composite overlay application	0.0145	249.5	30.86

Note: Damage stages cause a conductance drop and a leftward frequency shift; retrofitting reverses this trend, with the final retrofit exceeding the original stiffness.

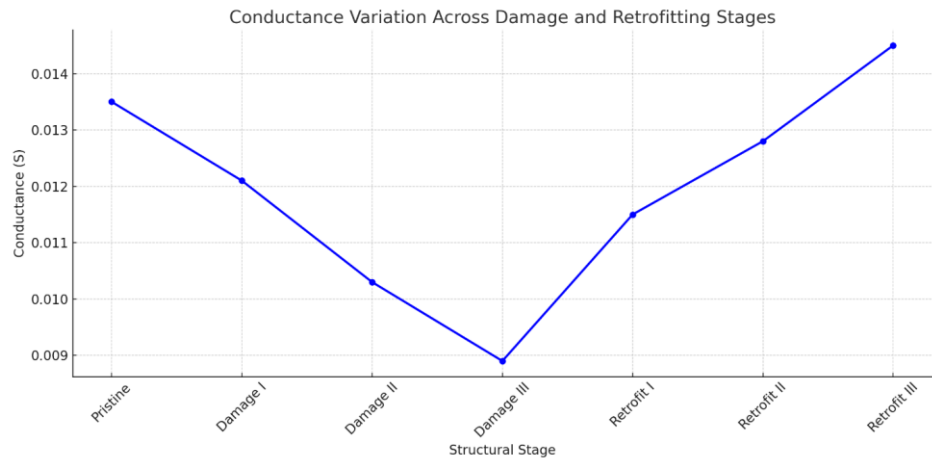


Figure 4. Conductance variation across the damage and retrofitting stages.

D. Structural Rehabilitation Evaluation

The beams were then repaired in three stages, and their mechanical response was captured with the same embedded sensors.

D.1. Conductance Recovery After Retrofitting

After repair, conductance climbed from 0.0089 S in the worst-damaged state to 0.0145 S at Retrofit III—above the pristine value of 0.0135 S—while the peak frequency recovered from 221.8 kHz to 249.5 kHz (Table 2). As Figure 4 shows, conductance trends upward through the retrofit stages, confirming that stiffness was not merely restored but slightly exceeded its original level.

D.2. Interpretation of Rising RMSD During Retrofitting

A less intuitive result was that RMSD continued to rise through the repairs: 18.15% after Retrofit I (welding), 25.00% after Retrofit II (patching), and 30.86% after Retrofit III (overlay) (Table 2, Figure 5). Because RMSD measures deviation from the original baseline, the stiffer and dissimilar repair materials introduce an impedance mismatch that the sensor reads as a large signature change. In this context the rising index signals mechanical transformation rather than damage—evidence that EMI can verify the quality of a retrofit as readily as it flags deterioration [14, 17].

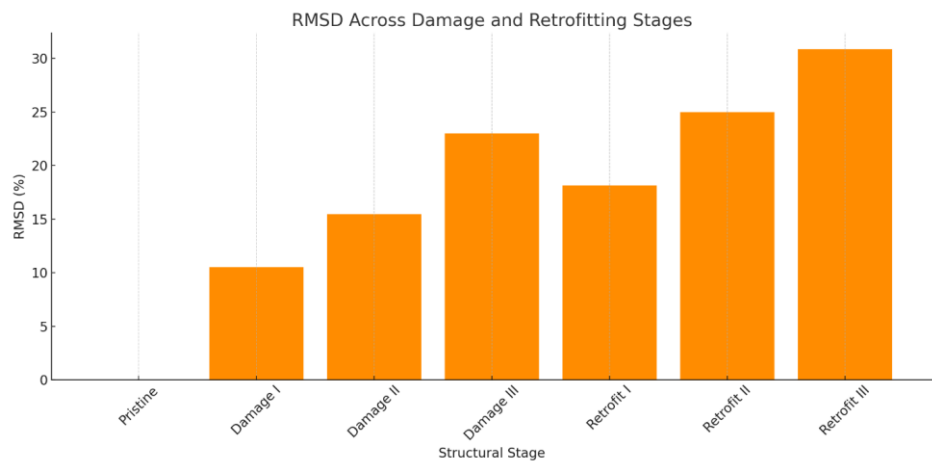


Figure 5. RMSD variation across the damage and retrofitting stages.

E. Comparative Analysis: CM versus RM under EMI-Based SHM

Table 3 sets the two mixes side by side. RM lags CM throughout, but only slightly: its final resonance frequency is 2.49% lower, its eight-hour RMSD 11.43% lower, and its conductance drop 35.90% smaller. Importantly, both mixes coupled stably with the sensors and returned clear signals, confirming that RDF concrete is fully compatible with EMI-based monitoring.

Table 3. EMI-based performance metrics for the control and RDF concrete mixes.

Parameter	Control Mix (CM)	RDF Mix (RM)	% Difference (RM vs CM)
Initial resonance frequency (kHz)	234.6	232.3	−0.98%
Final resonance frequency (kHz, 8 h)	248.3	242.1	−2.49%
RMSD at 8 h (%)	14.35	12.71	−11.43%
Conductance drop (initial to 8 h, S)	0.0039	0.0025	−35.90%
EMI sensitivity stability	Stable	Stable	—
Sensor-concrete coupling behaviour	Strong	Strong	—

Note: RDF ash slightly delays the resonance shift and RMSD growth but stays within acceptable engineering margins.

F. Engineering and Sustainability Implications

Table 4 gathers the interpretation across every phase. From hydration through damage to repair, the EMI signatures responded consistently to gains, losses, and transformations of stiffness. CM hydrated faster, RM followed a parallel but slightly delayed path, and during loading the sensors registered both subtle and severe failures through changes in conductance and RMSD. During repair the same signatures verified recovery and, ultimately, performance beyond the original.

Table 4. Interpretation of EMI signatures across all experimental phases.

Experimental Phase	EMI Trend	Engineering Interpretation	Remarks
Early hydration – CM	Increasing RMSD, peak shift ↑	Rapid stiffness gain from OPC hydration	Standard hydration profile confirmed
Early hydration – RM	Gradual RMSD rise	Delayed pozzolanic reaction of RDF ash	Acceptable alternative with minor delay
Damage Stage I	Conductance ↓, RMSD ↑	Minor loss of cover-concrete stiffness	Detected by embedded sensor
Damage Stage II	Conductance ↓↓, RMSD ↑↑	Major loss of tensile reinforcement	Sharp signature shift
Damage Stage III	Conductance ↓↓↓, RMSD ↑↑↑	Total tension loss and stiffness degradation	Highly sensitive to internal failure

Experimental Phase	EMI Trend	Engineering Interpretation	Remarks
Retrofit I (welding)	Conductance ↑, RMSD stable	Partial mechanical recovery	Interface regains stiffness
Retrofit II (patching)	Conductance ↑↑	Sectional stiffness enhancement	Near original performance
Retrofit III (overlay)	Conductance ↑↑↑, RMSD ↑	Composite system exceeds the original	EMI detects transformation, not damage

Note: EMI-based sensing distinguishes stiffness loss (damage) from stiffness gain (retrofitting), confirming its dual monitoring capability.

Taken together, Figures 1–5 and Tables 1–4 show that the combined EMI-PZT system acts as a single, dual-mode instrument for the real-time assessment of hydration and structural integrity. That dual capability is especially valuable for sustainable concretes such as RDF mixes, where both performance verification and life-cycle tracking are essential [1, 18].

IV. CONCLUSION

This study developed an integrated EMI-based scheme for monitoring both early-age hydration and the damage-repair behaviour of concrete containing refuse-derived fuel (RDF) ash, and demonstrated it on cube and beam specimens. Embedded PZT sensors followed hydration in real time, with the RDF mix attaining 88% of the control’s early stiffness gain within eight hours—confirmation that the ash performs acceptably from the outset. During controlled damage the signatures recorded a conductance fall from 0.0135 S to 0.0089 S and an RMSD rise to 23.01%, clearly marking the loss of capacity, while staged repair pushed conductance to 0.0145 S and RMSD to 30.86%, indicating that stiffness had been restored and slightly surpassed. By housing fresh-state and long-term diagnostics within one sensing framework, the approach links green binder technology with in-situ condition assessment and offers a scalable basis for life-cycle evaluation of structural concrete. Future work coupling these signatures with data-driven models could extend the method toward predictive, preventive maintenance, particularly in resource-constrained regions where efficient material use and proactive monitoring are paramount.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest relevant to this study.

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