Journal of Scientific and Technical Research
www.intellectink.in/ journal-of-scientific-and-technical-research
https://doi.org/10.67103/jstr/2026.16.1.02

Destructive and Non-Destructive Techniques for Evaluation of Strength Development for Agro-Waste Mortar

Dheeraj Sharma[1], Tushar Bansal[1]*, N.B. Singh[2]
[1]Department of Civil Engineering, Sharda School of Engineering & Science, Sharda University, Greater Noida 201310, India
[2]Department of Chemistry and Biochemistry, Sharda School of Engineering & Science, Sharda University, Greater Noida 201310, India
*Corresponding Author: tushar.bansal@sharda.ac.in

Abstract

The strength development of cement paste/mortar are of critical importance in structural health monitoring (SHM), as they directly influence early-age behaviour, long-term performance, and damage evolution in cement-based structures. This study explores the suitability of the electro-mechanical impedance (EMI) procedure in monitoring mortar strength development using agro-waste products such as rice husk ash (RHA), and sugarcane bagasse ash (SCBA) with embedded piezoelectric sensors (EPS). In order to measure the changes quantitatively, there are several statistical damage indices that are considered during the process of curing on the basis of EMI signatures. Moreover, the findings of the EMI-based sensing method are compared with others of other non-destructive and destructive testing techniques, such as rebound hammer and compressive strength (CS). The results show that the piezoelectric sensors installed in it can successfully record the strength behavior improvement during the curing process. Besides, the statistical indices as calculated based on the EMI signatures are correlated with the outcome of the destructive tests, to verify the accuracy and the efficiency of the EMI method regarding SHM in agro-waste-based cementitious materials.

Keywords: *Cement Mortar; Rice husk ash; Sugarcane Bagasse ash; Strength, Structural Health Monitoring.*

1. Introduction

Increasing carbon awareness and an ever-growing interest in energy security in recent decades have driven the world towards the further development of reliance on renewable energy sources and diversified patterns of energy production (Chowdhury et al., 2015). Among the other sources of energy, agricultural and forestry residues biomass have emerged as one of the viable and sustainable energy sources. The system of biomass-based power generation has significant benefits, such as the comparatively low operating expenses and an unlimited source of renewable energy (Rajamma et al., 2009). Biomass burning will also significantly reduce the number and weight of waste products, an effective and environmentally-sustainable method of waste management (Cheah and Ramli, 2012). Although these are the benefits, management of ash residues produced in the process of combusting biomass is a very important environmental issue. Very little of this waste is reused (approximately 70 percent dumped in landfills) and very small proportions are recycled as soil additives or otherwise (Campbell, 1990; Etiegni and Campbell, 1991). As agricultural and food waste products make almost 44 percent of all world waste production, there has been an ever-growing urgency to implement sustainable and value-added use of those by-products (Blesson and Rao, 2023).

Meanwhile, the cement industry can be recognized as one of the biggest sources of carbon emissions as the cement industry consumes approximately 7-8 percent of global CO_2 emissions, not to mention that it consumes tremendous amounts of natural resources. This has been widely explored on the utilization of other materials and more so, industrial by-products and ash of agro-wastes that can partially replace cement in construction works (Lin, 2005; Duchesne et.al, 1995; Batayneh et al., 2007; Monteiro et al., 2007; Zhao et al., 2024). The incorporation of these kinds of waste materials in cementitious systems not only minimizes the impacts on the environment, but also increases the manufacture of cost effective and sustainable building materials (Udoeyo and Dashibil, 2002; Udoeyo et al., 2006). The recent sources have also highlighted the fact that the performance of advanced concrete systems could be enhanced by the use of supplementary materials based on waste of agriculture due to the various chemical and physical characteristics (Zhao et al., 2024).

Rice husk ash (RHA) is one of the agro-waste materials that have attracted considerable attention because of its high pozzolanic activity, which is mainly because of the high silica content. RHA is mainly influenced by the amorphous silica content, particle size distribution, and specific surface area which can be optimized by means of controlled burning and grinding (Tangchirapat et al., 2008; Solomon et al., 2023). RHA addition to concrete has been reported to optimize pore structure, decrease the permeability, and chloride ion penetration resistance (Ramasamy, 2011). Another calcium silicate hydrate (C-S-H) gel formed as a result of pozzolanic reactions is what promotes greater strength and durability, especially at lower replacement rates (Godwin et al., 2018). Nonetheless, high replacement rates can have a negative impact on mechanical characteristics, including the modulus of elasticity (Poudyal and Jha, 2016; Tangchirapat et al., 2008). Experimental evidence indicates that a proper replacement level of approximately 5% can produce high compressive strength (CS) as compared to traditional concrete (MM Alsaed et al., 2024). Likewise, sugarcane bagasse ash (SCBA) which is a by-product of sugar industry has also been extensively studied as an additional cementitious material. SCBA is a pozzolanic substance that reacts with calcium hydroxide to produce more C-S-H gel which improves the mechanical strength of cementitious composites (Hernandez et al., 1998; Singh et al., 2000). Past research has shown that the replacement of cement partially with SCBA can have beneficial effects of enhancing strength and durability properties (Ganesan et al., 2007). The particle fineness and maximum particle size of SCBA have a significant effect on its reactivity (Cordeiro et al., 2008). Studies have shown that a replacement level of about 10 percent is the best in terms of CS, shrinkage and water and chloride ingress (Chi, 2012). Recent studies have documented significant increases in strength with over 25 percent improvement compared to control mixes and more intensive microstructural densification validated by microscopic examination (YM Krishna et al., 2024). Moreover, it has been demonstrated that the addition of other supplementary materials, e.g., metakaolin, can further improve the performance of SCBA-based systems, which suggests the possibility of ternary blended composites (Althaqafi et al., 2024). Economically, SCBA is very beneficial since it is a low cost or even negative cost material, which has led to large-scale savings in the total construction costs (Akram et al., 2009; Pippo et al., 2007).

Recently, the studies have also changed their focus to simultaneous use of various agro-waste materials in cementitious. Experiments on hybrid substitutes have shown that even low agro-waste ratios of combined materials can be added without affecting mechanical qualities (Jeyashree and Somesh, 2023). Different combinations of materials like RHA and SCBA have been reported to increase the properties of durability, such as penetration resistance to chloride and high-level microstructural performance (Prusty and Basarkar, 2016; Hasnain et al., 2021). High-level experimental studies have established the fact that these combinations result in the pore refinement and the development of other hydration products, which enhances the overall material performance (JR Nayak et al., 2025). Moreover, it has been reported that when RHA is incorporated in multi-component cementitious systems, the compressive and flexural strengths are increased significantly, and carbon emissions are reduced at the same time, indicating its potential in the practice of sustainable construction (Y Jing et al., 2025).

In order to measure the performance of agro-waste-based cementitious materials effectively, both non-destructive and destructive tests are used. The use of non-destructive testing (NDT) methods has become prominent because it can be used to determine the properties of materials without damaging them. The ultrasonic pulse velocity (UPV) testing is a popular method to measure the quality and the stiffness of the concrete, and the dynamic modulus of elasticity is estimated as the ratio between the wave velocity and the density of the material (Aragón et al., 2019). UPV measurements can offer good estimates when adjusted suitably to the ratio of Poisson and these estimates are in agreement with the traditional mechanical testing outcomes. Moreover, surface hardness is generally evaluated by rebound hammer tests, which are used to approximate CS (Jeyashree and Somesh, 2023). Recent research has shown that the results of NDT have strong correlations with destructive test outcomes of concrete that uses agro-waste materials, thereby proving the validity of the methods in performance assessment (PA Nadgouda et al., 2025). Destructive and non-destructive methods are then combined to fully analyze the hydration behavior, strength development and overall performance of sustainable cementitious composites. The strength and hydration kinetics are substantially influenced by the incorporation of RHA and SCBA. This incorporation of RHA and SCBA slows the early-age strength due to reduced cement content and also results in the improvement of the long-term performance of the concrete owing to pozzolanic reactions. For evaluating the performance and optimizing the design mix, monitoring of the changes occurring due to the incorporation of RHA and SCBA is necessary. The performance of the concrete (strength) can be tested by the conventional destructive methods at discrete intervals. While for checking the early microstructural changes, NDT methods such as UPV can be used, but it offers the limited sensitivity in capturing early microstructural changes (Helal et al., 2015). The limitation of the conventional NDT methods, such as UPV, has forced researchers to develop a different NDT technique, such as the electro-mechanical impedance (EMI) technique, for effectively capturing early microstructural changes. EMI is a highly sensitive method for monitoring the structural behavior of the concrete. It uses the interaction between a piezoelectric sensor and the host structure for obtaining structural behavior. In the EMI technique, the changes in the structural properties, such as stiffness and mass, are reflected in the electrical impedance signature (Liang et al., 1994; Park et al., 2003). As hydration progresses or damage occurs, measurable changes in impedance signatures provide insights into material behavior. A recent study by Kumar et al. (2025) has also demonstrated the effectiveness of the EMI technique in monitoring the hydration and strength development of the concrete. Parameters such as root mean square deviation (RMSD), which can be derived from data of the impedance, also show the correlation of structural changes and damage progression. Additionally, the research conducted by Bhalla and Soh (2004) and Na and Baek (2018) had also highlighted the capabilities of the EMI technique in detecting the micro-level damages and early-stage deteriorations, which were often not captured by conventional NDT methods. Thus, the objective of the current study is to examine the strength development of the cement mortar made by incorporating RHA and SCBA by using the EMI techniques via piezoelectric sensors. To support the EMI results, destructive compression tests and rebound hammer measurements were performed.

2. Experimental Setup and Testing Methodology

Ordinary Portland Cement (OPC) conforming to the IS 8112 was used as the primary binder during the whole experiment. The OPC used during the experimentation has exhibited the standard consistency, setting time, and strength characteristics that are suitable for blended cement systems. To investigate the strength development of the cement mortar, the OPC is partially replaced by the ash of the agro-waste (RHA and SCBA). The 10% of RHA and 20% of SCBA are used as supplementary cementitious materials, as shown in Figure 1. Ashes from both the agro- waste are obtained from the controlled-combustion processes. Before incorporation, these agro-wastes are subsequently ground to a fineness, i.e., comparable to cement. The ashes obtained from this agro-waste are rich in amorphous silica, which contributes to the pozonolysis activity and microstructural densification.

(a) (b) (c)

Figure 1: Materials (a) OPC, (b) SCBA, (c) RHA

Natural river sand conforming to Zone II as per IS 383 was used for mortar preparation. The sand was clean, well-graded, and free from deleterious materials. Potable water free of impurities was used to mix and cure all specimens. Cement mortar specimens were cast as per the mix design, and other specimens were cast with embedded piezoelectric sensors positioned centrally. Mortar specimens were cast in 70.6 mm cube molds. After casting, specimens were covered to prevent moisture loss and demolded after 24 hours to acquire the reading from LCR, rebound hammer, and compressive testing machine for 1-90 day of cube. All specimens were water-cured at laboratory temperature until the testing age. Mortar specimens were prepared using a binder-to-sand ratio of 1:3 as per IS 2250 as shown in Table 1.

The EMI measurements are conducted using a controlled excitation using a high-precision Keysight LCR meter (Keysight Technologies). A sinusoidal 1 V voltage signal is applied to the embedded PZT sensors over a predefined frequency range, typically from 30 to 400 kHz, and the corresponding electrical admittance impedance response is acquired (Gomasa et al., 2025), as shown in Figure 2. EMI data acquisition is performed at specific curing ages to capture the evolution of the strength of mortar over time. The EMI response obtained from embedded PZT sensors consists of frequency-dependent electrical impedance signatures that reflect the mechanical impedance of the mortar. As hydration progresses, the stiffness and damping properties of the mortar matrix evolve, which in turn alters the electro-mechanical coupling behaviour of the embedded sensor. These variations typically manifest as shifts in resonance peaks, changes in amplitude, and overall modification of the electrical impedance response (Bansal et al., 2022; 2025). However, the electrical impedance signatures are high-dimensional and contain a large amount of information distributed across the frequency domain. The coupled electro-mechanical interaction between host structure and PZT sensor is described by the numerical equation proposed by Soh and Bhalla, as shown in equation (1)

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

where G and B denote the conductance and susceptance, respectively, with j representing the imaginary unit; l, w, and t are the length, width, and thickness of the PZT patch; ω is the angular frequency; d_{31} is the piezoelectric strain coefficient; $\bar{\varepsilon}$ is the complex electrical permittivity of the PZT; $\bar{Y}$ is the complex Young's modulus of the PZT; ν is the Poisson's ratio; $Z_{s,eff}$ and $Z_{a,eff}$ are the effective impedances of the host structure and the PZT, respectively; and the complex tangent ratio accounts for $\overline{T}$.

To quantify the signatures, it is possible to quantify the change of the original conductance signatures through a variety of statistical parameters. Statistical parameters like RMSD were used in this research to determine variations of the signatures throughout the curing period of various materials. The RMSD of the conductance signatures is calculated here for strength quantification, as outlined below.

$$RMSD(\%) = \sqrt{\frac{\sum_{i=1}^{N}(G_i - G_{bl})^2}{\sum_{i=1}^{N}(G_{bl})^2}} \text{x } 100 \tag{2}$$

where: G_i is the resultant data points of conductance signature on exposure to corrosion, G_{bl} is the data points of the baseline, and N is the number of data points in the conductance signature.

Table 1. Mortar Mix Proportions

Mix ID	OPC (%)	RHA (%)	SCBA (%)	Binder : Sand	Water/Binder
M-OPC	100	0	0	1 : 3	0.45
M-RHA10	90	10	0	1 : 3	0.45
M-SCBA20	80	0	20	1 : 3	0.45

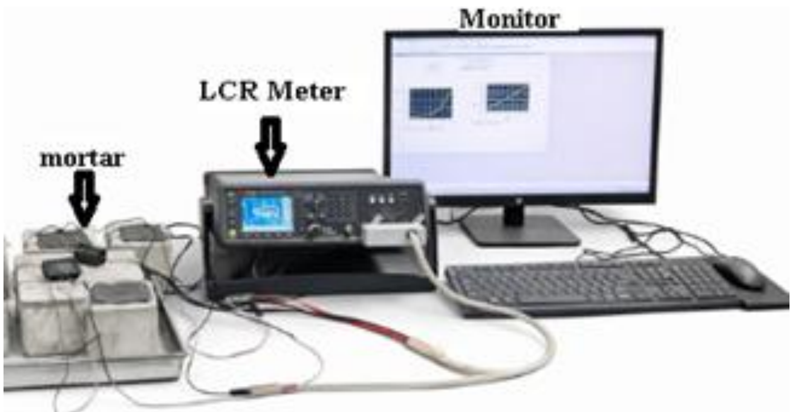

Figure 2. Data acquisition setup

2.1 Compressive Strength Test

Compressive strength tests were conducted using a compression testing machine at different curing ages in accordance with IS 516 as shown in Figure 3 and the results are shown in Figure 4. In the compression testing machine results (3–90 days), a more accurate and representative measure of CS is observed. The strength gain trend remains consistent, with OPC maintaining the highest values throughout the curing period. However, RHA exhibits significant long-term strength development, nearly matching OPC at 80–90 days, which highlights its effectiveness as a supplementary cementitious material. SCBA, on the other hand, shows the lowest CS among the three mixes, although it continues to gain strength steadily over time. The slower rate of strength development in SCBA-based mortar can be attributed to its relatively lower reactivity and possible variations in ash quality.

(a) (b) (c)

Figure 3. Images of testing of cube specimen through Compressive testing machine of different mortar (a) OPC, (b) RHA and (c) SCBA

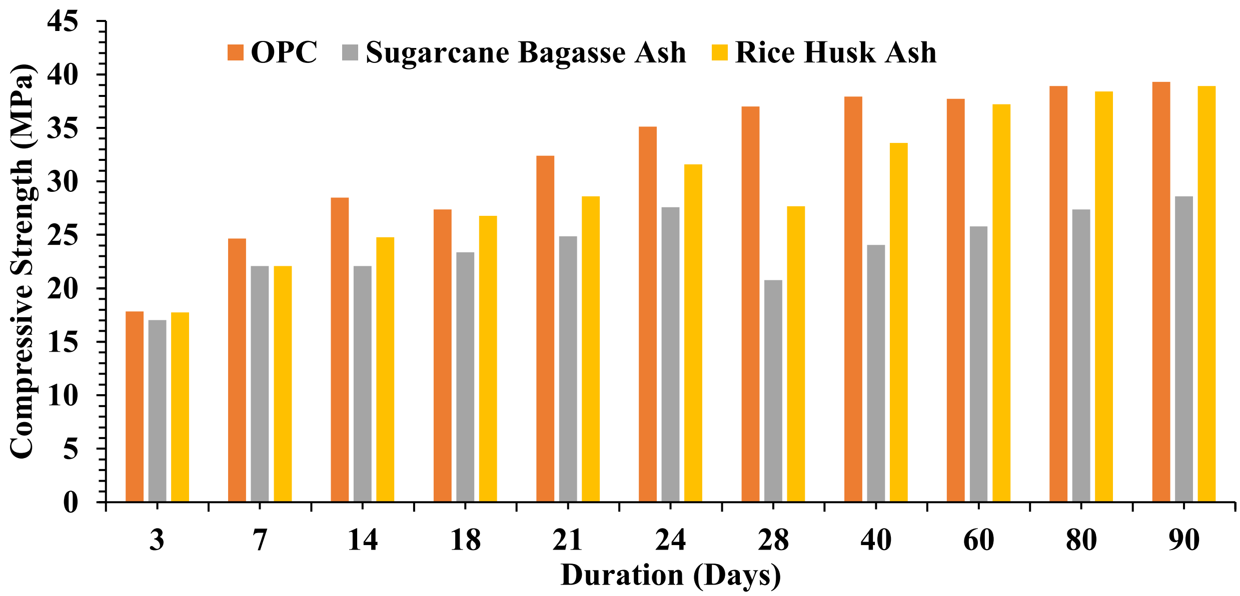

Figure 4: Compressive strength of cement mortar using compression testing machine

Figure 5 shows the rebound hammer tests that are conducted on mortar specimens at the curing age of 1 to 90 days and the results of the rebound hammer tests are presented in Figure 6. During the rebound hammer test at the early age of 1–11 days, the results show that the compressive strength (CS) of all mixes is increasing steadily with curing time, which indicates the progression of hydration and strength development. Out of all the samples, OPC has shown the highest strength at all curing ages and indicates its superior early-age performance. Between the agro-waste, RHA is showing higher strength than SCBA, particularly after the initial curing days. This indicates that the RHA has a higher pozzolanic reactivity and finer particle size. While the SCBA may have lower early strength, it shows a gradual improvement with time, which confirms the delayed pozzolanic action. Results at the later curing ages show that RHA has comparable strength to OPC, while the SCBA mix shows slightly lower strength as compared to RHA and OPC. The comparison between the rebound hammer test results and compressive strength results indicates that the rebound hammer test values are slightly overestimate the compressive strength due to their dependence on surface hardness. While conventional compression testing through the compression testing machine (CTM) provides a more reliable and accurate assessment of actual material strength. The findings from CTM indicate that the RHA has strong potential as a partial cement replacement due to its excellent long-term performance. While the SCBA requires further processing or optimization to achieve strength characteristics comparable to conventional cement systems.

(a) (b) (c)

Figure 5. Images of testing cube specimen through Rebound hammer test machine of different mortar (a) OPC, (b) RHA and (c) BA

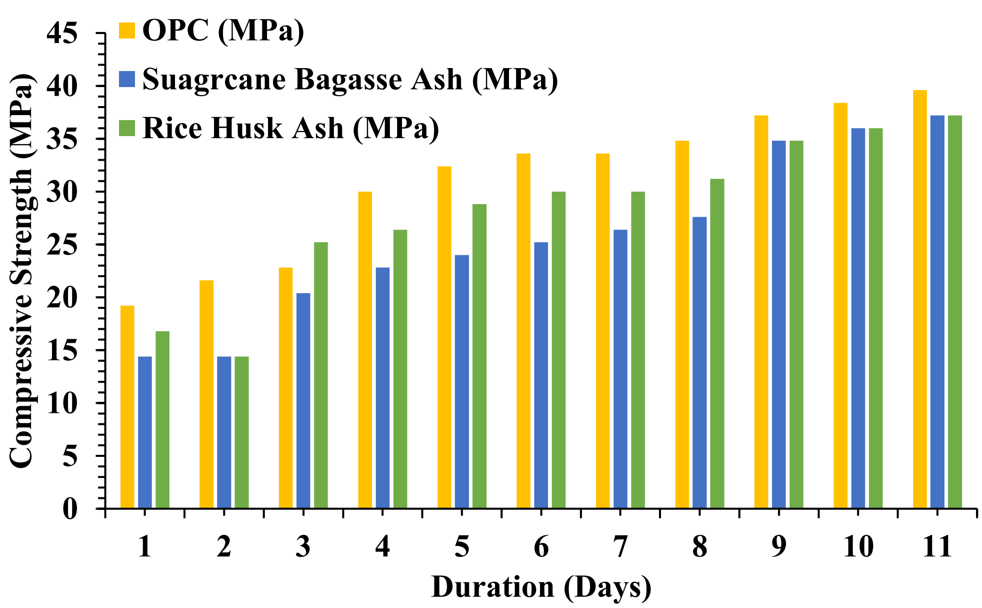

Figure 6: Compressive strength of cement mortar using rebound hammer test

4. Analysis:

4.1. EMI Analysis

The EMI signatures used to monitor the strength development of cement mortars over a 90-day period are shown in Figure 7. Figure 7(a) illustrates the baseline performance of conventional mortar made up of OPC. In the initial stages (Day 2 to Day 7), it can be seen that the conductance values are relatively low, and the peaks are less defined which represents the plastic or early hardening phase where the hydration products, such as Calcium Silicate Hydrate (C-S-H) gels, are just beginning to form a skeleton. As time progresses toward 28 and 90 days, there is a visible upward shift in the conductance signatures. The peaks are primarily concentrated between 250 kHz and 350 kHz, become more pronounced. This stabilization of the curves after 28 days suggests that the primary hydration process has reached a plateau, and the mortar has achieved its design strength. The SCBA mortar as shown in Figure 7(b) shows a similar trend but with subtle differences in peak intensity. SC is a pozzolanic material, meaning it reacts with the calcium hydroxide produced during cement hydration to form additional cementitious compounds. The graph for SCBA shows a very dense clustering of lines between Day 14 and Day 90. This indicates a consistent and steady gain in strength. Interestingly, the conductance peaks in the 250–300 kHz range for SCBA are slightly more localized than in the OPC sample, suggesting that the incorporation of bagasse ash might lead to a more uniform pore structure at later ages, though the overall magnitude of conductance remains comparable to the control. The RHA mortar exhibits the most remarkable variation among the three samples, as shown in Figure 7(c). The conductance values for RHA (reaching up to 0.0045 S) are significantly higher than those for OPC and SCBA (which peak around 0.0030 to 0.0035 S). RHA is known for its high silica content and high surface area, which triggers a very reactive pozzolanic response. The significant gap between the 2-day curve (light orange) and the subsequent days indicates a rapid early-age densification. The RHA curves show much sharper, higher-amplitude peaks between 250 kHz and 300 kHz. This elevated conductance response is a strong indicator that the RHA mortar has a higher dynamic stiffness and potentially higher CS than the other two mixes. The convergence of the lines from Day 28 to Day 90 shows that while the material becomes very strong early on, the later-age refinement of the pores continues to contribute to the structural integrity. When comparing all cement mortar samples, a clear pattern emerges regarding the frequency sensitivity of the EMI method. The frequency range of 200 kHz to 400 kHz appears to be the most "active" zone for monitoring mortar strength. In this region, the resonance of the PZT sensor is most sensitive to the hardening of the matrix. The gradual upward migration of the curves reflects the transition of the mortar from a semi-solid state to a hardened crystalline structure. The use of agro-waste ashes (SCBA and RHA) does not negatively impact the conductance signatures; instead, RHA significantly enhances the magnitude of the response, suggesting a denser microstructural packing. Hence, these graphs validate the use of EMI sensing as a non-destructive tool for real-time strength monitoring.

The data confirms that while all mortars gain strength over time, RHA-modified mortar exhibits superior microstructural development reflected in its higher conductance peaks and rapid early-age reaction.

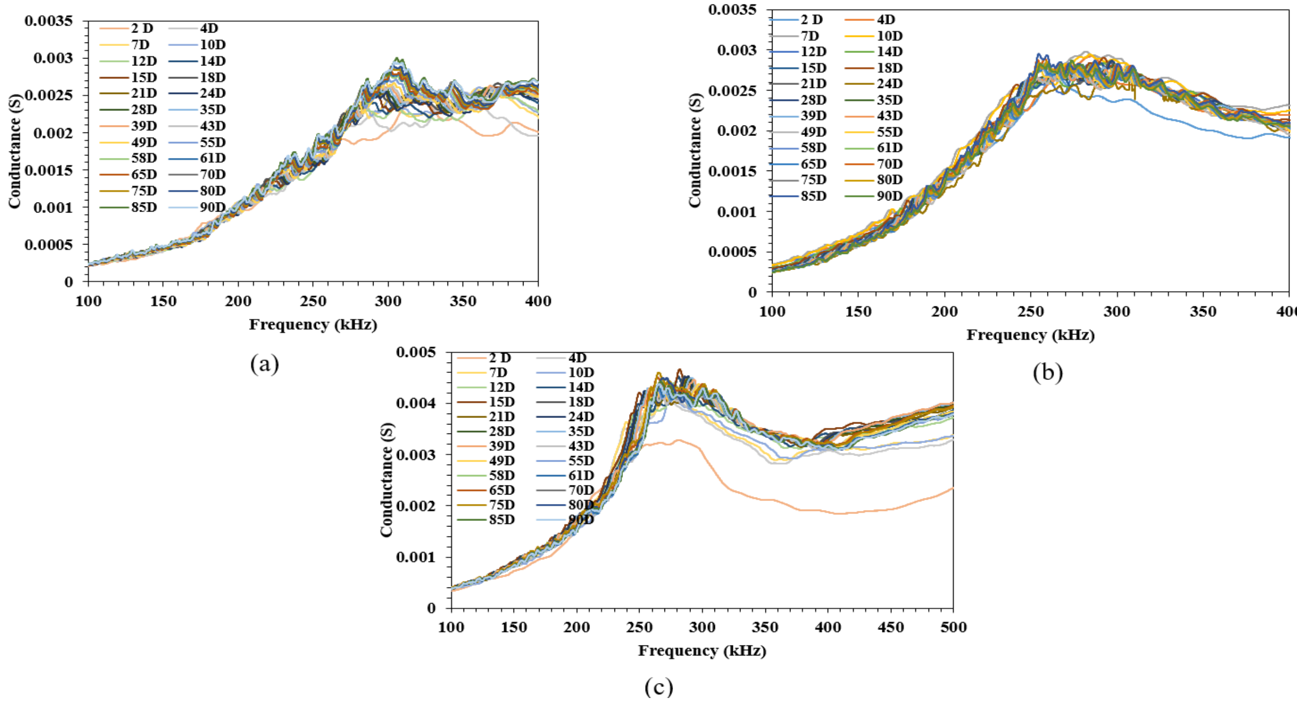

Figure 7: Conductance vs frequency response of Mortar during strength development (a) OPC, (b) SCBA and (c) RHA

4.2. Analysis of RMSD

The given scattered plots illustrate the RMSD indices, which are calculated from the EMI signatures for the three different mortar specimens over the 90-day curing period. The signature trend has been continuously increasing for all three different mortar specimens over the 90-day curing period. In the structural health monitoring (SHM) by the EMI technique, the RMSD index serves as the statistical scalar value. This RMSD index is used to quantify the “distance” or the change that occurs between the baseline signature and the next signature which is usually taken at an interval of an hour or a day. RMSD signatures are taken at the subsequent ages, which reflect the changes in the material condition. The continuous and significant rise in the RMSD value signifies the changes in the material properties, particularly in the stiffness, the density, and the damping characteristics. The rise in the RMSD values is directly correlated with the changes that are occurring in the material and is also an indicator that the material is transitioning from the fresh state to the hardened structural component. This also indicates that the structure has been gaining strength and stability over time. In Figure 8(a), the RMSD values show a steady climb from approximately 7% to 12% during the first 28 days and this indicates the continuous development in the material properties. This logarithmic-like growth curve is characteristic of the standard cement hydration and has been representing the typical hydration behavior. There is a notable amount of scatter in the data points between Day 10 and Day 30, which contributes to the internal stresses and the temperature fluctuations occurring as the C-S-H gel matrix is stabilizing. After the 28-day mark, the RMSD values plateau around 11.5% to 12.5%, indicating that the material has reached a stable mechanical state where further chemical changes are minimal. The SCBA plot (Figure 8(b)) exhibits more volatility in the early stages compared to the OPC control. It is observed that a significant spike and subsequent dip in the RMSD values within the first 20 days, followed by a steady ascent. This erratic behavior at early ages is often linked to the slower pozzolanic reaction of bagasse ash. The secondary reaction (where the ash reacts with calcium hydroxide) takes longer to initiate than the primary cement hydration. Once the pozzolanic activity stabilizes after Day 30, the RMSD settles into a range of 12% to 14%, which is slightly higher than the OPC sample. This suggests that the SCBA mortar ultimately undergoes a more comprehensive structural transformation than the pure cement mortar.

The peaks of RMSD of RHA are shown in Figure 8(c). The RMSD values are relatively low and stable (less than 10%) for the first 30 days, then a remarkable jump between Day 30 and Day 45, where the index jumps to 25%. It eventually peaks at about 30% by Day 90 This great variation of the RMSD index is a clear sign of the better densification in the RHA mortar. The high silica content in RHA causes an intense late-age pozzolanic reaction, which substantially alters the mechanical impedance of the mortar. The magnitude of the RMSD here is almost twice that of the OPC and SCBA samples confirming that RHA forms a more rigid and structurally evolved matrix. The overall behavior across all three different mortar specimens confirms the sensitivity of the EMI-based RMSD index to the internal evolution of cementitious materials. The clear differentiation between the three plots demonstrates that the EMI technique is not only capable of monitoring strength development but also of distinguishing the performance characteristics of different supplementary cementitious materials. The RHA mortar's high RMSD values suggest it would be the most suitable binder for high-performance or high-strength applications where maximum densification is required.

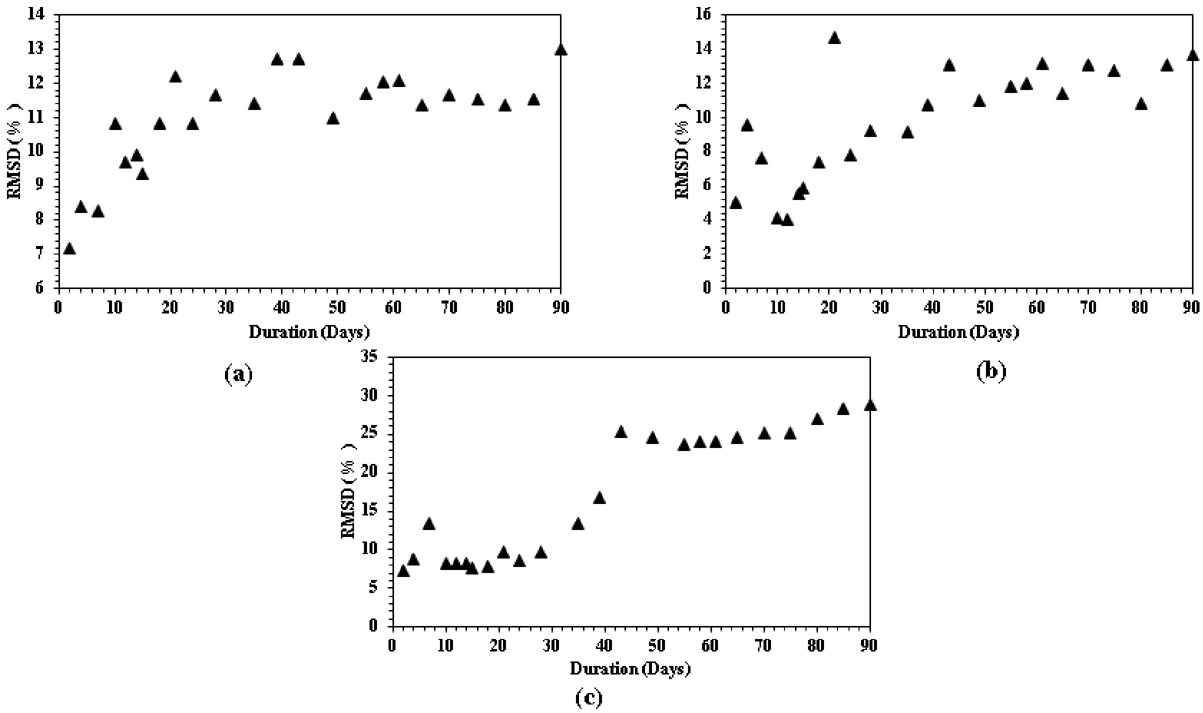

Figure 8: RMSD response of mortar during strength development (a) OPC, (b) SCBA and (c) RHA

5. Conclusions

This study examined the strength development of agro-waste-based cement mortars containing RHA and SCBA, drawing on both destructive testing and non-destructive techniques, with particular attention to the EMI method. The main findings can be summarised as follows:

- The EMI approach, based on embedded piezoelectric sensors, proved to be a fast and sensitive means of tracking strength gain in cementitious materials. Shifts in the conductance signatures and resonance peaks represented the microstructural changes taking place as the mortar cured, which points to the method's value for continuous, real-time SHM.
- Correlation was found between strength gain and RMSD obtained from EMI signatures over time. The increase in RMSD values with the increase in internal structure density of the mortar as it hardened supports its use as a reliable quantitative measure for strength assessment.
- The RHA mortar exhibited the highest long-term strength of the tested mixes. This was confirmed by its higher conductance peaks and significantly higher RMSD values, both suggesting stronger pozzolanic activity and better stiffness development. The early age strength gain of the SCBA mortar was slower but showed an optimistic trend thereafter, indicating that it has the potential to be a viable sustainable additive after further optimization of the mix design.
- Comparison of destructive (CS) and non-destructive (rebound hammer and EMI) techniques showed that the conventional techniques provide reliable strength values, but EMI provides a better insight of early-age behaviour and material evolution inside the concrete that cannot be captured well by conventional techniques.

- Combining agro-waste materials like RHA and SCBA with sensing techniques like EMI is a promising approach for more sustainable construction and smarter SHM. The results confirm that EMI monitoring can be a useful tool for evaluation of blended cementitious systems, with potential applications in mix design, durability assessment and long-term safety of structures.

References

1. Alsaed, M.M. and Al Mufti, R.L., 2024. The effects of rice husk ash as Bio-Cementitious Material in concrete. Construction Materials, 4(3), pp.629-639.
2. Akram, T., Memon, S.A. and Obaid, H., 2009. Production of low cost self compacting concrete using bagasse ash. Construction and Building Materials, 23(2), pp.703-712.
3. Althaqafi, E., Ali, T., Qureshi, M.Z., Islam, S., Ahmed, H., Ajwad, A., Almujibah, H. and Khan, M.A., 2024. Evaluating the combined effect of sugarcane bagasse ash, metakaolin, and polypropylene fibers in sustainable construction. Scientific Reports, 14(1), p.26109.
4. Aragon, G., Aragon, A., Santamaria, A., Esteban, A. and Fiol, F., 2019. Physical and mechanical characterization of a commercial rendering mortar using destructive and non-destructive techniques. Construction and Building Materials, 224, pp.835-849.
5. Bansal, T., Azam, A., Morwal, T., Talakokula, V. and Saravanan, T.J., 2025. Assessing cement paste strength evolution under curing: An experimental and numerical investigation through equivalent stiffness parameter identified by embedded piezo sensors. Measurement, 241, p.115713.
6. Bansal, T., Talakokula, V. and Sathujoda, P., 2022. Machine learning-based monitoring and predicting the compressive strength of different blended cementitious systems using embedded piezo-sensor data. Measurement, 205, p.112204.
7. Batayneh, M., Marie, I. and Asi, I., 2007. Use of selected waste materials in concrete mixes. Waste management, 27(12), pp.1870-1876.
8. Bhalla, S. and Soh, C.K., 2004. Structural health monitoring by piezo-impedance transducers. I: Modeling. Journal of Aerospace Engineering, 17(4), pp.154-165.
9. Blesson, S. and Rao, A.U., 2023. Agro-industrial-based wastes as supplementary cementitious or alkali-activated binder material: a comprehensive review. Innovative Infrastructure Solutions, 8(4), p.125.
10. Campbell, A.G., 1990. Recycling and disposing of wood ash.
11. Cheah, C.B. and Ramli, M., 2012. Mechanical strength, durability and drying shrinkage of structural mortar containing HCWA as partial replacement of cement. Construction and Building Materials, 30, pp.320-329.
12. Jing, Y., Lee, J.C., Moon, W.C., Jin, Y., Ng, J.L. and Yew, M.K., 2025. Ternary and quaternary sustainable cementitious composites containing rice husk ash: a comprehensive review. Discover Applied Sciences, 7(3), p.174..
13. Chi, M.C., 2012. Effects of sugar cane bagasse ash as a cement replacement on properties of mortars. Science and Engineering of Composite Materials, 19(3), pp.279-285.
14. Chowdhury, S., Maniar, A. and Suganya, O.M., 2015. Strength development in concrete with wood ash blended cement and use of soft computing models to predict strength parameters. Journal of advanced research, 6(6), pp.907-913.
15. Cordeiro, G.C., Toledo Filho, R.D., Tavares, L.M. and Fairbairn, E.M.R., 2008. Pozzolanic activity and filler effect of sugar cane bagasse ash in Portland cement and lime mortars. Cement and Concrete composites, 30(5), pp.410-418.
16. Duchesne, J. and Be, M.A., 1995. Effect of supplementary cementing materials on the composition of cement hydration products. Advanced Cement Based Materials, 2(2), pp.43-52.
17. Etiegni, L. and Campbell, A.G., 1991. Physical and chemical characteristics of wood ash. Bioresource technology, 37(2), pp.173-178.
18. Ganesan, K., Rajagopal, K. and Thangavel, K., 2007. Evaluation of bagasse ash as supplementary cementitious material. Cement and concrete composites, 29(6), pp.515-524.
19. Godwin, I.A., Deborah, S.N., Ponraj, I.J., Blessho, R.V. and Stephen, C., 2018. Experimental investigation on the

mechanical and microstructural properties of concrete with agro-waste. Int J Eng Technol, 7, p.33.

20. Gomasa, R., Talakokula, V., Jyosyula, S.K.R. and Bansal, T., 2025. Strength monitoring and prediction of blended concrete systems from very early to delayed curing age using embedded piezo sensor data: An experimental and machine learning approach. Journal of Building Engineering, 107, p.112677.
21. Helal, J., Sofi, M. and Mendis, P., 2015. Non-destructive testing of concrete: A review of methods. Electronic Journal of Structural Engineering, 14(1), pp.97-105.
22. Hasnain, M.H., Javed, U., Ali, A. and Zafar, M.S., 2021. Eco-friendly utilization of rice husk ash and bagasse ash blend as partial sand replacement in self-compacting concrete. Construction and Building Materials, 273, p.121753.
23. Hernández, J.M., Middendorf, B., Gehrke, M. and Budelmann, H., 1998. Use of wastes of the sugar industry as pozzolana in lime-pozzolana binders: study of the reaction. Cement and Concrete Research, 28(11), pp.1525-1536.
24. Helal, J., Sofi, M. and Mendis, P., 2015. Non-destructive testing of concrete: A review of methods. Electronic Journal of Structural Engineering, 14(1), pp.97-105.
25. Jeyashree, T.M. and Somesh, M.S., 2023. Characteristic study on concrete elements using agro-waste as a replacement of fine aggregate. Res Eng Struct Mater, 9(4), pp.1255-66.
26. Keysight Technologies, "Keysight E4980A Precision LCR Meter." [Online]. Available: https://www.keysight.com/in/en/product/E4980A/precision-lcr-meter-20-hz-2-mhz.html
27. Kumar, G., Bansal, T. and Sharma, D., 2025. Monitoring of corrosion in reinforced E-Waste concrete subjected to Chloride-Laden environment using embedded piezo sensor. Construction Materials, 5(3), p.46..
28. Liang, C., Sun, F.P. and Rogers, C.A., 1994. Coupled electro-mechanical analysis of adaptive material systems—determination of the actuator power consumption and system energy transfer. Journal of intelligent material systems and structures, 5(1), pp.12-20).
29. Lin, K.L., 2005. The influence of municipal solid waste incinerator fly ash slag blended in cement pastes. Cement and concrete research, 35(5), pp.979-986.
30. Monteiro, M.A., Raupp-Pereira, F., Ferreira, V.M., Dondi, M. and LABRHCLA, J., 2005. htweight aggregates based industrial wastes. Industrial ceramics, 25(3), pp.157-163.
31. Krishna, Y.M., Dhevasenaa, P.R., Srinivasan, G. and Satish kumar, C.N., 2024. Sugarcane bagasse ash as a partial replacement in concrete: a performance analysis. Innovative Infrastructure Solutions, 9(8), p.299.
32. Na, W.S. and Baek, J., 2018. A review of the piezoelectric electromechanical impedance based structural health monitoring technique for engineering structures. Sensors, 18(5), p.1307.
33. Nadgouda, P.A. and Sharma, A.K., 2025. Strength evaluation of concrete incorporating agro-industrial waste and M-sand using non-destructive testing. Innovative Infrastructure Solutions, 10(8), p.375.
34. Nayak, J.R., Gołaszewska, M. and Bochen, J., 2025. Physical and Mechanical Performance of Mortar with Rice Husk Ash and Sugarcane Bagasse Ash as Partial Cement Replacement. Materials, 18(20), p.4758.
35. Park, G., Sohn, H., Farrar, C.R. and Inman, D.J., 2003. Overview of piezoelectric impedance-based health monitoring and path forward. Shock and vibration digest, 35(6), pp.451-464.
36. Pippo, W.A., Garzone, P. and Cornacchia, G., 2007. Agro-industry sugarcane residues disposal: the trends of their conversion into energy carriers in Cuba. Waste management, 27(7), pp.869-885.
37. Poudyal, P. and Jha, A.K., 2016. Experimental study on the properties of concrete with the partial replacement of sand by rice husk. In Proceedings of IOE Graduate Conference (pp. 191-195).
38. Prusty, J.K., Patro, S.K. and Basarkar, S.S., 2016. Concrete using agro-waste as fine aggregate for sustainable built environment–A review. International Journal of Sustainable Built Environment, 5(2), pp.312-333.
39. Rajamma, R., Ball, R.J., Tarelho, L.A., Allen, G.C., Labrincha, J.A. and Ferreira, V.M., 2009. Characterisation and use of biomass fly ash in cement-based materials. Journal of hazardous materials, 172(2-3), pp.1049-1060.
40. Ramasamy, V.W., 2012. Compressive strength and durability properties of rice husk ash concrete. KSCE Journal of Civil Engineering, 16(1), pp.93-102.
41. Singh, N.B., Singh, V.D. and Rai, S., 2000. Hydration of bagasse ash-blended Portland cement. Cement and concrete research, 30(9), pp.1485-1488.

42. Solomon, A.E., Woubishet, Z.T., Vo, D.H. and Yehualaw, M.D., 2023. Rice husk ash in alsee

43. Tangchirapat, W., Buranasing, R., Jaturapitakkul, C. and Chindaprasirt, P., 2008. Influence of rice husk–bark ash on mechanical properties of concrete containing high amount of recycled aggregates. Construction and Building Materials, 22(8), pp.1812-1819.

44. Udoeyo, F.F. and Dashibil, P.U., 2002. Sawdust ash as concrete material. Journal of materials in civil engineering, 14(2), pp.173-176.

45. Udoeyo, F.F., Inyang, H., Young, D.T. and Oparadu, E.E., 2006. Potential of wood waste ash as an additive in concrete. Journal of materials in civil engineering, 18(4), pp.605-611.

46. Zhao, J., Sufian, M., Abuhussain, M.A., Althoey, F. and Deifalla, A.F., 2024. Exploring the potential of agricultural waste as an additive in ultra-high-performance concrete for sustainable construction: A comprehensive review. Reviews on Advanced Materials Science, 63(1), p.20230181.

47.