Innovative Use of Piezoelectric Sensors for Concrete Strength Monitoring and Identification of Concrete Damage

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ABSTRACT

Concrete stands as the primary material in the realm of civil engineering. Checking concrete strength early is vital for safe and speedy construction, preventing structural failures. In this study, the piezoelectric-based monitoring method was used for early concrete strength monitoring, and a piezoelectric base transducer called smart aggregate (SA) was embedded in the host structure for damage detection of civil structures. The study employed a piezoelectric lead zirconate titanate (PZT) sensor. It discusses two methods: attaching the sensor to the surface and embedding it within concrete structures. The investigation outcomes are disclosed at designated time points, encompassing 4 weeks. The results illustrate a graphical curve, affirming that the piezoelectric-based monitoring method can predict early-age concrete strength from its inception throughout its lifespan. This review explores the utilization of piezoelectric sensors, oscilloscopes, and electromechanical impedance (EMI).

1. Introduction

In civil engineering, concrete stands out as the primary material employed extensively. Strength development is a consequence of the hydration process, which comprises a sequence of reactions involving cement and water. The primary outcome of this exothermic reaction is the creation of cement gel. Monitoring early-age concrete strength is essential for expediting construction processes. Two primary approaches exist for this purpose: non-destructive evaluation and destructive evaluation. Destructive methods involve crushing concrete samples to ascertain strength but are impractical for monitoring extensive reinforced concrete (RC) structures. Consequently, non-destructive methods have gained prominence as it facilitates real-time monitoring of concrete strength and other properties in existing structures, providing immediate results. Among the three frequently utilized non-destructive methods are: The piezoelectric-based monitoring approach, the ultrasonic-based monitoring method, the hydration heat-based monitoring technique

Various advanced smart materials, including shape memory alloys, piezoelectric materials, and optical fibres, find applications in non-destructive techniques. Among these, piezoelectric sensors (PZTs) play a key role in monitoring the health of concrete structures, employing methods based on either impedance or vibration characteristics-based method. It consists of a piezoelectric patch bonded to the host structure on its surface or embedded inside. The commonly used piezoelectric material for this study was Lead Zirconate Titanate. The main characteristics of PZTs are high elastic modulus, low tensile strength, and brittleness. Creating a smart aggregate (SA) involves several steps. Initially, a piezoelectric patch is affixed to the smart aggregate, and this assembly is coated with insulation to safeguard it against water and moisture. Subsequently, it is integrated into a small concrete block incorporated into the larger concrete structure. These smart aggregates are versatile and cost-effective, relying on piezoelectric technology to fulfil various monitoring tasks, including structural health assessment, early-age strength estimation, impact detection, and overall evaluation of concrete structures. To assess initial stage concrete strength, one smart aggregate acts as an actuator, generating high-frequency harmonic signals, while another smart aggregate functions as a sensor to receive and interpret these signals. This monitoring process can be done using wired smart aggregates or wireless embedded systems. Top of Form Modern wireless systems, whether surface-based or embedded, are increasingly employed for their straightforward installation and remote accessibility. The piezoelectric method offers several advantages, including rapid response, adaptable shapes, and ease of implementation. The study presented how piezoelectric materials find utility in two essential areas: concrete strength monitoring and identifying damage within concrete structures.

Ai D et al. (2020) introduced a method for monitoring concrete strength by incorporating accelerator/retarder admixtures into the concrete to enhance the Electromechanical Impedance (EMI) technique. This approach employed a novel type of piezoelectric transducer known as cement/aluminium embedded PZT (CEP/AEP). These specialized PZT transducers were chosen for their unique properties and suitability for embedding within concrete structures to facilitate early-age concrete strength monitoring and damage detection [1]. Chena J et al. (2015)

described using a wireless sensor network as a substitute for wired data acquisition systems in concrete strength monitoring. The methodology necessitated using two smart aggregates: one designed as an actuator to produce high-frequency vibration waves and the other configured as a sensor to capture these vibrations as it propagated through the concrete structure. The study's findings highlighted the advantages of the wireless system's embedded design, offering benefits such as decreased system size and cost, enhanced robustness, and increased flexibility [3]. Dong B et al. (2015) proposed the objective of validating the suitability and practicality of a cement-based piezoelectric ceramic sensor composite for real-time stress monitoring in reinforced concrete (RC) structures exposed to static loads [4].

Han G et al. (2020) conducted an in-depth analysis of the underlying mechanisms of the electromechanical impedance technique, specifically focusing on its application for evaluating the progression of strength in cementitious materials. This research aimed to enhance our understanding of the EMI method and its utility in monitoring concrete strength's initial stage [5]. Hou S et al. (2019) introduced a three-direction stress sensor based on piezoelectric (PZT) technology designed for monitoring internal stresses along three mutually orthogonal directions [6]. Kaur N et al. (2020) delved into the function of the EMI technique to evaluate the performance of incorporated resin-jacketed piezo (RJP) sensors for concrete strength monitoring. This study aimed to determine the accuracy and persuasiveness of RJP sensors as an apparatus for monitoring concrete strength throughout its early-age development [7]. Kim W et al. (2019) introduced a novel wave mode decomposition approach for estimating early-age strength in alkali-activated concrete [8]. Kim J et al. (2014) examined the progression of strength in high-performance concrete (HPC) by utilizing electromechanical impedance (EMI) measurements with the integration of a piezoelectric sensor [9].

Kumbhar D et al. (2015) introduced a wireless sensor network system specifically engineered for monitoring temperature variations within early-age concrete structures. This innovative technology is tailored to provide accurate and real-time data on temperature changes occurring during the crucial initial stages of concrete formation. This system utilizes the Arduino platform to collect data that can be subsequently used to estimate concrete compressive strength. Additionally, Raspberry Pi is employed for monitoring, storing, analysing, predicting, and transmitting concrete compressive strength data [10]. Liu Q et al. (2023) initiated a research endeavour focused on the integration of incorporated Piezoelectric Lead Zirconate Titanate (PZT) sensors into concrete structures to enable quantitative monitoring of concrete stress using electromechanical impedance (EMI) techniques [11]. Lim Y-Y et al. (2016) presented a semi-analytical model employing surface-bonded piezoelectric wave propagation for assessing mortar strength [12]. Lu Y et al. (2011) introduced a high-frequency domain cement-based piezoelectric (PZT) composite sensor with enhanced acoustic emission (AE) signal detection capabilities for monitoring damage in reinforced concrete frames [13].

Mourched B et al. (2022) introduced an innovative approach for voltage measurement under mechanical load, achieved by embedding piezoelectric sensors. The analysis of data and the search for potential voltage variations were carried out using COMSOL Multiphysics, a finite element (FE) simulation tool [14]. Oh T-K et al. (2017) introduced the use of Artificial Neural Network (ANN) in combination with Electromechanical Impedance (EMI) for non-destructive concrete strength estimation [15]. Pan H-H et al. (2020) introduced an innovative technique that substituted traditional PZT (Lead Zirconate Titanate) sensors with piezoelectric cement and smart aggregates to monitor concrete structures. This novel approach opens up possibilities for more efficient and cost-effective concrete monitoring solutions. This approach demonstrated superior capabilities and sensitivity in monitoring concrete structures compared to traditional PZT sensors [16]. Park S et al. (2011) presented the utilization of the EMI for online monitoring of concrete strength development during the curing process, employing both wired and wireless systems [17]. Pham Q et al. (2021) presented a novel development using a piezoelectric sensor-embedded smart rock. This innovative technology was designed to monitor electromechanical impedance within the prestressed anchorage zone of concrete structures, aiming to detect and assess internal concrete damage [18].

Providakis, C et al. (2011) performed initial stage concrete strength monitoring using a compact wireless impedance device referred to as AD5933, along with a PZT patch (PIC151) with dimensions of 10x10x10 mm [19]. Qin L et al. (2015) proposed the utilization of a piezoelectric sensor (PZT) to perform dynamic monitoring of concrete structures [20]. Song G et al. (2008) introduced the use of piezoelectric-based smart aggregates (SA) to illustrate their multifunctionality when embedded in concrete structures [21]. Tareen N et al. (2021) introduced a method involving the incorporation of dispersed carbon nanotubes (CNTs) into cementitious materials alongside utilising piezoelectric material in the form of PZT ceramic. This approach aimed at assessing concrete strength without causing damage to the structure, and the fuzzy logic-based algorithms were used for estimating the compressive strength from the input data such as mix proportion, curing conditions, curing time & dynamic response [22]. Wang G et al. (2022) presented a study that explores the similarity between the initial stage strength development of cement mortar and its eigenfrequency. The research methods included wave propagation monitoring and eigenfrequency analysis [23]. Xu K et al. (2017) conducted research involving sandwiched concrete column specimens for the early determination of low-strength concrete presence [24].

2. Application of piezoelectric sensors, oscilloscope & electromechanical impedance (EMI)

This study involved thoroughly exploring various techniques for monitoring concrete strength and identifying structural damage, all of which incorporate piezoelectric sensors.

Various types of smart materials are used in the civil engineering field, and piezoelectric material is generally used worldwide. Piezoelectric materials come in multiple forms, such as single crystals, ceramics, and polymers. These are increasingly utilized in diverse applications, including sensors, actuators, energy harvesting, biomedical devices, and structural and environmental monitoring. Piezoelectric materials have the unique ability to generate electrical energy under mechanical stress. Quartz is a well-known example of such materials. These are characterized by their ability to create a voltage when mechanical strain is applied and to deform when subjected to an electric field. When embedded within structural components, piezoelectric materials can produce an electric field as a response to mechanical stress, making them integral to the development of sensors, transducers, Surface Acoustic Wave (SAW) devices, and other systems critical for structural health monitoring (SHM) in sectors such as aerospace. A piezoelectric sensor, often called a piezoelectric transducer, capitalizes on the piezoelectric effect to monitor parameters such as pressure, acceleration, temperature, strain, or force, transforming these variations into an electrical signal. The underlying principle of piezoelectricity involves generating electricity through mechanical stress applied to specific materials. The primary materials in piezoelectric sensors include piezoelectric ceramics, like PZT ceramic, and natural single-crystal substances like quartz. Ceramic materials are known for their higher initial sensitivity than natural single-crystal options; however, this sensitivity may diminish over time.

In contrast, natural single-crystal materials like quartz, gallium-phosphate, and tourmaline exhibit lower sensitivity but superior long-term stability. Electromechanical impedance, abbreviated as EMI, is commonly utilized for inspecting structural integrity in civil engineering due to its non-destructive nature and the integration of piezoelectric sensors attached to structures. Concurrently, oscilloscopes contribute to the field by detecting structural defects and offering visual representations of electrical signals to assist in analysis.

Ai D. et al. (2020) presented an innovative category of piezoelectric transducers named cement/aluminium incorporated PZT (CEP/AEP) designed for concrete strength monitoring through the EMI impedance method. The experimental setup was utilized to observe the concrete cubes containing the integrated AEP and CEP transducers. For this study, four concrete cubes measuring 150mm x 150mm x 150mm were utilized to evaluate the viability and efficacy of the CEP/AEP PZT transducers for monitoring concrete strength [1]. Chena J et al. (2015) presented a groundbreaking approach to monitoring concrete strength at the initial stage using a wireless embedded system based on smart aggregates. Comprising two essential components, the system features a wireless sensor and coordinator. The coordinator system incorporates crucial elements like the power management unit, the DAC circuit, and the wireless controller, which are essential for the technology's functionality. A signal conditioning circuit is crucial for converting charge to voltage, with the low-pass filter shaping single waves. The researchers established the experimental configuration to implement this pioneering method for concrete strength monitoring at the initial stage [3].

Kaur N et al. (2020) conducted the initial tracking of the first natural frequency of the piezoelectric (piezo) component played a pivotal role in monitoring the progress of concrete hydration and strength development. The conductance signature of the standalone resin-jacketed piezo (RJP) and the integrated RJP sensor in cube 1 was meticulously observed from day 0 to day 28 after the cube's casting. The variation in RMSD was systematically tracked as the concrete cube aged, with day 0 as the baseline reference for comparison. The findings provide valuable insights into the research's methodology and the significance of tracking the piezo's natural frequency in concrete strength monitoring [7]. Kim, W et al. (2019) presented a pioneering methodology termed the wave mode decomposition approach for the early-stage strength assessment of alkali-activated concrete. A detailed illustration of the concrete mixing procedure specifically designed for alkali-activated slag (AAS) concrete, a key component in this study. Steel plate-type embedded piezoelectric sensors were employed to enable the concrete specimens to be used for strength monitoring. These sensors integrated four piezoelectric transducers and were strategically affixed to the concrete specimens. This approach facilitates the accurate monitoring of concrete strength during the initial phases of development and provides valuable insights into the characteristics of alkali-activated concrete [8].

Kim J et al. (2014) introduced a self-sensing circuit crucial in monitoring impedance variations in the research. The Nuclear Power Plant concrete mix proportions were thoughtfully selected to meet the experimental requirements. The experimental arrangement consisted of several components: a test specimen, the NI-DAQ system, and the self-sensing circuit board. These components collectively facilitated the measurement and analysis of impedance variations within the concrete specimens, all part of the study's goal to provide valuable insights into the impedance-related characteristics of nuclear power plant concrete [9]. Liu Q et al. (2023) conducted an exhaustive inquiry, amalgamating numerical simulations and practical experiments to examine the utilization of electromechanical impedance (EMI) methodologies. This examination centred on employing incorporated sensors crafted from lead zirconate titanate (PZT) within concrete structures to precisely measure and supervise stress levels in the concrete [11]. Mourched B et al. (2022) introduced a novel concept for measuring the voltage generated by a mechanical load by integrating a piezoelectric sensor. To facilitate the design and analysis of the system, the researchers employed COMSOL Multiphysics, an FE simulation tool, to identify distinctive voltage patterns associated with mechanical loads. The structural design under investigation had three sensors placed on the right side and an additional three on the left side [14].

Oh T-K et al. (2017) employed lead zirconate titanate (PZT) with specific properties. The researchers cleverly enveloped it within a hemispherical hollow Styrofoam casing for non-destructive concrete strength assessment. This unique casing design is crucial in preserving a free boundary condition while integrating the sensor into the concrete test specimens, ensuring accurate data collection. The researchers carefully selected the concrete mix proportion and curing temperature to meet the requirements of their experimental setup. Given the inherent complexity of concrete, Oh and the team harnessed the power of Artificial Neural Networks (ANNs) to model and predict its strength. This computational methodology enhances comprehension of concrete behaviour and provides a valuable tool for estimating strength [15]. Pham Q et al. (2021) introduced an impedance measurement model that utilizes a smart rock incorporating a PZT sensor. The experimental setup included the fabrication of approximately three smart rock samples, and impedance measurements were systematically performed by applying loads ranging from 1.0 kN to 4.0 kN, with intervals of 0.5 kN [18].

Providakis C et al. (2011) presented a significant component of the study - a Teflon-based enclosure used as a protective cap for the piezoelectric material, specifically a PZT patch of PICI151 type. The inventive configuration fulfils a twofold role: shielding the PZT patch from potential harm and facilitating the PZT patch's repeated use to monitor the robustness of various concrete specimens. The applied realization of this arrangement incorporated diverse elements such as a computer, an evaluation board housing the AD5933 impedance measurement chip, and an 802.11g wireless USB 2.0 sender and receiver system. These elements played integral roles in the methodology and data collection for the research [19]. Meanwhile, Wang G et al. (2022) delved into the similarity between the initial-stage strength evolution of cement mortar and eigenfrequency. The smart aggregate the researchers developed functioned as an actuator and a sensor responsible for transmitting stress waves and receiving pertinent data [23].

3. Findings of piezoelectric sensors, oscilloscope & electromechanical impedance (EMI)

The revealed results illustrate the effectiveness and dependability of piezoelectric sensors in monitoring concrete strength and identifying structural damage.

Ai D et al. (2020) concluded the resonant frequencies falling within the range of 100-250 kHz were applicable for both the Cement-Embedded PZT (CEP) and Aluminium-Embedded PZT (AEP) samples. Nevertheless, a significant difference was noted in the principal resonant frequency of the signals: the AEP specimen demonstrated a greater principal resonant frequency in contrast to the CEP specimen. The electromagnetic impedance (EMI) patterns were gathered and scrutinized at three specific phases of the initial concrete maturation process: 24 hours, 1 to 7 days, and 7 to 28 days. This detailed analysis offers valuable insights into how the resonant frequencies change over time during the concrete's early age, which is essential for concrete strength monitoring and assessment [1]. Chena J et al. (2015) represented the final output obtained in the oscilloscope in the formed sine wave. The result obtained from the oscilloscope for 200 Hz of frequency is then plotted in the graphical representation of the relationship between amplitude (V) and time (Hour) for the first day [3].

Kaur N et al. (2020) examined the peak frequency curves for unbounded resin-jacketed piezo (RJP) and sensor failure before and after moisture ingress from the thin epoxy layer. The analysis demonstrated that after resoldering the piezo sensor, the peak frequency closely resembled the unbounded RJP. This finding highlights the potential of this method as a non-destructive tool for on-site applications, enabling the estimation of the optimal time for formwork removal by assessing concrete strength [7]. Kim W et al. (2019) generated 207 waves over 71 minutes following the concrete pouring to collect wave data. Subsequently, the wave information underwent categorization into two separate modes, S mode and A mode, employing the wave mode decomposition technique. The final results encompassed waves numbered from 1 to 100. The visual representation depicts the progression of time on the x-axis, data number along the y-axis, and amplitude along the z-axis. The investigation's findings propose that employing this methodology could extend the lifespan of concrete structures and reduce construction-related accidents by providing a more accurate estimation of early-age concrete strength during the initial construction phases [8].

Kim J et al. (2014) reached a significant conclusion regarding the evolution of concrete strength during the curing age. As the concrete's curing age advanced, indicating the continual enhancement of its strength, a gradual adjustment in the resonant frequencies within the impedance signals became evident, particularly leaning towards the right side. The observation represents the estimated strength development, relying on the cross-correlation coefficient index (1-CC). Notably, the correlation between compressive strength, measured in megapascals (MPa), and curing age, expressed in hours utilizing data obtained from the 1-CC calculations. The plot highlights the direct and impactful connection between the concrete's curing time and its compressive strength, reinforcing the study's critical insights into concrete strength development during the curing process. These findings hold significant implications for concrete-related construction and engineering practices [9]. Liu Q et al. (2023) concluded from the F.E. simulations that the efficiency of incorporating PZT sensors into concrete stress monitoring depends on the orientation in which these sensors are installed. This pivotal observation carries broad implications for the field. The study exhibits conductance signatures extracted from specimens embedded with flat PZT sensors at 0° and 90° orientations. Similarly, textured PZT sensors at the same 0° and 90° orientations, particularly under elastic deformation conditions. The impact of sensor orientation with conductance signatures stemming from specimens incorporating flat PZT sensors at 0° and 90° orientations. Concurrently, the conductance signatures correspond to specimens featuring textured PZT sensors at identical 0° and 90° orientations, albeit in the context of inelastic deformation. These sets of data emphasize the sensitivity of the sensors to their installation angles, a critical insight into concrete stress monitoring. Advancing, an index for RMSD derived from conductance signatures of specimens featuring flat and textured sensors, respectively. These metrics offer a quantitative assessment of sensor performance variations, elucidating the precision achievable with each sensor type. A1/8 symmetrical F.E. model is depicted, illustrating a PZT sensor with interfaces of both flat and textured nature. This visual depiction aids in understanding the sensor's geometry and its role in the experimental setup of the study. Additionally, it provides valuable insight into the strain distribution observed in areas surrounding 90° sensors, both flat and textured, during progressive compressive displacements along the z-direction. A parallel depiction is offered for the 0° sensors, both flat and rough, in the same conditions. These images demonstrate the intricate relationship between strain distribution patterns and sensor performance, a dynamic that the research team extensively explored through F.E. static analyses. These findings collectively contribute to a more comprehensive understanding of embedded PZT sensor behaviour and its suitability for concrete stress monitoring applications [11].

Mourched B et al. (2022) represented the data about voltage measurements from sensors L2 and R2 across seven distinct studies. The influence of load mass on voltage readings by the sensors and the voltage outputs from sensors L2 and R2 are illustrated for a 40 kg load mass across various simulated load positions. Additionally, the combined voltage readings from sensors L2 and R2 demonstrate the impact of different load speeds on the sensor outputs, ranging from 0.25 m/s to 1.25 m/s. This comprehensive data analysis aids in understanding the sensor response under varying conditions and load parameters [14]. Oh T-K et al. (2017) provide valuable insights into the evolution of internal temperature within concrete specimens over 28 days. This temperature variation is clearly observable and critical to the study's findings. Furthermore, the impedance variation across three distinct specimens over the same 28-day period. Notably, the impedance patterns closely mirror the variations in strength and temperature, underscoring their interconnectedness. The researchers establish a clear relationship between compressive strength (expressed in MPa) and curing time (in hours), employing an artificial neural network (ANN) model represented by a bold line. These comprehensive results significantly contribute to the study's conclusions regarding concrete strength and its relationship with curing time [15].

Pham Q et al. (2021) determined that the intelligent rock demonstrates a frequency spectrum within the 150-250 kHz range. The PZT-embedded smart rock proves to be an effective tool for detecting internal concrete damage through impedance features. The impedance reactions of PZT-A (exposed to axial force) and PZT-L (subjected to lateral force) manifest three primary resonant frequencies, registering approximately 200 kHz (peak 1), 245 kHz (peak 2), and 460 kHz (peak 3) within the 100-600 kHz frequency range under varying compressive forces (P1-P7). The RMSD indices exhibit a linear increase with the ascending compressive forces, with PZT-A's RMSD indices marginally surpassing those of PZT-L within the specified frequency range under forces P1-P7. A correlation of the RMSD rates for numerical and experimental impedance reactions under the influence of axial and lateral forces is delineated. The RMSD indices for PZT-S1 and PZT-S2 are calculated for 11 loading instances. These observations contribute to a deeper understanding of how smart rock and embedded PZT sensors perform under varying load conditions, facilitating concrete damage detection and structural health monitoring [18].

Providakis C et al. (2011) represented the result through a detrending residual error value, corresponding to the concrete's strength development conditions at 36 hours and 28 days. A red line represents the 99.5% generalized extreme value (GEV), and blue lines depict the 99.5% Gaussian confidence limits. A noteworthy observation indicates that between the 3-hour and 44-hour marks, the outliers fluctuate from 0 to 22. Subsequently, after the 44-hour point, this number diminishes to almost zero. This trend signifies that beyond 44 hours from the initial concrete casting, a reliable and consistent concrete hardening time criterion is established. The study's conclusions contribute valuable insights into assessing concrete strength development and can be instrumental in optimizing construction processes and project scheduling [19]. Wang G et al. (2022) provided valuable insights into the utility of eigenfrequency analysis with embedded piezoelectric transducers for initial-stage concrete strength monitoring. Notably, during the initial few days of hydration, cement strength exhibited the most significant changes, after which it reached a stable value in the formation process, demonstrating the signal filtration process aimed at eliminating 50 Hz power frequency noise during sweeping cycles performed for the first 7 days, on the 14th and 28th days for ordinary Portland cement 42.5 (P.O. 42.5). The correlation between resonant frequency and curing time is illustrated for ordinary Portland cement of P. O 42.5, P. O. 52.5, and Portland slag cement of P. S 32.5. Additionally, the first eigenfrequency at 4,738 Hz outperformed the second eigenfrequency at 10,913 Hz in detecting bending deformation for P.S. 32.5. Furthermore, the relationship between compressive strength and resonant frequency curves obtained from specimens with curing time demonstrated a high degree of similarity between the two curves [23].

4. Conclusion

A sensor employing Piezoelectric Lead Zirconate Titanate (PZT) was engaged in this investigation. These sensors use a hybrid approach, incorporating surface bonding and embedding techniques. This combination enables the real-time monitoring of the strength of initial-stage concrete and facilitates the identification of structural damage within concrete structures. The PZT transducers, once incorporated into the concrete structure, serve a dual role as both actuating devices and sensors throughout the concrete casting procedure. The investigation outcomes are disclosed at designated time points, encompassing 4 weeks. Significantly, the study's findings emphasize the feasibility of employing a wireless system in real-time for continuous monitoring.

Furthermore, piezoelectric-based methods offer distinct advantages such as rapid response times & versatility in shape. In summary, the results illustrate a graphical curve, affirming that the piezoelectric-based monitoring method can predict early-age concrete strength from its inception throughout its lifespan. This extensive examination explores the use of piezoelectric sensors, oscilloscopes, and electromechanical impedance (EMI) techniques in the civil engineering field. By examining these technologies' diverse uses and potential synergies, this review seeks to provide a deeper understanding of their roles in various fields, including structural health monitoring, material characterization, and non-destructive testing. Furthermore, beyond elucidating their technical aspects, this review endeavours to explain the practical implications and benefits of integrating these technologies into research, academic endeavours, and construction practices. The objective of thoroughly examining relevant literature and case studies is to empower researchers, educators, and construction practitioners with the knowledge and practical insights necessary to effectively leverage piezoelectric sensors, oscilloscopes, and EMI techniques within their respective domains.

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