



Research Article

Concrete strength monitoring and damage detection using piezoelectric-based wireless sensor

Raju Narwade ^a , Ruhita Jadhav ^{a,*} 

^a Department of Civil Engineering, Pillai HOC College of Engineering & Technology, Rasayani, 410207 Maharashtra, India

ABSTRACT

Concrete stands as the predominant and extensively employed structural material in civil engineering. Timely evaluation of concrete strength is essential for maintaining structural safety and minimizing construction delays, thereby avoiding possible structural failures. This early check also ensures that concrete structures can bear loads during construction and throughout their service life. A significant challenge in the construction industry is accurately determining the strength of early-age concrete and identifying potential damage without destructive testing. Conventional techniques often require time-consuming procedures and can be impractical for real-time monitoring. To overcome this issue, IoT-based monitoring systems with piezoelectric sensors provide a practical approach for continuous strength monitoring and damage identification in concrete structures. This study utilized a piezoelectric lead zirconate titanate (PZT) sensor, employing a surface-bonding technique to attach the sensor to the cube specimens. The experimental phase spanned four weeks, including intervals of 7th, 14th, and 28th days by standard construction codes to assess necessary strength levels and identify any damage within the structure. This study verified the results obtained by the piezoelectric-based wireless sensor network are practical and reliable. Correlation coefficient values are analyzed to validate the relationship between data from IoT-based testing and compressive strength. All the results are presented in graphical format, confirming that this non-destructive approach can accurately predict concrete strength and identify structural damage. This study uniquely contributed by validating the use of piezoelectric sensors for continuous, in-situ monitoring of concrete, providing a novel approach to early damage detection and evaluating the structural health of the structure.

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1. Introduction

Concrete is the predominant and extensively employed structural material in civil engineering. As the water content diminishes, concrete strength gradually rises, typically reaching its peak around 28 days after casting. 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.

After casting, cubes are dried under relative humidity at a constant temperature of 27 °C. This indicates that drying conditions significantly affect the degree of hydration, gradually increasing the compressive strength of concrete cubes (Shafiq and Nuruddin 2010).

Measuring concrete strength is crucial to ensure structural integrity and expedite construction. Two primary approaches exist for this purpose: non-destructive evaluation and destructive evaluation. Destructive methods involve crushing concrete samples to ascertain

* Corresponding author. E-mail address: ruhtasj21hmcivil@student.mes.ac.in (R. Jadhav)

strength but could be more practical for monitoring extensive reinforced concrete structures. Ivanchev (2022) explained that the destructive technique provides accurate information on the compressive strength of specimens, but it is more expensive and time-consuming and sometimes weakens the existing structures. Thus, non-destructive techniques are preferred for the real-time monitoring of concrete without damaging the structure. According to Akca et al. (2021), the non-destructive technique has more advantages than the destructive technique, as it can be used multiple times without damaging the specimens. Among the three frequently utilized non-destructive methods are the piezoelectric-based monitoring approach, the hydration heat-based monitoring technique, and the ultrasonic-based monitoring method. According to Hu et al. (2013), piezoelectric-based monitoring is highly effective for structural health monitoring in concrete structures. This method also helps detect any cracks and voids in the structure by utilizing sensors that are either surface-bonded or embedded in concrete. Zhang et al. (2024) explained that the hydration heat-based monitoring technique is crucial in reducing the risk of early-age cracking in concrete structures caused by temperature-induced stress. To prevent this risk, the main focus is monitoring the concrete mix temperature before and after pouring. Lorenzi et al. (2020) highlighted that ultrasonic-based monitoring methods help determine the integrity of the material, improve the quality assurance control during construction, and support rehabilitation decisions.

Various advanced smart materials, such as shape memory alloys, piezoelectric materials, and optical fibers, play an essential role in non-destructive techniques. Mavroidis and Pfeiffer (1999) described how shape memory alloys can regain their original shape after deformation when exposed to particular temperatures. Shape memory alloys are employed in non-destructive testing because of their capacity to change structural configurations, which makes it possible to identify flaws and improve the functionality of intelligent structures. According to Wang et al. (2023), piezoelectric materials generate an electric charge in response to mechanical stress and can conversely induce deformation when an electric field is applied. Due to this dual property, this material is used in structural health monitoring systems as sensors and actuators. This material is generally used for detecting cracks and voids in structures; along with this, it can also be used as a vibration control, energy harvesting, and as an integral component in smart structures. Kuang and Cantwell (2003) explained that optical fibers are used in structural health monitoring due to their sensitivity to strain and temperature changes. Eventually, without compromising the material's properties, the optical fibers help to detect impact damage and monitor structural integrity. Piezoelectric sensors, particularly those made from lead zirconate titanate (PZT), are vital for monitoring structural health. These sensors can be surface-bonded or embedded within concrete to assess integrity based on impedance or vibration data. PZTs are characterized by high elastic modulus and brittleness. Modern wireless systems, whether surface-based or embedded, are increasingly

employed for their straightforward installation and remote accessibility, enabling continuous monitoring of diverse structural types. Piezoelectric methods are noted for their cost-effectiveness, quick responsiveness, flexibility in design, and straightforward integration. In recent years, piezoelectric sensors have found utility in monitoring concrete strength and detecting damage by integrating them into the host structure. According to Hu et al. (2014), piezoelectric sensors can be used for damage detection by embedding the sensors in concrete slabs with the help of the electromechanical impedance method. The research demonstrated that correlation coefficient deviation and root mean square deviation indices effectively identify the structural damage. Han et al. (2020) explained that a piezoelectric sensor can be used to monitor the strength development of cementitious materials with the help of the electromechanical impedance technique. The study presented here highlights how piezoelectric materials find utility in two essential areas: concrete strength monitoring and identifying damage within concrete structures.

Chaliorisa et al. (2016) introduced WiAM's (Wireless Impedance/Admittance Monitoring System), an innovative real-time structural health monitoring technique. This system is intended to collect voltage-frequency responses from a network of piezoelectric sensors strategically placed on different parts of RC structures. To demonstrate the system's ability to identify damage, the study tested two flexural RC beams subjected to monotonic and cyclic loading and a shear-critical RC beam subjected to monotonic loading. The findings showed WiAM's capability to detect stiffness degradation and damage initiation observing impedance and admittance signature shifts. The results demonstrate that the system detects the course of damage in reinforced concrete structures, offering a valuable tool for structural integrity assessment. Chena et al. (2015) outlined using a wireless sensor network as an alternative to wired data acquisition systems for monitoring concrete strength. The methodology employed two smart aggregates: an actuator to generate high-frequency vibration waves and a sensor to capture these vibrations within the concrete structure. The study relied on two primary wireless nodes: the wireless controller, responsible for sensing and recording vibration data, and the sensing signal conditioner, acting as the wireless coordinator, which generated the actuation signal needed for the smart aggregate's operation. The software implementation was carried out in C language. The network coordinator produced frequencies around 200 Hz, subsequently captured by an oscilloscope for sine excitation. The study's results emphasized the advantages of the wireless system's embedded design, including reduced system size and cost, improved robustness, and enhanced flexibility.

Dumoulin et al. (2015) studied initial-stage concrete monitoring and damage identification using two approaches. The initial method involved tracking the evolution of P-wave velocity in prismatic moulds using smart aggregates known as SMAGs. This method helped assess the hydration process and mechanical property development of concrete. The second method entailed tracking damage evolution in three cube specimens, each

showing cone-shaped failures during pull-out tests. This method helps the piezoelectric transducers effectively capture variation in ultrasonic wave propagation, indicating progressive damage. Fani and Basil (2022) developed a groundbreaking approach called fuzzy linear regression (FLR) to forecast the compressive strength of lightweight foamed concrete. This novel approach integrated trapezoidal fuzzy numbers into the modelling process. The study conducted a comparative analysis to establish the usefulness of the FLR methodology in forecasting the compressive strength of lightweight foamed concrete vs alternative methods such as multivariable nonlinear regression and various single or hybrid machine learning models. Therefore, the study validated that FLR is a reliable alternative to conventional prediction models for lightweight foamed concrete. Feng et al. (2019) presented the innovative concept of the "smart aggregate." This pioneering strategy utilized an active sensing technique that seamlessly incorporated piezoelectric-based transducers. The primary goal was to provide real-time assessments of early-age concrete strength evolution across the critical 0 to 28-day period. To efficiently capture wave responses across the 28-day curing period, two smart aggregates (SAs) were used. One SA performed as an actuator, regularly releasing regulated stress waves, while the second SA served as a sensor capable of detecting stress waves.

Fotouhi et al. (2017) investigated the feasibility of using polyvinylidene fluoride (PVDF) as a sensor element in a passive structural health monitoring (SHM) system. The study explored the integration of piezoelectric nanocomposites into composite materials, emphasizing their high durability, flexibility, and improved signal-to-noise ratio. Their primary focus was on SE70 glass/epoxy laminates used in this sensor system to monitor and assess damage during indentation tests. The study revealed important information about the efficacy of PVDF in SHM for assessing structural integrity. Jerzy S. (2020) extensively examined smart materials in architectural and civil engineering. The study mainly highlighted integrating of smart materials into infrastructure for real-time monitoring, adaptive responses to environmental changes, and energy-efficient improvements. For example, shape memory alloys for adaptive building components, PZT sensors for structural health monitoring, and self-healing concrete for crack repair. This study looked at the various applications and potential benefits of such materials in these fields, emphasizing their contribution to the progress of structural engineering and building approaches. Kuczma et al. (2021) examined a previous inquiry into the sustainability of civil infrastructure and the use of smart materials in civil engineering. The investigation thoroughly examines how incorporating smart materials adds to structural sustainability. Li et al. (2023) proposed a groundbreaking technique for monitoring and forecasting at the initial stages of concrete strength evolution. This method integrates embedded smart aggregates (SAs) based on electromechanical impedance (EMI) technology and machine learning algorithms. The study uses machine learning models to find the correlation between the EMI signature and compressive strength. Because of its simplicity, precision, quanti-

tative capacity, and dependability, it stands out for evaluating and predicting concrete compressive strength.

Noori and Narjabadifam (2019) thoroughly examined a broad spectrum of smart materials and their varied uses within the building sector. This paper highlighted the importance of SHM systems by integrating IoT, AI, and sensor networks. These smart materials contribute to improve real-time data acquisition, enhance urban sustainability, reduce maintenance costs, and improve safety. This insightful analysis offered valuable perspectives into the creative methods employed by these materials to enrich and revolutionize different facets of construction methodologies. Prayuda et al. (2020) presented the implementation of a fuzzy logic methodology for forecasting flexural strength, compressive strength, and flowability in self-compacting concrete. The study utilized a fuzzy-logic prediction model and various mix proportions to estimate the self-compacting concrete based on key parameters for reducing the need for experimental laboratory testing. Providakis et al. (2014) introduced piezoelectric material for identifying damage in concrete reinforcement, utilizing the electromechanical admittance approach. This study presented the laboratory experiments on reinforced concrete specimens to effectively detect changes in structural conditions by monitoring impedance shifts, allowing early identification of reinforcement deterioration. Roy et al. (2016) evaluated smart materials and their various uses in modern structural engineering and building projects. This comprehensive study sheds light on the adaptability and importance of these new materials in defining the future of building and infrastructure development. Samadi and Farrokh (2022) used in-situ experiments and the Adaptive Neuro-Fuzzy Inference System (ANFIS) to forecast concrete's 28-day compressive strength. This ANFIS model predicted concrete strength using diverse input factors such as the water-to-cement ratio and the types of fine and coarse aggregate materials. Saravanan et al. (2017) presented an innovative technology for evaluating concrete strength during the initial stage (3–7 days) and later stages (beyond 7 days) under conditions of large-scale sensor deployment. Under crack opening conditions, this approach detects variations in the EMI signature on PZT-bonded concrete shear walls. This method helps develop a relationship between the strength parameter and root mean square deviation (RMSD).

Sha et al. (2021) demonstrated a compound material comprising cement, epoxy resin, a curing agent, and enhancers. This material was designed to monitor the structural health of concrete structures by utilizing the mechanical sensing capabilities of embedded smart piezoelectric (PZT) sensors. This study highlighted that through a series of experimental tests and numerical simulations, the sensors can detect strain variations, progressive deterioration, and damage initiation in concrete. Shin et al. (2008) presented using the conventional EMI sensing technique alongside PZT patches. This method served to identify and observe the initial development. The study uses an active sensing approach, where PZT sensors generated and received stress waves within the concrete. By analyzing changes in wave propagation characteristics, the study was able to correlate

the sensor data with compressive strength development. This study concluded that PZT sensors offer a practical and effective alternative to conventional destructive testing methods, enabling continuous, in-situ monitoring of concrete curing and early-age strength development. Sobczyk et al. (2021) thoroughly analyzed smart materials in civil engineering and architecture, focusing on using actuators and sensors. The study explained that actuator applications such as kinetic structures, self-regulating facades, and adaptive shading systems demonstrate how smart materials improve energy efficiency and indoor environmental quality. Sensor applications such as environmental sensing, SHM, and occupancy detection contribute to developing of responsive and intelligent buildings. Sun et al. (2020) proposed a computational simulation method to assess the utility of piezoelectric stress wave analysis for monitoring concrete strength. This method uses computer simulations to analyze and determine the effectiveness of concrete strength monitoring by analyzing stress waves generated by piezoelectric sensors. The study developed a finite element model to simulate the interaction between piezoelectric sensors and stress waves in concrete at various curing stages. The study highlighted the correlation between wave velocity and amplitude with the progressive increase in concrete strength. The study concluded that the PZT sensors effectively capture early-age strength development trends by indicating a strong relationship between wave parameters and concrete strength.

Vikram et al. (2023) presented a new piezoelectric cantilever beam electric sensor for pavement monitoring via the Internet of Things (IoT). This pioneering device includes a self-powered wireless acceleration sensor to detect vibrations in small and medium-sized bridges. The study utilizes a PZT sensor to convert mechanical vibrations and stress from vehicular movement into electrical signals, which are then analyzed to assess pavement conditions. Wang et al. (2010) executed an empirical study on monitoring the compressive strength of concrete by integrating embedded piezoelectric lead zirconate titanate (PZT) transducers with the EMI technique. The study concluded that as concrete cures and gains strength, the resonant frequency of the embedded PZT transducers increases, highlighting the strong correlation between resonant frequency and compressive strength. Wu et al. (2022) explained a uniaxial piezoelectric (PZT) sensor tailored to address issues linked to quantifying the output charge of the piezoelectric component. This specialized sensor was incorporated into the concrete framework and situated on its surface to monitor stress, establishing a relationship with the elastic modulus to establish a correlation. Yang et al. (2020)

developed a method for monitoring concrete's 28-day age strength by embedding piezoelectric smart aggregates (SA) within glass fiber-reinforced polymer (GRFP) tube columns filled with concrete. The study proposed an innovative, non-destructive method for early-age concrete strength monitoring using power spectral density and wavelet packet analysis by analyzing the vibration response of cube specimens. Zhu (2021) thoroughly analyzed many smart materials' unique properties and prospective applications. The author concentrated on the widespread application in civil engineering, highlighting its function in architectural innovation, strengthening structural integrity, and, ultimately, enhancing structural safety.

According to Zachariah et al. (2023), ThingSpeak is a popular and valuable platform for receiving, hosting, and visualizing sensor data by quickly creating channels. This ThingSpeak platform facilitates online analysis and processing using MATLAB and helps users instantly visualize data presented by devices. Therefore, this study used ThingSpeak, a cloud-based IoT analytics platform that facilitates real-time data visualization and analysis. In addition, NodeMCU, a low-power microcontroller with built-in Wi-Fi capability, processes data and transmits it wirelessly to the cloud for remote monitoring. NodeMCU is an open-source IoT platform with firmware running on the ESP8266 Wi-Fi SoC and hardware based on the ESP-12 module. Due to its affordability and user-friendliness, it is frequently used to create IoT applications with the help of the Lua programming language. According to Ayeni et al. (2024), NodeMCU functionality is based on written code, establishing Wi-Fi connectivity to a predefined network and managing sensor data. ThingSpeak ensures effective data transfer from sensors by enabling smooth interaction with microcontrollers like NodeMCU. ThingSpeak, an IoT-based platform, enables real-time data visualization by converting the transmitted data into graphical representations. ThingSpeak is also helpful for continuous structural health monitoring applications because it supports remote access and real-time data logging.

A statistical relationship between two variables is represented numerically by the correlation coefficient (r or R), which measures some linear association. These variables are derived from observed data, commonly referred to as samples. The correlation values range from -1 to $+1$, which indicates the most potent possible correlation, and 0 signifies no correlation between variables. Schober et al. (2018) highlighted that the most commonly used correlation coefficient is the Pearson correlation coefficient, which assesses the linear relationship between two continuous variables. Table 1 illustrates how strongly or weakly the variables are associated:

Table 1. Interpreting correlation coefficient values.

r or R (positive/negative values)	Strength or weakness of association between variables
1.0 to 0.90	Very strong
0.89 to 0.70	Strong
0.69 to 0.40	Moderate
0.39 to 0.10	Weak
0.10 to 0.00	Negligible

Previous studies primarily focused on conventional non-destructive testing methods with other integrated IoT and piezoelectric sensors for real-time monitoring of concrete strength and damage detection. Additionally, prior research lacked a well-defined correlation between amplitude values and concrete strength. In contrast, this study mainly focused on surface-bonding techniques for attaching sensors to the cube specimens with wireless data transmission via NodeMCU and ThingSpeak. This study combines compressive strength testing using a CTM and IoT-based testing, allowing for a direct comparison between traditional and advanced monitoring techniques through correlation coefficient analysis. Furthermore, IoT-based testing is used for both concrete strength monitoring and identifying the damage in cube specimens, enhancing the reliability of real-time structural assessment.

2. Methodology

This research was thoroughly investigated to monitor concrete strength and identify structural deterioration using piezoelectric sensors. The study is based on a single

circuit diagram, as shown in Fig. 1. This circuit comprised components such as the LM324N operational amplifier, resistors, and capacitors. The experimental configuration, illustrated in Fig. 2, encompasses several components: a waveform generator, a single processing circuit comprising a microcontroller, a Node MCU Wi-Fi module, dual $\pm 3.3V$ power supplies, a PZT sensor, and a laptop. The PZT sensors are spaced 120 mm from center to center, as shown in Fig. 3.

This study utilized a pair of PZT sensors measuring 30 mm each. One of these sensors functioned as an actuator, responsible for relaying input data received from the waveform generator operating at a frequency of 10 kHz. Meanwhile, the other sensor served as a receiver, collecting the output data and transmitting it to the microcontroller for subsequent processing. Select the ESP8266 board in the NodeMCU interface, then assign a communication port (COM5) for data collection and transmission to the ThingSpeak platform. ThingSpeak ensures effective data transfer from sensors by enabling smooth interaction with microcontrollers like NodeMCU. Therefore, ThingSpeak and NodeMCU make it possible to analyze and understand gathered data effectively.

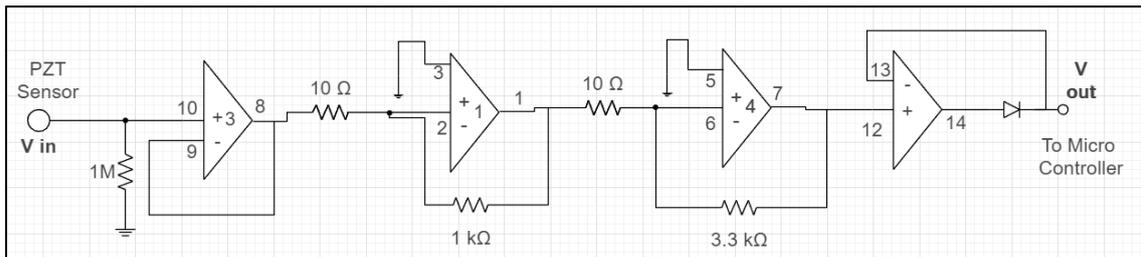


Fig. 1. Single processing circuit diagram.

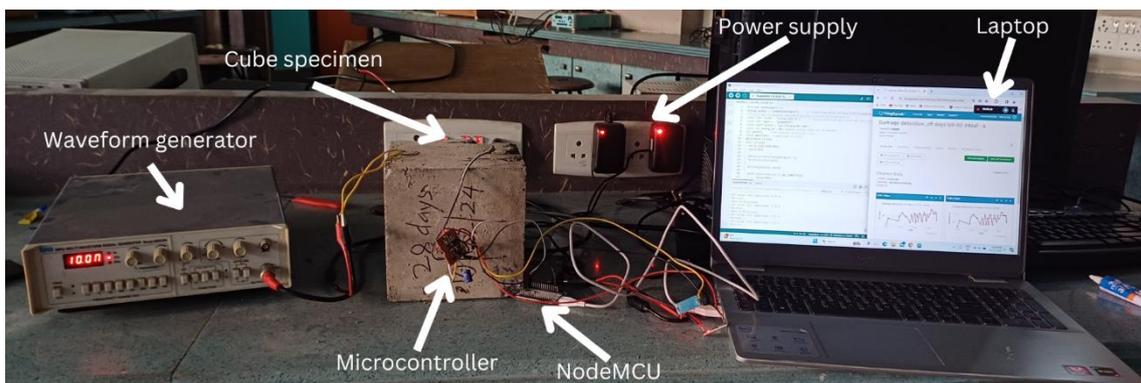


Fig. 2. Experimental setup.

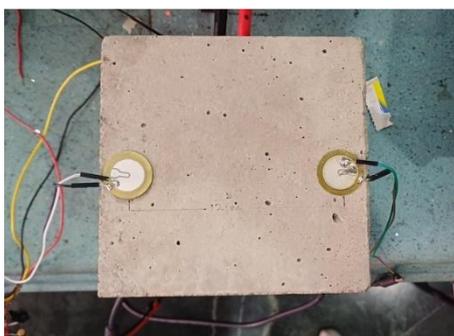


Fig. 3. The PZT sensor positioning.

For this investigation, M30 grade concrete was employed. The components utilized in fabricating the cube specimens were carefully selected to ensure the integrity of the study. These included coarse aggregates (10 mm, 20 mm), fine aggregate (crushed sand), cement (OPC-53 grade), and water. Table 2 provides an overview of the concrete mix proportions specifically designed for M30 grade concrete.

Following the guidelines outlined in IS 456:2000 and IS 516:1959, nine cube specimens were cast, each standard size of 150 mm x 150 mm x 150 mm. According to IS 516:1949, a minimum of three specimens were em-

ployed for each curing period (7th, 14th, and 28th days) to determine the standard testing requirements of strength progression. Despite the limited sample size, this approach ensures a statistically valid representation of compressive strength trends. Subsequently, the identical cube specimens, which were used for IoT-based testing for concrete strength monitoring, underwent testing us-

ing a CTM machine. After these tests, damage detection was performed through the IoT-based monitoring system on cube specimens to analyze variations in the results obtained from concrete strength monitoring and damage detection methods. This comparison helps in evaluating the reliability and effectiveness of IoT-based testing in detecting structural changes.

Table 2. The concrete mix proportion for M30 grade.

Sr. No	Item	kg/m ³	By weight	Volumetric mix	
1	Cement	405	50 kg	1 bag	
2	Fine aggregate	Crushed sand	726.9	89.6 kg	57.8 liter
3	Coarse aggregate	Metal-I	468.2	57.7 kg	38.5 liter
		Metal-II	702.3	86.6 kg	59.7 liter
4	Water	182.5	22.5 liter	22.5 liter	
5	Admixture (plasticizer)	Sikament	4.05	0.5 liter	0.5 liter

3. Result and Discussion

The results from the IoT-based testing were for both concrete strength monitoring and damage detection for specific time intervals, including the 7th, 14th, and 28th days. The results of this investigation are depicted graphically, illustrating parameters such as amplitude (V) plotted against time (sec) under the IoT-based method. All the graphs show the total 100 reading output data obtained from the IoT-based testing before CTM testing over cube specimens.

In Fig. 4, the amplitude data observed on the 7th day falls within the range of 0.8 to 1.3 V. Similarly, as depicted in Fig. 5, the amplitude data for the 14th day ranges approximately from 1.15 to 1.3 V. Furthermore, as illustrated in Fig. 6, the amplitude data for the 28th day spans from approximately 1.22 to 1.3 V. These outcomes are detailed at specific time intervals, as outlined in Table 3, providing amplitude data for monitoring concrete strength. As shown in Fig. 7, there is a clear increasing trend in amplitude as the days progress for monitoring concrete strength.

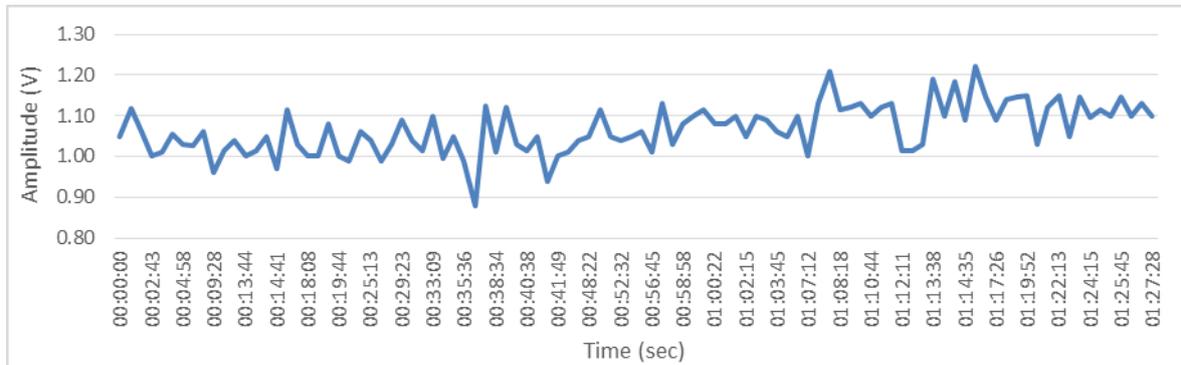


Fig. 4. Amplitude vs. time acquired from IoT-based testing before CTM testing on the 7th day.

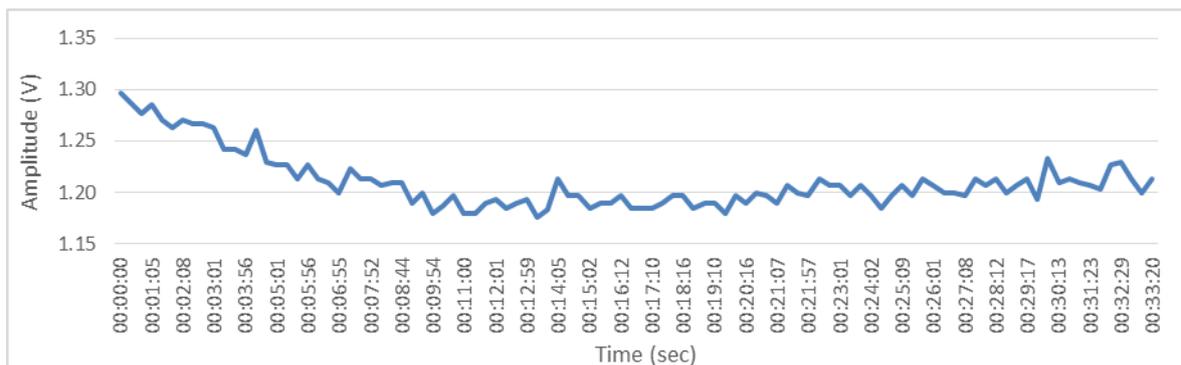


Fig. 5. Amplitude vs. time acquired from IoT-based testing before CTM testing on the 14th day.

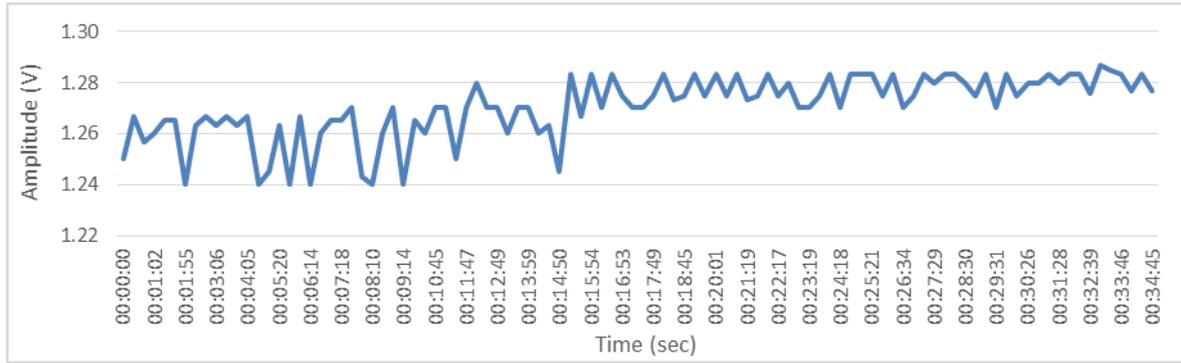


Fig. 6. Amplitude vs. time acquired from IoT-based testing before CTM testing on the 28th day.

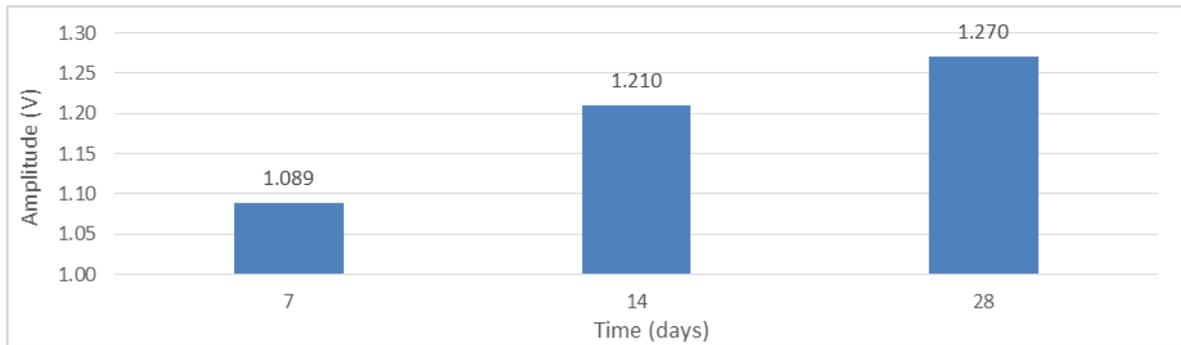


Fig. 7. Amplitude value comparison from IoT-based testing before CTM testing.

Table 3. Amplitude data from IoT-based testing before CTM testing.

Days	Amplitude (V)			
	Average	Cube 1	Cube 2	Cube 3
7	1.089	1.133	1.074	1.058
14	1.210	1.231	1.182	1.219
28	1.270	1.273	1.250	1.289

In addition to other methods, this study employs a compressive testing machine (CTM) to quantify the material’s compressive strength on the 7th, 14th, and 28th days. To validate the findings from the compressive testing machine (CTM), a formula is outlined in IS 456:2000 to compute the target mean strength of concrete. This mathematical expression is defined in Eq. (1).

$$f'_{ck} = f_{ck} + 1.65 \cdot s \tag{1}$$

where f'_{ck} is the target average compressive strength at 28th days, and s is the standard deviation (from Table 8 of IS 456:2000)

The calculated target compressive strength for M30 grade concrete, derived from the formula above, is 38.25 N/mm². The results of CTM testing are visually represented in Fig. 8 and detailed in Table 4. Consequently, the findings obtained during this investigation indicate a compressive strength of 38.113 N/mm² on the 28th day, which is deemed accurate.

Table 4. Cube compressive strength.

Days	Cube compressive strength (N/mm ²)			
	Average	Cube 1	Cube 2	Cube 3
7	22.868	22.668	22.512	23.424
14	32.396	32.113	31.892	33.184
28	38.113	37.780	37.520	39.040

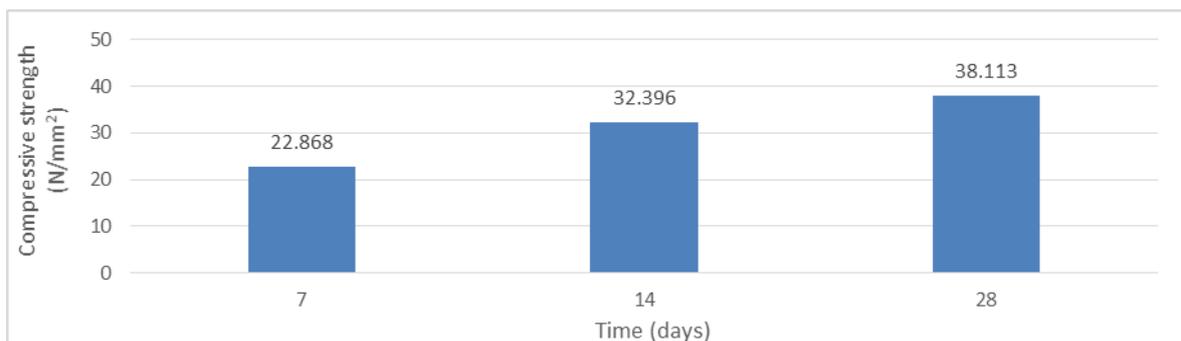


Fig. 8. Compressive strength using CTM testing.

After CTM testing, the damage detection results are depicted graphically, illustrating parameters such as amplitude (V) plotted against time (sec) under the IoT-based method. In Fig. 9, the amplitude data observed on the 7th day falls within the range of 1.0 to 1.6 V. Similarly, as depicted in Fig. 10, the amplitude data for the 14th day ranges approximately from 1.3 to 1.4 V. Furthermore, as illustrated in Fig. 11, the amplitude data for the 28th day

spans from approximately 1.4 to 1.44 V. Results are detailed at specific intervals, including the 7th, 14th, and 28th days, as presented in Table 5, showing amplitude data for damage detection after testing the cube specimens under CTM testing. As illustrated in Fig. 12, there is a clear increasing trend in amplitude as the days progress for detecting damage in cubes.

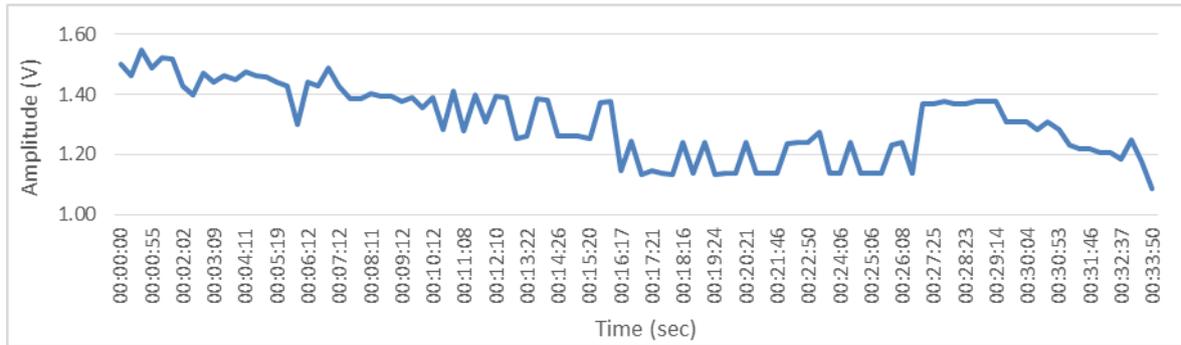


Fig. 9. Amplitude vs. time acquired from IoT-based testing after CTM testing on the 7th day.

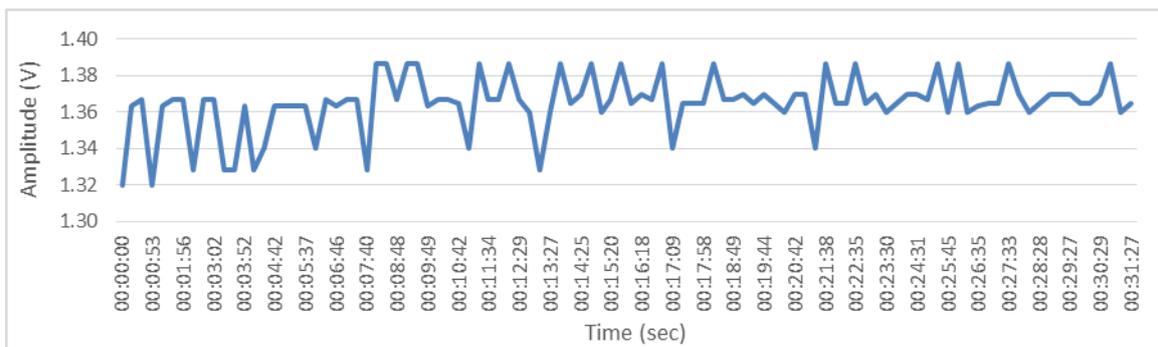


Fig. 10. Amplitude vs. time acquired from IoT-based testing after CTM testing on the 14th day.

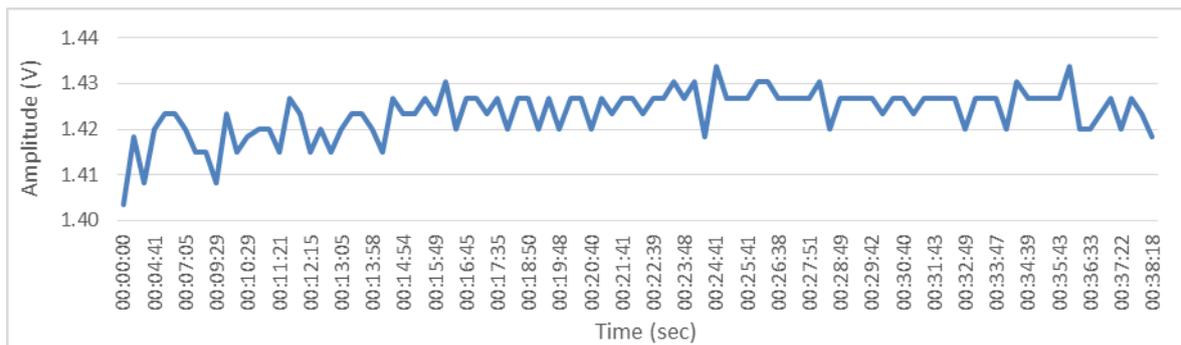


Fig. 11. Amplitude vs. time acquired from IoT-based testing after CTM testing on the 28th day.

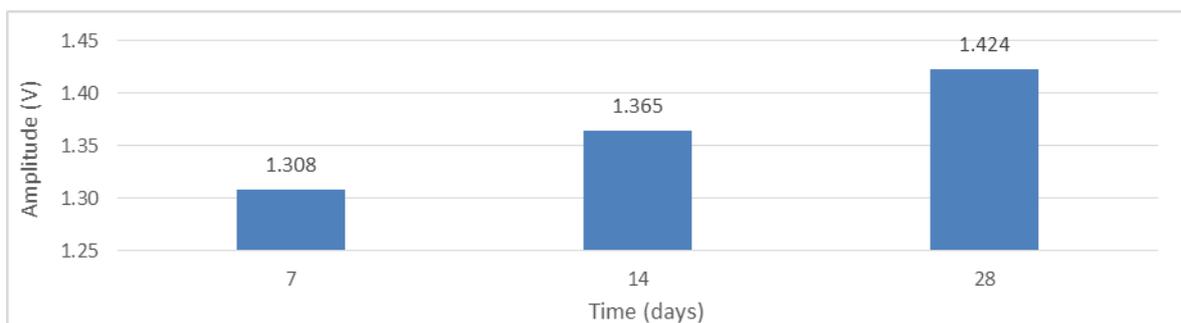


Fig. 12. Amplitude value comparison from IoT-based testing after CTM testing.

Table 5. Amplitude data from IoT-based testing after CTM testing.

Days	Amplitude (V)			
	Average	Cube 1	Cube 2	Cube 3
7	1.308	1.261	1.344	1.321
14	1.365	1.342	1.368	1.385
28	1.424	1.394	1.407	1.471

To validate the correlation between amplitude and compressive strength for concrete cubes, Fig. 13 presents a graphical representation between them with the

average data provided in Tables 3 and 4. The blue line represents the observed data, while the red dotted line denotes the regression trendline, indicating a positive correlation. The correlation coefficient (r) suggests that higher amplitude values correspond to higher compressive strength. Based on the result obtained from the graph, the correlation of $R^2 = 0.9796$ (approximately 0.98) is strongly acceptable for practical use in concrete strength monitoring. The linear Eq. (2) obtained from the graph in Fig. 13 is shown below:

$$y = 7.6227 \cdot x + 15.881 \tag{2}$$

where y is the compressive strength (N/mm^2), and x is the amplitude (V).

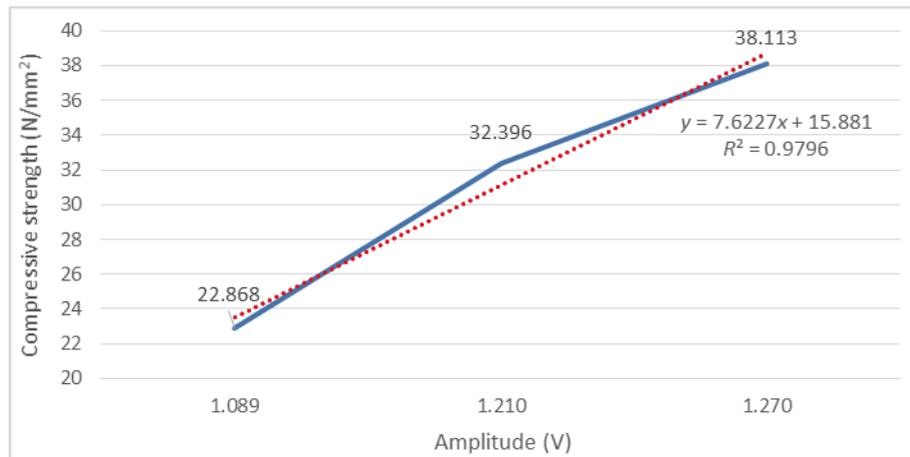


Fig. 13. Correlation between amplitude and compressive strength.

For comparison purposes, the results obtained from IoT-based testing for concrete strength monitoring and damage detection, as shown in Tables 3 and 5, are illustrated in Fig. 14. The results indicate an increase in the

values for damage detection compared to concrete strength monitoring on the 7th, 14th, and 28th days. The difference between both results falls within the range of approximately 0.15 to 0.2.

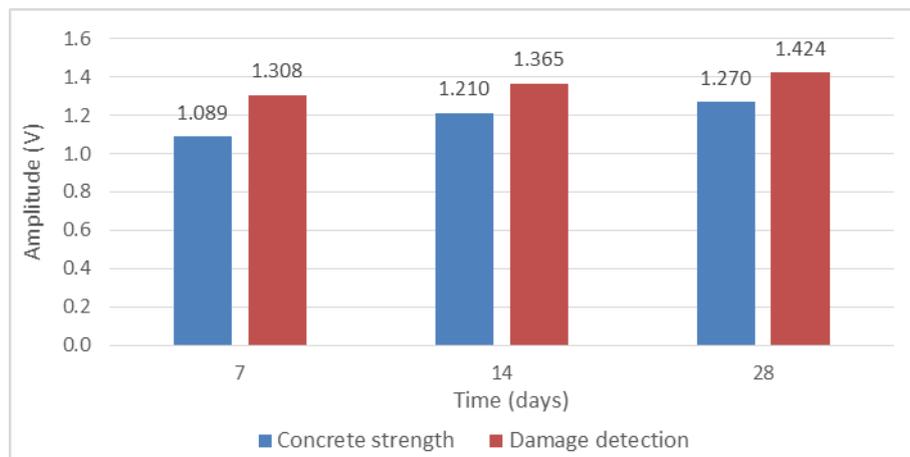


Fig. 14. Comparison between concrete strength and damage detection.

4. Conclusions

A key challenge in the construction industry is the reliance on destructive testing methods, which are time-consuming, labor-intensive, and impractical for real-

time concrete strength and structural health monitoring. The present study successfully integrates a piezoelectric lead zirconate titanate (PZT) sensor with an IoT-based monitoring system, offering a practical, non-destructive approach for concrete strength monitoring and damage

detection in concrete structures. The study was conducted on 7th, 14th, and 28th days following standard construction codes. The result demonstrated a strong correlation, $R^2=0.9796$ (approximately 0.98), between amplitude values and compressive strength, confirming the accuracy and reliability of this non-destructive approach. The recorded compressive strength of 38.113 N/mm² on the 28th day closely aligns with the target strength of 38.25 N/mm², confirming the effectiveness of the monitoring system. Additionally, damage detection results revealed a consistent increase in amplitude value post-CTM testing, highlighting structural deterioration. This study highlights the benefits of integrating PZT sensors with IoT-based wireless data transmission, enhanced precision, cost-efficiency, and automation in concrete assessment.

For future study, this piezoelectric-based monitoring system can be extended to large-scale structures such as beams, columns, and slabs in real-world applications. For real-time monitoring, some improvements in this monitoring system are necessary. Artificial intelligence (AI) and machine learning models can be integrated to enhance the prediction accuracy of concrete strength and automate damage classification. Additionally, other non-destructive methods can be used for a more holistic evaluation. Future studies should also focus on achieving more accurate results of correlation coefficients ($R^2=1$) on the same or different grades of concrete to validate the system's reliability further.

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Conflict of Interest

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Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

REFERENCES

- Arca B, Keskin SB, Göçüenci A (2021). Predictability of concrete damage level by non-destructive test methods. *Challenge Journal of Concrete Research Letters*, 12(4), 138-150.
- Ayeni PO, Adesoba OC (2024). IoT-based home control system using NodeMCU and Firebase. *Journal of Edge Computing*, Early Access.
- Chaliorisa C, Karayannis C, Angeli G, Papadopoulos N, Favvata M, Providakis C (2016). Applications of smart piezoelectric materials in a wireless admittance monitoring system (WiAMS) to structures—Tests in RC elements. *Case Studies in Construction Materials*, 5, 1–18.
- Chena J, Li P, Song G, Ren Z (2015). Piezo-based wireless sensor network for early-age concrete strength monitoring. *Optik*, 127(5), 2983–2987.
- Dumoulin C, Karaiskos G, Deraemaeker A (2015). Concrete monitoring using embedded piezoelectric transducers. *Encyclopedia of Earthquake Engineering*, 94(1), 1-12.
- Fani I, Basil K (2022). The use of fuzzy linear regression with trapezoidal fuzzy numbers to predict the compressive strength of lightweight foamed concrete. *Mathematical Modelling of Engineering Problems*, 9(1), 1-10.
- Feng Q, Liang Y, Song G (2019). Real-time monitoring of early-age concrete strength using piezoceramic-based smart aggregates. *Journal of Aerospace Engineering*, 32(1), 04018115.
- Fotouhi M, Xiao B, Pozegic T, Jalalvand M, Hamerton I, Wisnom M (2017). High performance piezo electric nanocomposite sensor nodes for structural health monitoring. *21st International Conference on Composite Material*, 1-9.
- Han G, Su YF, Lu N (2020). Mechanism for using piezoelectric sensor to monitor strength gain process of cementitious materials with the temperature effect. *Journal of Intelligent Material Systems and Structures*, 32(10), 1-12.
- Hu B, Kundu T, Grill W, Liu B, Toufigh V (2013). Embedded piezoelectric sensors for health monitoring of concrete structures. *ACI Materials Journal*, 110(2), 149-158.
- Hu X, Zhu H, Wang D (2014). A study of concrete slab damage detection based on the electromechanical impedance method. *Sensors*, 14(10), 19897-19909.
- IS 456:2000 (2000). Indian Standard Plain and Reinforced Concrete – Code of Practice (Reaffirmed 2005). Bureau of Indian Standards, Manak Bhavan. 9 Bahadur Shah Zafar Marg, New Delhi, India.
- IS 516:1959 (1959). Indian Standard Methods of test for Strength of Concrete (Reaffirmed 2004). Bureau of Indian Standards, Manak Bhavan. 9 Bahadur Shah Zafar Marg, New Delhi, India.
- Ivanchev I (2022). Investigation with non-destructive and destructive methods for assessment of concrete compressive strength. *Applied Sciences*, 12(23), 12172.
- Jerzy S (2020). Application of smart materials in civil engineering and architecture. *2020 World Symposium on Smart Materials and Applications*, 958, 012006.
- Kuang K, Cantwell W (2003). The use of plastic optical fibres and shape memory alloys for damage assessment and damping control in composite materials. *Measurement Science and Technology*, 14(8), 1305.
- Kuczma M, Tabrizikahou A, Nowotarski P, Kwiatek M, Javanmardi A (2021). Sustainability of civil structures through the application of smart materials: a review. *Materials*, 14(17), 4824, 1-29.
- Li G, Luo M, Huang J, Li W (2023). Early age concrete strength monitoring using smart aggregate based on electromechanical impedance and machine learning. *Mechanical Systems and Signal Processing*, 186, 109865.
- Lorenzi A, Stein K, Reginatto LA, Pinto da Silva Filho LC (2020). Concrete structures monitoring using ultrasonic tests. *Revista de la Construcción*, 19(3), 246-257.
- Mavroidis C, Pfeiffer C (1999). Conventional actuators, shape memory alloys, and electrorheological fluids. *Research in Nondestructive Evaluation*, 14, 1-32.
- Noori M, Narjabadifam P (2019). Innovative civil engineering applications of smart materials for smart sustainable urbanization. *Journal of Civil Engineering and Urbanism*, 9(4), 24-35.
- Prayuda H, Monika F, Saleh F, Prabandaru P, Emerald J, Maulida N (2020). Prediction of flowability compressive and flexural strength on self-compacting concrete using fuzzy logic. *Advances in Engineering Research*, 199, 89-97.
- Providakis C, Angeli GM, Favvata MJ, Papadopoulos N, Chaliorisa C, Karayannis C (2014). Detection of concrete reinforcement damage using piezoelectric materials - analytical and experimental study. *International Journal of Civil, Architectural, Structural and Construction Engineering*, 8(2), 197-205.
- Roy S, Mishraand H, Mohapatro BG (2016). Creating sustainable environment using smart materials in smart structures. *Indian Journal of Science and Technology*, 9(30), 1-9.

- Samadi H, Farrokh E (2022). Prediction of compressive strength of concrete using Adaptive neuro-fuzzy inference system. *International Conference on Civil Structural and Earthquake*, 1-9.
- Saravanan T, Balamonica K, Priya B, Gopalkrishnan N, Murthy S (2017). Piezoelectric EMI-based monitoring of early strength gain in concrete and damage detection in structural components. *Journal of Infrastructure Systems*, 23(4), 04017029.
- Schober P, Boer C, Schwarte LA (2018). Correlation coefficients: Appropriate use and interpretation. *Anesthesia & Analgesia*, 126(5), 1763-1768.
- Sha F, Xu D, Cheng X, Huang S (2021). Mechanical sensing properties of embedded smart piezoelectric sensor for structural health monitoring of concrete. *Research in Nondestructive Evaluation*, 32(2), 88–112.
- Shafiq N, Nuruddin F (2010). Degree of hydration of OPC and OPC/FA pastes dried in different relative humidity. *Concrete Research Letters*, 1(3), 81-89.
- Shin WS, Qureshi AR, Lee JY, Yun CB (2008). Piezoelectric sensor based non-destructive active monitoring of strength gain in concrete. *Smart Materials and Structures*, 17(5), 055002, 1-8.
- Sobczyk M, Wiesenhütter S, Noennig JR, Wallmersperger T (2021). Smart materials in architecture for actuator and sensor applications: A review. *Journal of Intelligent Material Systems and Structures*, 33(3), 379–399.
- Sun W, Fu TY, Li B, Sun L (2020). Numerical study of monitoring of early-age concrete strength development using PZT induced stress wave. *IOP Conference Series: Materials Science and Engineering*, 789, 012058.
- Vikram V, Rajkumar U, Jayaseelan D (2023). An initial investigation of a pavement monitoring platform based on the internet of things using a piezoelectric cantilever beam electric sensor. *Dogo Rangang Research Journal*, 13(3), 95-99.
- Wang W, Xiang Y, Yu J, Yang L (2023). Development and prospect of smart materials and structures for aerospace sensing systems and applications. *Sensors*, 23(3), 1545.
- Wang DS, Yu LP, Zhu HP (2010). Strength monitoring of concrete based on embedded PZT transducer and the resonant frequency. *Proceedings of the 2010 Symposium on Piezoelectricity Acoustic Waves and Device Applications*, 202-205.
- Wu C, Xiang H, Jiang S, Ma S (2022). Stress monitoring of concrete via uniaxial piezoelectric sensor. *Sensors*, 22(11), 4041.
- Yang X, Yang W, Li S, Wu C (2020). Early age concrete strength monitoring using power spectral density and wavelet packet analysis. *Advances in Civil Engineering*, 2020, 1-11.
- Zachariah T, Klugman N, Dutta P (2023). ThingSpeak in the wild: Exploring 38K visualizations of IoT Data. *SenSys'22: Proceedings of the 20th ACM Conference on Embedded Networked Sensor Systems*, 1035-1040.
- Zhang S, Liu P, Liu L, Huang J, Cheng X, Chen Y, Chen L, He S, Zhang N, Yu Z (2024). Heat of hydration analysis and temperature field distribution study for super-long mass concrete. *Coatings*, 14(3), 369.
- Zhu S (2021). Study on smart materials using in civil engineering. *Advances in Social Science, Education and Humanities Research*, 631, 1462-1466.