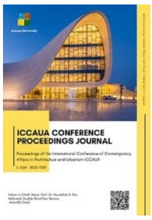

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Wireless Open-Source Sensor Technology for Monitoring Concrete Mechanical Properties in Sustainable Constructions

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Abstract

This paper explores the use of wireless open-source sensor technology to monitor concrete and environmental parameters in energy-efficient, resilient, and sustainable construction. Accurate monitoring of structural and environmental conditions is essential to optimize building performance. The proposed system employs low-cost, wireless sensors with NodeMCU ESP8266 WiFi modules to gather real-time data on concrete properties, including temperature and humidity, during the casting and curing stages, along with other environmental factors affecting the structure. By integrating open-source technology, the system provides a cost-effective solution for continuous monitoring, enabling early detection of issues such as material degradation or energy inefficiencies. This paper discusses the design, implementation, and benefits of the system, highlighting its role in improving building durability and reducing environmental impact. The results demonstrate the effectiveness of this approach in supporting sustainable construction practices and enhancing building resilience.

Keywords: Sustainable building, structural health monitoring, energy efficiency, resilient construction, Internet of Things.

1. Introduction

Concrete remains a foundational material in the construction sector, widely valued for its mechanical strength, durability, and adaptability across various structural applications. However, during its early-age phase, concrete is highly responsive to environmental influences such as temperature, humidity, wind, and solar radiation, which directly impact cement hydration a process crucial for the development of mechanical properties like compressive and tensile strength, stiffness, and cracking resistance (Hosseinzadehfard and Mobaraki 2024). These environmental factors can significantly affect the long-term structural performance and durability of concrete in both cast-in-place and precast applications (Garijo et al. 2025).

In its fresh state, concrete exhibits important mechanical-related properties such as workability, uniformity, and compactability, all of which influence the quality and structural integrity of the hardened material. Research has long sought to improve these early-age characteristics through optimized mix designs, admixtures, and curing conditions (De La Rosa et al. 2025). Recent advancements have enabled real-time and in-situ monitoring of key physical and mechanical parameters through the deployment of embedded sensors and data acquisition systems (Zanon et al. 2025), allowing on-site adaptation to ensure improved performance and quality control (De La Rosa et al. 2025).

Sensor technologies have evolved considerably over the past decades, transforming from basic electrical resistance sensors (Ahmad et al. 2019; Bucher et al. 2021) to more sophisticated methods such as ultrasonic wave analysis, electromagnetic field sensing, and acoustic emission techniques (Chakraborty and Katunin 2019; Mobaraki et al. 2021a). Cutting-edge developments have introduced fiber optic, piezoelectric, and magnetostrictive sensors (LECHOWSKA/AGNIESZKA et al. 2014), capable of measuring critical mechanical responses including stress, strain, cracking activity, and temperature gradients within concrete. Among these, piezoelectric sensors have gained notable attention due to their high sensitivity, small size, and ability to function as both actuators and sensors, making them ideal for structural health monitoring applications (Mobaraki et al. 2021b).

Innovative studies have explored novel sensor materials and smart composites, including cement-based carbon nanotube systems for capturing dynamic responses and intelligent piezoelectric arrays for monitoring mechanical stress and damage evolution (Sabato et al. 2016; Mobaraki et al. 2019). Reviews on piezoresistive cementitious sensors further emphasize how variations in conductive fillers and fabrication methods can influence the sensitivity and repeatability of mechanical property measurements (Porras Soriano et al. 2021). These multifunctional sensors are increasingly recognized for their potential to simultaneously track stress, strain, crack formation, temperature, and moisture, all of which are critical for evaluating structural performance and enhancing the sustainability of concrete infrastructures (Larson et al. 2012; Mobaraki and Vaghefi 2024).

With the growing push for digital transformation in construction, the integration of Internet of Things (IoT) technologies, machine learning, and artificial intelligence has opened new opportunities for intelligent infrastructure monitoring. These approaches enable real-time data acquisition, automated analysis, and predictive maintenance strategies, thereby supporting data-driven decision-making in the field (Vaghefi and Mobaraki 2021).

Despite these technological advances, challenges remain. The high cost, complexity, and durability concerns of specialized sensing equipment continue to limit their widespread implementation in typical construction settings [22]. In response, recent efforts have focused on the development of low-cost, wireless, and open-source sensor solutions that can deliver reliable data at a fraction of the cost. For example, sensors embedded with Bluetooth and Wi-Fi communication modules have shown effectiveness in monitoring concrete strength development and reducing energy consumption in wireless systems (Ahmad Nia and Atun 2016; Amen et al. 2023). Furthermore, affordable microcontroller platforms, such as Arduino, have been successfully utilized in diverse applications including concrete curing control (VALIPOUR et al. 2019), corrosion detection , and temperature and humidity monitoring (Mobaraki et al. 2022b).

The integration of these systems with cloud-based platforms and mobile applications further enhances their utility. Data collected from wireless nodes can be uploaded, analyzed, and visualized remotely, enabling engineers to monitor concrete strength gain, curing conditions, or stress evolution without being on-site. These platforms can also be linked with machine learning algorithms to predict performance trends and generate alerts when deviations occur. In parallel, integration with Building Information Modeling (BIM) (Mobaraki et al. 2023a) systems allows sensor data to be contextualized within a digital twin of the structure, supporting more informed decision-making across the lifecycle of the building (Vaghefi and Mobaraki 2021; Muhy Al-Din et al. 2023).

Moreover, open-source monitoring systems align closely with sustainable construction principles. By enabling early detection of flaws or curing issues, they reduce the likelihood of defects, overdesign, or material wastage. Their modularity and reusability also contribute to lower environmental impact compared to traditional systems. In precast and in-situ applications, these systems can help optimize resource allocation, ensure structural quality, and support certification for green building standards such as LEED or BREEAM (Wang et al. 2019; Mobaraki et al. 2022a).

Despite these advantages, challenges remain. Ensuring long-term durability of low-cost sensors in aggressive environments, maintaining data accuracy, and protecting against cybersecurity threats in IoT-based systems are all areas requiring further research and innovation. Within this framework, the present study introduces a wireless, open-source monitoring system designed to track the mechanical behavior of concrete during early-age and hardening stages. The system is built around NodeMCU ESP8266 and cost-efficient sensors, with a focus on capturing key variables such as temperature, humidity, and potentially stress and strain, to support the real-time evaluation of strength development and structural integrity (Cheddadi et al. 2020; Mobaraki et al. 2023b). Tailored specifically for sustainable construction practices, the proposed platform aims to improve material efficiency, reduce waste, and enhance quality assurance in both precast and in-situ concrete elements, particularly under challenging environmental or production conditions (Mobaraki et al. 2025).

2. Test description

To evaluate the performance of the proposed wireless sensor system for monitoring concrete mechanical properties, a laboratory-scale experiment was conducted using a standard concrete specimen. The objective of this test was to validate the functionality, stability, and data transmission capacity of the selected temperature and humidity sensors, as well as their ability to monitor critical environmental conditions during the 28-day curing period.

Figure 1 presents the process of concrete sample preparation. The specimen was cast using a conventional concrete mix commonly used in structural applications, and its dimensions were chosen in accordance with standard practices for material testing. During the casting process, the selected DS18B20 waterproof temperature sensors were embedded at different depths within the concrete to monitor the internal and surface temperature evolution throughout the curing phase (Mobaraki and Vehbi 2022).

Figure 1. Preparation of concrete specimen in the laboratory.

Figure 2 shows the prepared low-cost IoT monitoring system. TECNOIOT capacitive soil moisture sensors were installed at strategic positions to assess changes in internal humidity levels, which are closely related to hydration progress and the mechanical development of the concrete. Both types of sensors were connected to an Arduino-based microcontroller platform, which served as the central unit for data acquisition, signal processing, and wireless communication. The microcontroller was programmed to collect readings at regular time intervals and upload the data in real time to an IoT cloud platform via Wi-Fi. This setup enabled continuous monitoring without manual intervention and provided a live data stream accessible from any internet-connected device.

The 28-day monitoring campaign was designed to capture the complete early-age development of the concrete, including the initial hydration reactions, temperature peaks associated with exothermic cement reactions, and gradual stabilization of moisture levels as the concrete hardened. The use of real-time monitoring allowed for the identification of temperature and humidity trends that could influence cracking risk, strength development, or curing effectiveness.

This experimental setup demonstrated the feasibility of using low-cost, open-source sensor technology for continuous, remote monitoring of concrete curing in line with sustainable construction practices. The system's modularity also allows for adaptation to full-scale structural elements and field conditions in future implementations.

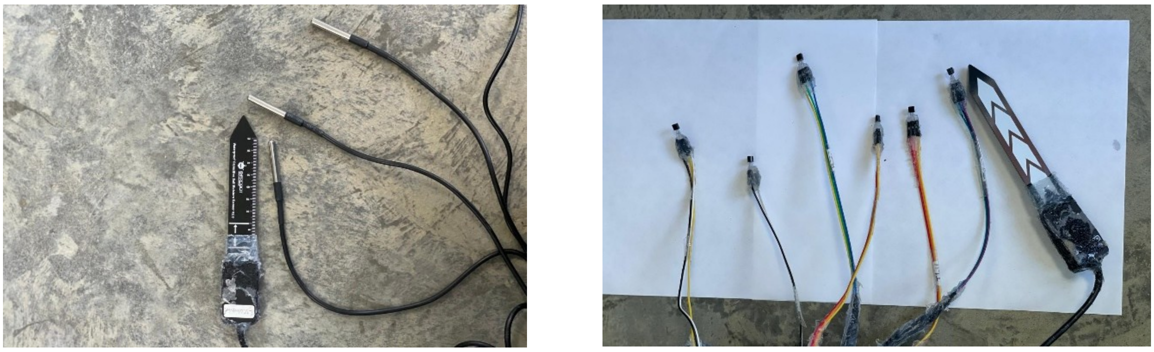

Figure 2. Preparation and installation of low-cost IoT monitoring system.

3. Results and discussion

The evolution of internal humidity during the 28-day curing period is illustrated in Figure 3, based on continuous measurements from two embedded TECNOIOT capacitive soil moisture sensors installed within the concrete specimen. Over the test period, a total of 4,239 data points were recorded, providing high-resolution insight into the moisture dynamics of the concrete matrix. At the start of the monitoring campaign, humidity readings from both sensors were consistently near 100%, reflecting the fully saturated condition of the freshly cast concrete (Mobaraki and Vaghefi 2015). As hydration progressed and water was consumed in chemical reactions and gradually evaporated from the surface, a steady decline in internal humidity was observed. By the end of the 28-day period, humidity values had decreased to approximately 48%, indicating substantial moisture loss. This trend is consistent with the expected behavior of concrete during curing, where internal moisture content diminishes as the material hardens and its capillary porosity changes.

The graph also demonstrates a strong alignment between the two sensors, with minimal divergence throughout the monitoring period. This suggests that the sensors maintained stable performance, and the placement strategy achieved consistent exposure to representative regions of the specimen. The gradual slope in the humidity reduction curve rather than abrupt changes indicates a controlled and uninterrupted curing process, with no external disturbances such as excessive drying, cracking, or water intrusion.

The ability to continuously monitor internal humidity in real time provides valuable data for assessing curing effectiveness, predicting early-age mechanical performance, and optimizing sustainability in concrete production.

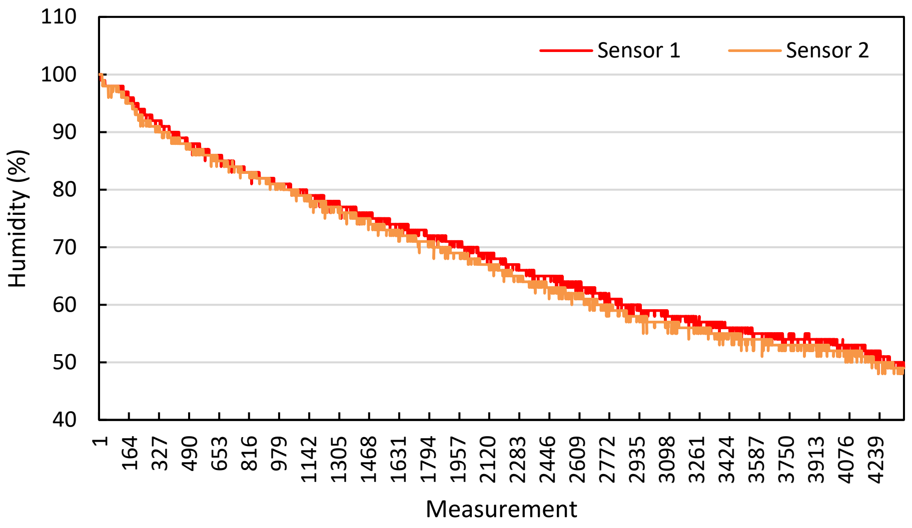

Figure 3. Variation of humidity during 28 days of monitoring captured by 2 copies of the sensors.

The temperature monitoring data collected over a 28-day period from two sensors placed inside the concrete specimen provides a comprehensive view of the thermal behavior within the material (Figure 4). A total of 4239 data points were recorded, with the minimum temperature reaching 15.29°C and the maximum temperature rising to 23.24°C. These temperature variations reflect the dynamic changes in the concrete specimen, influenced by both environmental conditions and the intrinsic properties of the cementitious materials used in the mix.

Figure 4 the temperature evolution over the 28-day period reveals significant daily fluctuations, which are characteristic of concrete's thermal behavior. Concrete, due to its high thermal mass, absorbs heat during the day and gradually releases it at night, resulting in cyclic temperature changes. The recorded data shows a steady increase and subsequent stabilization of temperature, which aligns with typical thermal patterns observed in curing concrete. The overall temperature fluctuation, from 15.29°C to 23.24°C, is moderate, indicating that the specimen has a relatively stable thermal profile during the monitoring period.

Portland cement's components Alite (C_3S), Belite (C_2S), Celite (C_3A), and Ferrite (C_4AF) have a direct influence on the heat generation and thermal behavior during hydration. These components contribute differently to the temperature variations observed in the concrete specimen over the 28-day period:

Alite is the primary contributor to the early exothermic heat of hydration. In the initial stages of hydration, Alite reacts with water to generate significant heat, which is reflected in the initial rise in temperature. This is expected to manifest in the graph as a sharp increase in temperature in the first few days, corresponding with the rapid hydration of Alite. While Belite contributes to hydration over a more extended period, it generates less heat compared to Alite. The slower release of heat from Belite is likely to be observed as a more gradual increase in temperature following the initial peak, as the cement continues to hydrate over time. Celite also contributes to early hydration heat, especially in the first few days. Its exothermic reaction may lead to an additional temperature rise, particularly during the first 24-48 hours of hydration. If the graph shows a pronounced early peak, this could be attributed to the reaction of Celite in the early stages. The Ferrite component of Portland cement contributes to a slower, more sustained hydration process, resulting in a more gradual and sustained heat release over time. This can lead to minor temperature increases towards the latter stages of the 28-day period, as the hydration process continues to progress.

The overall temperature behavior observed in the concrete specimen is influenced by the combined effect of these cement components. The early temperature rise, particularly in the first few days, is largely driven by the exothermic reactions of Alite and Celite. As the hydration process continues, the heat release becomes more gradual, with Belite and Ferrite contributing to the sustained temperature changes. This results in the observed temperature fluctuations throughout the 28-day period, with an initial sharp rise followed by a more moderate and steady change. The temperature profile observed in the concrete specimen also reflects the curing and hydration process. During the initial days, the heat of hydration is most intense, leading to rapid temperature increases. However, as the hydration slows after the first week, the temperature stabilizes and fluctuates within a narrower range. These temperature changes are critical for understanding the curing process and the material's thermal performance, providing insights into the kinetics of hydration and the long-term behavior of the concrete.

In summary, the temperature data collected over the 28-day period highlights the interplay between environmental factors and the cementitious materials' properties. The combined effects of Alite, Belite, Celite, and Ferrite in the Portland cement mix influence the temperature trends, which reflect the ongoing hydration process. The results offer valuable insights into the thermal behavior of the concrete, which is essential for optimizing curing conditions and understanding the material's overall performance.

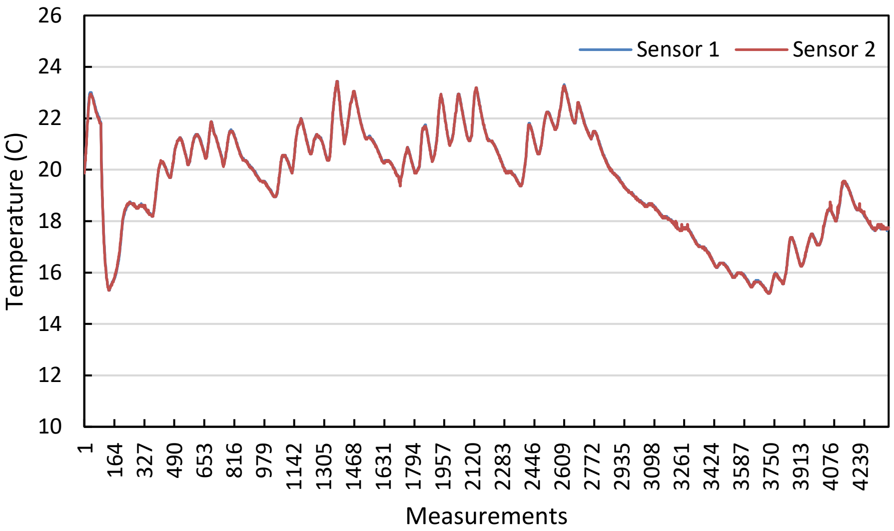

Figure 4. Variation of temperature during 28 days of monitoring captured by 2 copies of the sensors.

4. Conclusions

This study has successfully demonstrated the use of a low-cost temperature and humidity monitoring system for tracking the thermal and environmental behavior of concrete specimens over a 28-day curing period. With a total of 4239 data points collected, the system captured temperature fluctuations ranging from a minimum of 15.29°C to a maximum of 23.24°C. These recorded temperature changes provide valuable insights into the hydration process of concrete, reflecting the expected thermal dynamics influenced by the exothermic reactions of Portland cement components such as Alite (C_3S), Belite (C_2S), Celite (C_3A), and Ferrite (C_4AF).

The temperature trends observed in the data align with the expected phases of cement hydration. Initially, the system recorded a rapid increase in temperature, corresponding to the early exothermic reactions of Alite and Celite. These components are primarily responsible for the heat released during the first stages of hydration. As the hydration process continued, the temperature rise slowed, reflecting the slower reactions of Belite and Ferrite, which contribute to a more gradual and sustained heat release. The gradual temperature stabilization over the 28 days suggests that the hydration process was progressing as anticipated, with no anomalies in the expected behavior of the cement.

In addition to the temperature data, humidity was also monitored throughout the curing process. The humidity levels inside the concrete specimen played a crucial role in the hydration process, as they directly impact the availability of water required for the ongoing chemical reactions. A consistent level of humidity is necessary to maintain adequate hydration, especially in the early stages when the cement's hydration reactions are most vigorous. The humidity data indicated fluctuations consistent with the ambient environmental conditions, which can impact the rate of moisture evaporation from the concrete surface. The interplay between temperature and humidity in this system is important because it reflects the micro-environment inside the concrete and helps in understanding the efficiency of hydration over time.

The combination of temperature and humidity data provides a more complete picture of the curing process, allowing for a deeper understanding of the material's behavior and the factors that influence its strength development. For example, when temperature increases, it often correlates with a decrease in humidity as moisture evaporates, which can slow down hydration if not adequately controlled. By monitoring both variables, this low-cost system enables real-time insights into the hydration kinetics and the environmental conditions affecting the concrete.

The low-cost monitoring system proved to be effective not only in tracking temperature changes but also in capturing the environmental conditions that influence the hydration process. This dual monitoring capability is essential for assessing the curing performance and optimizing the curing conditions for improved concrete quality. The ability to continuously monitor temperature and humidity provides valuable data for researchers and engineers, facilitating better control over concrete curing processes and leading to higher quality and more durable concrete structures.

In conclusion, the developed low-cost monitoring system has successfully captured the expected chemical reactions and environmental conditions during the 28-day curing period of the concrete specimen. The temperature and humidity data confirmed that the hydration process proceeded as expected, providing further validation for the reliability of the system. This research underscores the potential of affordable, IoT-based monitoring systems to enhance the understanding and control of concrete curing, offering an invaluable tool for both research and practical applications in construction, materials science, and the optimization of concrete curing methods.

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Conflict of Interests

The Author(s) declare(s) that there is no conflict of interest.

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