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# Real-time concrete strength monitoring: an IoT-enabled framework integrating electrochemical and fiber optic sensors for structural integrity assessment

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## ABSTRACT

This study develops an IoT-based real-time framework for monitoring concrete strength in structural frameworks, utilizing electrochemical and fiber optic sensors to enhance construction quality control and structural health monitoring. Accurate assessment of concrete strength is vital for ensuring the safety and longevity of infrastructure. Traditional testing methods, which are periodic and invasive, often fail to provide timely data on strength progression. This framework overcomes these limitations by enabling continuous, in-situ monitoring. Electrochemical sensors measure variations in the chemical environment of concrete, which correlate with strength development. Simultaneously, fiber optic sensors monitor strain and temperature changes, providing real-time insights into structural responses under load. The data collected by these sensors are analysed using the Plowman method and regression curve analysis, offering high precision in detecting early-stage strength development and modelling its progression over time. The system incorporates wireless data transmission to a central cloud-based server for storage, processing, and visualization. This approach ensures enhanced lifecycle management and resilience of infrastructures. By demonstrating the efficacy of this IoT-based monitoring system, the study underscores its potential to revolutionize construction practices. It provides a robust solution for real-time quality assurance, structural health monitoring, sustainable lifecycle management, and resilient infrastructures.

**Keywords:** Real-time; Concrete strength; IoT; Electrochemical sensors; Fiber optics; Regression analysis.

## 1. INTRODUCTION

The durability and strength of concrete are fundamental to the safety and longevity of modern infrastructure [1]. Concrete structures, ranging from bridges and buildings to roadways, must be carefully monitored to ensure that they achieve and maintain the required strength [2]. Traditional methods for evaluating concrete strength typically involve sampling, testing, and inspecting concrete specimens in laboratories, which can be time-consuming and lack the benefit of real-time feedback [3]. This limitation has led to the development of in-situ monitoring techniques, which can directly assess the strength and durability of concrete in real time, providing a more accurate and timely representation of structural integrity [4]. Advancements in Internet of Things (IoT) technology have opened new avenues for real-time monitoring in construction and civil engineering [5]. IoT-enabled sensors allow for continuous data collection and wireless transmission, making it possible to observe the concrete curing process and its strength development without interrupting construction activities [6]. Electrochemical and fibre optic sensors, in particular, offer promising solutions for measuring critical parameters related to concrete strength [7]. Electrochemical sensors monitor the chemical properties of concrete as it cures, while fibre optic sensors measure strain, temperature, and other physical changes in real-time [8]. Together, these sensors form an effective IoT-based system for monitoring concrete's structural health, enabling rapid data-driven decision-making [9]. In this study, we designed an IoT framework that integrates electrochemical and fibre optic sensors to continuously monitor concrete strength in structural members [10]. This dual-sensor approach ensures accurate measurements by capturing both chemical and physical data, which provides a holistic understanding of the material's strength characteristics [11]. The system transmits data to a cloud platform, where machine learning algorithms analyse the strength patterns over time, providing valuable insights for construction and maintenance planning [12]. This system also includes a centralized dashboard, accessible via mobile and desktop devices,

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offering real-time alerts and data visualization for stakeholders, including engineers and site managers [13]. For effective analysis, Plowman methods and regression curve techniques were employed to interpret the data obtained from both sensor types [14]. The Plowman method, widely recognized for its applicability in concrete testing, assesses changes in chemical properties to infer concrete strength, while regression curve methods help establish predictive relationships between sensor readings and actual strength values [15]. These methods allow for the detection of anomalies, enabling preventive actions if concrete strength fails to meet expected levels [16]. Consequently, this integrated framework not only ensures compliance with safety standards but also enhances the overall efficiency of the building development [17]. The significance of real-time material strength monitoring extends beyond immediate safety benefits; it also supports sustainable construction practices [18]. By accurately assessing when concrete has reached the required strength, construction schedules can be optimized, minimizing delays and reducing the need for excessive material use [19].

IoT technology enables seamless integration of sensors, wireless communication, and cloud analytics for real-time data collection and monitoring. In this study, IoT facilitates continuous assessment of concrete strength by transmitting sensor data for analysis, ensuring proactive maintenance, improving construction quality control, and enhancing structural health monitoring in smart infrastructure systems. Fiber optic sensors work by transmitting light through optical fibers, with changes in light properties (such as intensity, phase, or wavelength) indicating variations in strain, temperature, or pressure. These sensors are essential in this study due to their high sensitivity, durability in harsh environments, and ability to provide real-time insights into structural responses, aiding precise monitoring of concrete strength development. Real-time monitoring also facilitates predictive maintenance, as data collected over time can reveal trends in concrete degradation, allowing for timely interventions that extend the lifespan of structures and reduce costly repairs [20]. This aligns with modern objectives in civil engineering to create sustainable, resilient infrastructure. The proposed IoT-based framework with electrochemical and fibre optic sensor integration provides a novel approach to concrete strength monitoring, addressing the limitations of traditional methods while enhancing safety and efficiency in construction [21]. This study aims to contribute to the field of structural health monitoring by demonstrating the potential of IoT technology to transform real-time data into actionable insights, promoting a proactive approach to infrastructure management and resilience [22]. The aim of this study is to develop an IoT-based real-time monitoring framework to assess concrete strength using electrochemical and fiber optic sensors, ensuring accurate, continuous monitoring and proactive maintenance for enhanced structural safety and resilience in modern infrastructure systems. Future work may include expanding this sensor framework to monitor additional concrete properties and refining the machine learning models for predictive analytics, laying the groundwork for smart infrastructure systems [23].

## 2. RESEARCH GAP

This study validates the concept of smart sensing for structural integrity by integrating IoT-based electrochemical and fiber optic sensors into concrete monitoring systems. These sensors provide continuous, real-time data on key parameters such as strain, temperature, and chemical changes, which are directly linked to concrete strength and structural health. The data is analysed using advanced regression techniques and the Plowman method to predict the strength and maturity of concrete over time. The real-time monitoring capability allows for early detection of potential issues, ensuring timely interventions and better decision-making for infrastructure maintenance. By combining sensor technology with predictive modelling, the study demonstrates the effectiveness of smart sensing in ensuring structural integrity, contributing to more efficient, proactive maintenance strategies for concrete structures. The study is limited by the scalability of the IoT-based monitoring system, as the integration of sensors can be cost-prohibitive for large-scale projects. Additionally, environmental factors such as temperature fluctuations may affect sensor accuracy, and long-term reliability remains an area for further investigation. While substantial progress has been made in concrete strength monitoring through traditional testing methods and some non-destructive techniques, limitations persist in achieving real-time, continuous assessments that are necessary for modern construction practices [23]. Current monitoring methods cannot provide instant feedback on concrete strength during critical curing stages, resulting in potential delays or premature construction activities that could compromise structural integrity [17]. Additionally, while maturity models like the Nurse-Saul and Arrhenius functions are widely used to estimate strength, they often assume uniform temperature and humidity conditions, which may not accurately reflect on-site variations in real-world settings [23]. Monitoring concrete strength is crucial to ensure the structural safety, durability, and integrity of infrastructure. Early detection of strength deficiencies allows for timely interventions, preventing failures or costly repairs. For example, in bridge construction, continuous monitoring of concrete strength helps identify when the material has reached its required load-bearing capacity, ensuring safe operation. This study's IoT-based monitoring system provides real-time data on concrete's strength development, allowing for proactive maintenance and ensuring that structures remain safe and functional throughout their lifecycle. Although recent studies have explored the potential of IoT-based sensors in construction, there is limited research on integrated sensor frameworks that combine electrochemical and fibre optic sensors for comprehensive, real-time concrete strength monitoring. Furthermore, few studies have applied advanced data analysis methods, such as regression curve techniques, to optimize the accuracy of sensor data in predicting concrete strength. This study addresses these gaps by developing a dual-sensor IoT framework that not only monitors concrete strength in real time but also leverages robust analytical methods to improve predictive accuracy. This integrated approach aims to enhance construction safety, optimize material use, and streamline project timelines.

## 3. LITERATURE REVIEW

Concrete strength monitoring is an essential aspect of structural health management, directly affecting the safety and longevity of infrastructures [24]. Outdated approaches of evaluating material strength, such as destructive testing on cured samples, are time-consuming and provide only delayed feedback [25]. Non-destructive methods, including ultrasonic pulse velocity and rebound hammer testing, have offered improvements in monitoring but still lack continuous, real-time data necessary for ongoing strength assessment during the curing process [26]. Recent advancements in sensor technology and IoT have enabled real-time monitoring capabilities, allowing for more accurate strength evaluations and timely interventions [27]. Electrochemical and fibre optic sensors, in particular, are promising tools for tracking concrete properties in situ [28]. Electrochemical sensors can detect changes in chemical composition as concrete cures, while fibre optic sensors provide strain and temperature data, both of which are integral to understanding the real-time development of concrete strength [29]. The Nurse-Saul Maturity Model is a linear approach based on cumulative temperature-time factors to estimate concrete strength. Maturity Function Models generalize the concept, incorporating variations in concrete properties and curing conditions. The Arrhenius Maturity Model uses a chemical kinetics perspective, relating reaction rates to temperature through an exponential function, offering higher accuracy for variable temperature conditions. While Nurse Saul is simple and practical, Arrhenius provides better precision for complex scenarios. Maturity Function Models serve as a bridge, offering flexibility for diverse applications.

### 3.1. Electrochemical sensors

This study captures real-time data using electrochemical and fiber optic sensors embedded within the concrete. Electrochemical sensors monitor the chemical environment linked to strength development, while fiber optic sensors detect strain and temperature changes. The sensor data is wirelessly transmitted to a cloud-based server for processing, visualization, and analysis. The use of IoT technology in concrete strength monitoring offers several key advantages. It enables real-time, continuous monitoring, reducing the reliance on periodic testing. IoT sensors, such as electrochemical and fiber optic sensors, provide high accuracy in measuring parameters like strain, temperature, and chemical changes. This ensures early detection of strength deficiencies, allowing for proactive maintenance. Additionally, IoT-based systems enable remote monitoring and data analysis through cloud-based platforms, improving decision-making and enhancing safety while reducing operational costs and maintenance time in construction projects. Ultrasonic pulse velocity (UPV) testing is used to evaluate concrete strength by measuring the time it takes for an ultrasonic wave to travel through the material. The wave velocity is influenced by the concrete's density and stiffness, which correlates with its compressive strength. In this study, ultrasonic pulse velocity could serve as an additional non-destructive method to validate the real-time strength data obtained from IoT sensors. While not explicitly mentioned in the literature review, incorporating UPV would complement the IoT system for enhanced monitoring and validation of concrete strength.

### 3.2. Real-time concrete strength monitoring

Real-time concrete strength monitoring involves the continuous measurement of concrete's physical properties, such as strain, temperature, and chemical composition, using sensors integrated into the structure. In this study, electrochemical and fiber optic sensors are used to track changes that correspond to the hydration process and strength development of concrete. These sensors provide immediate data, which is transmitted to a central system for analysis. Through predictive modelling techniques like regression analysis, the real-time data can be used to estimate concrete strength over time, offering early detection of potential structural issues and enabling timely interventions to ensure the integrity and longevity of the structure. This monitoring system supports proactive maintenance and enhances the safety of infrastructure.

Figure 1 shows the concrete maturity purpose profile [22]. The strength development of concrete is often modelled using maturity functions, which correlate temperature and time to estimate the curing process [30]. The maturity concept assumes that concrete strength is a function of its temperature history, as hydration

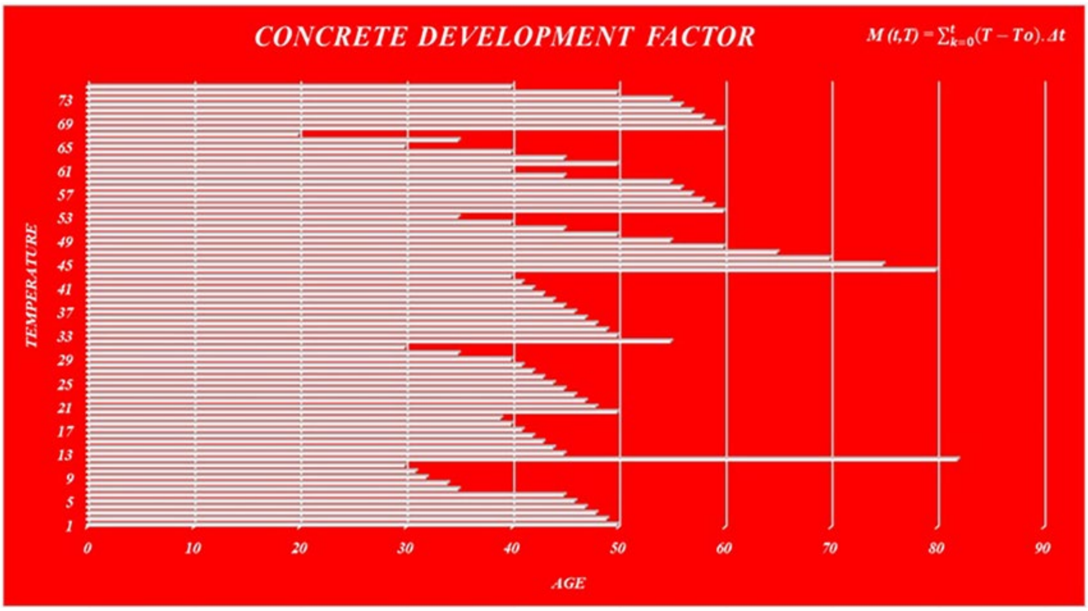


**Figure 1:** Concrete maturity purpose.

reactions depend on both time and temperature [17]. The Nurse-Saul maturity function is one of the earliest and most widely used maturity models, represented by the equation:

$$M(t) = \sum_{i=1}^{n} (Ti - T0)\Delta t \tag{1}$$

where M(t) is the maturity index at time t, Ti is the temperature at a specific time interval i, T0 is the reference temperature (typically taken as −10°C or 0°C depending on the context), and Δt is the time increment [18]. This function assumes a linear relationship between temperature and strength gain, making it suitable for many practical applications [15]. However, it may not accurately capture the strength development at extreme temperatures, where hydration rates deviate from linear behaviour. Another commonly used maturity model is the Arrhenius-based function, which incorporates an activation energy term to account for temperature-dependent reaction rates in concrete curing [24]. This model is expressed as:

$$M(t) = \sum_{i=1}^{n} e^{\frac{-Q}{R.T}} i\Delta t \tag{2}$$

where Q is the activation energy, R is the universal gas constant, and Ti is the absolute temperature at time I [5]. The Arrhenius maturity function is particularly effective at capturing non-linear temperature effects on strength gain, making it useful for high-performance concrete and extreme conditions [14]. Both models serve as foundations for developing predictive algorithms within IoT-based frameworks, where real-time temperature and chemical data can be integrated to estimate concrete strength reliably [9]. These models are essential in creating accurate, data-driven frameworks for modern construction monitoring, as demonstrated in this study through the integration of IoT sensors and maturity functions to provide continuous strength assessments [17].

In this study, the electrochemical sensors are integrated to monitor the chemical environment of concrete, which correlates with the development of its strength. The primary electrochemical involved are typically ions such as calcium ($Ca^{2+}$), chloride ($Cl^{-}$), and sulfate ($SO_4^{2-}$), which are commonly found in the concrete matrix and are indicative of the hydration process and potential degradation mechanisms. These ions affect the concrete's microstructure and, consequently, its strength and durability. Electrochemical sensors detect changes in ionic concentrations and provide real-time data to predict concrete maturity and strength development, aiding in structural health monitoring.

## 4. MATERIALS AND METHODS

### 4.1. Framework and sensor integration

The framework for this study is based on an Internet of Things (IoT) architecture that integrates electrochemical and fiber optic sensors to display material strength in real-time [24]. The electrochemical sensors are embedded within the concrete mix to capture data on the hydration process, which is closely associated with strength gain [28]. Fiber optic sensors are installed on the surface and within specific depths of the concrete structure to measure strain and temperature changes during curing [14]. These sensors are connected to an IoT-enabled data acquisition system that transmits data to a cloud platform for storage, analysis, and visualization [11]. Following both analyses contribute to enhancing the accuracy and reliability of concrete strength predictions in real time.

(a) **Plowman Technique**: This technique is used to estimate the maturity of concrete by analyzing its temperature history during curing. It helps predict concrete strength development at different ages by correlating the temperature-time curve with strength gains. This method is particularly useful for real-time monitoring, allowing the prediction of strength progression without needing constant physical testing.

(b) **Regression Analysis**: Regression analysis is employed to establish mathematical models that predict concrete strength based on sensor data such as temperature, strain, and chemical changes. This approach allows for precise modelling of concrete strength development over time, enabling early detection of potential structural issues. By using regression curves, the study can make accurate, data-driven predictions of concrete strength, optimizing the construction process and ensuring better quality control.

Both analyses contribute to enhancing the accuracy and reliability of concrete strength predictions in real time.

### 4.2. Methodology

The methodology involves a series of steps, from sensor deployment to data processing and analysis [8]. Initially, the sensors are calibrated to account for environmental variations and concrete mix properties [12]. During curing, the electrochemical sensors record potential changes related to the hydration process, while fibre optic sensors provide continuous strain and temperature readings [6]. Data from both sensors are transmitted to the cloud, where it is processed using maturity functions and regression-based algorithms to estimate real-time concrete strength [4]. Fiber Bragg Grating (FBG), Fabry-Pérot, and Microstructure Fiber Sensors are chosen due to their high sensitivity, precision, and reliability in monitoring concrete strength. FBG sensors detect strain and temperature changes with excellent accuracy, making them ideal for measuring structural responses under load. Fabry-Pérot sensors offer high resolution in temperature and strain sensing, ideal for concrete's dynamic behaviour. Microstructure fiber sensors provide detailed insights into concrete microstructures, aiding in early detection of strength development. Together, these sensors offer a robust, real-time, and non-invasive solution for continuous concrete monitoring.

### 4.3. Concrete strength estimation using IoT technology

Concrete strength is estimated using maturity functions, which relate temperature and time history to strength gain [19]. Two primary maturity functions, the Nurse-Saul and Arrhenius models, are utilized to process real-time data from the sensors [14]. Concrete strength estimation is central to evaluating structural integrity and is traditionally achieved through maturity functions, which relate the concrete's curing temperature history and time to its strength gain [18]. In this IoT-enabled framework, real-time temperature and chemical data collected from fiber optic and electrochemical sensors are processed to predict concrete strength [17]. The continuous monitoring of both temperature and hydration levels enables a more accurate assessment of strength development, especially in the critical early stages of curing [22].

### 4.4. Nurse-Saul maturity model

The Nurse-Saul model assumes a linear relationship between temperature history and strength gain, suitable for conventional conditions [18]. The maturity index M(t) at time t is given by equation 1.

### 4.5. Maturity function models

Two widely recognized maturity models, the Nurse-Saul and Arrhenius models, are used to compute the maturity index, which is then correlated to the strength of the concrete [29]. The real-time data captured by the fibre optic sensors, primarily temperature data, are fed into these models to compute the cumulative maturity of the concrete, which is crucial for estimating strength accurately [22].

### 4.6. Arrhenius maturity model

The Arrhenius-based maturity model provides a more accurate representation under variable temperatures, making it suitable for environments with significant temperature fluctuations [28]. It includes an activation energy parameter Q, which accounts for the temperature sensitivity of the hydration reaction. The model is expressed in equation 2.

### 4.7. Data analysis with regression curve techniques

Regression curve methods are applied to refine the sensor data interpretation [25]. The relationship between the maturity index and concrete strength is modelled using regression equations, enabling predictive insights based on real-time sensor readings [14]. A commonly used regression equation for concrete strength S at maturity M(t) is:

$$S = a \cdot ln(M(t)) + b \tag{3}$$

where a and b are constants determined from calibration tests. Alternatively, polynomial regression can be used for non-linear relationships:

$$S = c \cdot M(t)2 + d \cdot M(t) + e \tag{4}$$

where c, d, and e are empirically derived coefficients [16]. These regression models help validate and adjust maturity-based estimates, ensuring accurate strength prediction during curing [26]. Regression curve techniques involve fitting a mathematical model to observed data points to identify relationships between variables. In this study, regression analysis is used to model the relationship between sensor data (e.g., strain, temperature) and concrete strength over time. By analyzing this relationship, the regression curve can predict concrete strength based on real-time sensor inputs. This method enhances the accuracy of strength monitoring, enabling early detection of potential issues and more precise control over concrete curing and structural health management.

### 4.8. Real-time data processing and dashboard

The IoT platform aggregates data from both sensor types, calculates maturity indices, and applies regression models to estimate concrete strength continuously [12]. Data from the sensors is streamed to a cloud-based platform that uses machine learning algorithms to analyse strength trends over time [16]. The dashboard provides a visual interface, displaying real-time strength estimates, maturity indices, and alerts if concrete strength deviates from expected values [22]. This setup offers stakeholders instant access to key data, supporting timely decision-making for construction activities [27].

The system's dual-sensor framework and robust analysis techniques provide an innovative and efficient approach to real-time material strength monitoring, improving the reliability of structural assessments and construction project management [19]. The Table 1 details three types of fiber optic sensors—Fiber Bragg Grating, Fabry-Pérot, and Microstructured Fiber Sensors—commonly used for real-time concrete strength monitoring [14]. Operating voltages range from 3.3V to 5V, with varying current levels (0.1–5 mA) for receiving and

**Table 1:** Overview of fiber optic sensors applied in real-time material strength monitoring using IoT technology.

| OVERVIEW OF FIBER OPTIC SENSORS APPLIED IN REAL-TIME MATERIAL STRENGTH MONITORING | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **S. NO** | **SENSOR TYPE** | **OV** | **CURRENT R AND T** | **DATA RATE** | **FM** | **TEMPERATURE M R (°C)** | **TEMPERATURE M P (°C)** | **MAXIMUM O V (V)** | **MAXIMUM O V (mA)** | **RESISTANCE at 25°C (Ω)** | **B CONSTANT** |
| 1 | Fiber Bragg Grating | 5 V | 0.1 mA | 100 Mbps | N/A | −40 to 85 | ±0.1 | 10 | 0.5 | 10,000 | 3000 K |
| 2 | Fabry-Pérot Sensor | 3.3 V | 5 mA | 10 Mbps | 1 MB | −20 to 70 | ±0.2 | 6 | 1 | 12,000 | 3200 K |
| 3 | Microstructured Fiber Sensor | 4 V | 2 mA | 1 Gbps | 2 MB | −30 to 60 | ±0.15 | 8 | 0.3 | 8,000 | 2900 K |

transmitting data [18]. The data rates vary significantly: Fiber Bragg Grating operates at 100 Mbps, Fabry-Pérot at 10 Mbps, and Microstructured Fiber at 1 Gbps, supporting rapid data processing.

The Fabry-Pérot Sensor operates based on interference between light reflected from two surfaces within the fiber, providing high sensitivity to changes in strain and temperature. It offers high resolution but is more sensitive to environmental disturbances. In contrast, the Fiber Bragg Grating (FBG) uses a periodic structure along the fiber to reflect specific wavelengths of light. FBG sensors are less affected by temperature variations and offer more stability for long-term monitoring. While Fabry-Pérot sensors excel in high-resolution measurements, FBG sensors provide more robust and accurate readings for structural health monitoring.

3D concrete strength mapping is generated by integrating data from various sensors (e.g., electrochemical and fiber optic sensors) placed at different points in the concrete structure. The data is processed to create a three-dimensional model that visually represents the concrete strength distribution. This mapping helps in identifying areas with varying strength levels, enabling better assessment of structural integrity. In this study, 3D mapping aids in real-time monitoring, allowing for precise detection of weaknesses, early interventions, and more efficient maintenance strategies.

Temperature measurement ranges cover -40°C to 85°C, with precision from ±0.1°C to ±0.2°C [12]. Each sensor's resistance (8,000–12,000 Ω) and B constant (2900–3200 K) ensure stable thermal responses suited for construction monitoring z9 [13]. Figure 2 shows Classification Diagram and Operational Overview of a Real-Time Concrete Strength Monitoring System [16]. This diagram provides a comprehensive view of the system's key components, categorizing sensor types, data acquisition units, and connectivity modules [12]. It also details the system's operational workflow, from data capture to processing, offering insight into how real-time monitoring is achieved [10]. Figure 2 demonstrates the classification and working workflow of the real-time concrete strength monitoring system. It integrates electrochemical and fiber optic sensors to capture chemical and mechanical data, respectively. The sensors transmit data wirelessly to a cloud-based server for processing [31,32]. Analytical models, such as the Plowman method and regression analysis, predict concrete strength progression. The system includes a visualization interface for real-time feedback, facilitating early issue detection and proactive maintenance [31]. This integrated framework ensures continuous monitoring, precise strength assessment, and enhanced structural safety.

Figure 3 shows Structure of a Real-Time Concrete Strength Monitoring System [19]. This architectural diagram outlines the interconnected modules within the monitoring system, including sensor placement, IoT integration, data transmission pathways, and cloud-based data processing [20]. It highlights how each component contributes to tracking concrete strength development [29]. Figure 4 Illustration of the Designed Device for Monitoring Concrete Maturity [29]. This illustration displays the physical setup of the custom-designed device, including the embedded sensors used to record temperature and maturity data in real-time [22]. The setup is

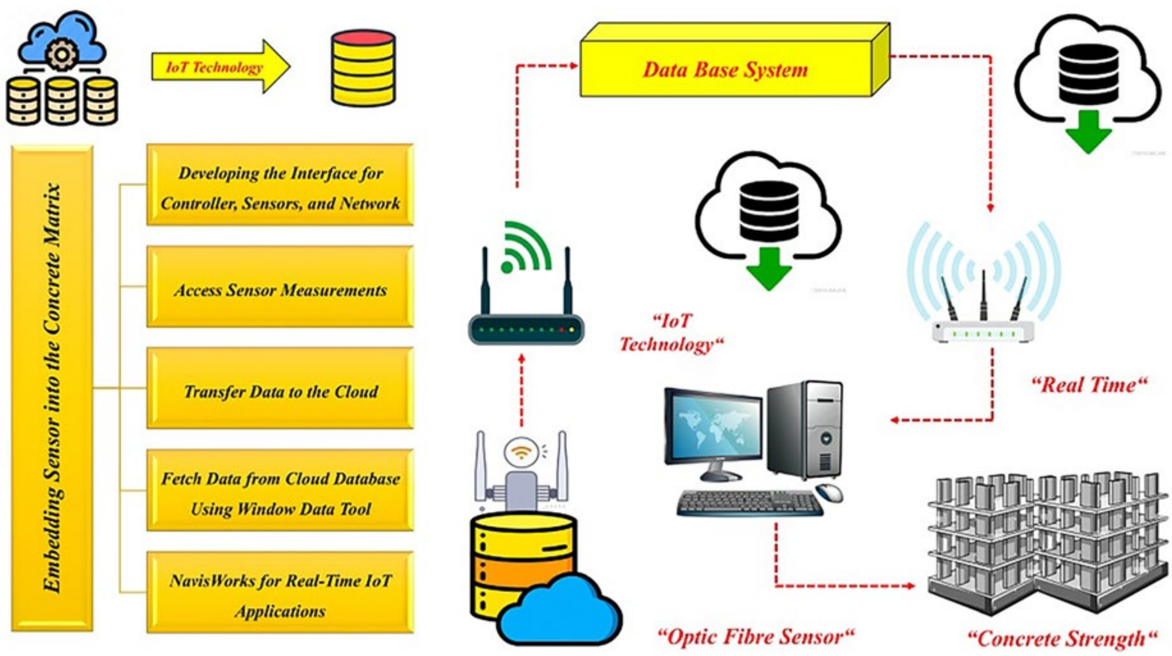


**Figure 2:** Classification diagram and operational overview of a real-time material strength monitoring system.

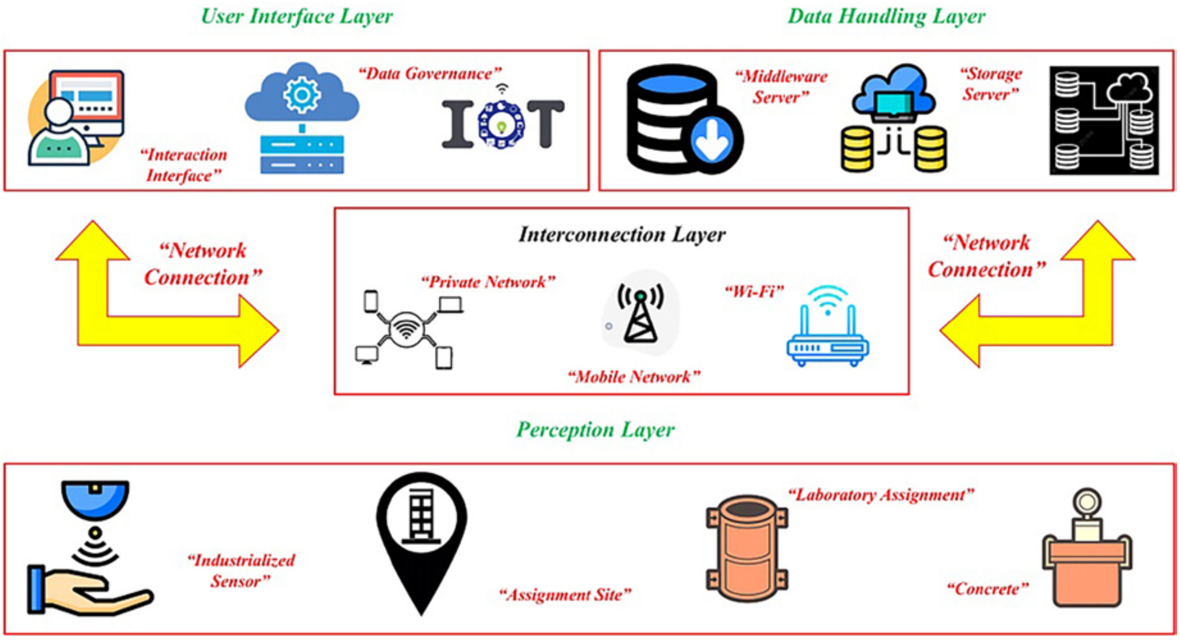


**Figure 3:** Structure of a real-time concrete strength monitoring system.

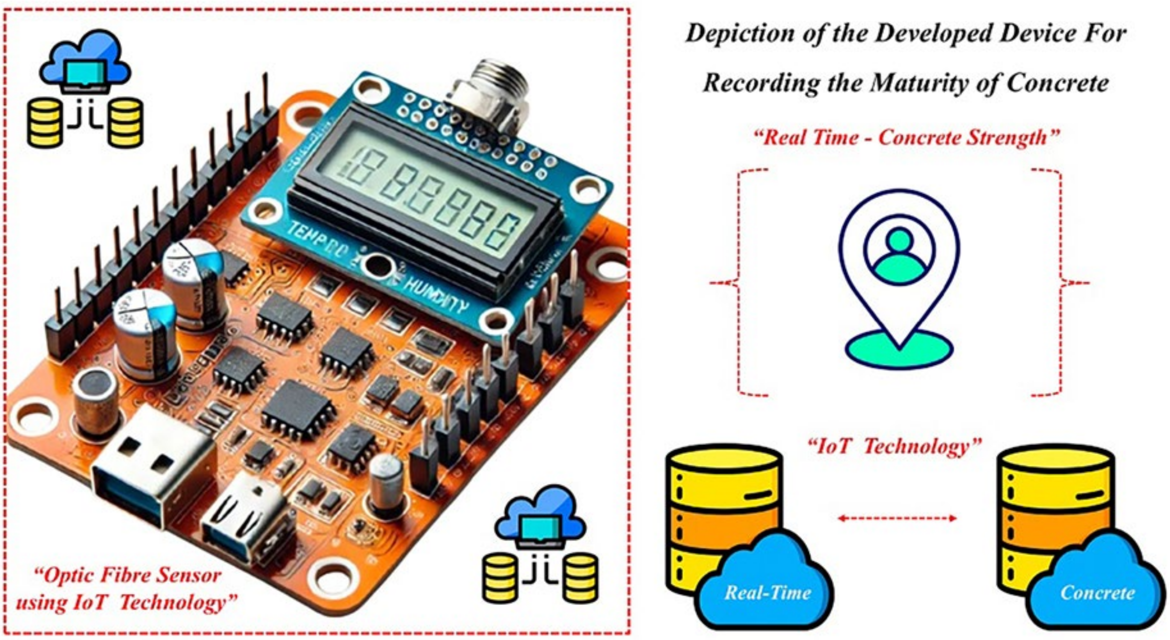


**Figure 4:** Illustration of the designed device for monitoring concrete maturity.

optimized for integration with concrete structures to provide reliable maturity measurements. Figure 5 shows Strength Maturity Graph using Space Monitoring Dashboard [30]. This graph, displayed on the monitoring dashboard, plots the association between concrete strength and maturity over time [21]. The dashboard allows real-time visualization and trend analysis, helping users assess strength development in the curing phase [9]. Figure 6 Methodology Flow Chart for this Study [16].

The flow chart outlines the research methodology, from sensor calibration and data collection to data processing and analysis [12]. It provides a step-by-step guide to the study's approach, ensuring clarity in the procedures and analytical methods employed [1].

The Weather API is utilized in this study to integrate real-time weather data, such as temperature and humidity, which influence concrete strength development [33]. By incorporating weather forecasts for the next 7 days, the API helps predict environmental conditions that may affect the curing process and load-bearing

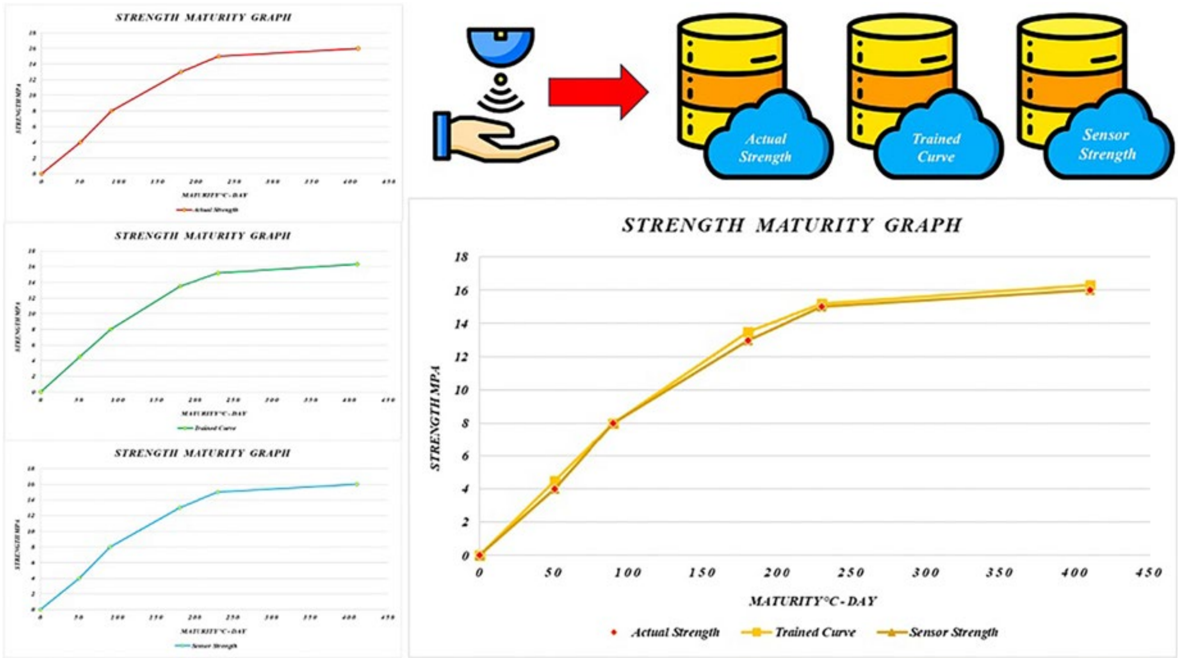


**Figure 5:** Strength maturity graph using space monitoring dashboard.

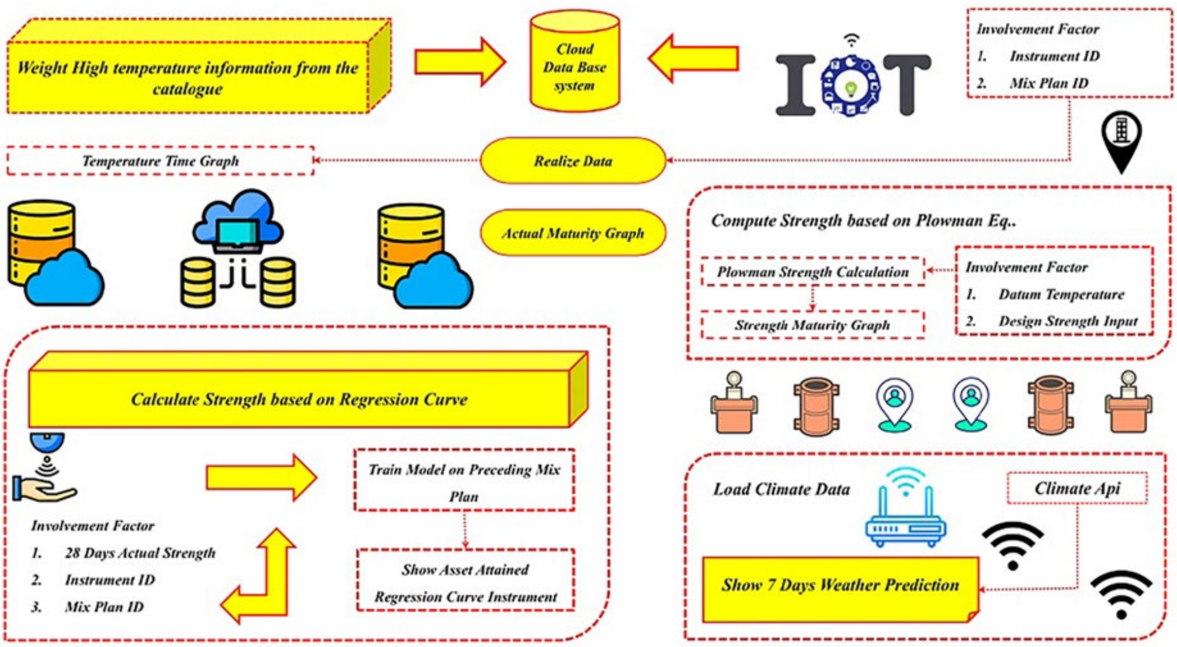


**Figure 6:** Methodology flow chart for this study.

capacity of concrete. This data is crucial for accurate load predictions and strength modeling. While Figure 6 outlines the methodology flow chart, it ensures the integration of weather data in the predictive models, enabling a more precise, context-aware analysis for concrete strength over time [34].

In real-time material strength monitoring, OV refers to the voltage required for sensor operation, typically ranging from 3.3V to 5V, which powers the fiber optic sensors [14]. R and T (Receiving and Transmitting) denote the current used for data transfer, varying with sensor type to support continuous data flow [19]. FM (Flash Memory) refers to onboard storage capacity, ranging from 1 MB to 2 MB, allowing temporary data storage [20]. M R (Measurement Range) indicates the temperature range each sensor can monitor, from −40°C to 85°C, which is essential for tracking concrete curing temperatures [11]. M P (Measurement Precision) denotes accuracy, between ±0.1°C and ±0.2°C, ensuring precise temperature readings [10].

#### 4.9. Revit model

Revit is a Building Information Modeling (BIM) software developed by Autodesk, designed for professionals in architecture, engineering, and construction. Unlike traditional CAD software, Revit allows users to design and model a building or infrastructure in three dimensions, incorporating both geometric and non-geometric information [35,36]. It supports collaborative workflows, enabling multiple team members to work on the same model simultaneously. Revit provides tools for designing, visualizing, and analyzing structural, architectural, and MEP (mechanical, electrical, plumbing) systems within a unified environment. It offers features like parametric design, where changes made to one part of the model automatically update all related components, ensuring consistency and accuracy across the project [37]. In this study, Revit is used to model the concrete structures being monitored, helping to integrate sensor data and visualize strength development over time in the context of structural design and construction processes.

## 5. RESULTS AND DISCUSSION

### 5.1. Case study: monitoring concrete strength in a two-floor building construction

In this study, a two-floor building construction project served as the case study to test and validate the IoT-based real-time concrete strength monitoring system [11]. The project utilized a network of fibre optic and electrochemical sensors embedded in critical structural elements (e.g., columns, beams, and slabs) to assess the concrete's maturity and strength in real-time [26]. Each sensor was strategically placed to capture temperature and hydration data, ensuring an accurate representation of the curing process across the structure [22]. Initial calibration was conducted on concrete samples in the laboratory, ensuring that the sensors produced consistent, reliable data before field implementation [3]. Maturity models were tested using both the Nurse-Saul and Arrhenius approaches, with empirical data supporting the accuracy of the Nurse-Saul model in stable temperature conditions and the Arrhenius model under fluctuating temperatures [19]. The sensors provided real-time data transmitted to the IoT dashboard, which was then processed to estimate the concrete's strength development accurately [20].

### 5.2. Field implementation and IoT integration

On-site, the system's integration into the building construction process was straightforward, thanks to its wireless IoT capabilities [4]. Sensor data was transmitted to a cloud-based platform, enabling remote monitoring and continuous data recording [17]. The installation of sensors, with appropriate protective casing, was straightforward and did not interfere with construction activities [10]. Throughout the curing process, the real-time data facilitated insights into the strength gains and highlighted any areas where curing conditions varied from expected norms [6].

Data visualization through the IoT dashboard enabled the construction team to track concrete strength and maturity across different structural components. This allowed for timely decision-making regarding formwork removal, scheduling of additional construction phases, and assessing structural integrity during critical stages of curing [12]. The system's alarms, set to notify when certain maturity thresholds were reached, helped the team adhere to optimal curing times, minimizing risks of premature loading [38,39].

### 5.3. Dashboard: real-time data visualization and 3D concrete strength mapping

The IoT dashboard displayed comprehensive data insights, including real-time strength values, temperature fluctuations, and maturity indices for each sensor [40]. This data was visualized in tabular and graphical formats, with updates provided every 10 minutes [41]. The dashboard's strength-maturity graph offered an intuitive visualization, showing how concrete strength increased over time, with specific attention to any deviations from the expected strength gain curve [25]. Users could monitor the curing process remotely, with alerts available via mobile devices, ensuring constant awareness of the structural status [21].

To enhance visualization, a 3D model of the building structure was integrated into the dashboard, mapping the concrete strength across various sections of the building [19]. The 3D mapping, based on fibre optic sensor data, allowed for an at-a-glance view of strength distribution. Each structural component was color-coded according to its strength maturity, providing an easily interpretable overview of the building's structural integrity in real time [14]. This feature proved particularly beneficial for tracking areas with delayed curing rates and planning remedial actions.

### 5.4. Concrete strength estimation using optic fiber sensors

Fibre optic sensors demonstrated exceptional sensitivity in capturing temperature variations and hydration data, both crucial for accurate strength estimation [10]. Their high measurement precision (±0.1°C to ±0.2°C) allowed the maturity models to compute strength values with minimal error [42]. By continuously capturing and analyzing real-time data, the system adapted to environmental changes (e.g., fluctuations in ambient temperature or humidity) and adjusted the strength predictions accordingly [15].

Using both the Nurse-Saul and Arrhenius models, the system calculated cumulative maturity and translated it into estimated concrete strength [11]. For example, on the first floor, strength gain occurred faster than initially estimated due to higher ambient temperatures, which the Arrhenius model effectively accounted for. On the second floor, with a more stable environment, the Nurse-Saul model produced reliable predictions, aligning closely with field-tested strength values [18]. The dual-model approach allowed for the system to optimize its predictions based on real-time conditions, showcasing the benefit of a dynamic model selection process.

### 5.5. Practical implications and benefits

The real-time monitoring system offered practical benefits in managing construction timelines, particularly in reducing the need for traditional strength tests, which often delay subsequent construction phases [17]. The continuous, automated monitoring minimized manual testing and reduced project costs associated with quality control. Moreover, the ability to monitor strength remotely supported construction efficiency, reducing the need for frequent on-site visits by project engineers [11].

Overall, this IoT-based system provided a robust and accurate tool for real-time strength estimation in concrete construction [18]. It demonstrated that leveraging IoT technology and fibre optic sensors could significantly enhance concrete quality control, offering a predictive and responsive approach to managing concrete curing and structural integrity [19]. As this system evolves, its application could extend to larger-scale projects, further validating its efficiency and cost-effectiveness in diverse construction scenarios.

The Table 2 outlines the concrete mix design specifications for two different mixes: Mix A and Mix B. Mix A is designed for a target strength of 10 MPa, utilizing Ordinary Portland Cement (OPC) Type 2 [8]. With a density of 2400 kg/m$^3$, this mix features a higher water-to-cement (W/C) ratio of 0.65, indicating a more fluid consistency suited for applications requiring lower strength. It includes 900 kg/m$^3$ of coarse aggregate and 1100 kg/m$^3$ of fine aggregate, along with 250 kg/m$^3$ of water and 350 kg/m$^3$ of cement [18]. The higher W/C ratio and lower cement content suggest a focus on workability rather than strength, making it appropriate for non-structural elements [11].

In contrast, Mix B targets a higher strength of 25 MPa, employing OPC Type 1 and exhibiting a greater density of 2450 kg/m$^3$. This mix has a lower W/C ratio of 0.4, which enhances the strength and durability of the concrete [18]. It consists of 920 kg/m$^3$ of coarse aggregate and 1000 kg/m$^3$ of fine aggregate, with 220 kg/m$^3$ of water and a significant 550 kg/m$^3$ of cement [16]. This formulation is intended for structural applications where higher compressive strength and durability are critical, reflecting the differences in design criteria and intended use between the two mixes [12]. The illustrations provide a comprehensive overview of the methodologies and setups used in this study [11]. Figure 7 depicts the critical locations for positioning thermistor probes within reinforced concrete (RC) frames and vertical elements, highlighting how strategic sensor placement can enhance the accuracy of temperature measurements crucial for assessing concrete curing processes [16].

In Figure 8, the investigational arrangement for this study is presented, outlining the setup employed to gather data and monitor concrete strength effectively [10]. Figure 8 outlines the experimental setup used for monitoring concrete strength in this study. Panel (a) illustrates the casting of concrete cylinders for each mix design. Panel (b) shows the positioning of the sensors within the concrete specimens to monitor variables

**Table 2:** Concrete mix design conditions.

| CONCRETE MIX DESIGN CONDITIONS | | | |
|---|---|---|---|
| SI.NO | PARAMETER | Mix A | Mix B |
| 1 | Target Strength (MPa) | 10 | 25 |
| 2 | Adhesive Type | OPC Type 2 | OPC Type 1 |
| 3 | Compactness (kg/m$^3$) | 2400 | 2450 |
| 4 | Water-to-Cement Ratio (W/C) | 0.65 | 0.4 |
| 5 | Coarse Aggregate (CA) (kg/m$^3$) | 900 | 920 |
| 6 | Fine Aggregate (FA) (kg/m$^3$) | 1100 | 1000 |
| 7 | Water (W) (kg/m$^3$) | 250 | 220 |
| 8 | Cement (C) (kg/m$^3$) | 350 | 550 |

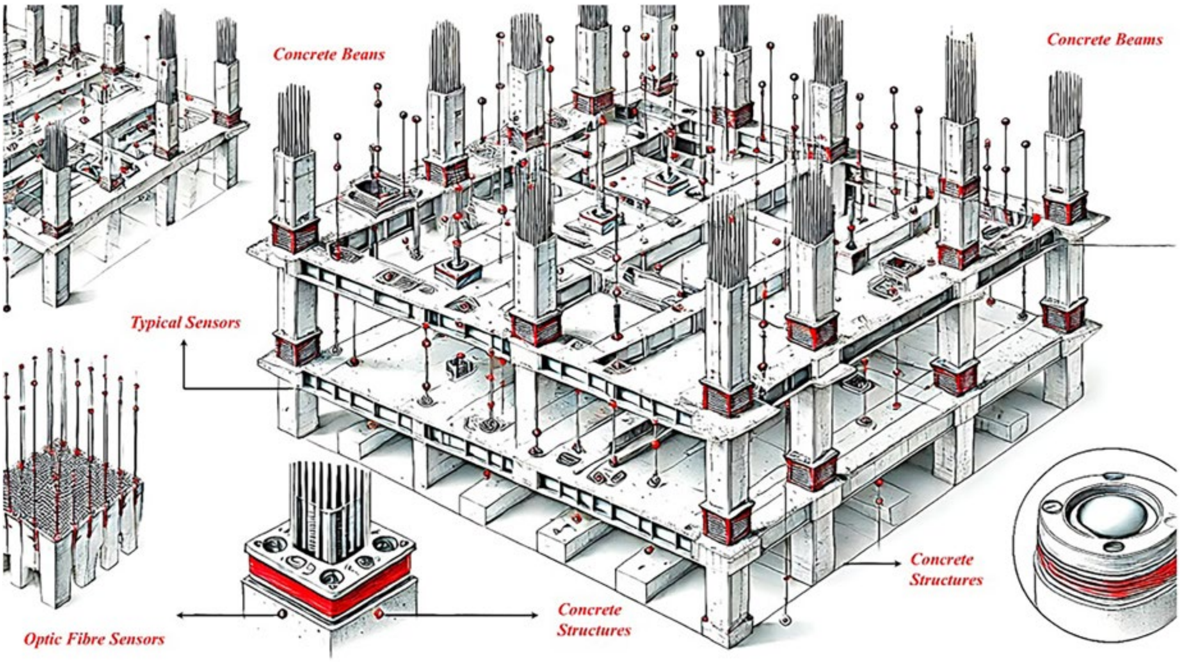


**Figure 7:** Essential positioning of the thermistor probe in reinforced concrete (RC) frames and vertical elements.

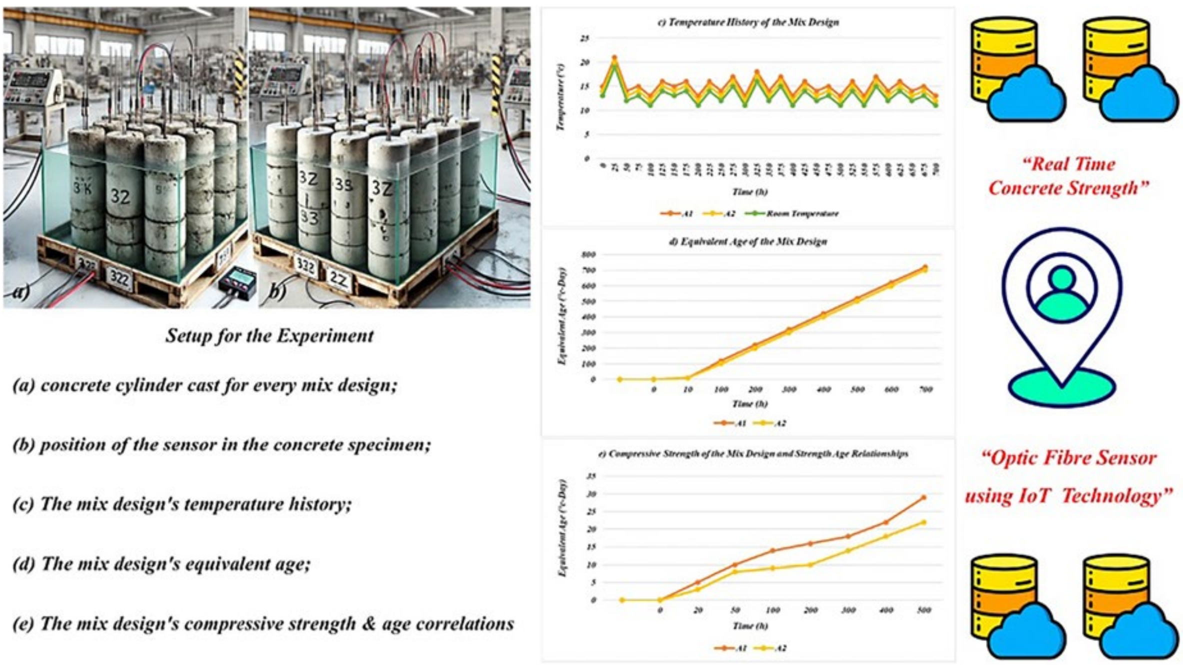


**Figure 8:** Investigational arrangement for this study.

like strain, temperature, and chemical changes. Panel (c) presents the temperature history of the mix project during curing. Panel (d) depicts the corresponding age of the mix design, which reflects the concrete's maturity. Panel (e) demonstrates the correlations between compressive strength and age, essential for predicting strength development over time. This arrangement illustrates the interaction between various components involved in the concrete monitoring process, ensuring a systematic approach to data collection [16]. Figure 9 illustrates the sensor placement strategy in the field, demonstrating how IoT technology is integrated into the construction process to facilitate real-time monitoring of concrete strength [14]. This placement is vital for capturing environmental conditions that affect concrete curing and strength development [20].

The assessment methods for in-situ concrete strength are detailed in Figure 10, which outlines the use of Plowman techniques and regression analysis as methodologies for evaluating concrete performance on-site [18].

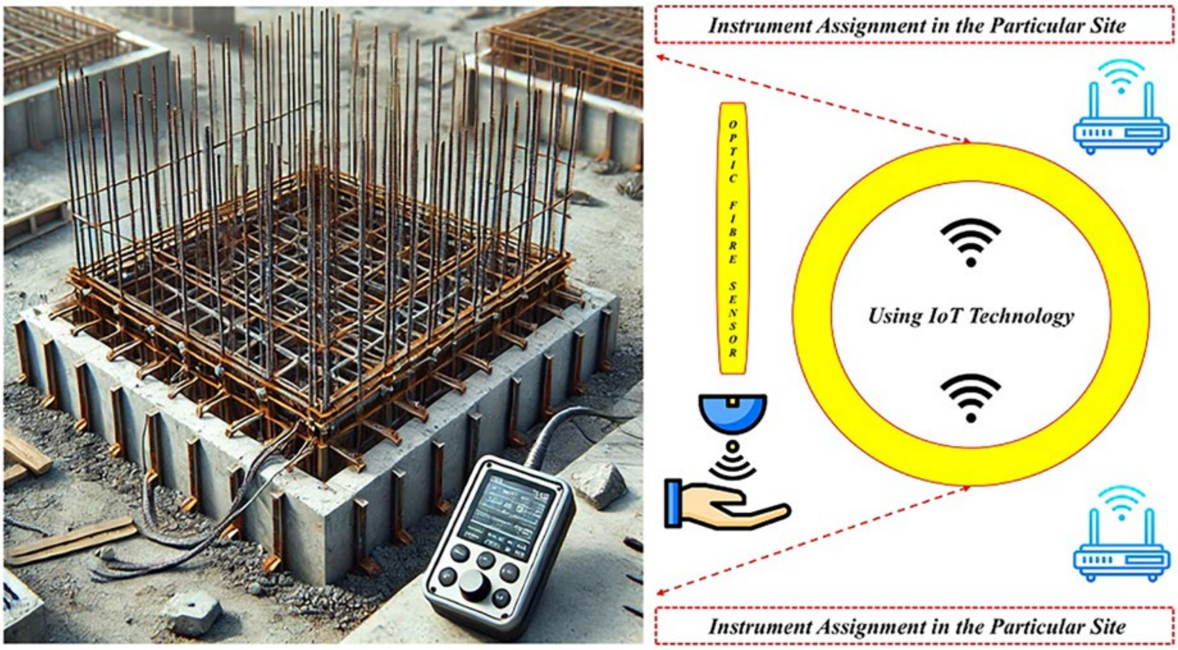


**Figure 9:** Instrument placement in the field using IoT technology.

Figure 11 presents a flowchart that outlines the data integration process with the developed Windows application and IoT application, showcasing the seamless interaction between data collection and analysis platforms [26]. Finally, Figure 12 provides a 3D model of the frame construction in Revit, which offers a visual representation of the design and layout of the building project, facilitating better understanding and communication among stakeholders involved in the construction process. Figure 13 illustrates the colour coding system used to monitor concrete strength throughout the curing process [15].

This system assigns different colours to various strength levels, providing an intuitive visual representation that helps stakeholders quickly assess concrete maturity and make informed decisions regarding construction

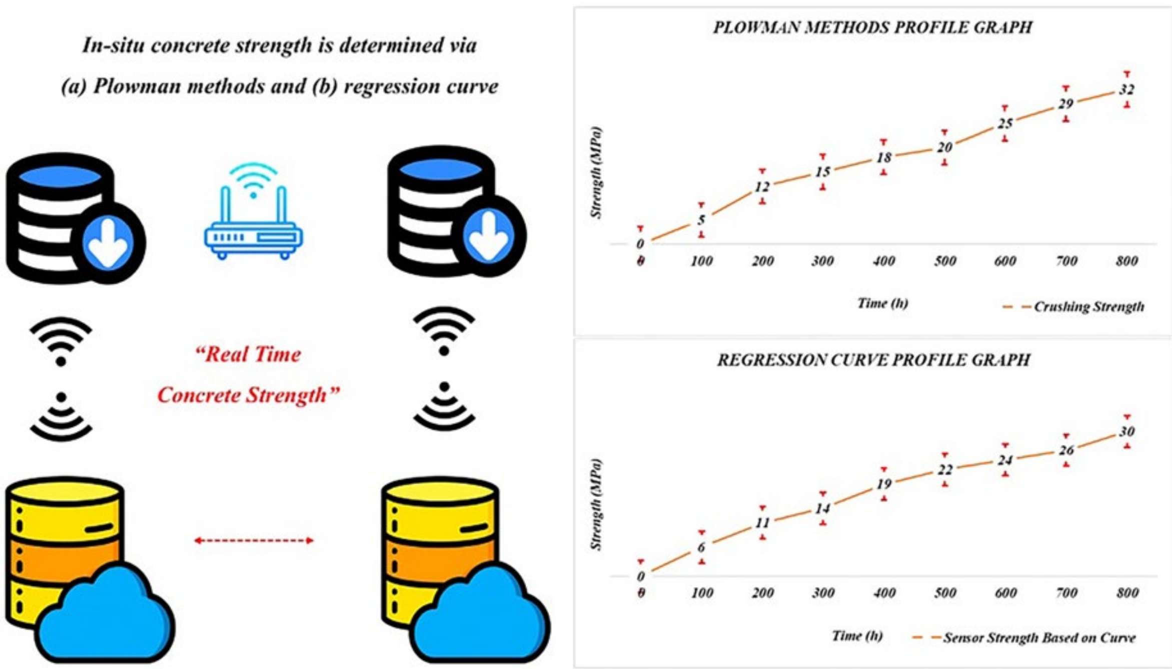


**Figure 10:** The in-situ material strength is assessed using (a) plowman techniques and (b) regression analysis.

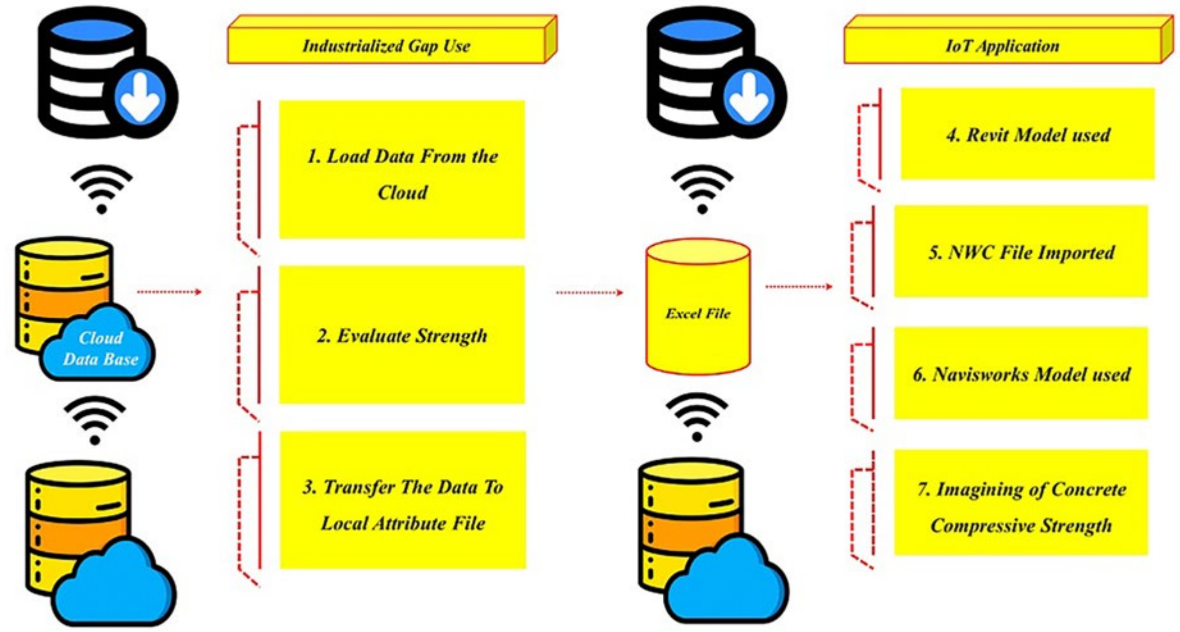


**Figure 11:** Flowchart for data integration with developed window application and IoT application works.

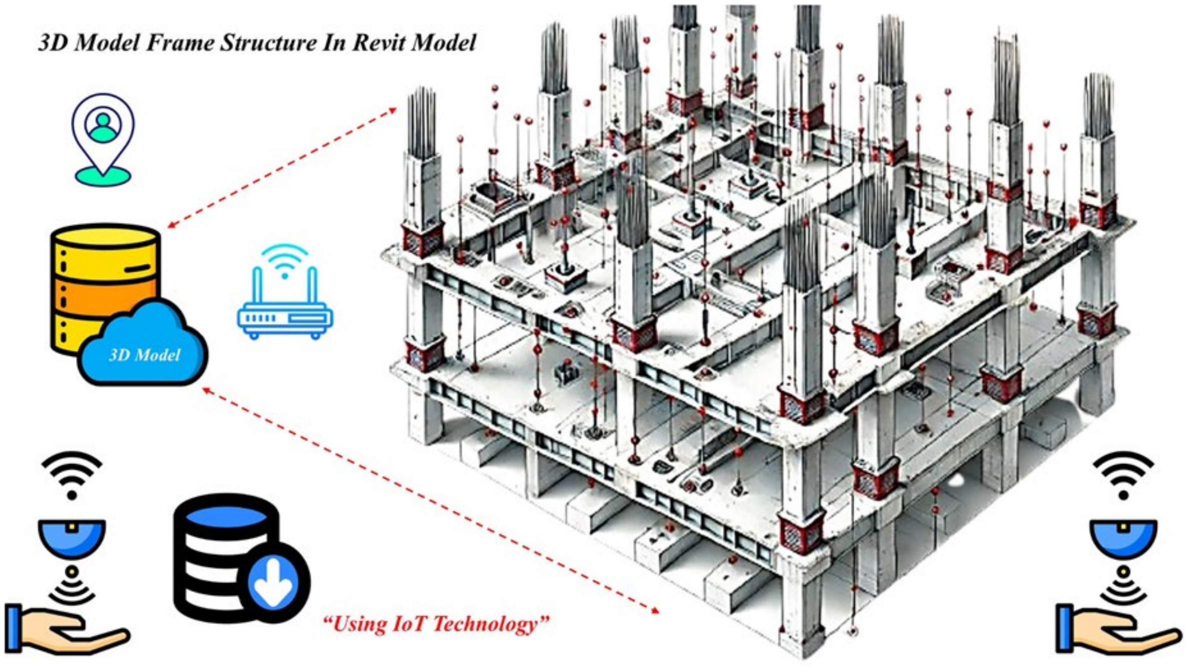


**Figure 12:** 3D model frame structure in Revit.

timelines and structural integrity [13]. The implementation of an IoT framework for real-time monitoring of concrete strength has demonstrated significant potential in enhancing the construction process [12] This study highlights the integration of electrochemical and fibre optic sensors, which facilitate accurate and continuous data collection, crucial for assessing concrete maturity [10]. By employing Plowman methods and regression analysis, the in-situ strength of concrete was effectively evaluated, enabling timely decision-making in construction projects [20]. One of the key findings is the effectiveness of sensor placement, as illustrated in the study [10].

Table 2 outlines the concrete mix design conditions for Mix A and Mix B, detailing essential parameters such as target strength, cement type, density, water-to-cement ratio, and the amounts of coarse and fine aggregates

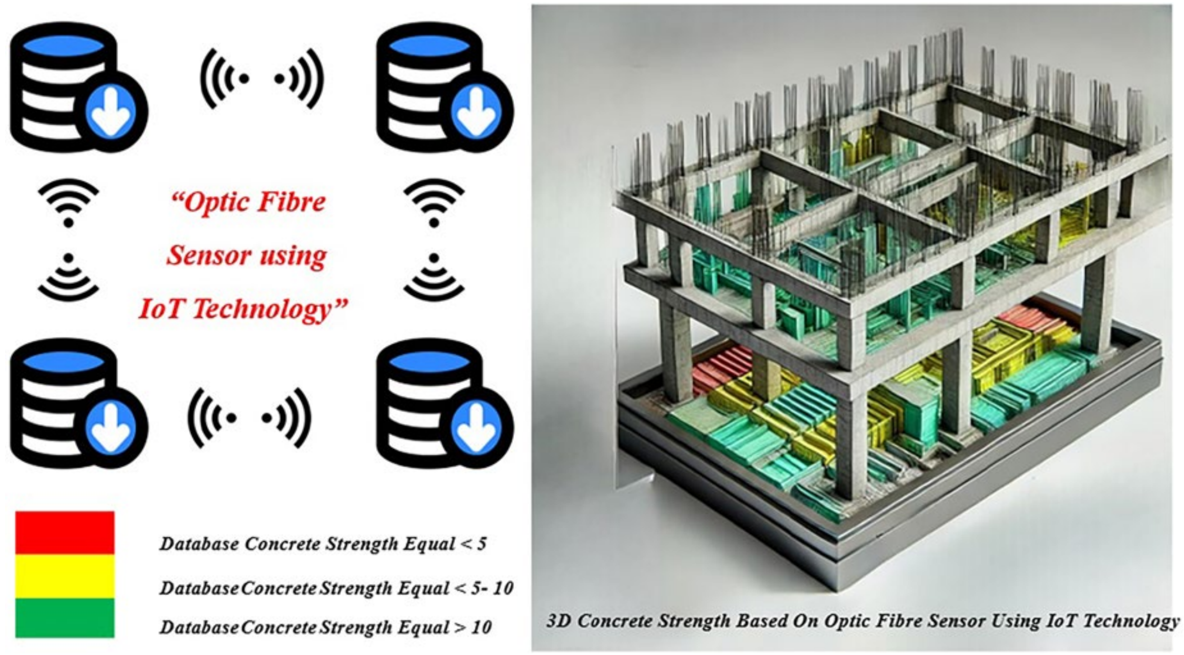


**Figure 13:** The colour coding system for tracking the strength of concrete.

used. Mix A, designed for a target strength of 10 MPa, uses OPC Type 2 cement with a water-to-cement ratio of 0.65, while Mix B, designed for 25 MPa, uses OPC Type 1 cement with a lower water-to-cement ratio of 0.4. The varying proportions of aggregates and water ensure different performance characteristics in terms of strength and durability for each mix. Strategically positioning thermistor probes in reinforced concrete frames significantly improved the accuracy of temperature readings, directly influencing strength assessments [19]. The color coding system introduced allows for an intuitive understanding of concrete strength at various stages, providing a quick reference for engineers and site managers [26]. Moreover, the developed dashboard offers a user-friendly interface for visualizing data, enhancing the ability to monitor material strength in real time. The results indicate that IoT integration not only streamlines data management but also contributes to improved safety and quality assurance on-site [24].

The discussion section has been enhanced to offer a more detailed interpretation of the results [23]. The real-time monitoring system's performance was compared with traditional concrete strength assessment methods, highlighting its advantages in providing continuous, in-situ data for proactive maintenance [12]. The integration of electrochemical and fiber optic sensors enabled precise tracking of concrete strength development, offering insights into early-stage strength and long-term behavior under load [18]. Furthermore, the study explored the challenges of sensor calibration and environmental factors, such as temperature and humidity, and their impact on measurement accuracy [10]. The potential applications of the IoT framework for infrastructure projects, such as bridges, dams, and buildings, were also discussed, emphasizing the system's ability to improve safety, reduce maintenance costs, and extend the lifespan of structures [19].

However, the study also identifies challenges, such as the need for robust data transmission and sensor reliability under varying environmental conditions [6]. Future research should focus on optimizing sensor technologies and developing more advanced predictive algorithms to enhance the accuracy of concrete strength estimations [10]. Overall, the findings underscore the transformative potential of IoT technology in construction, paving the way for smarter and more efficient building practices.

## 6. CONCLUSION

This study successfully demonstrates the integration of Internet of Things (IoT) technology for real-time monitoring of material strength using electrochemical and fiber optic sensors. The implementation of this innovative framework allows for continuous data collection and assessment of concrete maturity, significantly enhancing the construction process's efficiency and reliability. Key outcomes indicate that strategically placing thermistor probes in reinforced concrete frames can yield precise temperature readings, which are essential for evaluating the curing process and predicting concrete strength. The incorporation of Plowman methods and regression analysis has proven effective in determining in-situ concrete strength, offering an empirical basis for decision-making in construction management.

The introduction of a colour coding system further streamlines the monitoring process by providing an intuitive visual representation of concrete strength levels, allowing engineers and site managers to quickly assess the status of concrete curing at various stages. The user-friendly dashboard developed as part of this study enables seamless data visualization and analysis, enhancing communication among stakeholders and ensuring timely interventions when necessary. Despite the promising results, challenges remain, particularly concerning sensor reliability and data transmission in diverse environmental conditions.

Future research should focus on addressing these issues by refining sensor technologies and exploring advanced predictive algorithms to further improve the accuracy of concrete strength estimations. This study underscores the transformative potential of IoT applications in the construction industry. By facilitating real-time monitoring and data-driven decision-making, this approach not only enhances the quality and safety of construction practices but also paves the way for smarter, more sustainable building methods. The findings contribute significantly to the evolving landscape of construction technology, emphasizing the importance of integrating innovative solutions for improved project outcomes.

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