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IoT Based Real Time Early Age Concrete Compressive Strength Monitoring

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ABSTRACT. *Concrete Strength determination has been an expensive and hectic job due to its orthodox methodology of measuring concrete strength where cylinders are filled with concrete. Its strength is measured using the crushing of concrete (Compression Test). A significant amount of waste is generated while performing this test multiple times during the execution of the project. The present study proposes a new IoT-based framework comprising a low-cost sensor and a window dashboard to estimate and monitor the real-time early-age concrete strength. This system will significantly help the construction industry to avoid the onsite laboratory testing of concrete for strength. In this study, a temperature sensor, along with an ESP32 microprocessor is used to acquire and transmit the recorded temperature in real-time to a cloud database. The window application developed load data from the cloud database and presented it as figures and graphs related to concrete strength with time. The strength calculated using the developed sensor was compared with the actual strength determined using a compression test for the same mix design, which showed a significant match. The project is a contribution toward the non-destructive testing of concrete. By knowing the concrete strength of any structural member in advance, the practitioners can make decisions well before time to avoid delays in the project.*

Keywords: Concrete Maturity; Internet-of-Things; Nondestructive Testing; Real Time Concrete Strength; Structural Health Monitoring (SHM)

1. INTRODUCTION

In concrete buildings, early age strength prediction is crucial. It assists in expediting the construction process by calculating the best time to carry out any construction activity and determining the safest time for form stripping and post-tensioning of prestressed concrete. Using the maturity method in IoT embedded framework, the in-place concrete strength can be determined during the construction process in real-time. The technique offers a comparatively straightforward way of considering the temperature-time history of the concrete since its fresh state. The process can be traced back to the research done on the steam curing of concrete in the late 1940s and early 1950s by various researchers [1].

The concrete maturity method has been adopted by several standards and construction regulations worldwide as a non-destructive testing technique for evaluating onsite concrete strength. Following the ASTM C1074 standard, the designed framework continuously monitors the temperature of concrete after pouring and placing, followed by an assessment of the concrete's strength using a calibration curve that has already been established in the laboratory. The effective adoption of this approach in construction projects may significantly enhance speed and efficiency, avoiding project completion time delays [2].

2. BACKGROUND AND OBJECTIVES OF THE RESEARCH

2.1. Background

The hydration process of Portland cement increases the strength of concrete. The degree of strength build-up can depend on many factors, including curing temperature, curing age, type of material used to make concrete, type of cement, water-to-cement ratio, etc. Generally, the degree of early strength of concrete, hardened at high temperatures, is relatively high. In the first decades of the 19th century, attempts were made to measure the combined effects of time and temperature on the strength development behavior of concrete [3]. In the 1950s, various researchers proposed combining the effects of time and temperature in one factor [3]–[5]. Saul first called this feature maturity [5]. Maturity is measured as a time and temperature component of the data resulting from concrete pouring. The maturity principle states that a concrete sample of a particular mix design would show comparable strength characteristics at the same maturity level, regardless of its thermal conditions. This means that there is a unique relationship between hardness and the aging ability for any combination of time and temperature.

2.2. Objectives

- To develop an economical sensor with significant accuracy that would measure concrete temperature in real-time.
- To monitor concrete strength using IoT framework.

2.3. Concrete's Maturity Concept

The "maturity concept" of concrete refers to the technique of determining the strength of concrete by measuring its maturity index, or in other words, the degree to which it has hardened. The concept relies on the fact that concrete strength increases as the cement hydrates and the concrete matures. By measuring the maturity of the concrete, it is possible to estimate its strength at any point in time, even before traditional strength testing methods can be used. Concrete maturity is typically measured by determining the "maturity index," which is a function of the cement content, the temperature, and the time of curing. Since the early 1950s, various models have been developed to estimate concrete maturity. One of the most widely adopted maturity index equations proposed by Saul [5] is:

$$M\,(t, T) \;=\; \sum_{k=0}^{t} (T - T_0).\,\Delta t \qquad (1)$$

Where M (t, T) denotes the maturity index of concrete, T is the measured temperature at Δt interval, and T_0 represents the datum temperature of concrete's mix design. The temperature at which the strength ceases and no change occurs with time is referred to as datum temperature. As per the ASTM standards, the datum temperature was 0°C for OPC [6].

2.4. Strength Maturity Model

The strength maturity model is utilized to estimate the strength of concrete based on the maturity index. The equation is typically determined by calibrating the crushing strength with the maturity index for a particular mix design through curves. Plowman attempted to draw a connection between the strength of concrete and maturity [7]. The model expresses the real-time compressive strength as a linear function of the logarithmic maturity index as proposed by Nurse-Saul's model:

$$S \;=\; a + b\ \log(M) \qquad (2)$$

Where S is the concrete compressive strength, M is the maturity index, and a and b are constants. The constants a and b depend on the type and grade of cement, water-to-cement ratio, and other parameters of mix design adopted in the mix design. These constants can be estimated when the strength maturity curve is calibrated experimentally. Once determined, these constants can be utilized whenever the mix design is used in construction. The equations (1) and (2) were programmed in the window application of our IoT framework to calculate the concrete maturity index and compressive strength.

2.5. IoT in Structural Health Monitoring

The Internet of Things (IoT) is an innovative wireless approach currently being implemented across various business sectors. The Internet of Things is helpful in many aspects of civil engineering. Structural health monitoring is one of the most beneficial applications that can be achieved.

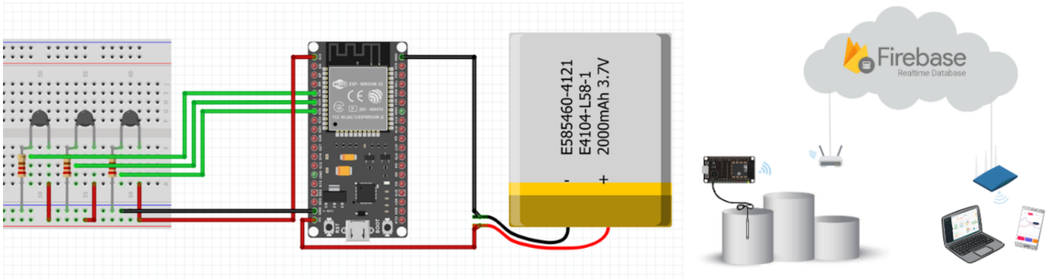
SHM makes it easier to anticipate accidents and calculate a building's expected lifespan. Sensing data is the basis of any SHM, yet keeping track of it at all hours can be difficult. The Internet of Things (IoT) has allowed SHM to be connected to the web so that information may be monitored from anywhere at any time [8].

However, Civil Engineering is no longer in its infancy when implementing embedded sensors into civil infrastructures. Several examples of integrated physical/chemical sensors are used for structural control, energy efficiency, or transportation. This project's use of temperature sensors represents a new frontier in civil engineering, opening up countless opportunities for monitoring infrastructure from a distance and in real-time.

3. RESEARCH METHODOLOGY

3.1. IoT Framework

Similar to earlier SHM studies, the present procedure is also based on a well-established IoT framework. Using epoxy resin, an economical temperature sensor is developed by covering the 10K Ohm Precision NTC Thermistor in a copper sleeve. The thermistor is connected to the ESP32-Wroom microprocessor, which records the temperature of the concrete sample at regular intervals as per ASTM specifications. The recorded data is transferred to google firebase (cloud database) through a wireless network.



(a) (b)

Fig - 1: (a) Schematic diagram of the developed sensor and (b) Overview of IoT framework

From the cloud, the data is retrieved back to the computer using the developed Window application through sensor ID. The application first calculates the maturity using equation 1; after that, the maturity index is utilized to calculate the strength of concrete. To confirm the accuracy of the designed sensors, a thermistor was dedicated to measuring the air temperature, which was regularly checked with a digital thermometer. A schematic diagram for the developed sensor can be seen in Fig. 1(a), followed by a general overview of the IoT framework in Fig. 1(b).

3.2. Specimen Preparation for Initial Testing

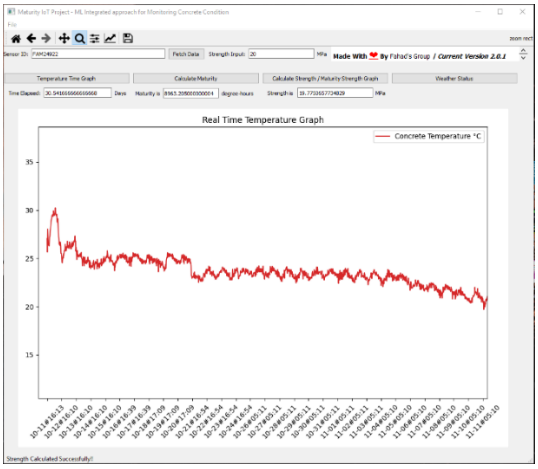
The initial experiment was conducted on the mentioned testing matrix to confirm the precision and accuracy of the developed sensor and framework. M20 grade concrete was prepared according to Indian Standards [9], with 1:1.5:3 mix design ratios and 0.5 water-to-cement ratios. The aggregates were washed and air dried before use to remove dirt and reduce surface water content. Table 1 illustrates the mix design adopted to carry out the initial testing experiment using ordinary Portland cement. Ten cylindrical concrete specimens were cast and cured indoors with sensors placed in two specimens. The compressive strengths of the concrete cylindrical specimen were determined using uniaxial compressive machine tests at 3, 7, 14, and 28 days.

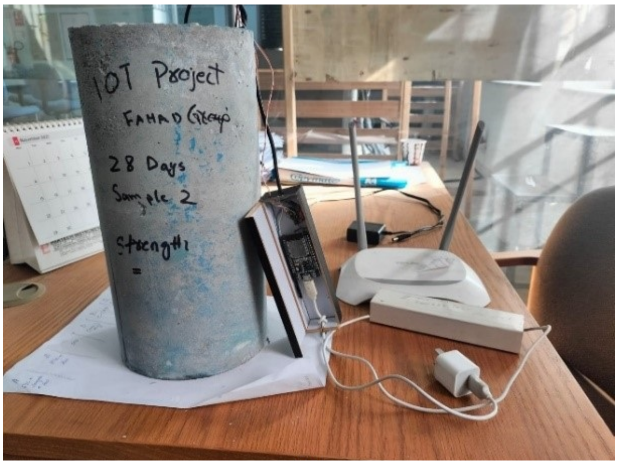
Table - 1: Concrete mix design for a trial batch of 5 cylinders

Sample	Cement	Coarse Aggregate	Fine Aggregate	Water
01	9 Kg	13 Kg	30 Kg	4.5 Kg

3.3. Window Application Development

A window application was developed using Python with PyQt, Matplot lib, and Firebase auth libraries. The User interface was designed using PyQt5 and QT Designer. Matplot lib was utilized in displaying the graphs. While the Firebase auths are responsible for connecting the window application with the google firebase database to load data on pc. The data retrieved from the firebase is in the form of a Jason array which was further converted to tabular form utilizing the pandas and NumPy libraries [10]. The developed window application and the sensor are shown in Fig - 2.





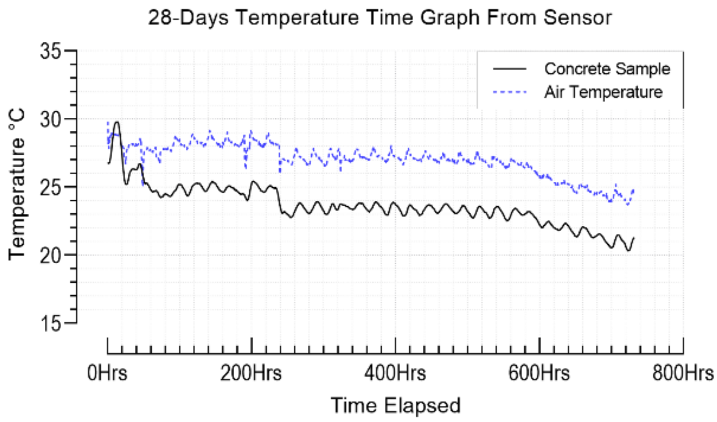
(a) (b)

Fig - 2: (a) Developed Window Application (b) and Sensor

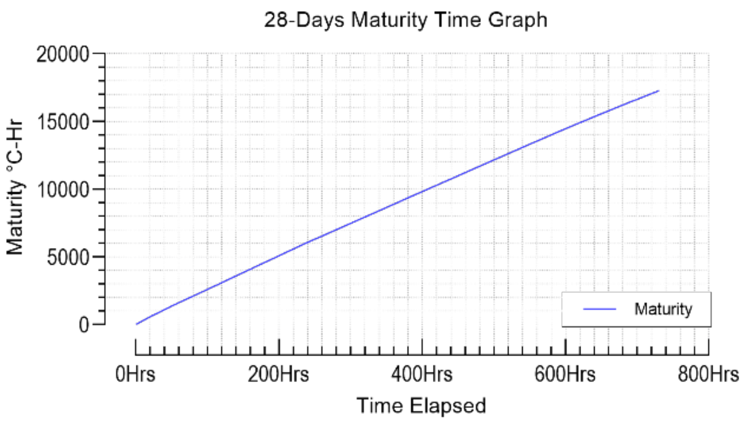
4. RESULTS AND DISCUSSION

4.1. Concrete Maturity and Temperature

Twenty-eight days of temperature data for samples and the room temperature was recorded using the developed sensor and was stored in the cloud. The window application was used to check the data regularly and plotted it as shown in Fig. 3. The graph's initial peak shows the concrete's early hydration reaction, decreasing with time until a minimum constant value. Some drops can also be seen in the data, resulting from thunderstorms on those days.



(a)



(b)

Fig - 3: (a) Temperature and (b) Maturity time graph for 28 days

4.2. Strength Comparison of Maturity Method and Uniaxial Compression Testing

The strength obtained from the uniaxial compression machine on 3, 7, 14, and 28 days was compared with strength calculated using the maturity method as shown in Fig - **4**, which shows an almost negligible difference since this is an approximate method to calculate and predict concrete strength, the negligible difference is admissible.

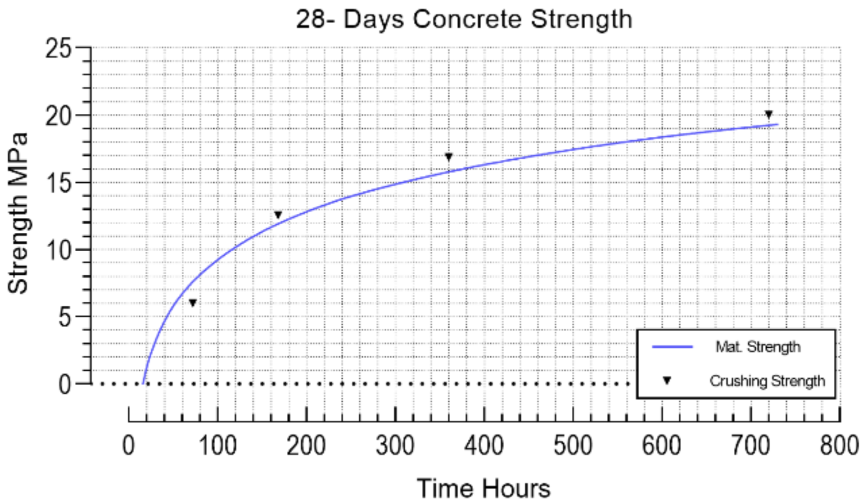


Fig - 4: Strength Comparison from Maturity Method and Uniaxial Comparison Test

5. CONCLUSION

In this paper, an economical loT-based SHM sensor was developed using esp32 along with a Windows GUI application. The embedded temperature sensor uses the maturity technique to monitor the compressive strength of concrete.

- The proposed farmwork enables remote data monitoring, which can be accessed in real-time through window application and IoT framework.
- It will be a helpful tool for construction engineers and managers, as it allows them to monitor the progress of concrete curing and estimate the strength of the concrete at any point in time.
- It can help to ensure that the concrete is strong enough to support the loads it will be subjected to and can also help to identify potential problems early on.

In a nutshell, the proposed framework can be adapted to monitor the concrete compressive strength minimizing the need for a technician or extra labor associated with existing procedures, such as formwork stripping, removal of slab formwork, beam formwork, column formwork, opening traffic on the concrete pavement [11], post-tensioning, concrete curing or any other similar activity during construction, where such is required. This approach may be considered user-friendly, consistently safe, and transparent for real-time strength monitoring of concrete buildings worldwide without any location restriction.

It is strongly recommended that in future studies, the capabilities of the developed sensor be expanded to predict concrete strength using machine learning algorithms, incorporating future predicted ambient temperature data and past performance of concrete mix designs.

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