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DEVELOPMENT AND APPLICATION OF CONCRETE SENSOR TO MEASURE ONSITE STRENGTH OF CONCRETE

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Abstract

According to sustainable development goals 13 which emphasized on Infrastructure, Innovation and Industry. Innovation through creation and development of device is important in order for developing countries like Nigeria to attain her self-realization in industrialization. In this paper, a concrete sensor called "ConSor" was developed to measure onsite strength of concrete using the principle of maturity described in ASTM C-1074. The materials used are DB1386 thermocouple, arduino board having wireless modules and components to enable seamless and wireless communication of data to the web. The device was programmed using C++ to read temperature (heat data) generated from the concrete and convert it using the maturity function (equation) to maturity. The maturity was thereafter converted to strength through calibration from crushed laboratory samples of same mix. The results obtained from the developed device was compared with industry-established concrete sensors (Commandcenter sensor and Hilti concrete sensor) and laboratory samples using appropriate standards of concrete testing. The results obtained at each curing ages for the Consor was closer in accuracy of ±0.05N/mm^2 to the industry- established concrete sensors for strength and ±0.5°C and for temperature readings. This is a clear indication that the developed device has capacity and suitability to be deployed for onsite strength of concrete.

1.0 INTRODUCTION

Concrete is the predominant construction material on a global scale. Thorough monitoring of the setting process is essential to ensure that it has achieved the necessary structural integrity. Utilizing dependable methods to evaluate the progress of the construction process on-site and in a non- intrusive manner helps expedite construction by accurately predicting the timing for removing formwork, post-tensioning, and opening the pavement to traffic. This principle also applies to the manufacture of precast concrete structures, where demolding can occur once the setting process has progressed to the point where the structure can support itself. As a result, moulds can be reused more quickly, leading to increased production [1].

With the 1947 presentation of the Nurse-Saul equation of maturity, the use of sensors has become more widely accepted and recognized in research. Most concrete sensors, whether used in industry or research, are built using this maturity equation as their foundation. The onsite concrete strength measuring device is another concrete that provides real-time data and performance of the concrete over time, according to a review by [12] on five key sensors for monitoring concrete structures namely; temperature sensors, humidity sensors, pH sensors, corrosion sensors, and strain/stress and crack monitoring sensors. Concrete sensors employ live data to enhance construction operations and ensure the soundness of structures. These sensors monitor and assess several properties of concrete, such as temperature, humidity, and strength. These state-of-the-art instruments are designed to monitor and assess various properties of concrete both during and after construction [2].

In a study conducted by researchers [3] and [4], the performance of a wireless sensor used for monitoring concrete strength was evaluated. The researchers found that the accuracy of the proposed sensor solution was comparable to the conventional compressive strength approach, and outperformed both direct and indirect techniques for testing concrete strength. The sensors offer real-time data on variables such as temperature, humidity, and strength, providing valuable information about the performance and structural integrity of the concrete. Concrete sensors utilise advanced technology to optimise building procedures and ensure the durability and quality of concrete structures. Their ability to acquire accurate and rapid information makes them indispensable tools in the construction industry, aiding in improved decision-making and long-term maintenance strategies [5]. The utilisation of Arduino and ESP8266EX boards for device development has proven to be highly beneficial, as stated in [6]. The researchers determined that by integrating suitable sensors, their node design can serve not just for experimental reasons but also for monitoring real-time events in the field.

Concrete curing is the exothermal process [16] in which heat is released through cement hydration. During the early stages of concrete curing, the internal temperature of the concrete increases significantly and then gradually declines afterwards [17]. The concrete's enduring strength progression over several years suggests that its chemical reaction is persistent. Monitoring the temporal changes in the internal temperature presents significant advantages in the context of concrete construction. It aids in making accurate judgements on the removal of the formwork and the loading of the structures, and it has an impact on the speed of construction [18]. This aspect of concrete has been examined in several prior studies [17], [18], [19], [20], and [21].

Empirical evidence demonstrates that the interaction between time and temperature allows for the estimation of the concrete's true compressive strength. The concept of concrete maturity [7], which is a metric that measures the change in strength of the material after it has cured, is the basis for concrete sensors. This metric is influenced by both temperature and age. Temperature variations within concrete elements, such as columns and beams, are monitored at various depths using two types of sensors, depending on the intended method of temperature measurement.

While wireless sensors transmit data through RFID technology, wired sensors utilise integrated probes that are connected to a data recorder. These sensors monitor changes in temperature that happen throughout the process of curing and are usually placed at important depths, such as 25%, 50%, and 75% of the concrete's depth. The collected data is compared to a maturity curve [7], which correlates concrete strength with temperature and age. The sensors aid in assessing the concrete's strength and ensuring it complies with the specified design criteria. By removing the sensors once the goal strength is achieved, data analysis can be conducted to enhance the long-term durability of the building by making any required modifications to the construction process [8], [9], and [10].

Utilizations of sensor-enabled approach to determine onsite strength of concrete has been researched recently. These researchers dwelt much on application of thermal resistivity or conductivity of their sensors to measure strength of concrete. In a research carried out by [22], [23], [24] and [25] their research focused on utilization of sensors cable of measuring resistivity of concrete with no attention to its maturity properties.

2.0 MATERIALS AND METHODS

2.1 Concrete Sensor Material

The concrete sensor was constructed using supplies obtained from multiple vendors, including an ESP32 with Arduino and a type J thermocouple with a temperature range of 0°C-750°C. The device operates at a temperature of 1250 degrees Celsius and is equipped with a real-time clock. It uses a USB type B connection and is powered by a 5V lithium cell battery. Additionally, it has a solar panel with a capacity of 12V. The text refers to Figures 1-7. All of these components adhered to the necessary standards and safety requirements for use during the development process. Following the established protocol, the maturity mix method, the concrete samples were prepared according to the procedures specified in reference [7]. To calibrate the device, the initial temperature of several concrete mixes/grades (M10, M15, M20, and M25) was measured using a temperature data logger over a period of 28 days [27], [28]. The collected data was then analyzed to identify the appropriate interval for capturing temperature data in the device. After successfully completing the task, beams of 1000 mm x 300 mm x 300 mm were utilized for additional calibration, as specified in [7].

The Arduino board, equipped with both Bluetooth and wireless modules, was programmed to retrieve temperature data from the concrete using type J thermocouples (Figure 2) that were linked to it. Two J-type thermocouples with distinct addresses were employed to measure the heat released by the concrete during the hydration process. The thermocouples were labelled as T1 and T2, and the temperature measurements from both thermocouples were then averaged using the Andromo integrated environment, following Equation 1. In order to completely adhere to the requirements stated in [7] and Equation 1, the recording interval was set at 1 hour. The device was designed to measure temperatures from two distinct concrete beams using thermocouples. It calculates the average temperature and then subtracts the reference temperature, typically denoted as To, from the average. The resulting value is then multiplied by the elapsed time interval, which can range from 1 hour to 672 hours (equivalent to 28 days). The data is continuously kept in the device's memory using a 4Gb memory card for offline access. Online data transfer is achieved by a Wi-Fi modem, which provides internet access to the device. To ensure a consistent and uninterrupted power supply to the device, it was linked to a 5V lithium cell battery (as shown in Figure 6) which was in turn connected to a 12V solar panel (as depicted in Figure 7).

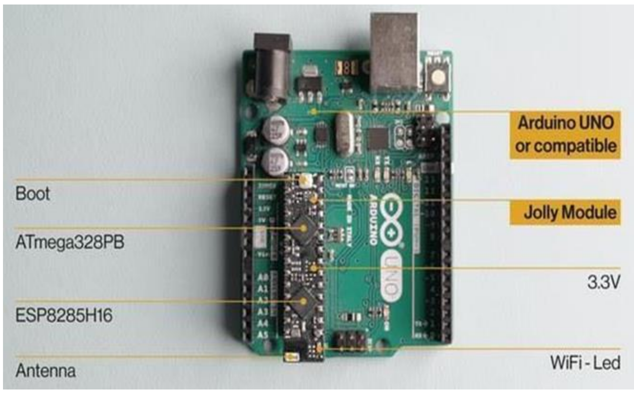

Figure 1: ESP32 with Arduino

Figure 2: Type J thermocouple

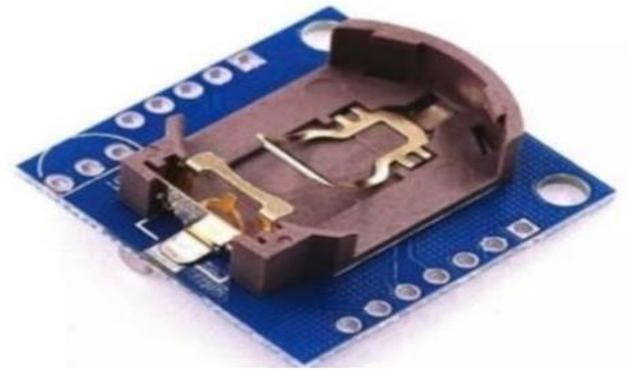

Figure 3: Real time clock

Figure 4: USB Type B

Figure 5: Wifi device

Figure 6: Lithium cell battery

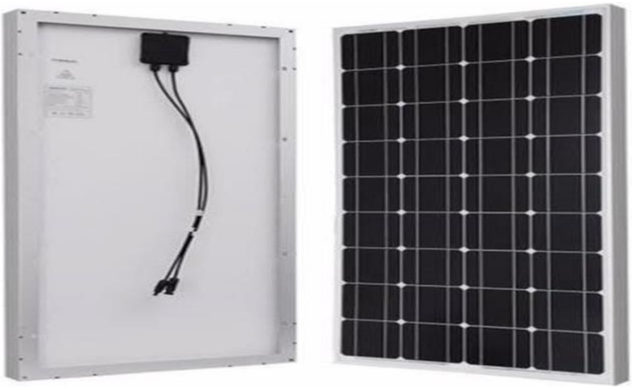

Figure 7: Solar panel

The maturity equation (Equation 1) used to determine the temperature-time relation of the concrete as hydration progresses during concrete strength gain has been established by [7].

$$(M) = \sum(T_a - T_o)\Delta t \qquad (1)$$ [Source: [7]]

$M(t)$ is the temperature-time factor at age t, degree-days or degree-hours, Δt *is* time interval, days or hours, T_a *is* average concrete temperature during time interval, Δt, °C, and T_o *is* datum temperature, °C taken as 10°C.

2.2 Description of Interface and Algorithm

The algorithm is visually depicted in Figure 8. The diagram illustrates the flow charts of the pre-implementation process of the device, while Figures 9 and 10 provide an explanation of the device's architecture and schematic diagram for communication with external resources. This system architecture was adopted and modified from [3]. Furthermore, Figure 10 illustrates a schematic representation of the device, depicting the external connection, the physical sensor, and the wireless communication interface used for online access. The URL to retrieve and view the data from the device is [www.concretesensor.com.ng.](http://www.concretesensor.com.ng) The connection is provided with administrator login access to ensure that only authorized individuals can access the data uploaded from the device to the web.

The device is linked to two temperature thermocouples, specifically identified as T1 and T2, within the andromo integrated development environment. The average temperature is calculated and then adjusted by subtracting the reference temperature of 10°C at regular intervals of 1 hour. The process persists for a duration of 28 days.

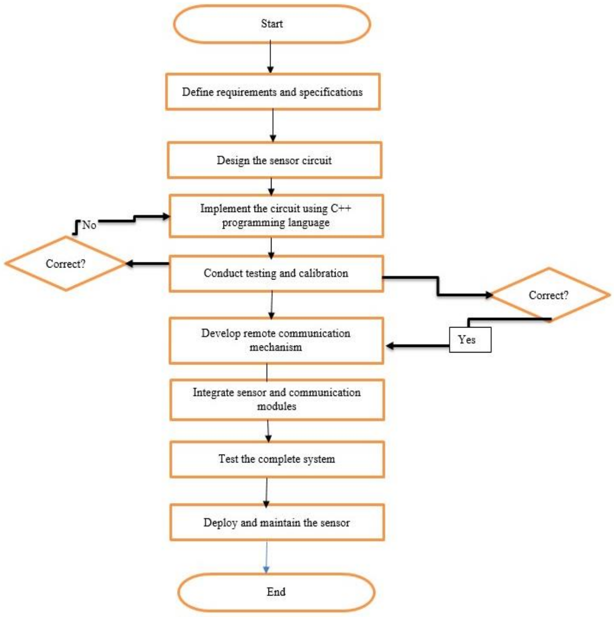

Figure 8: The device algorithm

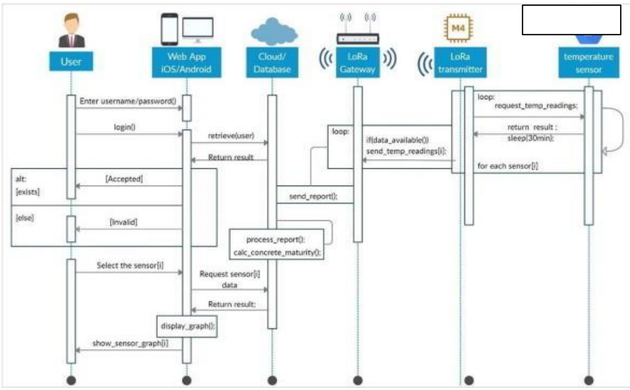

Figure 9: Typical architecture of Device communication interface [Source: [3]]

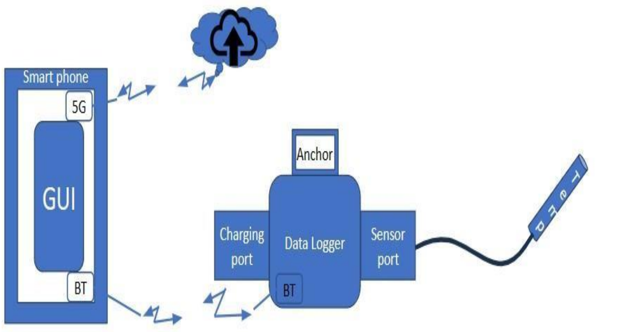

Figure 10: Typical schematic diagram of the whole system

2.3 Preparation of concrete samples for calibration

The concrete sample were fabricated with Type I Portland cement, a commonly employed material in Nigeria. The coarse aggregate used in this experiment was derived from nearby quarries and consisted of crushed limestone that had undergone processing. Based on reference [11], the mean specific gravity and absorption of the coarse aggregates were determined to be 2.5 and 1.3%, respectively. The fine aggregate used was medium coarse sand. The fine aggregates have a specific gravity of 2.6 and an absorption rate of 0.40 percent, respectively. Thirteen samples were created with beam diameters of 1000 x 300 by 300mm to calibrate the device, following the guidelines in references [7] and [14]. The samples were prepared in the following manner: three samples were prepared for each of the durations of three days, seven days, 14 days, and 28 days. Additionally, one sample was prepared specifically for the concrete sensor. The samples were transported to a flexural testing equipment with a capacity of 2000kN in order to ascertain their flexural strength. The intensities acquired from the machine for each beam were utilised to calibrate the instrument for accuracy and precision. The correctness of the data obtained from the "Consor" was verified using industry-established sensors, specifically the Hilti and Commandsenter concrete sensors.

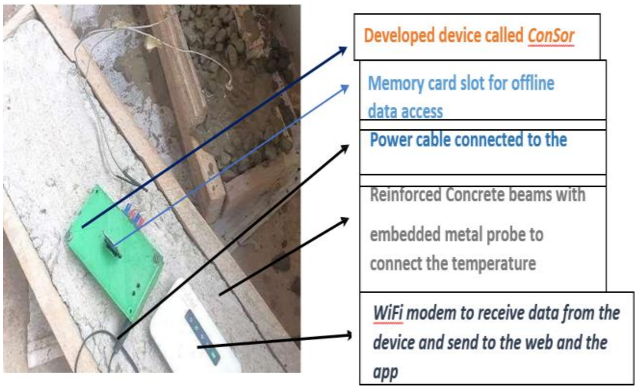

Figure 11: The developed device during trial

3.0 RESULTS AND DISCUSSION

3.1 Fully Developed Device

The device "ConSor" seen in Figure 11 demonstrates its use during the trial and testing phase with a standard reinforced concrete beam. The gadget facilitated uninterrupted data flow from the concrete by applying the maturity equation after conversion to maturity. The device presents a comprehensive depiction (as shown in Figure 11) of the temperature and maturity data acquired from the concrete. This information is provided in the form of an output that can be read and interpreted. Additional details regarding the outcomes can be found in Figure 11. The image is a screenshot of the outcomes, which are processed by the gadget and transmitted via the Wi-Fi module to the internet.

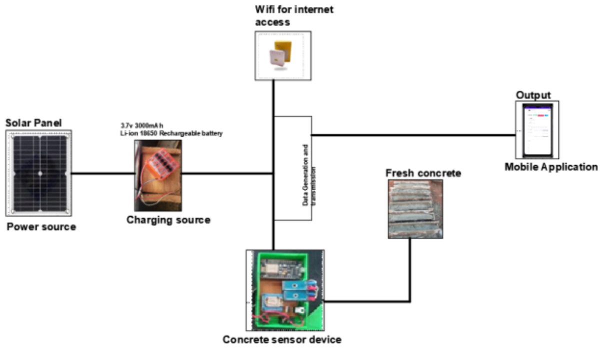

Figure 12: Full description of the entire process

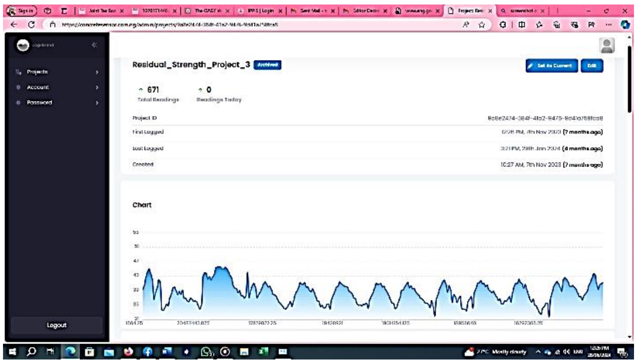

Figure 13: Screenshot of the data page online

3.2 Comparison of Results of Strength

The device's findings regarding strength and other properties are displayed in Table 1. Additionally, Figures 14 and 15 depict graphical representations of the relationship between strength and maturity, as well as temperature and maturity, for all the methods employed to determine the concrete's strength. According to the table, the greatest temperature of 28.95^0C was recorded during the early stage of the hydration process. However, no maturity or strength has been achieved yet because no time has passed, as indicated by maturity Equation 1. The highest strength achieved after 28 days, or 672 hours, is a maturity value of 19824^0C-hr, which is equivalent to 8.42N/mm^2.

This outcome demonstrates convergence properties in terms of accuracy when compared to both industry-established sensors and laboratory data. The sensor that is widely used in the industry produced a result of 23780^0C-hr/8.84N/mm^2 after 28 days, but the laboratory results showed a value of 23710^0C-hr/8.33N/mm^2. The temperature readings obtained from the *ConSor* sensor demonstrated a precision of up to ±0.5^{0}C when compared to data from existing industry sensors and laboratory measurements. The temperature increases in direct proportion to the temperature of the laboratory and Commandcenter concrete sensor.

This is consistent with the findings of the study conducted by [13]. Previous research conducted by [15] found that the initial temperature during the first 3 days of the test utilizing the sensor was as high as 50^{0}C. This finding aligns with the results observed in our investigation.

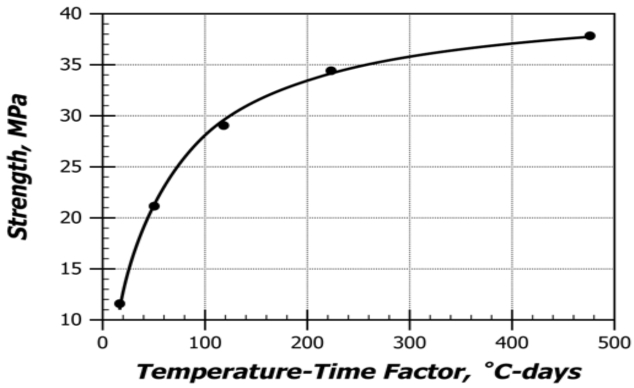

Figure 14: Calibration curve culled from ASTM C-1074

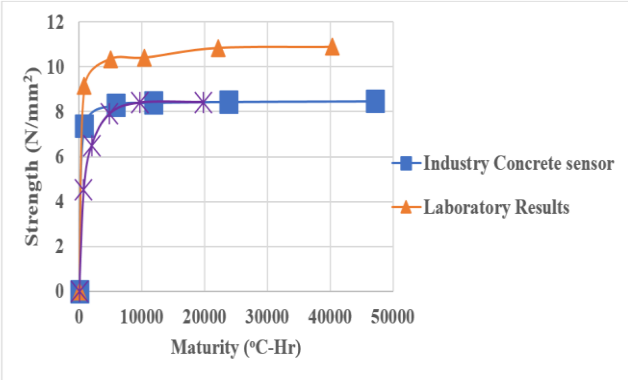

Figure 15: Strength against maturity for all the methods

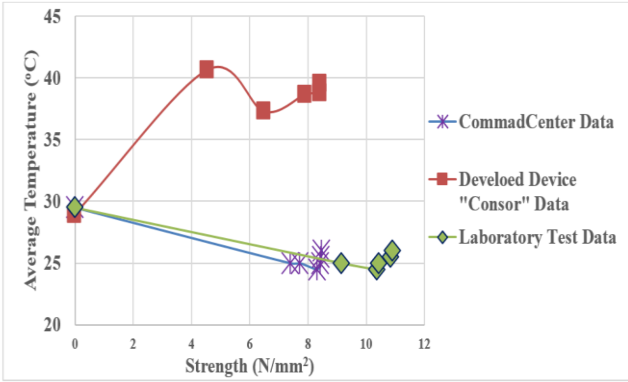

Figure 16: Average temperature against maturity for all the methods

Table 1: Data recorded from the developed device (*ConSor*)

T1 (^{0}C)	T2 (^{0}C)	Taverage (^{0}C)	Interval (hr)	T(Room) (^{0}C)	Maturity Index (^{0}C –hr)	Time Stamp	Strength (Mpa)
28.75	29.15	28.95	0.00	10.00	0.00	14.00pm	0.00
39.00	42.25	40.63	24.00	10.00	735.00	14.00pm	4.54
37.25	37.25	37.25	72.00	10.00	1962.00	14.00pm	6.50
36.75	40.50	38.63	168.00	10.00	4809.00	14.00pm	7.90
37.50	40.00	38.75	336.00	10.00	9660.00	14.00pm	8.40
38.50	41.25	39.50	672.00	10.00	19824.00	14.00pm	8.42

4.0 CONCLUSION

From the foregoing, the following conclusions on the development and application of the developed device were drawn;

- Utilization of resources within our environment and deployment of right ICT expertise coupled with enabling environment, development of alternative means of generating onsite strength of concrete is possible and attainable.
- The results obtained from the device showed how promising it would be using the device on real-time construction project.
- The developed device (*ConSor*) provided not only strength/maturity of concrete, it also provided progressive increase or decrease in hydration (exothermic reaction) going on in the concrete.
- The developed device though tested on concrete grade of 15N/mm2, it will perform very well in higher concrete grade due to the properties of the thermocouples used.

5.0 CONFLICT OF INTEREST

The authors declare no conflict of interest

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