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Automated concrete curing and assessment of strength and durability using IoT system

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ABSTRACT

Manual water curing is a widespread practice, yet achieving proper curing to prevent plastic cracking and ensure long-term strength and durability poses a difficulty. Aside from being labor-intensive, manual water curing is also uneconomical and has negative effects on aesthetics. As an alternative, certain researchers suggest an automated curing method that estimates water loss and replenishes it using a theory-based calculation and taking into account the weather conditions. However, their effectiveness is restricted as the estimated water loss may not be completely accurate due to several factors that impact it. To address these challenges, we propose a conceptual automated water curing system that utilizes real-time monitoring with the Internet of Things (IoT) technology. The system involves wireless sensors for temperature and relative humidity, a smart water valve, water sprinklers, and an IoT gateway. As per ASTM F2170, the sensors can be positioned, and data will be collected, examined, and handled in real-time using an IoT gateway. The IoT gateway transmits data to the smart water valve, which then sprays water when the moisture level drops below the preset threshold. This process continues until the concrete reaches a certain strength level estimated using internal concrete temperature data and the Maturity method. Moreover, the data can be transmitted continuously to cloud storage to keep track of the concrete's durability. The proposed automated water curing system offers numerous advantages, such as eliminating the risk of concrete failure caused by inadequate curing, being efficient in terms of time and resources, monitoring real-time strength development, not being impacted by other factors, and having practical benefits for both stakeholders and society.

1. Introduction

Concrete remains the most crucial construction material worldwide for the development of civil infrastructure. Nevertheless, its strength and durability are subject to various factors. One of the factors that can negatively impact the strength and durability of concrete is improper curing. The process of curing facilitates the cement hydration reaction that occurs between water and cement, resulting in the formation of calcium silicate hydrate (CSH) gel. This gel binds the aggregate together, creating a solid mass that reduces the porosity of the concrete and enhances its physical and mechanical properties [1]. It is noteworthy that the hydration reaction responsible for the early strength development of the concrete is initiated by tricalcium silicate (Ca_3SiO_5) and dicalcium silicate (Ca_2SiO_4), the two silicate compounds present in Portland cement. These compounds are represented by Eqs. (1) and (2), respectively.

$$2Ca_3SiO_5 + 7H_2O \rightarrow 3CaO.2(SiO)_2.4H_2O + 3Ca(OH)_2 + 173.6KJ \quad (1)$$

$$2Ca_2SiO_4 + 5H_2O \rightarrow 3CaO.2(SiO)_2.4H_2O + Ca(OH)_2 + 58.6KJ \quad (2)$$

The reactions that occur during hydration (as seen in Eqs. (1) and (2) generate a significant amount of heat, which can cause water loss within the concrete through self-desiccation. This, coupled with the possibility of rapid water evaporation due to high ambient temperatures, can result in plastic shrinkage. As time passes, this shrinkage can create cracks in the concrete, compromising its durability by providing openings for harmful substances

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to enter. Water evaporation can also occur due to low relative humidity, and while the accumulation of evaporated water molecules above the concrete can raise perimeter humidity and reduce evaporation, the presence of wind can remove these molecules, lowering the ambient relative humidity. This can lead to the formation of a less uniform CSH gel, ultimately decreasing the concrete's strength and durability over time.

To ensure the desired strength development and long-term durability of concrete, it is important to prevent water evaporation from the concrete surface in the early stages after placement. This can be achieved through various methods such as water curing (which involves ponding, sprinkling, and wet coverings), membrane curing (which involves using plastic sheeting or formwork), and steam curing. In addition to these traditional methods, super-absorbent polymers (SAP) are also commonly used as internal curing agents in high-performance concrete (HPC). By introducing SAP into the concrete mix, its high-water storage capacity can help to maintain the necessary level of moisture within the concrete matrix. As a result, any water loss that occurs due to either self-desiccation or external environmental factors can be compensated for by the stored water being released back into the concrete.

The selection of a curing method is influenced by a variety of factors such as site conditions, the type of structure, climatic conditions, and material-related parameters. In developing countries, where the climate is hot, water curing remains a popular method of curing. However, achieving effective curing to prevent plastic cracking and ensure long-term durability is challenging. This is because the amount of water required to replenish concrete is difficult to determine, as it is influenced by the rate of water evaporation, which in turn is affected by environmental factors such as air temperature, relative humidity, and wind speed. The ACI nomograph is commonly used to estimate the rate of water evaporation from concrete based on these climatic factors. Different codes recommend a threshold value for the water evaporation rate to ensure adequate curing and prevent cracking. For instance, ACI recommends taking precautions for normal concrete when the water evaporation rate exceeds 1.0 $kg/m^2/h$ [2]. In Canadian and Australian codes, this value is 0.75 and 0.5 $kg/m^2/h$, respectively. Nonetheless, plastic shrinkage cracking has been observed in hot and arid environments even at low evaporation rates of 0.2 $kg/m^2/h$ [3].

Manual water curing, despite its ability to reduce the temperature and increase surface moisture of concrete, has several drawbacks. Firstly, it is challenging to water concrete while accurately monitoring evaporation rates. Secondly, manual water curing can result in under- or over-cured concrete, which leads to less effective curing and a waste of water resources through overwatering. In the worst-case scenario, poorly cured concrete may not achieve the intended strength and could develop structural cracks. Thirdly, unevenly spraying water on the concrete surface can result in uneven coloration on the outer surface of the concrete due to varying hydration reactions. Lastly, manual water curing is a cumbersome process. To address these issues, it is essential to develop an innovative method that automatically waters the concrete surface when required by sensing the amount of water evaporation from the concrete. To this end, the aim of this study is to propose an internet-of-things-based conceptual design that overcomes the limitations of traditional concrete water-curing methods. The proposed conceptual design enables optimal automatic water curing without human intervention by continuously measuring the actual amount of water evaporating from concrete in real-time.

2. Literature review on automated curing

In recent times, there have been notable efforts to develop automated systems specifically designed for the curing of concrete. One such attempt was made by H. Liu and Y. Fang [4], who created an automatic curing system for mass concrete pouring. The system consists of two layers: the monitoring layer and the control layer. The monitoring layer comprises an industrial computer that communicates with the control unit through a long-range (LoRa) network to obtain the overall system's operating status. The control layer comprises a microcontroller that uses temperature, humidity, and wind speed sensors to collect climatic data. The microcontroller-based control units use this data to regulate the water spraying time by actuating the butterfly valve. To improve the cooling effect, a 25 mm diameter water pipe made of high-density polyethylene (HDPE) with high thermal conductivity was laid in a double-circulation serpentine shape with 1.5-meter spacing. According to the researchers, the control system they designed significantly improves the efficiency of water pipe cooling and sprinkling water to meet the curing requirements.

An automatic curing system was developed by J. Yang et al. [5] which employed the hydration heat release law to determine the theoretical water loss, and replenished it with a mist sprayer. The authors utilized relative humidity and temperature sensors installed on the surface of the concrete to estimate the evaporated water, and the communication module of the sensors transmitted the data wirelessly to the main signal receiver of the automated curing system. The mist sprayer was governed by a programmable logic controller (PLC) and operated with variable frequency technology, while maintaining a constant water pressure. To assess the efficacy of the automated curing system, the authors carried out a field test on 20 box-section beams. According to their evaluation, the automatic curing system proved to be superior to the traditional manual curing system in achieving early-age compressive strength, providing a better appearance, and preventing premature cracking. In addition, the authors asserted that, despite the initial purchase cost, the overall expense of the proposed automated system was 71.5% less than manual water curing, while minimizing labor costs and intensity, and reducing water consumption by 51.2% for 10 beams.

K. C. Lo et al. [6] devised an automatic curing mechanism that incorporates all the parameters mentioned in the ACI nomograph, such as temperature, humidity, and wind speed. Through the usage of sensors, the system detects these environmental variables and transmits the data to a microcontroller for analysis and computation. The microcontroller then adjusts the water sprayer to control the supply of curing water and regulates the spray time. As per the authors, the automatic water curing system was able to maintain a consistent level of surface moisture in the concrete for an extended period when compared to manual curing. Additionally, it prevents plastic shrinkage cracks before the concrete has fully cured while preserving 59% of the water used in manual curing. Another study conducted by Y. Wei et al. [7] also proposed an automated curing mechanism that accounts for all environmental factors as specified in the ACI nomograph. The system consists of three subsystems: field measuring and controlling, remote displaying and controlling, and remote server. The field measuring subsystem is responsible for monitoring environmental variables and transmitting the data to the remote server, which in turn provides controlling instructions to the field controlling subsystem to manage the water pump and spray time. This system was implemented for the water curing of underground structure sidewalls. The authors claimed that the system could enhance concrete quality by minimizing the irregularities caused by manual labor and cracking. They also asserted that the system has lowered labor expenses while enhancing construction information.

The works mentioned above reveal that automated water curing for concrete is more effective than manual methods in terms of achieving crack-free concrete and early compressive strength without water loss. Despite their significant contribution to producing durable concrete, automated systems have limitations and room for improvement. A major constraint is that water loss calculations for concrete rely on ambient environmental factors and predetermined rules, while actual water loss can vary due to factors like cement type, water-to-cement ratio (w/c), concrete element size, and even environmental factors such as solar radiation. It is worth noting that concrete strength and durability depend on its temperature and relative humidity, rather than the surrounding atmosphere, so it is essential to monitor both parameters within the concrete element. Sensing devices and connectivity are crucial components of any IoT system. The next section explores concrete sensors and communication methods required to materialize the conceptual automated concrete water curing system.

3. Concrete sensors and communications

The rapid advancement of sensor technology has enabled its integration into various industries, including construction. Internet of Things (IoT) has revolutionized structural health monitoring by allowing more frequent, accurate, and comprehensive monitoring of civil infrastructure. The application of IoT-based concrete durability monitoring is also expanding, with several recent studies demonstrating the viability of real-time monitoring of early-age concrete parameters for ensuring its long-term durability and strength [8]. A detailed overview of sensors based on different principles can be found in [9], which includes temperature and relative humidity sensors that have been available for several years. Wired sensors require a connection cable to be pulled out of the concrete element, and a data logger can be connected to download temperature and relative humidity values. However, wired sensors increase the cost of designing, implementing, and maintaining monitoring systems, making them impractical for field use, especially in distributed systems. Advances in electronics and wireless technology have led to the development of self-contained wireless sensors that can be fully embedded in concrete. Wireless temperature and relative humidity sensors that can be fully embedded in concrete are already available on the market, such as those produced by Giatec Scientific Inc [10] and Hilti Corporation [11]. These sensors can store measured values of the concrete's internal temperature and relative humidity, which can be downloaded using various wireless communication protocols.

Several low-power wireless communication protocols have been developed for IoT applications, and their practical application has been demonstrated in several testbeds. These protocols differ in terms of communication range, latency, data rate, and power consumption and are classified based on range (short-range vs. long-range) or spectrum type (licensed vs. unlicensed). Short-range wireless communication technologies such as Bluetooth Low Energy (BLE) [12], ZigBee [13], and WirelessHART [14] require multi-hop mesh networks to cover larger areas. Most of these technologies operate in the unlicensed 2.4 GHz ISM band, which is often congested and subject to high losses. Long-range, low-power wireless communication technologies, such as Sigfox [15], LoRaWAN [16], Narrowband IoT [17], are usually configured in a star topology and form a low-power wide area network (LPWAN). LPWAN is gaining attention in the research community due to its ability to provide low-cost, large-scale connectivity over large geographic areas. Most of these technologies operate in the unlicensed sub-GHz band, offering robust, dependable, low-power communications. The sub-GHz band is less prone to attenuation, multipath fading, and congestion than the 2.4 GHz band. These technologies often utilize robust modulation and spread spectrum techniques to achieve reliable, low-power, and interference-resistant communications.

4. Design principle of a conceptual automated curing system

Our proposed system differs from other automated concrete water curing systems in that it utilizes sensors to measure actual water loss and automatically water the surface of concrete. The system's architecture, as shown in Fig. 1, includes multiple wireless temperature and relative humidity sensors embedded in the concrete infrastructure, smart water valves, water pipes with sprinklers, and an IoT gateway. The temperature sensor determines the optimal timing for the watering cycle and monitors the concrete's strength development. Conversely, the relative humidity sensor tracks the concrete moisture, enabling the measurement of water loss from the concrete element. For precise moisture content representation throughout the concrete, the sensors can be installed following the ASTM F2170 [18] guidelines. The IoT gateway plays a vital role in collecting and processing sensor data. It comprises various hardware and software modules [19], such as MCUs (processors), wireless connectivity modules (e.g., WiFi, ZigBee, Bluetooth, 2G/3G/4G), and others. The gateway software is responsible for gathering, preprocessing, and filtering data from the embedded temperature and relative humidity (T/RH) sensors. Furthermore, IoT gateways play a crucial role in enabling communication between the smart water valve and the concrete element by converting various network protocols. They also employ robust encryption networks to guarantee the security of the system, safeguarding it against unauthorized access and malicious attacks.

The IoT gateway collects real-time temperature and relative humidity data from the concrete infrastructure that requires watering, processing it in close proximity to the source. This enables prompt responses and helps minimize data transmission costs. It sends information to the smart water valve based on sensor data analysis to spray water when the moisture content of the concrete falls below the set threshold and to stop spraying when the concrete is sufficiently hydrated. This process is repeated until the concrete reaches the desired strength level, which is estimated using internal concrete temperature data and the Maturity method. This method assumes that the compressive strength of the hardened concrete is proportional to its internal temperature–time history during the early stages of development [1]. The detail of this process is presented in Section 5.

This system ensures that the concrete receives the precise amount of water needed, mitigating the risks of plastic shrinkage and cracking without requiring human intervention. It operates independently of the type of cement, water-to-cement ratio (w/c), or concrete depth, which can otherwise affect the effectiveness of traditional curing systems due to the difficulty in controlling all the factors influencing concrete hydration. For example, fly ash concrete exhibits slower hydration rates, and improper curing practices can have detrimental effects on the final product [20]. Moreover, thicker concrete sections are less prone to cracking compared to thinner sections due to the heat of hydration promoting the pozzolanic reaction [20]. One example of a concrete structure that would benefit from automatic water curing is a large-scale concrete pavement, such as a highway or airport runway. The primary rationale behind this is as follows: i) Size: These pavements typically cover a vast area, rendering traditional curing methods ineffective in ensuring consistent and uniform moisture distribution throughout the entire pavement. In contrast, an automatic water curing system can efficiently achieve this. ii) Uniformity:

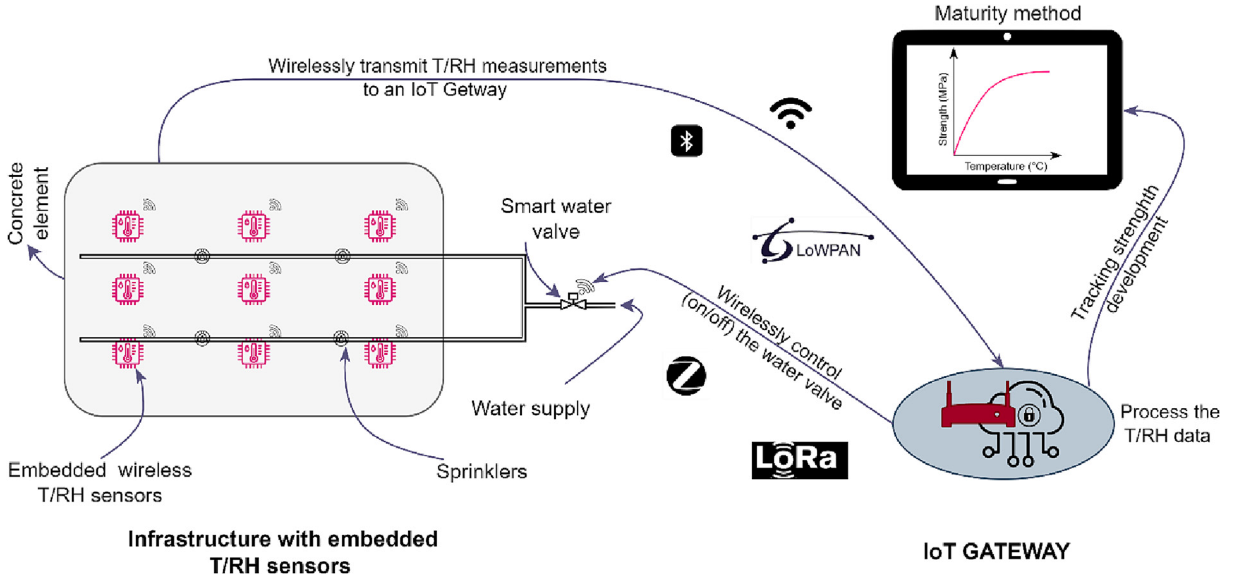

Fig. 1. Architecture of the automated concrete water curing system.

By employing automatic water curing systems, water can be evenly distributed across the pavement, minimizing the likelihood of uneven drying and facilitating uniform curing. iii) Continuous Curing: Concrete pavements require continuous moisture during the initial curing stages to maintain optimal hydration and strength development. Manual watering may fall short in providing round-the-clock coverage, while an automatic water curing system can supply water as needed, guaranteeing consistent curing throughout day and night. iv) Quality Control: Automatic water curing systems can aid in upholding consistent curing conditions, diminishing the dependence on manual monitoring and potential human errors. This, in turn, enhances the overall quality of the pavement by establishing a controlled curing environment. v) Time-Sensitive Projects: Concrete pavements often form part of time-sensitive endeavors where rapid construction and early strength development are vital. The proposed automatic water curing systems expedite the curing process by delivering continuous moisture, enabling faster strength gain and earlier opening for traffic.

5. Implication on strength and durability assessment

The proposed automated system extends its utility beyond the conventional concrete curing process. By leveraging embedded temperature sensors and employing the Maturity method, the IoT gateway integrated into the system holds the potential for real-time monitoring of concrete strength evolution. The Maturity method relies on the premise that the compressive strength of hardened concrete in its early stages is directly correlated to its internal temperature–time history. This method is widely acknowledged and recommended as a standard test procedure in both ASTM C1074 [21] and the fib Model code [22].

According to the ASTM C1074 comprehensive strength of concrete at an early age can be calculated using Eq. (3).

$$f_{cm} = a + b\log(M) \tag{3}$$

where f_{cm} is early-age comprehensive strength in MPa at M, a and b are curve fitting parameters related to w/c, and cement type and M is the maturity index in °C-h given by Eq. (4)

$$M = \sum_{0}^{t}(T_a - T_o)\Delta t\,, \tag{4}$$

where Δt is a time interval in h; T_a is the average concrete temperature during the time interval, Δt, in °C; and T_o is the datum temperature in °C.

The early-age strength of concrete, according to the fib Model code, can be estimated from its strength at 28 days using Eqs. (5) and (6):

$$f_{cm}(t) = \beta_{cc}(t).f_{cm,28}, \tag{5}$$

with:

$$\beta_{cc}(t) = \exp\left(s.\left[1-\left(\frac{28}{t}\right)^{0.5}\right]\right) \tag{6}$$

where $f_{cm}(t)$ is the mean compressive strength in MPa at age t in h; $f_{cm,28}$ is the mean compressive strength in MPa at 28 days; t is the concrete age in h, adjusted according to Eq. (7) to account for curing temperature; s is a coefficient that varies with cement strength class.

$$t_T = \sum_{i=1}^{n}\Delta t_i\left(\exp\left[13.65 - \frac{4000}{273+T(\Delta t_i)}\right]\right) \tag{7}$$

where t_T is the temperature-adjusted concrete age in h which replaces t in Eq. (6); Δt_i is the number of h where a temperature T prevails; $T(\Delta t_i)$ is the mean temperature in °C during the time period Δt_i.

The embedded wireless temperature sensors capture internal temperature variations resulting from the hydration process and provide timestamped data. Utilizing this information, the Maturity method allows for the assessment of concrete strength development. Through the gateway, this data can be transmitted to the cloud, enabling real-time monitoring of concrete strength from any location with internet access via a computer or mobile device. This approach offers several advantages over traditional methods of assessing concrete strength, which involve molding fresh concrete into cubes or cylinders, curing them in place, and conducting break tests after 28 days. Furthermore, cube or cylinder samples may not accurately represent the in-situ concrete due to potential errors introduced during sample preparation by unskilled laborers.

The proposed method offers three key benefits: real-time strength tracking, resource and time efficiency, and accurate strength values. These advantages have significant practical implications. Early knowledge of concrete strength is particularly advantageous as it facilitates timely decisions regarding formwork removal, allowing contractors and stakeholders to progress without delays, reducing project time and costs while ensuring safety.

Depending on the intended use of the concrete element, the embedded relative humidity sensors provide critical information about the moisture content of the concrete for subsequent work. For example, before applying flooring materials or other protective coating to a concrete slab, the moisture level within the concrete must be reduced to an acceptable level. Because moisture can accumulate beneath the flooring or coating if the moisture content exceeds acceptable level, it can cause buckling, discoloration, adhesive failure, cupping, blistering, and/or mold growth. As a result, the same infrastructure used for automated concrete curing system will assist in making timely informed decisions, preventing unintended damage, and saving time and money.

The moisture content of the concrete is also one of the most critical factors affecting the durability of the concrete structure [23]. This is primarily due to the fact that the presence of moisture-filled pores in the concrete has a significant impact on the kinetics of transport processes. As a result, it has a significant impact on multiple deterioration mechanisms, including reinforcement steel corrosion, alkali-aggregate reactions, freezing and thawing, and sulphate attack [24]. Temperature also influences chemical reactions and the amount of moisture that the concrete retains, which governs some of the deterioration mechanisms. Hence, depending on the intended use of the structure, monitoring internal relative humidity and temperature of the concrete of the structure throughout its life is imperative. To this end, the proposed automated concrete curing system can be used by incorporating a cloud layer. The IoT gateway used at the edge layer can continuously transmit the temperature and relative humidity of the concrete to the cloud, which offers enormous computing and storage capacity for handling big data. The monitored data could provide insight into the durability condition of the infrastructure caused by environmental factors, allowing the property owner to make timely and informed maintenance decisions. Furthermore, because the sensors data will be stored in the cloud, different streams can be accessed and shared from any location with Internet access. It also allows for the recording of temperature and moisture dynamics in various types of concrete exposed to varying environmental conditions. The availability of such data is critical for a better understanding of the effect of hygrothermal interactions in various types of concrete under various environmental loads and beyond. Indeed, in order to monitor the condition of concrete structures over their lifetime, the sensors must meet certain criteria, such as being stable and invariant to chemical and thermal changes in the concrete, tolerant to varying weather conditions, energy-independent, and stable in the long run without requiring maintenance. Today, the availability of long-lasting sensors that can be embedded in concrete and are claimed to have a lifespan of 100 years, for example,[25], are becoming a reality. Self-powered IoT devices that charge themselves with energy from their surroundings are also becoming more common.

The proposed automated concrete curing systems will have the capability to gather real-time, continuous temperature and relative humidity data from the concrete. Indeed, the availability of low-cost sensors for monitoring various concrete degradation mechanisms, such as corrosion sensors, is increasing [26], and such sensors can be embedded alongside temperature and relative humidity sensors. This will allow for a more detailed assessment of the structure's current and future condition, with the possibility of predicting its service life. Therefore, the proposed conceptual automated concrete water curing system has the potential to become an essential component of next-generation concrete structures capable of self-watering for efficient curing, monitoring strength development and performance, and predicting its remaining life.

6. Conclusions

The study proposes a system for automated water curing of concrete that utilizes IoT technology. The system measures the concrete's water loss through internal relative humidity readings, which are processed by the IoT gateway at the edge layer. Using this data, the gateway instructs the smart water valve to provide the concrete with the precise amount of water needed and halt the spraying process once the concrete has reached its optimal hydration level. This procedure is repeated until the concrete reaches the desired strength level, which is estimated using internal concrete temperature data and the Maturity method. Additionally, real-time data on the internal temperature and relative humidity of the concrete can be transmitted to the cloud for long-term durability monitoring of the concrete structure.

The proposed automated concrete curing system has several advantages. Firstly, it eliminates the possibility of concrete failure due to improper curing and is not affected by the water-to-cement ratio, cement types, or size of the concrete element. Secondly, it is both time and resource efficient. Thirdly, it tracks real-time strength development, and fourthly, it monitors the long-term durability of the structure. The advantages of this system have significant implications for stakeholders and society. By replenishing the concrete with the precise amount of water required without the need for manpower, contractors and property owners can save on water and labor costs while preventing plastic shrinkage and subsequent cracking. By knowing the concrete's actual strength and moisture content at an early stage, the appropriate time for formwork removal and surface treatment can be determined, allowing the next activity to begin without delay. This reduces project time and costs while ensuring the structure and user's safety. Long-term temperature and relative humidity data for concrete elements aid in monitoring concrete durability and even predicting the useful life of the structure. Additionally, researchers can utilize this information to understand the impact of hygrothermal interactions in different types of concrete under varying environmental loads.

CRediT authorship contribution statement

Woubishet Zewdu Taffese: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Ethiopia Nigussie:** Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] A.M. Neville, J.J. Brooks, Concrete Technology, 2nd ed., Pearson Education Limited, Harlow, 2010.

[2] ACI 305.1-06, Specification for Hot Weather Concreting, Farmington Hills, MI, 2007.

[3] F. Sayahi, Plastic Shrinkage Cracking in Concrete: Mitigation and Modelling, Luleå University of Technology, 2019.

[4] H. Liu, Y. Fang, Design of Distributed Curing Control System for Mass Concrete Pouring, in: 2019 IEEE 17th International Conference on Industrial Informatics (INDIN), 2019: pp. 623–628. https://doi.org/10.1109/INDIN41052.2019.8972307.

[5] J. Yang, J. Fan, B. Kong, C.S. Cai, K. Chen, Theory and application of new automated concrete curing system, Journal of Building, Engineering. 17 (2018) 125–134, https://doi.org/10.1016/j.jobe.2018.02.009.

[6] K.C. Lo, H.W.T. Kwok, M.F.F. Siu, Q.G. Shen, C.K. Lau, Internet of Things-Based Concrete Curing Invention for Construction Quality Control, Advances in Civil Engineering. 2021 (2021) 13, https://doi.org/10.1155/2021/9933615.

[7] Y. Wei, J. Lin, W. Zhao, C. Hou, Z. Yu, M. Qiao, B. Liu, An Internet Based Intelligent System for Early Concrete Curing in Underground Structures, in: W. Wu, H.-S. Yu (Eds.), Proceedings of China-Europe Conference on Geotechnical Engineering. Springer Series in Geomechanics and Geoengineering, Springer, Cham, 2018: pp. 743–746. https://doi.org/10.1007/978-3-319-97112-4_166.

[8] W.Z. Taffese, E. Nigussie, Autonomous corrosion assessment of reinforced concrete structures: Feasibility study, Sensors (Switzerland). 20 (2020) 6825, https://doi.org/10.3390/s20236825.

[9] S. Taheri, A review on five key sensors for monitoring of concrete structures, Constr Build Mater. 204 (2019) 492–509, https://doi.org/10.1016/j.conbuildmat.2019.01.172.

[10] Giatec Scientific Inc., Build Concrete Structures Faster, Safer, and More Economically, (2022). https://www.giatecscientific.com/products/concrete-sensors/smartrock-maturity-meter/.

[11] Hilti Corporation, Concrete Sensors, (2022). https://www.hilti.com/content/hilti/W1/US/en/business/business/trends/concrete-sensors.html.

[12] C. Gomez, J. Oller, J. Paradells, Overview and evaluation of bluetooth low energy: An emerging low-power wireless technology, Sensors (Switzerland). 12 (2012) 11734–11753, https://doi.org/10.3390/s120911734.

[13] S. Farahani, ZigBee Wireless Networks and Transceivers, Newnes, Oxford, 2008.

[14] J. Song, S. Han, A. Mok, D. Chen, M. Lucas, M. Nixon, W. Pratt, WirelessHART: Applying Wireless Technology in Real-Time Industrial Process Control, in, IEEE Real-Time and Embedded Technology and Applications Symposium 2008 (2008) 377–386, https://doi.org/10.1109/RTAS.2008.15.

[15] A. Lavric, A.I. Petrariu, V. Popa, Long Range SigFox Communication Protocol Scalability Analysis Under Large-Scale, High-Density Conditions.pdf, IEEE Access. 7 (2019) 35816–35825. https://doi.org/10.1109/ACCESS.2019.2903157.

[16] R.S. Sinha, Y. Wei, S.H. Hwang, A survey on LPWA technology: LoRa and NB-IoT, ICT Express. 3 (2017) 14–21, https://doi.org/10.1016/j.icte.2017.03.004.

[17] R. Ratasuk, N. Mangalvedhe, Y. Zhang, M. Robert, J.-P. Koskinen, Overview of narrowband IoT in LTE Rel-13, IEEE Conference on Standards for Communications and Networking (CSCN) 2016 (2016) 1–7, https://doi.org/10.1109/CSCN.2016.7785170.

[18] ASTM F2170-19a, Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes, ASTM, 2019. https://doi.org/10.1520/F2170-19A.

[19] M.A. Iqbal, S. Hussain, H. Xing, M.A. Imran, Enabling the Internet of Things: Fundamentals, Design and Applications, First, JohnWiley&SonsLtd, Hoboken, NJ, 2021.

[20] R. Lewis, L. Sear, P. Wainwright, R. Ryle, Cementitious Additions, in: J. Newman, B.S. Choo (Eds.), Advanced Concrete Technology: Constituent Materials, Butterworth-Heinemann, 2003: pp. 4/3-4/36. https://doi.org/https://doi.org/10.1016/B978-0-7506-5686-3.X5246-X.

[21] ASTM C1074-17, Standard Practice for Estimating Concrete Strength by the Maturity Method, ASTM, 2017. https://doi.org/10.1520/C1074-17.

[22] fib (International Federation for Structural Concrete), fib Model Code for Concrete Structures 2010, Ernst & Sohn, 2013.

[23] W.Z. Taffese, Data-driven method for enhanced corrosion assessment of reinforced concrete structures, University of Turku, 2020.

[24] W.Z. Taffese, E. Sistonen, Neural network based hygrothermal prediction for deterioration risk analysis of surface-protected concrete façade element, Constr Build Mater. 113 (2016) 34–48, https://doi.org/10.1016/j.conbuildmat.2016.03.029.

[25] Corrochip, Control and evaluation of corrosion in reinforced concrete, (2022). https://corrochip.com/en/about-corrochip/.

[26] W.Z. Taffese, E. Nigussie, J. Isoaho, Internet of things based durability monitoring and assessment of reinforced concrete structures, Procedia Comput Sci. 155 (2019) 672–679, https://doi.org/10.1016/j.procs.2019.08.096.