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Implementing a technically and economically viable system for recording data inside concrete

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HIGHLIGHTS

- Decision-making in construction projects is key to the quality of structures.
- Integrated monitoring systems play an important role in concrete structures.
- A wireless network facilitates decision-making for builders and project management.
- Cost of the proposed system offers savings of 45.37% compared to existing controls.

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ABSTRACT

As information and communication technologies continuously develop and improve, they are increasingly incorporated into the fields of civil engineering, construction and infrastructure. Decision-making in construction projects is key to being competitive and guaranteeing the quality of structures. Integrated monitoring systems play an important role in concrete structures. Tracking humidity and temperature provides information on concrete hydration and hardening processes. This study focuses on creating a technically and economically viable data recording system. To this end, general purpose dual sensors have been incorporated (for temperature/humidity). With the aim of measuring these values in the interior of concrete, different options for encapsulating the sensors have been examined. An economical proposal of this kind consists of a wireless network that provides data in real time, and therefore facilitates decision-making for builders and project management. Obtaining reliable data from the concrete interior allows us to verify if the hardening process has evolved correctly. In the future, this type of verification test could replace the inspection currently mandated by regulations. The cost of the proposed system offers savings of 45.37% compared to existing controls.

1. Introduction

Recent developments in information and communication technologies have led to their incorporation in the fields of civil engineering, construction and infrastructure. Effective information management for decision-making in construction processes is key to improving one's competitive edge and guaranteeing the quality of the structures. One of the challenges that builders and developers face nowadays consists of determining, first hand and in real time, what is happening on the inside of a structure during the construction phase. With this type of information, they can take steps to accelerate the building process and cut costs, or on the other hand, eliminate any defective structural elements that could compromise the building's structural integrity.

The quality of the building and its capacity to support the design loads depends on the mechanical properties of the concrete when the setting and curing phases have finalized. Unlike steel, concrete is a heterogeneous material that needs a period of time to hydrate and acquire the desired consistency and mechanical resistance [1]. The processes of setting and curing are the result of chemical hydration reactions occurring among the components of cement. During the initial hydration phase (setting), the material changes from a liquid to a solid state. Then, hydration reactions occur until all the concrete has been affected, causing the material to harden and mechanical resistance to increase progressively.

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Under normal conditions, standard concrete begins to set 30–45 min after mixing, and is completely set after 10–12 h. Then, the process of hardening begins, which occurs more rapidly during the first month and then more slowly during the following months, until it is completely stabilized after approximately a year.

The pace of the curing process can be regulated by the amount of plaster added to the clinker while the cement is being made. Furthermore, in a concrete manufacturing plant, different products can be added to control the setting time.

Nevertheless, concrete curing is not affected solely by its composition. But rather, various other factors come into play, such as the dimensions of the structural element, the effectiveness of compaction, and weather conditions during the entire process [2]. The first factor is clearly inherent to the design of the structural element, and the second can be mitigated by efficient on site control of the product's mixing and compaction. The third factor, however, is more difficult to control and can severely affect the curing process. For example, high temperatures with low levels of humidity and high winds can lead to rapid evaporation of water, even from already compacted concrete. In such circumstances, the loss of water must be compensated by curing the concrete to further hydrate it and increase its mechanical resistance. Meanwhile, high levels of atmospheric humidity can delay the hardening process so that the structural component is not ready in time to support the loads (for example, columns needed to support the concreting of the slab above it).

1.1. Monitoring the concrete setting process

In the construction sector, the quality of concrete is traditionally measured by compression tests conducted on cylindrical specimens extracted 28 days after being poured, as established by current Spanish regulations for structural concrete (EHE) [3]. The quality and resistance performance of the concrete are determined according to European regulations [2]. Thus, some control batches are established, samples are used to create cylindrical specimens [4], and consistency is compared with a slump-test [5]. These sample cylindrical specimens [6] are used to measure concrete's resistance properties, after standard curing in moist chambers [7] and the compression test [8,9]. Nevertheless, this system has significant flaws, given that the resistance properties obtained from the cylindrical specimens, which have been cured in a laboratory, can have a very low correlation with concrete that has been exposed to real extreme weather conditions and whose dimensions are greater than those of the specimen.

Based on the abovementioned factors, monitoring the setting and curing processes of concrete in real time and in accordance with on-site conditions (building site) can offer a competitive edge when it comes to making decisions during the evolution of a construction project. Such control would offer greater precision and detail regarding the curing of construction components, effectively increasing the efficiency of the construction process and shifting the decision-making process to an online system. These decisions can influence the pace of construction or decisions regarding demolition as soon as any sort of anomaly is detected in the curing process.

Integrated monitoring systems play an important role in building and maintaining concrete structures. At this time, various different sensors are capable of monitoring long-term structural changes, such as corrosion in the framework, the chemical composition of concrete, humidity and temperature [10].

Over the past few years, interest has grown in developing sensors for concrete structures with the objective of monitoring parameters characteristic of concrete's early ages or of environmental conditions that can lead to structure deterioration. Past research has examined concrete strength at early ages and during the initial stage of hydration [11,12]. Other studies have aimed to detect bond deterioration with sensors combined with ultrasonic waves [13]. Other sensors have utilized fiber optics to monitor cracking in concrete [14]. The sensor proposed in the cited study does not require prior knowledge of the crack locations which represents a significant improvement over existing crack monitoring techniques. And furthermore, the authors claim that one sensor is capable of detecting, locating and monitoring several cracks at the same time. In this same field of research, a more recent study utilized radio frequency technology to locate cracks [15]. Regarding corrosion, Duffó and Farina [16] present an integrated sensor to monitor the state of reinforced concrete structures. This sensor provides measurements of rebar potential, corrosion density, electrical resistivity of concrete, available oxygen, concentration of chloride ions in concrete, and the temperature inside the structure. In 2013, another study investigated how resonant frequency is related to corrosion potential [17]. Walter D. Leon-Salas employs radio frequency to determine corrosion in reinforcements [18].

Monitoring corrosion is feasible when different sensors and methods are employed that are capable of working in the alkaline environment of concrete for several years. Data compiled regarding concrete's corrosion potential and electrical resistance, obtained from real structures exposed to the elements, can be used to determine the rate of corrosion in a particular structure [19–21]. Sensors embedded in concrete close to the surface (less than 50 mm deep) allow the spatial and temporal distribution of the electrical properties of concrete within the cover-zone to be measured [22]. Other studies correlate corrosion with properties of the sensor [23]. In fact, researchers have attempted to quantify corrosion by measuring the time-of-flight of waves passing through rebar [24].

The monitoring of concrete structures could make significant progress if technicians specialized in concrete collaborated with scientists to develop control systems and wireless networks. One such example is found in wireless networks connected to intelligent nodes capable of measuring behavior, filtering, sharing, and combining logs from a vast range of sensors. Key factors of these systems are calibration of the embedded sensors, the reliability of the sensors to be introduced in concrete, as well as their durability in regards to the required service life of the structure in question [25]. Sensors are affected by their location's environmental conditions. Regarding sensors used to measure deformations, a study has examined the performance of different sensors when subjected to variations in temperature [26]. Additionally, in this field, high resolution images have been employed to estimate deformation in concrete beams [27].

Monitoring humidity and temperature provides information about the hydration and hardening processes of concrete. Techniques for tracking temperature and humidity inside concrete have evolved in recent years thanks to various different studies. In 2008, Norris utilized nanotechnology and microelectromechanical systems to measure temperature and internal relative humidity. However, this study found serious problems in the long-term behavior of these sensors, therefore, further research is necessary before they can be put to use [28]. Incorporating a radio frequency integrated circuit (RFIC) and temperature/humidity sensors confirmed the difficulty of emitting data long-distance [29]. Sensors were used in an alkaline environment in the case of civil engineering structures, wherein data collection lasted two months [30]. Other research has focused on examining different frequencies for improving data collection [31]. A particular study combined measuring the concrete's temperature and stress [32]. More recent research has explored the possibility of using acoustic waves to measure concrete temperature [33]. Meanwhile, other studies utilize wireless networks to monitor concrete's permeability [34]. Another study conducted research in the laboratory to design a sensor capable of determining the depth of chloride ion penetra-