Innovative and intelligent technology for in situ early diagnosis and prediction of concrete carbonation progress for predictive maintenance of bridges

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1. Introduction

Carbonation, which is the penetration of atmospheric CO2 into concrete, can lead to corrosion of steel reinforcement, becoming one of the most frequent and serious problems in reinforced concrete structures, which is accelerated by climate change. Carbonation reduces the alkalinity of concrete, deactivating the protective layer of steel and facilitating steel corrosion. By the time, structural damage caused by carbonation becomes visible; it is already at a very advanced stage, which may make it too late to implement preventive or protective measures.

Traditionally, the assessment of the depth of carbonation is done by a semi-destructive test, which consists of spraying a coloured indicator (phenolphthalein) on a sample taken from the structure. This technique is inefficient for large structures, as repetition of the test at multiple points is required to assess the variability of the depth of the carbonation process.

Currently, there is no technology that can accurately quantify the depth of carbonation and predict its evolution in real time. To address this need, this work has been proposed to develop and demonstrate, in an operational environment, an innovative system composed of several modules. This system will include a multi-sensor unit coupled to advanced data processing based on artificial neural networks to accurately determine the depth of carbonation from continuous recordings of the bridge surface.

In addition, a probabilistic approach to predict the evolution of carbonation and a specific algorithm to integrate these developments with existing vibration-based technology for structural diagnosis of bridges will be developed.

2. Methods

The methodology of this study involves a detailed analysis of the factors relevant to the experimental design, as well as the identification of the sensor modules and other components necessary for the assembly of a required multi-sensor unit.
The electrical resistivity of concrete, measured using the **Wenner Probe** [1], is a crucial factor in the study of carbonation. This method involves the excitation of the concrete sample by the ends of the four-pronged electrode, measuring the voltages at the intermediate points. In

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addition, a sensor is incorporated which measures the circulating current. Dividing the voltage by the measured current gives the electrical resistance of the sample, which is then used to calculate the resistivity of the concrete, assuming a homogeneous distribution of voltages over a half-sphere. This provides valuable information on the degree of carbonation and the state of deterioration of the concrete.

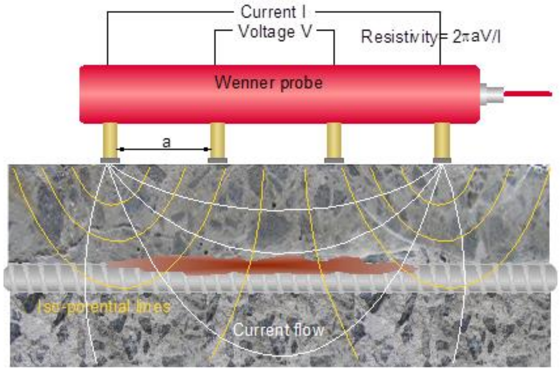

Figure 1. Wenner Probe configuration. Image from [2]

$$\rho = \frac{2\pi a V}{I}$$

Where: ρ is the electrical resistivity (kΩ-cm), a = distance between electrodes (cm), V is the voltage (V) and I is the current (A).

It is proposed to develop a new multi-sensor unit that also incorporates humidity and temperature recordings on the surface of the concrete element, in order to improve the accuracy of electrical resistivity measurements.

From the carbonation depth measurements determined from the developed equipment, probabilistic algorithms will be developed for the prediction of carbonation depth over time. These algorithms will be derived using an advanced mathematical approach that will take as input the results of various laboratory tests on different concrete specimens subjected to different levels of accelerated carbonation [3]. These tests involve the production and curing of concrete specimens according to a combination of different specified mixtures.

Taking into account all developments, advanced data processing techniques are employed to extract meaningful information about the carbonation depth of the concrete from the collected data. The data obtained are subjected to detailed analysis using algorithms based on artificial neural networks (ANN). In the neural network, a variety of factors are taken into account, including the type of cement, the water/cement ratio, the aggregates used, the admixtures present, as well as the percentage of carbon dioxide (%CO2) in the atmosphere, the ambient temperature, the ambient humidity, the presence of water, among others. These factors are critical to understanding and predicting the carbonation depth of concrete accurately and efficiently.

$$x(t_f) = x_0 + \int_{t_0}^{t_f} k(t) \cdot \sqrt{t}\, \mathrm{d}t = x_0 + \sum_{t_0}^{t_f} K_{tx} \cdot \sqrt{t_x - t_{x-1}}$$

Where x represents the carbonation penetration in mm, K is a factor depending on environmental conditions and t is the elapsed time in years.

In addition, a concrete carbonation prediction system will be implemented to detect the propagation period and the carbonation period [4]. This system will use predictive models based on historical data and concrete characteristics to predict the progression of carbonation and the times when the carbonation depth will reach certain critical thresholds. This will enable better maintenance planning and management, as well as a proactive response to concrete deterioration problems due to carbonation.

Multiple configurations will be generated and validated to integrate the devices in different scenarios, considering bridge locations, recording frequencies, and model complexity. A cloud platform will be developed to process and visualise data, with infrastructure in AWS and storage in MongoDB. The configurations will then be validated through installation simulations on concrete structures with different degrees of carbonation, adjusting the system as necessary for implementation on real bridges.

3. Results

The key outcome of this study is that the neural network, by taking into account all relevant factors, will provide an approximation of the level of carbonation in concrete. The neural network will be trained using a comprehensive and diverse dataset, covering a wide range of scenarios and conditions.

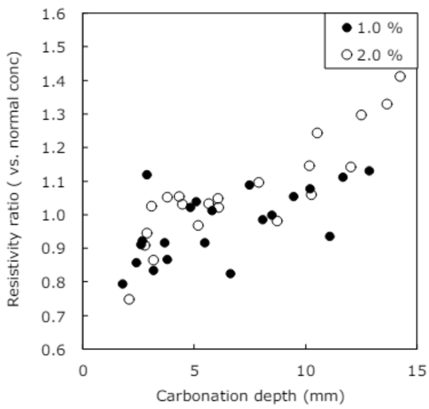

Figure 2. Resistivity VS Concrete Carbonation. Image from [5]

The results of the work will contribute to the acquisition of knowledge on data science, predictive maintenance, automation and smart infrastructures thanks to a disruptive approach that proposes the use of probabilistic methods to determine the evolution of a concrete deterioration process such as carbonation in civil infrastructures and its integration with a Digital Twin of the structure.

4. Conclusions

The findings of this study highlight the importance of the application of non-destructive techniques in the condition assessment of concrete infrastructure. This innovative approach represents a significant advance in the ability of civil engineering to effectively understand and manage the carbonation process in critical structures.

By obtaining an accurate estimate of carbonation through this non-invasive approach, engineers and maintenance managers can make informed decisions about infrastructure management and maintenance. This includes implementing preventive and corrective measures in a timely manner, helping to ensure the long-term safety and durability of structures.

Ultimately, the results of this study support the importance of technological innovation in civil engineering by providing advanced tools and methodologies that enhance the ability to manage and maintain critical infrastructure in an efficient and sustainable manner.

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