Portable Measurement Systems Based on Microcontrollers to Test Durability of Structures: Mini-Review

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Corrosion presence is a recurrent concern in buildings and structures that use steel as their core or as reinforcement, due to the change of steel's properties caused by this phenomena. Therefore, methods to detect and quantify corrosion had been developed; some are based on electrical and electrochemical measurements. On reinforced concrete structures, sometimes there are exposed steel bars which are visible, but on those, a visual inspection could determine corrosion presence. There exist different options to measure the steel bars’ corrosion and its level. The more straightforward consists of cutting through the concrete until the bar is exposed and connecting a measurement device there. A disadvantage of this technique is that steel has to be exposed to the environment during the measurement; as an alternative, novel contact-less electrochemical techniques are getting more popular. Recent advances in low-cost and portable electrochemical devices and embedded sensors can change how the structures are tested. Moreover, there is a discussion about how those devices, if developed for other fields as biosensors, can assist in other areas. This mini-review also gives some hints of what the future trends could be due to the combination of those areas.

Keywords: portable device, cyclic voltammetry (CV), steel corrosion, electrochemical impedance spectroscopy (EIS), corrosion

INTRODUCTION

From long ago, humans had been building bridges to connect cities, countries, and overcome obstacles; the materials used in these constructions have changed over the times, from the stone and wood to the modern bridges made of steel and concrete. These structures require periodical maintenance to keep them well, but a common cause of problems in bridges is corrosion in the steel bars due to the environment. In particular, the changes in temperature can cause small dilatations and contractions; also, the rainfalls could raise the humidity. These factors increase the probability that corrosion appears on the steel bars used during the construction. However, some researchers had developed models to predict corrosion (Tuutti, 1982; Guo et al., 2019) that are used to estimate the aging of a structure and the corrosion in advance. A fast approach to these models is using a Finite Element Method (FEM) and simulating Reinforced Concrete behavior due to corrosion as in Bossio et al. (2015). This corrosion could affect the durability of the steel and also reduce its ability to sustain strain, reducing the stress threshold as modeled in Deng et al. (2018).
For example, the ultimate flexural capacity of reinforced concrete elements is decreased due to the corrosion of steel, as pointed out by Bossio et al. (2019b), they compared a set of experimental data against a non-linear FEM model. Nethertheless, the seismic capacity is directly affected by the corrosion level (Bossio et al., 2019a) shows how the mechanical properties such as ductility of the structure are affected, leading to structural failure during an earthquake. However, some researchers (Bossio et al., 2018) are working in a High-Performance Concrete (HPC) that could aid the structure to sustain stress and improve the structure ductility even in advanced corrosion levels. However, researching (Formisano et al., 2018, 2019) discussed the use of non-destructive tests such as the leed hardness test to measure steel properties. These tests use a penetration device, which punctures a sample with a fixed force and measure the dent on the steel. Which using conversion tables can achieve the estimation of the material hardness. Otherwise, Di Lorenzo et al. (2019) and Rizzo et al. (2019), present corrosion wastage models; which could be used to predict corrosion in steel. The model proposed by Rizzo et al. (2019) can estimate the corrosion depth in structures made of wrought iron. Meanwhile, the model of Di Lorenzo et al. (2019) based on experimental data obtained a model calibrated with measurements on both mild carbon and weathering steels.

There exist experimental measurements of corrosion propagation that use steel plates and a corrosion chamber that simulate environmental conditions (Odrobiñak and Gocôl, 2018). Such conditions are set to induce accelerated corrosion to model the behavior of steel of similar specifications on bridges. Authors of Alexander and Beushausen (2019) present a review of different ways to determine durability or service life prediction of RC structures. However, it critiques some of the current approaches and proposes the use of worldwide specifications and models that improve those parameters. Some common ions speed up the corrosion in the RC structures. One of the most studied is the Chloride ion, the penetration in the concrete (Wang et al., 2018), how it interacts with cracked concrete (Kušter Marić et al., 2020), and how it is transported to the steel. These studies lead to models that can characterize how the transport changes depending on the wetting/drying cycles (van der Zanden et al., 2015; Kušter Marić et al., 2020).

In this mini-review, standard corrosion detection methods are presented, including commercial devices used; the third section shows recent developments in terms of low-cost and portable devices that meet similar criteria, also embedded sensors, and a benchmark. Finally, the last section presents a vision of future trends that gives hints about what problems these devices could solve.

**TYPICAL TECHNIQUES OF MEASUREMENT**

For bridges made of reinforced concrete, it is necessary to estimate the corrosion rate of steel embedded inside the concrete; for this, several techniques had been developed throughout the years. Usually, a routine inspection consists of a visual test looking for rust or cracks in the structure, which could not give an accurate measurement of corrosion and its level inside the structure. On Marić et al. (2019), authors present some study cases of bridges and how the use of non-destructive techniques in routine inspections can lead to more accuracy in finding steel corrosion and their level inside structures. The most used technique is the Half-cell potential (HCP) (Poursae, 2016), which is used to detect corrosion resistance of steel bars using a single contact point in the bar (electrode), and a second electrode on the concrete surface (Kawaai et al., 2019). Another common technique is linear-polarization-resistance (LPT). This technique involves applying a small voltage (usually about 30 mV) above and below its corrosion potential to the steel bar while the current is measured; with this, the polarization resistance (Rp) could be estimated, which is defined as the slope of the current-potential curve. Also, making use of the Tafel plot obtained, the corrosion rate could be estimated (Alexander and Orazem, 2020a). This technique requires a direct connection to the steel, which in some cases, implies digging across the concrete to expose the steel. To avoid this situation, researchers had explored the use of electrochemical analysis (Keddam et al., 2009; Alexander and Orazem, 2020b), with contact-less measurements, which could calculate steel corrosion using Electrochemical Impedance Spectroscopy (EIS). Those tests are made with lab potentiostats such as Gamry Reference 3000 (Gamry, USA) or VersaSTAT 4.0 (Princeton Applied Research).

The LPT analysis of reinforced concrete by EIS is used to obtain the polarization resistance (Rp) of the bar; this is on the EIS Nyquist charts. The typical impedance values could vary from 100 kΩ to 10 kΩ; this difference could vary by electrodes distance and position, as described by Alexander and Orazem (2020a), where the Rp measured in the same reinforced concrete sample changed by 10 times due to the position of the electrodes on the surface. However, the corrosion measurement by impedance techniques could also test the effectiveness of anti-corrosive coatings, testing coated and uncoated samples (Alvarez-Pampliega et al., 2014; Raj et al., 2020) to test anti-corrosive coats properties. Those tests and measurements require an advanced electrochemical device such as the Autolab PGSTAT302 and algorithms developed to extract the information from the data like MATLAB.

**ELECTRONIC TECHNIQUES AND PORTABLE DEVICES**

There are currently attempts to reduce the size of electronic measurement devices, while keeping their characteristics and operation ranges. A field with a significant amount of these devices is the biosensors, in which they research low-cost and portable potentiostats suited for electrochemical tests. Some of those devices can carry out most of the standard electrochemical tests. For example, Segura and Osma (2017) developed a miniaturized potentiostat that can do Cyclic Voltammetry (CV). With applied voltages from $-1.65$ to $1.65$ V, measured currents from 80 µA to 10 mA, and impedances in the range of 50 Ω to 20 kΩ. Other devices, like a low-cost amperometric device, can do...
CVs with a voltage range from 0 V to 5 V, and current measures up to 4.5 µA, with USB and Bluetooth connectivity (Agustini et al., 2020). Some of them had EIS measurement capabilities with a portable setup (Pruna et al., 2018; Barreiros dos Santos et al., 2019; Jenkins et al., 2019), with voltage and current ranges that could be used to measure corrosion. There are even open-source projects which share all the information required to build one of those portable devices. For example, Dobbelaere (2017) presents a potentiostat/galvanostat, design, and fabrication. Also Steinberg et al. (2015) developed an open-source potentiostat ABE-Stat with the EIS technique; this technique could be used on corrosion detection, as illustrated by Eid et al. (2020), Etim et al. (2020), and Kenny and Katz (2020). Figure 1, presents some of the portable devices mentioned in this section, those devices are portable and their cost is a fraction of commercial laboratory equipment.

However, other elements, such as embedded sensors, could improve a portable device corrosion measurement. For example, chloride-induced corrosion is a significant threat to reinforced concrete (Sandra et al., 2020); this is common in places near saltwater (Honglei et al., 2020). This effect had been studied for a long time, leading to experimental data and simulations (Chen et al., 2020). However, there exist researchers who are working on the detection of the presence of chloride ions. For example, Torres-Luque et al. (2017) developed a chloride-ion detector made to be placed inside the reinforced concrete during the building process. This sensor detects and measures the concentration of chloride-ions, using capacitors made of Calcium Aluminate. Due to the geometrical disposition of the capacitors, it had the potential to measure the corrosion direction. Furthermore, its low cost and small size make it possible to be placed throughout the entirety of the bridge or structure. Table 1 presents a comparison between commercial devices and some of the portable devices mentioned in this section.

**DISCUSSION**

Corrosion and electrochemical tests, in general, require complicated and expensive devices and specialized laboratories.
Nevertheless, due to recent advances in technology, some researchers had developed their own low-cost and portable devices, which gives technological independence. Additionally, those custom made devices had small dimensions, making them portable and a perfect choice for fieldwork. The portability also refers to the supply voltage independence, which is usually of 5 V. This voltage could be easily provided by batteries or any USB port from a laptop. Some of them even could be powered remotely by NFC technology, which makes them perfect for embedding inside the concrete, and carrying out measurements in place, reporting data wirelessly to a smartphone or a laptop. This option could yield to obtain and process the data in situ, which gives an advantage over the commonly used processes.

Therefore, some commercial brands have also started developing their own portable devices, but they still are expensive. However, they have excellent specifications, and this takes advantage of the know-how and the infrastructure that backs them up. Nevertheless, there exists a gap when there are large structures such as bridges or buildings, for which it may be beneficial to have more readouts and even to have embedded sensors and devices that allow continuous monitoring of the corrosion. In the future, those low-cost devices could be embedded in a large structure, and using IoT technologies and lots of sensors, can create a mesh that could get a fast measurement of the status of the structure and how the environment affects it over time.

**AUTHOR CONTRIBUTIONS**

Both authors made substantial contributions to the present review in equal shares.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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