IBRACON Structures and Materials Journal
Revista IBRACON de Estruturas e Materiais
ISSN 1983-4195 ismj.org

ORIGINAL ARTICLE

Durability monitoring of existing reinforced concrete structures: concepts, advancements, and prospects

Monitoramento da durabilidade de estruturas de concreto armado existentes: conceitos, avanços e perspectivas

Alessandra Augusto Costa[a]
Valdecir Angelo Quarcioni[b]

[a]Instituto de Pesquisas Tecnológicas – IPT, Programa de Pós-graduação em Habitação: Planejamento e Tecnologia, São Paulo, SP, Brasil
[b]Instituto de Pesquisas Tecnológicas – IPT, Laboratório de Materiais para Produtos de Construção, São Paulo, SP, Brasil

Received 20 October 2023
Revised 12 January 2024
Accepted 14 February 2024

Abstract: This article explores the fundamental concepts related to the durability of existing reinforced concrete structures, focusing on its monitoring. It compares the current approach adopted in major projects with that applied to other structures in service. It presents the principles of Structural Health Monitoring (SHM) and examines various sensor solutions available on the market and developed in research projects. It emphasizes the feasibility of democratizing structural monitoring, which is currently limited by cultural barriers. To achieve this, it highlights the need for collaboration among technical professionals, researchers, professional associations, and government agencies to overcome the challenges that have led to the so-called "control blackout" in the built environment.

Keywords: durability, prevention, monitoring, sensing, reinforced concrete.

Resumo: Este artigo explora os conceitos essenciais relacionados à durabilidade de estruturas de concreto armado existentes, com vistas ao seu monitoramento. Compara a abordagem atual adotada em grandes obras com aquela aplicada às demais estruturas em serviço. Apresenta os princípios do Structure Health Monitoring (SHM) e explora diversas soluções de sensores disponíveis no mercado e desenvolvidas em projetos de pesquisa. Destaca a viabilidade de democratizar o monitoramento estrutural, atualmente limitado por barreiras culturais. Para isso, enfatiza a necessidade de colaboração entre profissionais técnicos, pesquisadores, entidades de classe e órgãos governamentais, a fim de superar os desafios que levaram ao chamado "apagão" de controle no conjunto construído.

Palavras-chave: durabilidade, prevenção, monitoramento, sensoriamento, concreto armado.

How to cite: A. A. Costa and V. A. Quarcioni, "Durability monitoring of existing reinforced concrete structures: Concepts, advancements, and prospects" *Rev. IBRACON Estrut. Mater.*, vol. 17, no. 6, e17614, 2024, https://doi.org/10.1590/S1983-41952024000600014

1 INTRODUCTION

The use of reinforced concrete in Brazil dates to the early 20th century and has since been increasingly employed in the construction of buildings, warehouses, bridges, tunnels, dams, monuments, and more.

Of the four stages in the construction process - conception, design, execution, and utilization - the latter is the longest-lasting and generally lacks the supervision of qualified professionals. As a result, the initial assumptions of the project and construction may deteriorate without knowledge of its occurrence [1].

Considering that older civil construction materials and technologies do not favor structural durability, the performance of materials and their structures decrease over time. Additionally, there is no established and widespread practice of civil maintenance, creating a concerning scenario regarding the safety of aging buildings in service. This situation results in a "control blackout" within the built environment.

Corresponding author: Alessandra Augusto Costa. E-mail: acosta@planuseng.com.br
Financial support: None.
Conflict of interest: Nothing to declare.
Data Availability: Data-sharing is not applicable to this article as no new data were created or analyzed in this study.

Continuous use of buildings without maintenance actions or inadequate implementation of such actions may lead to situations where the technically and/or economically feasibility of recovery is no longer viable, leading to demolition. This is the case of the São Vito and Mercúrio buildings in the city of São Paulo/SP, which were built in the 1950s as solutions for low-income housing and demolished in 2011, resulting in the loss of hundreds of housing units.

It is essential to emphasize that the end of the design service life should not be interpreted as an automatic decision to demolish.

In a country with a housing deficit estimated at 5.8 million dwellings, according to data from the João Pinheiro Foundation [2], the preservation of structures goes beyond technical aspects and strongly contributes to social issues.

Furthermore, in times of global environmental preservation efforts, demolition techniques are being reevaluated, since the construction industry generates more than 3.1 billion tons of waste worldwide annually [3] and consumes between 40% and 75% of the raw materials produced on the planet [4].

If "It is unfeasible, from an economic standpoint and unacceptable from an environmental perspective to consider buildings as disposable products, subject to simple replacement by new buildings (...)" [5, p. VI], then the degradation of structures must be monitored throughout their life cycle. This monitoring provides the basis for interventions at the appropriate time, thereby maximizing the building's service life within desirable parameters of reliability and safety.

Based on the reasons mentioned and associated with economic, social, and environmental aspects, this paper explores relevant topics on the durability monitoring of existing reinforced concrete structures. It emphasizes the importance of using sensors in this context and explores the possibilities of making this practice accessible to a wide range of structures, aiming at its democratization.

2 FUNDAMENTALS OF DURABILITY

Throughout their service life, all structures are subject to aging, whether natural or accelerated, as a result of the influence of aggressive agents present in the environment, changes in use, accidents, and other factors.

Effective monitoring of structural durability requires a suitable monitoring design. This, in turn, demands knowledge of important concepts, presented in this section.

2.1 Main concepts

Durability is understood as the ability of a structure, system, subsystem, or component to meet performance requirements, withstand environmental influences, and perform its functions, under conditions of use and for the defined service life period, provided that planned maintenance actions, preventive and corrective, as outlined in the operation and maintenance manual, are implemented [6]–[8].

Performance can be defined as the capacity of a building, structure, system, subsystem, or component to fulfill its predetermined functions. It can also be represented by the behavior in use [7] or by the impact on economic, environmental, societal, or quality of life conditions, for which requirements are those demanded by the involved parties, including users, owners, contractors, society, and the environment [9], [10].

Service life is described as a time measure of durability, which can be extended if maintenance actions are implemented from the time of delivery [7]. It is the period during which the structural characteristics are maintained without significant interventions [6] or when the performance requirements are met [9].

From this concept, two others derive: the design service life, concerning the period in which performance requirements must be met [9] or exceeded [8], defined in the design stage and guiding the entire construction process [7]; and residual service life, the remaining period during which the performance requirements are met, considering the implementation of the established service criteria such as maintenance and quality control [9].

A relevant factor that directly affects the durability and, consequently its performance and service life, is related to environmental aggressiveness. The interaction between them results in physical and/or chemical changes in the structures, components, and systems of a building. Therefore, the classification of environmental exposure is valuable not only for the design phase, but also for defining the parameters to be monitored during structural monitoring.

In Brazil, the structural design standard NBR 6118 considers the environmental aggressiveness as one of the guidelines for durability and establishes four classes of aggressiveness according to the type of environment and the potential for structural deterioration, forming main groups. However, a more comprehensive definition of environmental exposure classes is found in ISO 22965-1 standard, adopted by the European Committee for Standardization (ECS). In this technical standard, the main groups of structural deterioration are discretized into 18 classes and grouped according to the source of corrosion and/or deterioration risks, including categories such as concrete carbonation, presence of chlorides, freeze/thaw cycles, and chemical actions [9].

Regarding structural degradation, based on Tuutti's principle [11], it can be divided into two phases: formation and development. In this context, the Initiation Limit State (ILS), which marks the beginning of a significant deterioration process or the gradual transition to the undesirable performance domain [12], can be understood as the transition point between these two phases, as illustrated in Figure 1.

It is observed that the identification of the ILS, which precedes the visualization of anomalies, plays an essential role in ensuring durability, as it favors the implementation of interventions, preventing the structure from reaching critical levels of degradation and thus maximizing its service life.

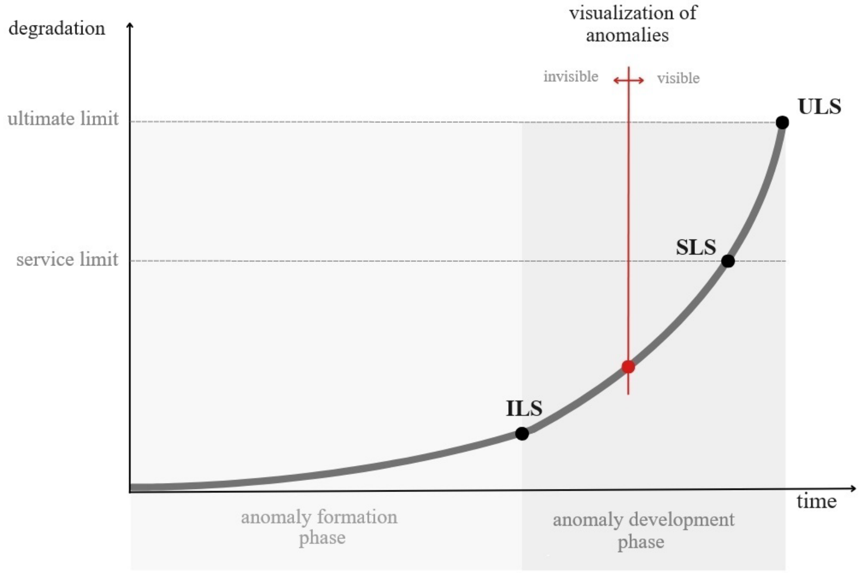


Figure 1. Illustration of the process of formation and development of anomalies and the relationship with Initiation Limit State (ILS), Serviceability Limit State (SLS) and Ultimate Limit State (ULS).

2.2 Agents, mechanisms, and effects of degradation

Degradation in reinforced concrete structures can affect the concrete components, the reinforcement, or both.

To understand the degradation processes and the aspects that should be addressed in structural monitoring, it is essential to explore concepts from the field of *construction pathology*.

The term anomaly refers to irregularities and can be subdivided into mechanisms and effects of degradation. A degradation mechanism is understood as any action, internal or external to the structures, promoted by an agent capable of reducing their capacity or function over time, such as abrasion, temperature, fatigue, and chemical attack. The physical manifestations of these mechanisms are referred to as degradation effects, such as cracks, disintegration, and segregation.

In summary, there is a causal relationship: an agent triggers a mechanism, which, in turn, results in a degradation effect.

ISO 19208 standard classifies degradation agents as mechanical, electromagnetic, thermal, chemical, and biological [10]. ACI 349.3R standard lists the mechanisms and effects of degradation for reinforced concrete structures degradation related to nuclear safety [13]. Apart from irradiation, the content is applicable to other concrete structures.

The correlation between the elements of this causal relationship is presented in Table 1.

2.3 Factors influencing the durability of reinforced concrete structures

The parameters discussed in this section are directly related to the durability of structures and the rate of damage propagation, influencing their vulnerability to degradation agents. In the context of monitoring, these parameters are crucial for building an understanding of the structure's behavior as it ages and for identifying the risks that structures are exposed to. They also play a role in predicting residual service life.

Table 1. Correlation between agents, mechanisms, and effects of degradation

	Degradation agents	Degradation mechanisms	Degradation effects
Mechanical	Gravity	External loads	Cracks, deformations, collapse
	Forces imposed or restricted by deformations	Settlement loads	Cracks, deformations, collapse
	Kinect energy	Volume changes	Cracks, deformations
		External loads	Cracks, deformations, collapse
	Vibrations and perturbations	Fatigue	Cracks, deformations, collapse, human discomfort
Electromagnetic	Radiation	Thermal exposure	Stains, cracks, concrete spalling, deformations, collapse, human discomfort
	Electricity	Corrosion	Cavitation, loss of material, cracks, concrete spalling
	Magnetism	Corrosion	Cavitation, loss of material, cracks, concrete spalling
Chemical	Water and solvent	Chemical attack	Stains, efflorescence, loss of material, cracks, concrete spalling, corrosion
		Abrasion / erosion	Cavitation, loss of material, cracks, concrete spalling
		Leaching	Efflorescence, corrosion, cracks, concrete spalling, deformations, collapse
		Steam impact	Stain, loss of material
	Oxidizing agents	Chemical attack	Stain, loss of material, cracks, concrete spalling, corrosion
	Reducing agents	Chemical attack	Stain, loss of material, cracks, concrete spalling
	Acids	Chemical attack	Stain, loss of material, cracks, concrete spalling, corrosion
	Bases	Chemical attack	Stain, loss of material
	Salt	Chemical attack	Stain, loss of material, cracks, concrete spalling, corrosion
	Chemically neutral	External loads	Cracks, deformations, collapse
Biol.	Vegetal and microbial	Biological attack	Stain, loss of material
	Animal	Biological attack	Stain, loss of material

Font: Adapted by the authors based on ISO 19208 [10] and ACI 349.3R-18 [13].

2.3.1 Material parameters

Two main intrinsic characteristics of hardened concrete indicate its ability to resist the penetration of aggressive agents present in the environment, whether they are in the liquid or gaseous form: diffusivity and permeability. This is because the transport of ions in concrete occurs through the processes of ionic diffusion and gas and liquid permeation, which trigger chemical reactions leading to the dissolution and hydrolysis of hydrated products and precipitation of compounds. These processes can result in increased porosity, cracking, spalling, and loss of mechanical strength [14].

Another influential characteristic of durability is the type of cement. In general, all of them are appropriate for a wide range of structures and applications. However, for specific cases, certain types of cement, such as high-alumina cements, pozzolanic cements, and sulfate-resistant cements, prove to be more advantageous, particularly in chemically aggressive environments [15].

2.3.2 Structural parameters

For reinforced concrete structures, the concrete cover depth is a paramount factor for their durability. The thicker the cover, the greater the protection (both physical and electrochemical) it provides to the reinforcement, especially against the external environment, which is often more acidic than the concrete itself.

Mechanical stresses and forces must also be considered, as they can lead to cracking, making the affected element susceptible to the aggravation and acceleration of chemical attacks [14].

The durability is also influenced by its shape, considering its geometry and dimensions, as well as its location. Structures exposed to tidal zones, wetting and drying cycles, or even different climatic conditions, such as a pillar with one face exposed to the elements and the others protected, can all be affected differently.

2.3.3 Environmental parameters

According to Escadeillas and Hornain [14], the chemical durability parameters related to the environment include the following: the physical nature of the agent (whether it's liquid, gaseous, or solid), the chemical nature of the agent (its concentration and triggering action); the relative humidity of the environment; the temperature, and the mobility of the aggressive medium.

The classification of environmental aggressiveness proposed in ISO 22965-1 standard, mentioned earlier, is quite comprehensive and helps to define the environmental parameters.

2.3.4 General parameters

Economic aspects of construction are reflected in the construction standards, representing a greater or lesser susceptibility of the structure to the effects of aging, depending on the quality of materials, labor, and techniques employed [14].

The history of a structure has a significant influence on its longevity, and therefore, must be documented and considered when characterizing a structure for monitoring. In this context, events (such as accidents, incidents, etc.) and interventions, whether corrective or preventive, carried out or planned, should be recorded.

3 MONITORING THE DURABILITY OF EXISTING REINFORCED CONCRETE STRUCTURES

3.1 Current approach

Technical inspection and structural monitoring routines are employed in large-scale infrastructure projects, such as dams and special structures.

The National Dam Safety Policy, Brazilian Federal Law No. 12.334/2010, in its article 2, defines "dam safety" as a condition that aims to maintain its structural and operational integrity and the preservation of life, health, property, and the environment. To achieve this, the legislation requires the development and implementation of the Dam Safety Plan (DSP), a technical document specifically prepared for each dam. The DSP establishes detailed guidelines and procedures for inspection, monitoring, maintenance, and risk control. All the collected information is organized and made available in the National Dam Safety Information System [16].

The Itaipu Dam website provides information about the composition of its DSP, which includes visual inspection, auscultation, seismological monitoring of the dam and reservoir area, as well as instrumentation, consisting of a set of 2,400 instruments and over 5,000 drains for monitoring the performance of concrete structures and foundations [17].

Special structures are also cited as structures that are commonly monitored. According to Santos [18], the Rio-Niterói Bridge, inaugurated in 1974, already contained measurement equipment for evaluating the behavior of concrete, such as vibrating string strain gauges and thermocouples. Wires and a clinometer were also installed to evaluate vertical and horizontal displacements relative to the deck and monitor rotations, as shown in photographs taken at the time of construction and presented in Figure 2.

Figure 2. Instrumentation for the Rio-Niterói Bridge installed during its construction [18, p. 3].

Currently, although there is no information on the monitoring system on the website of the company responsible for the operation and maintenance of Rio-Niterói Bridge, it is generally known that instruments for real-time monitoring of structural behavior and durability parameters are maintained in special structures.

The Regulatory Agency for Delegated Public Transport Services of the State of São Paulo requires concessionaires to carry out systematic inspections of bridges and viaducts as a fundamental measure to ensure the safety of the road infrastructure and users. These inspections are divided into three categories: initial, routine, and special, and in each of them, classifications are assigned to assess structural, functional, and durability requirements, to identify damage and promote interventions when necessary.

Tunnels, ports, and airports also benefit from structural monitoring systems. It is notable that buildings were not mentioned in the technical literature and legislation consulted, therefore, monitoring systems remain limited to infrastructure works, especially large-scale and/or relevant ones.

Given the above, it can be observed that there is no shortage of knowledge, methodologies, tools, and equipment to support structural monitoring. However, when it comes to other buildings, which also age and have the potential to cause serious accidents and irreparable losses, the same level of safety concern is not perceived compared to infrastructure works.

At the end of 2022, a bill that had been under consideration since 2014, aimed at creating a National Building Maintenance Policy, similar to that of dams, was permanently archived in the Brazilian Federal Senate.

Its content established the mandatory periodic technical inspections in public or private buildings, whether residential, commercial, industrial, among others. Furthermore, among the objectives of this bill were ensuring compliance with safety standards for buildings and promoting a safety culture in their use [19].

The disparity in efforts to monitor and ensure the safety of different types of structures is evident, which can be explained by the lack of awareness, non-specific legislation, resource prioritization in other areas, among other factors.

A joint effort involving technical professionals and government agencies will be crucial to promote public awareness and establish a culture that encourages the adoption of structural monitoring processes for all types of buildings, not just infrastructure projects.

3.2 SHM (structure health monitoring) concepts

SHM, an acronym for Structure Health Monitoring, has been studied since the 1960s and its application is aimed at equipment and structures, such as bridges, aircraft, machines, etc. In general terms, it consists of a set of non-destructive techniques that aim at the early detection and characterization of damage, allowing the maintenance management and the control of the safety of structures [20].

In practice, the process involves installing sensors in the structure, and the data collected is stored, processed, and analyzed using interpretation algorithms to characterize this damage. This whole system is referred to the SHM platform - from input to output, from hardware to software.

Mesquita [21] proposes a classification of SHM platforms into five levels, expanding the model proposed by Rytter (1993). They are:

- *Level 1*: platforms that allow for early damage detection;
- *Level 2*: those that provide data on the onset and location of the damage;
- *Level 3*: those that provide, in addition to the previous information, data on the type, intensity, and geometry of the damage;
- *Level 4*: those that characterize the structural risks, in addition to providing the information from the previous levels; and
- *Level 5*: platforms that, in addition to all the previous information, enable the prediction of the remaining service life of the monitored structure.

According to Chandrasekaran [22], the implementation of SHM is structured in seven stages, described below:

1. *Definition of eligible structures*: based on technical and strategic data, the structures to be monitored are listed. For example, structures that feature innovations in design, construction, or materials; structures associated with uncommon environmental risks, such as geotechnical, seismic, or those placed in corrosive environments; structures of strategic importance, such as offshore installations, nuclear reactors, dams; structures whose failure results in significant impacts, such as railways, bridges, aqueducts, reservoirs, etc., existing structures with known deficiencies, among others.
2. *Identification and analysis of risks*: in this stage, the risks to which the structures to be monitored are subjected are identified and the potential events and degradation agents that could potentially affect them are listed.

   The parameters described in item 2.3 should be taken into account to guide this step.

3. *Responses of structures to risks*: for each of the risks identified in the previous stage, the anticipated consequences, such as physical and chemical changes that result in safety or durability issues, are assigned. These consequences must be quantified and the locations of the highest probability of occurrence mapped, which is crucial for sensor placement.
4. *Development of the SHM project*: the project should preferably be developed by a multidisciplinary team, considering that expertise in civil, electrical, electronic, and computer engineering is required. In this stage, suitable types of sensors are selected, their quantity, location, and reading range are defined, and the installation requirements, whether embedded or surface-mounted, are listed. It's also crucial to identify technical and economic constraints.

Also in this phase, the data acquisition system is defined, listing the types, quantity, and location of data collectors, which will transform the data into information to be monitored.

Finally, the data management system is defined, i.e. the software. The SHM project should include: the sensor list, the architectural layout with installation locations, the installation plan, the wiring layout, and the installation procedures for each type of sensor.

Throughout the SHM project development process, three types of constraints must be verified: technical, technological, and economic. Technical constraints involve assessing the suitability of devices for the environment, accessibility to installation sites, power supply, data transmission, noise considerations, and other factors. Technological constraints include assessing the suitability of sensors, transducers, and transmitters for the specific application, such as operating ranges, data flow capacity, acuity, etc. Finally, economic constraints cover resource limitations, component availability, and operating costs.

In some cases, constraints may require the implementation of the monitoring system in phases. For these cases, the project must be structured considering a planned sequence of deployment packages, allowing monitoring to begin for the most critical aspects and enabling its completion within the established deadline.

5. *Installation and calibration*: the phase of installing the monitoring system, with procedures that should adhere to the sensor manufacturers' recommendations and the project specifications. Once installed and interconnected, the sensors need to be calibrated and tested, a process known as Field Acceptance Testing, in other words, the commissioning or delegation of the installed system.
6. *Data acquisition and management*: the data acquisition system, which is designed to receive, prepare, and store data collected by sensors for subsequent transmission and analysis, is generally operated by development platforms that use microcontrollers, such as *Arduino* and *Raspberry Pi*. Continuous data acquisition may require initial processing on-site to filter and reduce the amount of data transmitted, to avoid system oversizing and facilitate subsequent analysis [23].

Transmission can be performed through different means, such as cable, radio frequency, Wi-Fi, Bluetooth, and others.

In the data processing phase, the information resulting from the acquisition system is processed through algorithms and programming, organizing it into outputs useful for subsequent analysis, such as graphics, tables, and reports. Alarms are also configured in this phase, which indicate the need for interventions.

7. *Evaluation of monitoring data*: In this stage, data is periodically assessed and it is the responsibility of the person in charge to identify the incipient onset of any type of damage.

The action plan is defined, listing the procedures to be adopted, ranging from simple interventions to the withdrawal of the monitored structure from service.

In addition, the analysis of the monitoring results allows the manager to identify trends, schedule interventions, as well as predict service life remaining, which are crucial information to understand the real structural condition, prevent failures, and minimize losses.

As presented, SHM can be defined as the risk management process, tailored to the specificities of a given structure and the environment in which it is situated, based on data collected by a network of sensors, throughout the structure's lifespan, facilitating early damage detection and timely action.

3.3 Sensors

The development of industrialization processes has led to the need for reading and understanding various physical quantities. This served as the catalyst for the creation and improvement of sensors, supported by knowledge of electronics and data processing.

Their use, originally stemming from industrial demands, has expanded to a variety of sectors, including health, safety, agriculture, the environment, and technology.

In the construction industry, sensors are used, for example, in concrete plants, material management on the construction site, home automation, and, more recently, in clothing and some personal protective equipment, enhancing the safety of workers on site.

Specifically, in terms of structural monitoring, sensors are commonly used to measure vibrations, accelerations, and displacements in static and dynamic load tests and in the monitoring of special structures. Deformometers, water level gauges, and inclinometers are also used in the continuous monitoring of dams, which is a well-established practice.

For other buildings, as mentioned, it is noted that both the monitoring of structural durability and the use of sensors in these systems, which would provide guidance data for decision-making, are very rarely disseminated and practiced.

Furthermore, the market offers a multitude of sensor options and functionalities for various applications, making it feasible to leverage them as an enhancement to the monitoring system for the durability of existing concrete structures.

Given the availability of knowledge and technical tools compared to the existing demand, the limited use of structural durability monitoring appears to be a cultural issue that needs to be discussed and promoted within the technical community.

3.3.1 Types of sensors

Sensors are devices that are sensitive to kinetic, luminous, or thermal energy and measure physical quantities, emitting an output signal that typically needs to be processed through an interface circuit, such as amplifiers, for effective use. Transducers are complete devices capable of reading and converting the monitored quantity into readable data, eliminating the need for interface circuits [24].

In this article, the term “sensor” is used to refer to both sensors and transducers.

There are several ways to classify sensors. Regarding the output signal, typically an electrical quantity that can be processed by an electrical or electronic circuit [25], it can be analog or digital.

According to Thomazini and Albuquerque [24], analog sensors are those that can take any value within their operating range and vary continuously and proportionally with the change in the measured quantity. On the other hand, digital sensors are those that have two values in the output signal: on and off, open and closed, which can be interpreted as a binary system, and provide discrete readings.

An example of an analog sensor is the fuel gauge in vehicles, which moves gradually as the measured level changes. Another example is a mercury thermometer, which responds gradually to the changes in the monitored temperature.

As for digital sensors, examples include part counters on a conveyor belt, end-of-travel sensors used in electric motors and contact sensors.

The numerical representation of analog signals is done through converters, which can be analog-to-digital (AD). There are also digital-to-analog converters (DA). It is important to note that the sensor’s output, whether analog or digital, does not necessarily correlate with higher or lower accuracy.

Sensors can also be classified according to their function, including meters, indicators, recorders, controllers, or alarms.

Based on their operating mechanism, sensors can be mechanical, resistive (electrical), optical fiber, vibrating wire, magnetic, piezoelectric, among others.

There is also a classification based on the power source. Sensors can be active, meaning they depend on an external power source for their operation, or passive, which do not require an external power source to emit the output signal. This feature is of utmost relevance for the structural monitoring process in construction, since the monitoring period is long - years or even decades - and the sensor must have the capacity to deliver output signals over this extended period.

Regarding the classification based on usage, there are various types of sensors, such as presence sensors, position sensors, velocity sensors, acceleration sensors, temperature sensors, pressure sensors, level sensors, flow sensors, load sensors, voltage sensors, current sensors, power sensors, humidity sensors, gas sensors, pH sensors, verticality sensors, etc.

Rubio [26] lists static and dynamic characteristics of measuring instruments, some of which are presented below. These characteristics are essential for determining the devices to be used in a monitoring system:

- Sensitivity (S): the ratio of the change in output (y) caused by a change in input (x);
- Gain (G): the ratio of the output signal and the input signal;
- Accuracy: the ability of an instrument to provide responses that coincide with the actual value of the quantity;
- Precision: the dispersion of results read repeatedly, under the same conditions, by the same instrument;
- Time constant (t): the time interval that elapses from the moment when an abrupt change in the input occurs until the final value is reached at the output;
- Natural frequency: the frequency of free oscillation, which should be five to ten times greater than the maximum working frequency of the measuring instrument.

In addition to all the characteristics listed here, there are other factors to consider when choosing sensors, such as ease of maintenance, dimensions, and lifespan [24].

Lastly, but no less important, noise must be evaluated. Noise is understood as any external interference that interacts undesirably with the signal during the measurement process, typically originating from external magnetic or electrical fields. However, there are ways to reduce this interference, such as the use of electrostatic grids, shielded cables, galvanic isolation, and the use of amplifiers [26]. Another option is to use fiber optic sensors, which are not affected by electromagnetic fields and do not require an electrical power source at the measurement point [21].

The range of possibilities that arises from the characteristics of sensors, combined with the influence parameters on aging, specific to each structure, highlights the importance of developing a monitoring project, to make the system feasible, both technically and economically.

3.3.2 Sensors applicable to structural durability monitoring

With the technological advances of recent years, numerous devices have been developed to monitor parameters of the object of study and that can be interpreted as indicators of material durability. These can be utilized for structural monitoring needs, and there are already specific solutions available in the market for this purpose.

Currently, there are technologies developed for structural monitoring which include but are not limited to: Radio Frequency Identification (RFID), fiber optics, acoustic emission, strain gauges and Frequency Selective Surface (FSS) [27]. These technologies are related to sensors or their communication with reading systems.

Taheri [28] lists the top five sensors used in concrete structure monitoring as follows: fiber Bragg grating sensors, piezoelectric sensors, electrochemical sensors, wireless sensors and self-sensing concretes. Self-sensing concrete is not precisely a sensor but is defined as such for having properties capable of being sensitized and transmitting information about changes in the material.

Next, focusing specifically on existing reinforced concrete structures, some solutions in terms of sensors will be addressed, aimed at the recurring technological challenges related to structural durability.

3.3.2.1 Reinforcement corrosion sensors

The corrosion of reinforcements is a phenomenon that affects the aesthetics, functionality, durability, and structural safety of a concrete structure. In extreme cases, it can lead to the collapse of a reinforced concrete structure. Furthermore, since the rehabilitation methods are invasive, laborious, costly, and at times ineffective, monitoring is of utmost relevance and has been extensively studied by the technical and scientific community on a global scale.

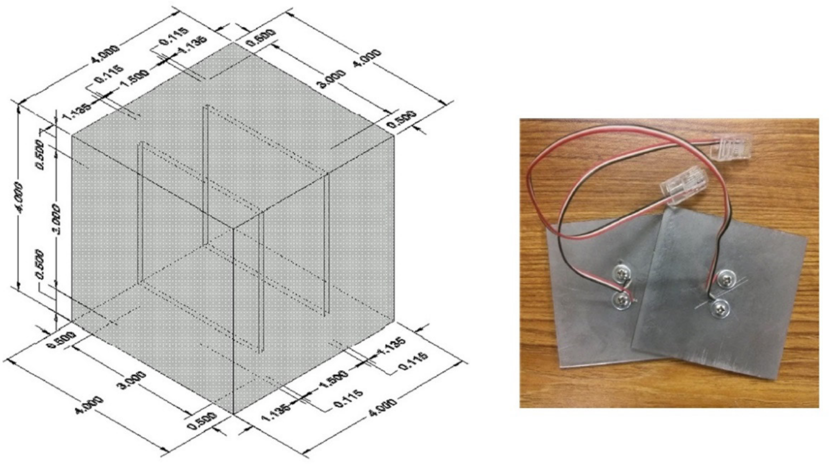
Araújo [29] identifies monitoring as a means to assist in understanding and controlling the initiation and propagation phases of corrosion, such as the rate of penetration of aggressive agents that influences the initiation period, as well as the penetration of water with the availability of dissolved oxygen that influences the propagation phase of corrosion.

The researcher further explains that, in practice, the process involves the installation of sensors or reference electrodes embedded in the cover layer, usually of galvanic nature, meaning they form an electrochemical cell. Monitoring the integrity of the anode by measuring galvanic current and/or the open circuit potential represents the control of the risk of corrosion of the embedded reinforcements in the structure.

From the research conducted by Taheri [28], dozens of types of corrosion sensors, both electrochemical and non-electrochemical, for direct or indirect, qualitative or quantitative detection were mentioned. Among these, electrode sensors or multi-sensors are highlighted, with the function of determining linear polarization resistance, open circuit potential, resistivity, chloride ion ingress front advancement trend, and temperature. These apply to both new and existing structures. It is noted that research aiming to employ Fiber Bragg grating (FBG) sensors in optical fiber for direct measurements, such as corrosion and reinforcement mass loss, are dominant [28].

In technical literature, numerous experiments are found aiming to create sensors for structural monitoring, such as the example of the electrical resistivity sensor composed of two parallel flat steel plates, interconnected by electrical wires and embedded in concrete [30], as shown in the Figure 3. After conducting tests both in the laboratory and in the field, on a bridge undergoing structural rehabilitation in the state of Virginia, USA, researchers found that the sensor proved effective in monitoring the risk of corrosion. Additional advantages cited include the simplicity of the solution and its cost-effectiveness.

The Fraunhofer Institute in Germany developed a passive sensor for corrosion detection, specifically designed for European bridges subjected to de-icing procedures with sodium chloride. This sensor, which is embedded in the concrete cover, has two metal filaments at different heights that act as anodes, indicating the electrochemical protection state provided by the concrete cover to the steel, presented in Figure 4. A portable device measures the impedance of these filaments, providing information about their integrity and, consequently, about the quality of the cover layer, allowing for preventive actions against structural damage [31].



(a) (b)

Figure 3. (a) Electrical resistivity sensor geometry (inches) in concrete and (b) two embeddable parallel flat steel plates and electrical wires [30, p. 1021].

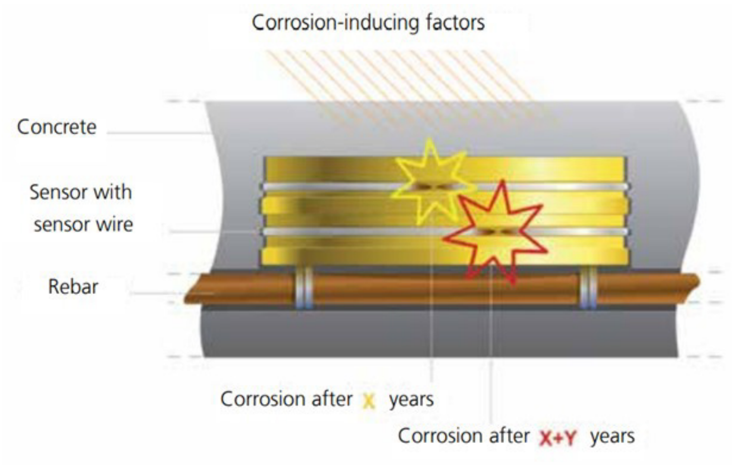


Figure 4. Passive sensor for corrosion detection [31, p. 2].

There are other sensors on the market, such as the Anode Ladder from Sensortec GMBH, designed to monitor the risk of reinforcement corrosion in structures, with principles similar to those mentioned earlier. The sensor consists of a ladder with six anodes positioned at various depths between the reinforcement and the concrete surface, along with a titanium oxide cathode bar and a temperature sensor. It assesses the corrosion of the anodes based on the corrosion potential, corrosion current and electrolytic resistivity, allowing inference about the ingress of aggressive agents and the prediction of reinforcement depassivation through periodic measurements [32].

In the presented context, it can be seen that there is a range of sensor solutions available for monitoring corrosion at different levels of complexity. Additionally, there is the development of economically more accessible alternatives, which may lead to the adoption of monitoring practices.

3.3.2.2 Humidity sensors

The deleterious effects of moisture on concrete structures, as well as on other components of a building, are widely known. Monitoring humidity levels facilitates the taking of preventive actions before the installation or propagation of damage.

There are several ways to monitor surface humidity in concrete structures, such as resistive or capacitive sensors. However, these sensors do not exhibit good resistance to aggressive environments. Consequently, more recent studies focus on the use of Fiber Bragg Grating (FBG) sensors, which are resistant to harsh environments and offer the advantage of integrating other sensors [28], referred to as multiplexing.

FBG sensors for humidity monitoring operate on two principles: through the absorption or scattering of light that propagates through the fiber, resulting from its interaction with humidity; or through the volumetric change of hygroscopic coatings in contact with humidity, which generates a mechanical response [28].

A study conducted by Guerra [27] tested the use of a Frequency-Selective Surface (FSS) sensor to monitor the relative humidity of the surface of concrete sealing blocks. The research results confirmed, as expected, that the sensor's resonance frequency varies in response to humidity changes. Therefore, this methodology has potential applicability and can serve as a basis for further studies aimed at expanding its use to different types of materials. This represents an important step in the development of applications focused on monitoring humidity in concrete structures.

The mentioned examples refer to surface sensors.

There are also humidity sensors incorporated into the concrete during pouring, which measure the change in electrical impedance caused by the moisture content, providing real-time data on the curing process.

Lima [33] developed a prototype to monitor internal moisture in curing concrete. The insertable sensor, with reduced dimensions (9 mm^2), as illustrated in Figure 5, and radio communication, was tested in the laboratory for condensation evaluation. Subsequently, it was applied in the field, through a hole drilled in concrete using a drill. The results, collected over seven days, indicated a gradual decrease in internal moisture, consistent with the reality of curing concrete. The prototype, characterized by its simplicity and low cost, shows great promise for use in existing concrete structures. However, additional studies are needed, especially over longer monitoring periods.

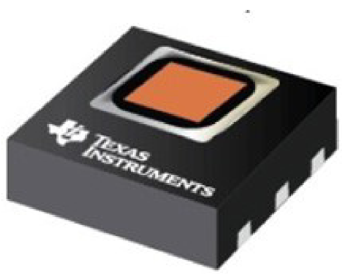


Figure 5. Reduced dimensions insertable moisture and temperature sensor [33, p. 34].

The use of embedded sensors, capable of monitoring the internal moisture of existing structural elements over time allows, for example, the detection of failures in waterproofing systems, promoting predictive maintenance and providing information for indirect assessment of reinforcement corrosion.

3.3.2.3 Strain gauges

In the technical field, the use of strain gauges (SG), electrical resistance strain gauges, is quite common for measuring deformations, attached to the surface of the element to be monitored. This resource allows for the measurement of displacement during mechanical strength tests on concrete specimens and, when combined with other instruments, provides data on stress, force, and acceleration.

It is a sensor that converts small dimensional changes into variations in its electrical resistance, characterizing it as a means of measuring deformation as an electrical quantity. It consists of a grid made from a thin metal sheet - whose design is formed by the removal of parts; a cutout promoted by chemical corrosion - attached to an insulating material [24], as shown in Figure 6.

Figure 6. Strain gauge [34].

The operating principle of the SG is based on the variation of its electrical resistance (Ω). The resistance decreases when it is compressed - as a result of the compression that occurs in the element to which it is attached - and increases when it is stretched.

The use of SG to measure deformations, which are nanometric, is associated with the use of a Wheatstone Bridge, an electrical circuit consisting of four resistors of equal power which plays an essential role as an auxiliary circuit to enhance the sensitivity and accuracy of measurements. Another favorable feature of its use is the compensation of the effect caused by temperature.

3.3.2.4 Water level sensors

The action of groundwater can interfere with the durability and stability of constructions, as foundation elements exposed to the effects of moisture can undergo accelerated corrosion processes. Additionally, soil saturation or waterlogging, such as during floods, can impact the stability of slopes and structures [21].

In this context, the importance of monitoring parameters beyond the structure itself, such as those of the environment and the surroundings of the structure, becomes evident.

In an experiment conducted by Mesquita [21], to develop a system for monitoring water level variations, a segment of plastic optical fiber was used. One end of this fiber was marked with equidistant grooves, exposing the fiber core and transforming it into a sensor based on the principle of Bragg gratings. The opposite end was connected to a data acquisition system, consisting of four LED channels and four photodetector channels, along with a microcontroller and a signal converter. The sensor was tested in a laboratory environment, simulating fluctuations in the water table.

In each created groove, there was a partial signal loss due to the difference in refractive indices between the fiber core and the surrounding environment. When the water level underwent changes and these grooves were submerged, a reduction in the optical loss was observed. This behavior demonstrates that these sensors are capable of effectively monitoring changes in the water level, making them suitable for field applications [21].

3.3.2.5 CO_2 and RH sensors

Another way to assess the durability of concrete structures is to monitor the aggressiveness of the environment in which they are located. Two important parameters to be controlled are the concentration of carbon dioxide (CO_2) and the relative humidity of the air (RH).

The chemical reaction between ambient CO_2 and the calcium hydroxide present in the cement paste results in the carbonation of concrete, leading to the progressive dissolution of calcium hydroxide in the water-filled pores, forming calcium carbonate ($CaCO_3$). This reduces the pH of the concrete, subsequently causing a loss of passivity in embedded reinforcements. The rate at which the carbonation front advances depends on the permeability of the concrete, the relative humidity, temperature and concentration of CO_2 in the environment. According to the guidelines of the ACI 201.2R standard, the carbonation rate is higher when RH is between 50% and 75% [35].

It's worth mentioning that the rate of deterioration of concrete structures has been significantly impacted by climate change, as the probability of corrosion-induced corrosion increases with rising emissions [28].

There are no fixed values that establish a direct relationship between CO_2 concentration and the likelihood of corrosion due to its interdependence with other parameters, as mentioned. However, it is feasible to carry out monitoring to track typical CO_2 concentrations in specific environments, such as tunnels or underground areas, for example. When events result in a significant increase in typical CO_2 concentration, it is advisable to carry out inspections and tests to assess the possible impacts on the structure.

Various sensors and multisensors for monitoring RH, CO_2, and temperature are readily available in the market and economically accessible.

4 CONSIDERATIONS

The adoption of structural durability monitoring through sensors offers several advantages when compared to the traditional approaches. In the latter, only a minority of buildings undergo periodic inspections, and their conditions remain unknown until the next inspection campaign, and even fewer have parameters monitored over time.

The main advantage to be mentioned is the assurance of the structure's safety and integrity, as well as the well-being of the users and the surrounding environment. Additionally, durability monitoring contributes to cost reduction during the usage phase by allowing for scheduled preventive interventions, thus minimizing unexpected expenses. It also ensures the use of assets throughout their design service life, optimizing the resources invested in construction.

Furthermore, it is important to highlight that the losses resulting from structural degradation significantly outweigh the investment in monitoring, underscoring the decisive importance of this approach for preservation.

The exploration of sensors reveals a considerable variety of devices available on the market, that can be adapted for structural monitoring.

In this context, notable is the effort made by researchers in seeking practical and cost-effective solutions that, when combined with the open-source community's practices, represent tangible possibilities for democratizing structural monitoring, which has historically been restricted to large infrastructure works.

Limited adoption of structural durability monitoring, despite the availability of knowledge, methodologies, tools, equipment, and their advantages, is largely related to the following cultural factors evident in practice:

• Conservative approaches that restrict the adoption of new technologies;
• Lack of communication and dissemination on the subject, making it difficult to understand the cost-benefit ratio;
• Absence of regulations and/or technical standards that make this practice mandatory..

To promote its dissemination, a joint effort is essential among technical professionals, researchers, government agencies and professional associations. Initiatives such as the creation of a building safety policy, similar to the one applied to dam constructions, and the inclusion of structural monitoring design in the project's conception phase, developed concurrently with the structure itself, can significantly contribute to ending what has been referred to as a "control blackout" in the construction industry.

5 REFERENCES

[1] Associação Brasileira de Engenharia e Consultoria Estrutural, Instituto Brasileiro de Avaliações e Perícias de Engenharia de São Paulo, Instituto Brasileiro do Concreto, "Manifesto público: segurança das obras civis," *Rev. Concreto*, vol. 33, no. 37, pp. 4, 2005.

[2] Brasil. Ministério da Integração e do Desenvolvimento Regional. "O que é o déficit habitacional". https://web.archive.org/web/20230201201854/https://www.gov.br/mdr/pt-br/assuntos/habitacao/casa-verde-e-amarela/o-que-e-o-deficit-habitacional (accessed Sept. 28, 2022).

[3] G. S. d. Reis, M. Quattrone, W. M. Ambrós, B. Grigore Cazacliu, and C. Hoffmann Sampaio, "Current applications of recycled aggregates from construction and demolition: a review," *Materials (Basel)*, vol. 14, no. 7, pp. 1700, 2021., http://dx.doi.org/10.3390/ma14071700.

[4] Globo Ciência. "Construção civil consome até 75% da matéria-prima do planeta". http://redeglobo.globo.com/globociencia/noticia/2013/07/construcao-civil-consome-ate-75-da-materia-prima-do-planeta.html (accessed Sept. 28, 2022).

[5] Associação Brasileira de Normas Técnicas, *Manutenção de edificações - Requisitos para o sistema de gestão de manutenção*, NBR 5674, 2012.

[6] Associação Brasileira de Normas Técnicas, *Projeto de estruturas de concreto - Procedimento*, NBR 6118, 2023.

[7] Associação Brasileira de Normas Técnicas, *Edificações habitacionais - Desempenho. Parte 1: Requisitos gerais,* NBR 15575-1, 2021.

[8] International Organization for Standardization, *General Principles on the Design of Structures for Durability*, ISO 13823, 2008.

[9] Fédération Internacionale du Béton *Model Code for Concrete Structures*, Lausanne: FIB, 2010.

[10] International Organization for Standardization, *Framework for Specifying Performance in Buildings*, ISO 19208, 2016.

[11] K. S. Tuutti, "Corrosion model", in *Corrosion of Steel in Concrete.* Stockholm: Swedish Cement Concrete Res. Inst., 1982.

[12] International Organization for Standardization, *General Principles on Reliability for Structures*, ISO 2394, 2015.

[13] American Concrete Institute, *Report on Evaluation and Repair of Existing Nuclear Safety-Related Concrete Structures*, ACI 349.3R-18, 2018.

[14] G. Escadeillas and H. Hornain, "A durabilidade do concreto frente a ambientes quimicamente agressivos", in *Durabilidade do Concreto: Bases Científicas para a Formulação de Concretos Duráveis de Acordo com o Ambiente*, J. Oliver e A. Vichot, Eds., São Paulo: IBRACON, 2014, ch. 11, pp. 433–508.

[15] A. F. Battagin, "Cimento Portland", in *Concreto: Ciência e Tecnologia*, G. Cechella, Ed., São Paulo: IBRACON, 2011, vol. 1, ch. 6, pp. 185–232.

[16] Brasil, "Lei nº 12.334 de 20/09/2010", *DOU*, Sept. 21, 2010. https://legis.senado.leg.br/norma/585331 (accessed Sept. 28, 2022).

[17] Itaipu Binacional. "Pesquisa sobre instrumentação da barragem". https://www.itaipu.gov.br/energia/instrumentacao (accessed Sept. 28, 2022).

[18] L. O. Santos, "Monitoramento e ensaio de pontes", in *An. 7º Congr. Bras. Pontes Estrut.*, Rio de Janeiro, Brasil. http://www.abpe.org.br/trabalhos/trab_110.pdf (accessed Sept. 28, 2022).

[19] Brasil, "Projeto de Lei da Câmara nº 31 de 03/04/2014". https://www25.senado.leg.br/web/atividade/materias/-/materia/116814 (accessed Sept. 28, 2022).

[20] D. R. Louzada, *Detecção e Caracterização de Danos Estruturais através de Sensores a Rede de Bragg e Redes Neurais Artificiais*, Rio de Janeiro: PUC, 2013. https://www.maxwell.vrac.puc-rio.br/colecao.php?strSecao=resultado&nrSeq=37156@1 (accessed Sept. 28, 2022).

[21] E. F. T. Mesquita, "Structural characterization and monitoring of heritage constructions", Ph.D. dissertation, U. Porto, Porto, 2017. [Online]. Available: https://repositorio-aberto.up.pt/handle/10216/105447

[22] NPTEL-NOC IITM. "Long Term SHM (Structural Health Monitoring)". https://www.youtube.com/watch?v=52nfRisxw1U (accessed Sept. 28, 2022).

[23] Structural Assessment Monitoring and Control, *Guideline for the Assessment of Existing Structures*, F08a, 2006.

[24] D. Thomazini and P. U. B. Albuquerque, *Sensores Industriais: Fundamentos e Aplicações*, 9. ed. São Paulo: Érica, 2020.

[25] F. R. Fonseca, "Sensores". Adoro Robótica. https://www.adororobotica.com/Sensores.pdf (accessed Sept. 28, 2022).

[26] M. G. Rubio, *Curso de Introdução à Instrumentação em Engenharia: Módulo Básico*. São Paulo: IPT, 2000. [Online]. Available: https://www.lsi.usp.br/~gongora/Cursos/Apostila.pdf (accessed Sept. 28, 2022).

[27] J. R. F. Guerra, "Monitoramento da saúde estrutural na construção civil usando sensor com superfície seletiva em frequência," Doctoral dissertation, Univ. Fed. Rio Grande do Norte, Natal, 2022.

[28] S. Taheri, "A review on five key sensors for monitoring of concrete structures," *Constr. Build. Mater.*, vol. 204, pp. 492–509, 2019.

[29] A. Araújo, "Monitoramento de corrosão das armaduras de estruturas de concreto armado". AECweb. https://www.aecweb.com.br/academy/ipt-quiz/monitoramento-de-corrosao-das-armaduras-de-estruturas-de-concreto-armado/20535 (accessed Sept. 28, 2022).

[30] U. B. Halabe, J. Kavi, and H. V. S. GangaRao, "Innovative sensors for monitoring the corrosion of steel embedded in concrete structural components", in *Geotech. Structural Eng. Congr. 2016*, Phoenix, Arizona. Reston, VA: Amer. Soc. Civil Engineers, 2016, pp. 1016–1031. https://doi.org/10.1061/9780784479742.086

[31] Fraunhofer IMS. "Passive sensor for corrosion detection". https://www.ims.fraunhofer.de/content/dam/ims/en/newsroom/business-units/industry/Passive-Sensor-for-Corrosion-Detection.pdf (accessed Sept. 28, 2022).

[32] Sensortec GmbH. "Corrosion Sensor Anode Ladder". http://www.sensortec.de/images/pdf/Data_Sheet_Anode_Ladder_eng.pdf (accessed Sept. 28, 2022).

[33] F. T. Lima, "Sistema de monitoramento e controle de umidade em concretos em processo de cura", Trabalho de graduação, Univ. Fed. Uberlândia, Patos de Minas, 2017.

[34] Autocore. "Pesquisa sobre strain gauge". https://www.autocorerobotica.com.br/strain-gauge-extensometro-de-resistencia-eletrica (accessed Sept. 28, 2022).

[35] A. Araújo, J. L. Cardoso, M. S. Pacheco, M. L. Pereira Fo., and Z. Panossian, "Corrosão do aço-carbono em concreto armado", in *An. 14ª Conf. Sobre Tecnol. Equip.*, Rio de Janeiro, Brasil: COTEQ, 2017.

Author contributions: AAC: data curation, conceptualization, writing; VAQ: methodology, conceptualization, supervision.

Editors: Samir Maghous, Daniel Carlos Taissum Cardoso.