Monitoring of materials degradation
a sustainability factor and a way to decrease solid waste

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Abstract – Natural stone and reinforced concrete are the main materials used in construction due to its versatility and mechanical and chemical properties. However, when exposed to certain harsh environments these materials tend to degrade more rapidly than would expectable. The speed of degradation is also a function of the quality of the materials used and the quality of processing. With regard to the reinforced concrete, the quality depends on the cement/ inert and water/cement ratios used in the production. The quality of natural rock is related with stone type and machinery used, in particular, how the rock is worked and finished. Thus, there is a great concern of industry to have information that allows monitor the process in order to take corrective action during production and maintenance. The degradation of these building materials leads to high economic and environmental impacts, such as a high production of waste requiring treatment and an appropriate valuation. The development of systems for continuous monitoring of the degradation of these materials can minimize the effects of degradation phenomena, enabling more timely interventions with an important consequence in terms of increasing structures lifetime and decreasing the generation of solid wastes due to reparation works.

This work focuses on the analysis in the environmental impact, in particular, in the generation of solid waste, resulting from the repair of works of art exposed to marine environments and the impact of the use of your degradation monitoring systems. Experimental results were used of two monitoring systems that use ionic resistivity information one to monitoring natural rock and another to reinforced concrete degradation. Ionic conductivity monitoring systems of natural rock has the principle of monitoring the formation of crystalline salts or ice that is a detrimental action in degradation of natural rock. The system measure the ionic conductivity attenuation that is an indication of salt formation and the variation of ionic free concentration (Mauricio, 2005). The concrete monitoring system determines the resistivity of concrete was used the technique of the two electrodes, which apply an alternating electric field between two stainless steel electrodes located inside concrete outside layer (Romano, 2013).

Structural repairs, such as bridges, overpasses, buildings, particularly those found in maritime environments, involve costs very similar to the execution of a new work. Such interventions require that a significant part of the structure be dismantled and rebuilt. This situation involves the production of significant amounts of solid waste.

Considering the results of evolution of deterioration over time of structures obtained in this work with the monitoring systems, as well as the results of monitoring of public works in Portugal, it is estimated that it would be possible to increase the lifetime of structures subject to maritime environments, without an intervention, in at least 15 years. The monitoring systems will give information on the evolving of the degradation processes allowing go taking corrective measures to lower cost and without much need for interventions. Such time increment, in addition to a positive impact in economic terms, also has a very positive impact in terms of amount of solid waste produced that need treatment and recovery.

Keywords: Sustainability, Durability, Monitoring.

1. Introduction

A large part of the waste produced in our modern society is demolition waste which can reach more than 30% of the waste produced in some countries. Such waste generates significant environmental and economic problems that need to be minimized. Demolition and construction wastes are usually divided into two major groups: inert materials (ie, rocks, sand, bricks, and concrete) and non-inert materials (ie, plastic, glass, paper, wood, vegetation, and other organic Materials). Some strategies with potential to minimize the pollution of C&D waste have been proposed, ranging from reducing waste insource, reusing and recycling waste, to disposing of waste in landfills. In environmental and economic terms the minimization of waste generation is the most interesting and the most important investment. If on the one hand there is a large percentage of waste that is generated by interest in urban regeneration, on the other hand there is a significant component that is the result of deep degradation of structures that no longer have operating conditions in terms of safety.

The use of preventive maintenance strategies based on continuous monitoring systems of the degradation processes of building materials can significantly minimize the level of repair intervention and increase the useful life of the structures, thus reducing the generation of waste demolition and construction.

In this work some results of the monitoring of stone and concrete materials over long periods of time are presented, which show that the monitoring of the evolution of the behavior of the materials allows the increase of the useful life of the structures.

2. Monitoring techniques

a) Concrete

Concrete is from the mid-twentieth century the leading solution for building structures, among other reasons, for its versatility and ease of execution. However, environmental sustainability is currently one of the weaknesses of reinforced concrete structures due to high energy and environmental costs, resulting largely from the cement consumption associated therewith.

The increased of the sustainability of concrete structures can be obtained by improving the performance of the cement or the partial replacement of the binder by other components with lower environmental costs[1]. Another way to look at this problem is stimulating increasing the life of the structures acting on these over time, making their proper maintenance [2], [3].

Therefore monitoring of the reinforced concrete can have a central role in increasing the longevity through early detection of damages or degradation leading to timely intervention to ensure the continuation of the use of structures, reducing the economic and environmental costs associated with their replacement[4].

The monitoring of reinforced concrete structures, to monitor the variation, over time, of one or more characteristic parameters of the concrete, in order to determine an initial phase significant changes indicating the existence of a degradative process of development. Since the seventies of the last century are developing measurement processes of degradation of reinforced concrete. The first durability tests aimed at measuring parameters to quantify the concrete damage processes. Among these trials contained the change in weight, measuring the length variation, flexural strength, the ultrasonic measurement of pulse, optical microscopy, electron microscopy and the scattering of X-rays.

The first sensors for monitoring of reinforced concrete appear in the 90s, these may stand out the sensors consist of two electrodes, a black steel (anode) and the other of a noble metal (the cathode), embedded in the concrete which gives corrosion protection anode and through which, one could measure the passage of electric current. These sensors are based on the principle that an early stage, while the concrete has a high pH, the passage of electric current is negligible or zero, and at a later stage, either by effect of carbonation or penetration of chloride, the low concrete Ph creating conditions for corrosion of the anode and, simultaneously, for the passage of electric current between the electrodes, which will increase with the development of the steel corrosion process[5].

In recent decades many techniques have been proposed and applied in the monitoring of reinforced concrete, including various magnetic, electromagnetic and electrochemical techniques, namely X-ray, CT, Surface Penetration Radar, Magnetic Field Disturbance, Electrochemical Noise, Linear Polarization Resistance (LPR), Electrochemical Impedance Spectroscopy (EIS), localized Electrochemical Impedance Spectroscopy (LAWS), Galvanostatic Pulse Method (GPM), Electrical Resistance Bar (BER), Surface Potential Survey, Concrete Resistivity, Galvanic Cell, among others[6], [7], [8], [9].

This paper presents monitoring results of concrete resistivity and potential corrosion of the reinforcement of RC specimens exposed to the action of chlorides. These results show that the degradative processes of reinforced concrete structures can be monitored over time allowing earlier repair operations.

b) Natural rock

Natural stone has always played a significant role in building important buildings in Europe. Already in classic antiquity and in the middle ages the degradation of building materials caused the concern of builders and architects in their conservation and protection.

The increasing urbanization and industrialization, with the consequent increase in atmospheric pollution, poses the problem of the degradation of the stone materials with greater acuity. Acid rains containing carbon dioxide and sulfate ion from the combustion gases from cars and factories are primarily responsible for the most common damages. But there are many factors that contribute to the degradation of stones and involve various and complex processes of degradation. The action of water and ice (in colder climates), bacteria, corrosive agents and temperature depends on the rock properties of the stone, particularly the soluble impurities and the discrete network of pores and channels that constitute it. The method of extracting the rock and the treatment that the stone suffers before being placed in the building can influence the formation of microcracks which, in turn, contribute to the increase of water infiltration.

The main methods of diagnosis and study of stone degradation generally involve techniques of direct observation and comparison with previous observations, possibly with the aid of photographs (general or local). The diagnosis should involve the analysis of the archives on the nature of the monument and previous interventions, comparison with the original stone, analysis of the surrounding atmosphere, analysis of the mechanical and petrographic properties of the geomaterial. For this purpose, optical or electronic microscopy (SEM, EDAX, EPXMA) may be used, as well as techniques for the propagation and dispersion of mechanical and electromagnetic waves such as ultrasonic analysis. Other methods of use are infrared thermography (for the study of moisture inside the stone), XRD and XRF, chemical analyzes of the stone, the runoff, in particular with the aid of ion chromatography and atomic absorption spectroscopy.

These methods are almost all very time-consuming requiring sophisticated and expensive handsets and highly experienced staff for their performance and interpretation of results. Furthermore, they are almost always destructive techniques involving the collection of samples of larger or smaller size and only a few can be carried out in situ.

This paper presents monitoring results of natural rock exposed to the action of chlorides by a resistivity method.

2. Experimental

a) Concrete

The tests that are the basis for this work were performed in the laboratory with the use of reinforced concrete specimens with 40 × 30 × 15 cm 3. The specimen was armed with an orthogonal mesh of steel bars with 10 mm diameter spaced 10 cm and protected by a coating layer of 5 cm thickness. It was used a concrete C30 / D16 XC3 37 (P) 0.2 Cl S2 prescribed dosage according to NPEN Standard 206-1, incorporating a CEM II / AL 42.5 R, with a dosage of 340 kg / m3 and a plasticizer, Chrysoplast 775, with a dosage of 3.4 kg / m3. Granulated inert continues were used, consisting of fine sand (302 kg / m3), coarse sand (506 kg / m3) and gravel 1 (1016 kg / m3). The water used (170 kg / m3) corresponds to a ratio A / C 0.5. The test pieces were subjected to a 28-day cure immersed in water. After curing, one of the faces of the specimens was exposed to a sodium chloride solution of 3% for a period of two years.

Monitoring of the specimens was performed using two types of sensors embedded in the concrete to allow the collection of a set electrochemical parameters, namely, the potential and the corrosion rate of the reinforcement and the resistivity of the concrete. It was used ordinary steel reinforcement, galvanized steel and coated steel.

To determine the corrosion rate of the reinforcement was used the MonIcorr$^{\text{Pat.Pend.}}$ monitoring system. This system consists of two pairs of electrodes (a pair made of the same soft steel reinforcement and other stainless steel AISI 304), an electrode of reference (pseudo-reference graphite) and an electric cable for connection to the reinforcement. The sensor measures the corrosion rate of the reinforcement by Linear Polarization Resistance technique (LPR) [10].

To determine the resistivity of concrete was used the technique of the two electrodes, spaced 5 cm for measuring the resistivity of the concrete to depths of 1.5 and 3.0 cm from the exposed surface. Its operation is based on the creation of an alternating electric field (172 Hz) between the stainless steel electrodes located at the same depth, imposing a current and measuring the potential difference of the response [11], [12].

a) Natural rock

Cubic samples of "Pedra de Ançã" measuring 3,0x3,0x3,0 cm^3 were prepared. It is a whitish Jurassic limestone with total porosity ranging from 5 to 24% and air permeability ranging from 18 to 460mD according the rock stratification. After contaminating each of the samples by soaking it with one of the previously tabulated salt solution concentration, the samples were completely sealed with epoxy resin, in such a way as to close as much as possible the system. Before the sealing process, two AISI 316L stainless steel cylinder electrodes were introduced in the stone, in such a way as the distance between the two electrodes were 15mm apart and the two holes carved in the stone were 10mm deep. Each electrode was connected to a copper wire, the connection was isolated within the epoxy resin as well.

The ionic conductivity measurement system is operated in the following way: 1- an alternate electrical tension of about 12V is imposed to the circuit; 2 - the electrical potential drop between C_1 and the reference, and the electrical potential drop between C_2 and the reference (respectively corresponding to the stone and the electrical resistance) is measured; 3 - using Ohm Law, it is possible to estimate the stone electrical resistance in the following way:

3. Results and Discussion

a) Degradation monitoring

The following graphs resulting from the monitoring of the specimens exposed to the action of chlorides in terms of concrete resistivity and the potential for corrosion of reinforcement.

The ionic resistivity of concrete is a parameter that shows great variability due to the heterogeneity of the concrete itself. However there are commonly accepted boundaries as lines from which there are significant changes of the concrete has implications for the protection of reinforcement [12]. Table I shows the resistivity values and their correlation with the risk of corrosion.

The corrosion potential measures the tendency of the material has, in this case steel reinforcement, to react with the surrounding medium or electrolyte, the concrete that involves reinforcement [12]. Table II shows the correspondence between the corrosion potential, Ecorr, and associated risk of corrosion. It should be noted that the results of the resistivity and corrosion potential were measured with different autonomous systems. Analysis of the graphs can be seen that the resistivity of the concrete has a tendency to decrease over time, with the exception of Figure 4 where the resistivity remains constant. In terms of corrosion potential, it can be seen that with the exception of Figure 4, all figures show values tend to decrease over time and there is a point at which this decrease becomes more pronounced.

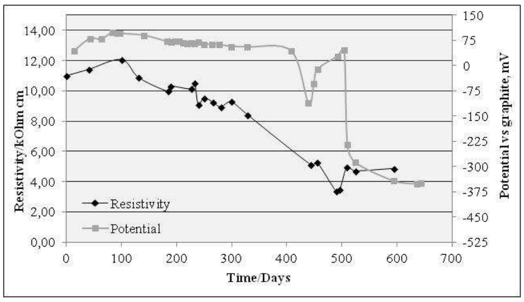

Figure 1. Provete S1 (armadura corrente) Resistividade "versus" Potencial

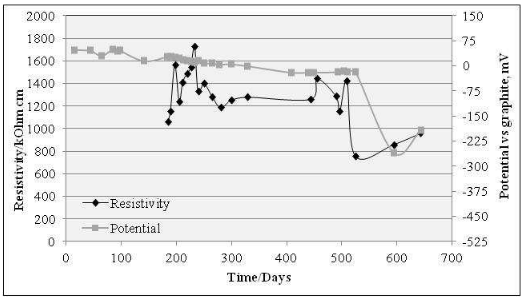

Figure 2. Provete S2 (armadura corrente) Resistividade "versus" Potencial

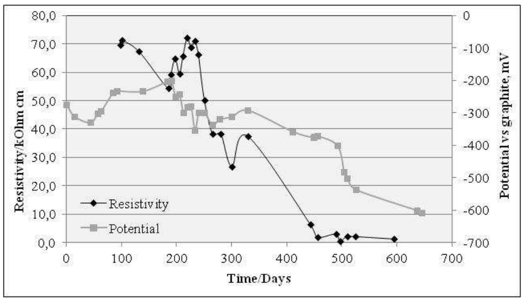

Figure 3. Provete G3 (armadura galvanizada) Resistividade "versus" Potencial

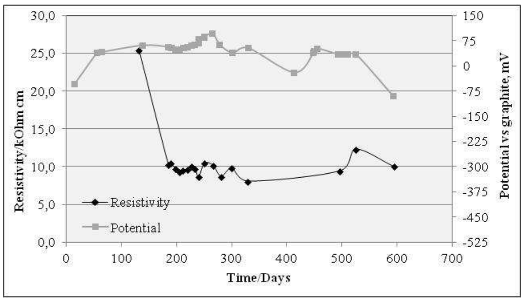

Figure 4. Provete R1 (armadura revestida) Resistividade "versus" Potencial

Table I. Resistivity - corrosion risk [12].

Resistivity (kOhm.cm)	**Corrosion risk**
R > 20	Negligible
20 > R > 10	Low
10 > R > 5	High
R < 5	Very high

Table II. Potencial - corrosion risk [12].

Potencial of corrosion (mV)	**Corrosion risk**
$E_{corr} > -200$	Low (10 % risk of corrosion)
$-200 > E_{corr} > -350$	Intermediate corrosion risk
$E_{corr} < -350$	High (90 % risk of corrosion)
$E_{corr} < -500$	Severe corrosion

Conjugating the observation of the figures can be seen that the resistivity and corrosion potential show similar trends throughout the test. Figure 1 shows that the resistivity of the concrete, from the 500 days' test down to levels considered alarming in terms of reinforcement corrosion risks. In the same figure can be seen that the potential reinforcement corrosion accompanying the decrease in resistivity in the same period into the high risk of corrosion zone. The second figure shows very high resistivity values throughout the test showing a significant drop after 500 days had elapsed since the start of the test. The power monitors the progress of corrosion resistivity graphic maintaining a range of values which corresponds to moderate risk of corrosion of armor.

Figure 3 shows the resistivity at an early stage very high values. During the test these values lower indicating a very high risk of reinforcement corrosion from the 450 days. If we analyze the potential reinforcement corrosion, we can see that from the 400 days the potential values indicate high risk of reinforcement corrosion. This risk becomes very high from 500 days. Figure 4 shows that the resistivity of the concrete little change throughout the test, while remaining within a range that indicates a low risk of corrosion of reinforcement. At the same time the potential features a range of high values in a range that indicates low risk of corrosion. The comparative analysis of different figures allows to affirm that there is a good correlation between the corrosion potential of the armature and the resistivity of the concrete. Both monitoring systems detect changes in behavior of the reinforcement and the concrete leading to an increased risk of corrosion.

In Figure 5, the evolution of the ionic conductivity of a "Pedra de Ançã" stone over time is presented for a solution of sodium chloride at 20ºC. It will be seen that when the conductivity remains constant, conditions are created for the formation of crystalline salt structures which cause internal stresses and cracking in the materials.

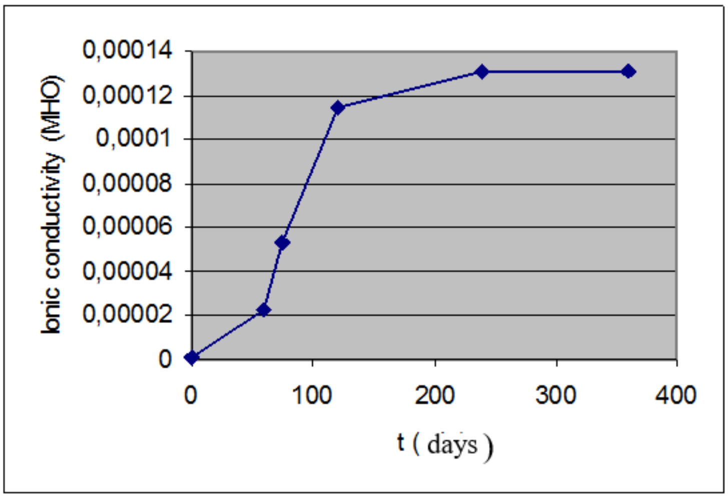

Figure 5 - Variation of the conductivity as a function of time for a stone contaminated with a solution of NaCl.

a) Service life

The results show that the monitoring systems follow the various phases of the material degradation process. Such knowledge allows, on the one hand, to estimate the useful life of a structure and, on the other hand, to make timely interventions in structures and materials. Timely maintenance interventions make it possible to extend the service life of the structures. Based on the results obtained with these materials it is clear that a 30% prolongation in the useful life of a structure is possible equivalent to an increase of at least 15 years. The economic result of this increase is significant, as well as the consequent reduction of waste.

One of the issues of degradation of these materials is the difficulty in detecting the degradation processes over time. When the degradation is evident, already the repair has high costs and the waste produced as well. This type of strategy allows timely identifying pockets of degradation and defining minimization strategies. Installed systems can be connected to information and communication systems by sending online warning signals to construction managers. We are in the way of intelligent materials.

The installation of monitoring systems is already being used in several works in which are used structures of reinforced concrete and natural stone. Bridges, viaducts, tunnels, monuments are structures with high maintenance and repair costs, which allow the development of monitoring strategies, however, it is also possible to install a monitoring system in smaller buildings and structures, increasing the possibility of extending their useful life.

4. Conclusions

Monitoring of reinforced concrete and natural rock materials structures allows to obtain real-time information on the behavior of the materials, which is a key tool to increase the sustainability of the use of this material.

The measurement results of the variation of resistivity clearly identify the start of concrete and natural rock degradation process. The potential for corrosion of the reinforcement can be seen in the figures by changing the steel behavior, identifying the beginning of the reinforcement corrosion process.

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