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TYPES OF CORROSION IN REINFORCED CONCRETE STRUCTURES

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Abstract: The purpose of this research is to present a study of corrosion in reinforced concrete structures, with the aim of exposing professionals and society to the magnitude and seriousness of this pathology, and to show the different forms, types, and principles of the corrosion process and provide solutions and treatments for this anomaly. Initially, theoretical content was proposed through bibliographic research, providing an explanation of all the pathologies present in civil construction. Then, a theory containing an explanation of the main pathology to which this work refers, namely corrosion, explaining from its inception to its total propagation in the reinforcement, mentioning some types of corrosion in reinforced concrete structures, treatments, and various methods of prevention for this pathology.

Introduction

Civil construction is one of the fastest growing sectors in Brazil, and therefore one of the areas that generates the most jobs in the country. With development and population growth, large construction projects are growing significantly, demonstrating the power and growth of civil construction. Even though it is the sector that offers the most jobs in the country, there is a shortage of skilled labor to fill the positions, thus requiring a large investment in professional training in addition to the search for new materials.

Due to the arrival of countless materials in civil construction, new alternatives and possibilities for carrying out projects are emerging, with steel being one of the materials that has been gaining market share within the construction sector and providing a more comprehensive vision for design professionals.

Steel is the most recycled product in the world, with around 40% of global production coming from ferrous scrap. Another part is made from iron ore in steel mills. Steel is an essential material in construction and can be found in countless projects, providing quality and safety (PANNONI, 2015).

When talking about steel in civil construction, its main pathology immediately comes to mind: corrosion, which is the destructive interaction of the material with the environment resulting from chemical and electrochemical reactions, thus causing the deterioration of the material (HELENE, 1993). This phenomenon is present in most engineering projects, and some engineers in the field, when faced with this problem, are hamstrung by their lack of specific knowledge, carry out the work as normal, without correcting the flaws and often without taking precautions to prevent such errors from happening again.

When corrosion occurs, it causes the steel to lose part of its cross-section, thus allowing a real reduction in the strength of the bar and the structure, thus causing an alert for the structure, and if the problem persists and there is no treatment or recovery, the structure may be condemned, as it poses risks to its users (HELENE, 1993).

Corrosion in reinforcement occurs due to several factors, which must be analyzed with a systemic view to obtain a correct diagnosis. Steel as reinforcement has protection provided by the concrete covering, forming a physical barrier around it. The loss of protection can occur mainly due to inadequate execution of the covering layer,

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cracks and fissures, temperature variations, and exposure to the environment, thus accelerating the corrosive process already present (HELENE, 1993).

If companies and professionals maintain strict control over the corrosive process in their projects, there will logically be a significant reduction in this pathology.

Corrosion is a phenomenon that can occur in any type of construction project that uses steel, large or small, from the construction of a small room to huge projects such as hydroelectric plants, buildings, and bridges, and can occur both in reinforced concrete reinforcement and in structures made entirely of steel.

The problem of corrosion occurs daily around the world, with countless incidents resulting in accidents, some of them fatal, such as the collapse of awnings, cantilevered slabs, and even retaining walls. To prevent such corrosion incidents from occurring, the professionals responsible must have up-to-date and comprehensive technical knowledge of the problem. This represents a major step forward in the advancement of engineering (HELENE, 1993).

There are different types and forms of corrosion, and treating these anomalies is a decisive step toward success. Each type of steel requires a specific treatment, thus seeking maximum protection efficiency (OLIVEIRA, 2012).

Thus, this literature review aimed to describe the main corrosive processes in reinforced concrete structures, identifying the different forms, types, and principles of the corrosion process.

Pathologies

The term Pathology, of Greek origin (páthos, disease, and lógos, study), is widely used in various fields, where anomalies or problems (possible diseases) in certain areas are studied. In civil engineering, pathology can be understood as the part of engineering that studies the symptoms, mechanisms, causes, and origins of defects in civil constructions (OLIVEIRA, 2013).

Civil construction works are designed for appropriate uses and requirements. If projects are exposed to inappropriate stresses, the construction may present serious maintenance problems over time, thus leading to anomalies in the structure (GRANATO, 2002).

Defects can be congenital, i.e., acquired during the execution of the works (inappropriate use of materials and construction methods), or during the useful life of the building. Inspection and evaluation of pathologies must be carried out regularly, and once such anomalies are identified, they will be analyzed so that, whenever necessary, maintenance and rehabilitation of the work can be carried out. Among the different principles that contribute to the degradation of structures, there are some factors, such as temperature changes, erosion, vibrations, and chemical reactions, which cover one of the main pathologies present in civil construction, corrosion, responsible for much of the degradation in buildings (GRANATO, 2002).

Identification of Problems

When talking about construction, one immediately thinks only of the execution phase of the work. However, it is after this phase that problems begin to appear, as the-

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re is no longer a service provider team present on site and, in some cases, the financial resources for the work are already scarce, which can then hinder maintenance (OLIVEIRA, 2013). Therefore, several anomalies are identified in the works, resulting from problems in the design or execution, exposing the lack of supervision throughout the progress of the work.

According to Silva and Jonov (2011), there can be several causes of these problems, including:

Loads;

- Humidity variation;
- Intrinsic and extrinsic thermal variations in concrete;
- Biological, physical, and chemical agents;
- Material incompatibility;
- Atmospheric agents;

Types of Pathologies

There are numerous pathologies present in civil construction works, and the most common are:

- Cracks and fissures;
- Due to thermal movements;
- Due to hygroscopic movements;
- Due to overloads;
- Excessive structural deformation;
- Foundation settlement;
- Shrinkage of cement-based products;
- Chemical changes in construction materials;
- Delayed hydration of lime;
- Sulfate attack;
- Corrosion of reinforcement;
- Pathologies resulting from moisture.

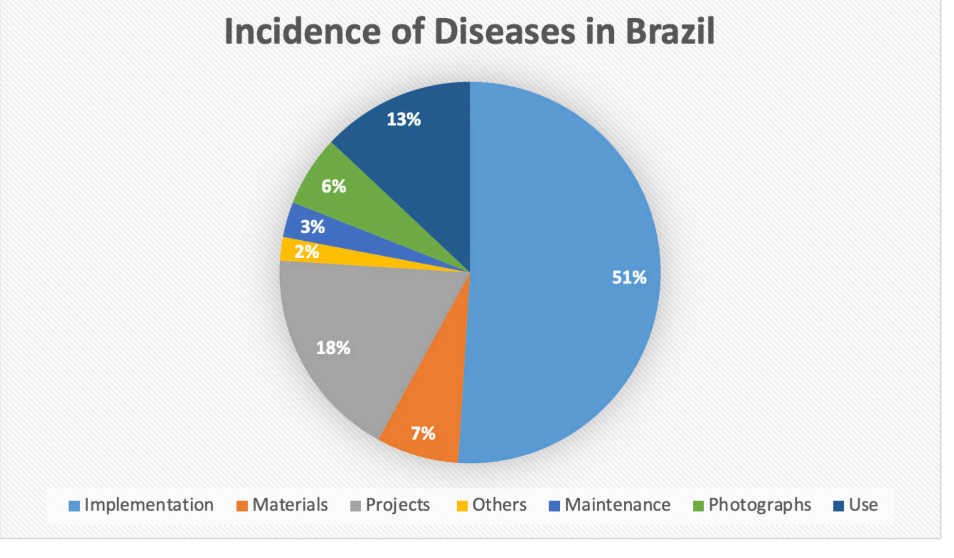

Figure 1 - Incidence of the origins of diseases in Brazil

Source: Silva, Jonov (2011)

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Origins of Pathologies

For reinforced concrete, the origins of pathologies can be classified as follows:

- Design deficiencies;
- Execution deficiencies;
- Poor quality of materials, or inappropriate use thereof;
- Accidents or unforeseeable causes (fires, floods, accidents, etc.);
- Inappropriate use of the structure;
- Improper maintenance

Due to environmental effects on structures and their subsequent response, structural improvements are not achieved solely through the use of good materials, but rather through execution techniques, well-designed and easy-to-read projects, preventive maintenance, and inspection procedures.

Every pathology has its origin. In Brazil, the incidence of origins is as shown in Figure 1 below:

Recovery Costs

All these disorders are progressive and, if specific treatment is not carried out for each pathology, they can worsen further, thus becoming more than one disease. The sooner such corrections are made, the easier, more durable, and, above all, cheaper they are to perform (SILVA; JONOV, 2011).

Recovery costs, as mentioned above, vary depending on the length of time the condition has been present. The longer the time, the greater the severity of the disease and, consequently, the higher the cost of correcting the anomalies. Figure 2 below shows a graph of the law of cost evolution presented by Sitter (1984), showing the relationship between the high costs associated with the interventions mentioned above.

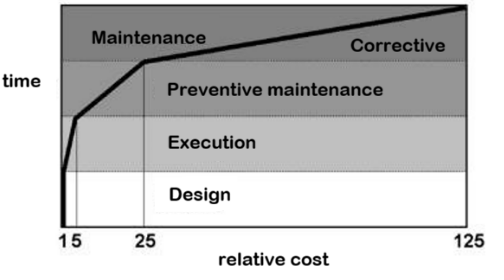

Figure 2 - Law of cost evolution (SITTER, 1984 CEB-RILEM)

Source: Silva (2011)

If measures are taken at the design stage, there can be a significant reduction in failures and financial losses. Most execution pathologies can be consequences of design pathologies, but this does not mean that if the design pathology is null, the execution pathology will be. Even with high-quality designs, execution pathologies will not always disappear. These can only be minimized with good execution, a good design, and extreme supervision during the completion of the work (OLIVEIRA, 2013).

Pathologies x constructions

When studying pathologies in construction, the type of structures that suffer most from these anomalies are reinforced concrete structures, which undergo changes in their characteristics and properties, thus acquiring various defects. As it is a non-inert material, it is subject to these changes. Often, such diseases can compromise the performance of structures, causing them to lose their aesthetic quality and thus causing discomfort to their users. When struc-

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tures have their performance threatened or compromised, the anomaly is characterized as a disease or illness, requiring immediate repairs in order to have a healthy structure (PIANCASTELLI, 1997).

There are several ways to reduce pathological manifestations in buildings, and they can be employed by various companies in the civil construction industry. Such measures may include: investing in skilled labor, hiring specialized workers, or investing in the training of their own employees; investing in technology; the need for preventive maintenance, raising awareness among designers, builders, and users (SILVA, 2011).

Due to the complexity of each specific pathology, which involves natural phenomena and chemical reactions, analyses cannot be performed by lay citizens, given the seriousness of the subject. However, it is an under-explored area and there is a severe shortage of professionals specialized in the subject. An immediate example is corrosion in structures. The symptoms and causes of corrosion are often unknown, but knowledge of them is necessary to obtain appropriate correction methods and procedures so that interventions are effective.

Among all these different types of pathologies, this paper will address one of the major pathological problems in buildings, corrosion in reinforced concrete structures, studying theories, types, controls, and methods of analysis.

Corrosion in Reinforced Concrete Structures

Corrosion of Reinforcement

When some civil engineering professionals encounter situations where corrosion of reinforced concrete reinforcement is occurring, some are at a loss due to the complexity of the subject, not knowing why the problem has arisen, the degree and level of the situation, and how to treat the location where the problem is occurring.

Corrosion can be understood as the destructive interaction of a material with the environment, resulting from chemical or electrochemical reactions that cause the deterioration of the material, which may or may not be associated with physical or mechanical actions (HELENE, 2014). In the case of metal, it is converted to a non--metallic state, thus losing its main qualities, which are mechanical strength, elasticity, and ductility (CASCUDO, 1997).

Corrosion in concrete reinforcement occurs when there are flaws in the execution, i.e., failure to cover the steel with a layer of concrete, called a cap, failure to vibrate correctly when filling the form, causing drill holes, and also when there is no preventive maintenance on buildings, because over time, buildings begin to deteriorate, resulting in the displacement of the protective concrete layer, thus exposing the reinforcement to the environment and allowing the corrosion process to occur in the reinforcement.

When the reinforcement is corroded, it loses area of its section, causing the steel to lose part of its mechanical strength, a reduction and eventual loss of adhesion of the main reinforcements, that is, a whole process of deterioration that leads to a serious compromise of structural safety over time (HELENE, 2014).

All reinforcement introduced into concrete structures is, in theory, protected by a layer of concrete, called concrete cover, forming a physical barrier around the reinforcement that protects it from external agents and also prevents water penetration.

According to Helene (2014), with the loss or rupture of this concrete cover layer, a process of reinforcement deterioration may begin, which can be progressive or self-accelerating. The loss of this protective layer occurs mainly due to carbonation phenomena and chloride contamination in the concrete. Other factors that can contribute to the displacement of the protective concrete layer are cracking, improper execution, materials of various types, wetting and drying cycles, fungi, soot, cyclic stresses, aggressive atmosphere, and temperature variations.

According to Ribeiro and Cunha (2014), in regions where concrete cover is inadequate, corrosion becomes more progressive with the consequent formation of iron oxyhydroxide, which occupies a volume 3 to 10 times greater than the original volume of the steel reinforcement, and can cause internal expansion pressures of up to 15 MPa. These stresses initially cause cracks in the concrete in the direction parallel to the corroded reinforcement, thus favoring carbonation and the penetration of aggressive agents and CO_2, and consequently the spalling of the concrete, as seen in Figure 3 below.

a) Penetration of aggressive agents;

b) Cracking due to expansion forces from corrosion products;

c) Concrete spalling and severe corrosion;

d) Significant reduction in the section of the reinforcement.

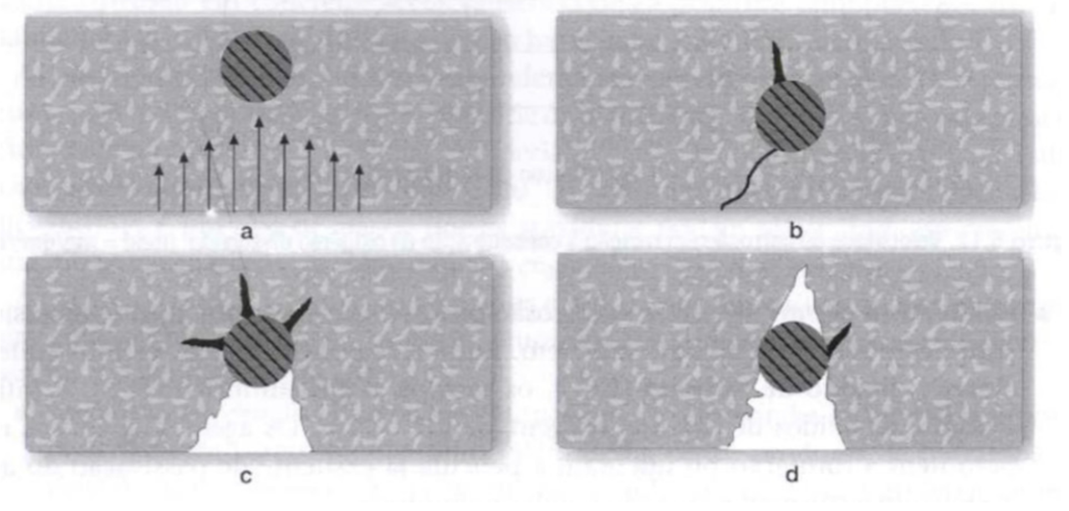

Figure 3 - Corrosion deterioration of reinforcement

Source: Ribeiro, Cunha (2014)

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Visible symptoms of corrosion only appear several years after the structure has been completed, around 10 to 15 years. However, problems rarely appear during the execution phase; they may begin at this stage and only become visible after a certain period of time.

But currently, there is a difficulty in raising awareness among design and construction professionals to understand how important it is to implement the correct measures to protect the reinforcement, which are: increasing the characteristic strength, reducing the water-cement ratio, increasing the thickness of the reinforcement cover (coating), ensuring that this cover is maintained even after the work is completed, installing gutters, drip edges, flashings, and cap strips, and, above all, ensuring a good finish on the structures, improving the waterproofing of the concrete surface.

Initiation of corrosion

For the corrosion process to begin in the reinforcement, aggressive agents must pass through the reinforcement cover layer and reach the reinforcement in sufficient concentrations to cause the steel to become depassivated. The loss of the natural passivity of the concrete reinforcement can be caused by the presence of chloride ions in sufficient quantities to destroy the passivating layer or by a reduction in the pH of the concrete due to the effect of carbonation (RIBEIRO; CUNHA, 2014).

The corrosion initiation process involves, in addition to the depassivation of the reinforcement, the transport mechanism of chloride ions and CO_2. This process occurs through the pores present in concrete. Another important factor that has a major influence on the corrosion initiation process is cracking, which can facilitate the presence of oxygen and moisture, as well as the rapid penetration of aggressive agents into the concrete reinforcement (RIBEIRO, CUNHA; 2014).

Corrosion propagation

In addition to the depassivation of concrete, the development or propagation of corrosion occurs due to various thermodynamic conditions, which determine the speed and intensity of corrosion. Therefore, the moisture content of concrete is the main parameter in corrosion control, and with this principle in mind, temperature is a determining factor in the process, as it controls the evaporation and condensation of water inside the concrete. In addition, temperature plays another important role in the development of corrosion in reinforcement, as it can stimulate ionic mobility and favor the transport of ions through the microstructure of concrete (RIBEIRO; CUNHA, 2014).

Actions of chlorides

The main cause of metal corrosion is chloride, as it can be unintentionally introduced into concrete as a hardening agent or setting accelerator, or it can also be introduced during the concrete mixing process, as the water added to the mixer may contain chlorine. Chlorine penetration can come from antifreeze salts (in places with extreme winters), industrial brines, and sea breezes or mists from marine environments (CASCUDO, 1997).

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Deterioration of reinforced concrete structures

The concrete covering the reinforcement is of paramount importance for the prevention of corrosion. Once this protective layer deteriorates, it can allow aggressive agents to reach the rebars. The main agents responsible for corrosion are carbon dioxide (CO_2) and chloride ions (RIBEIRO; CUNHA, 2014).

According to Gentil (2007), cited by Ribeiro and Cunha (2014), the corrosion and deterioration observed in concrete structures can be associated with several factors, namely: Mechanical, physical, biological, and chemical factors.

- Mechanical: Vibration and erosion.
- Physical: Temperature variations.
- Biological: Bacteria.
- Chemical: Chemicals such as acids and salts.

Among the mechanical factors, vibration can cause cracks or fissures in concrete structures, allowing the reinforcement to come into contact with aggressive agents and initiate or accelerate the corrosion process. As for physical factors, we can mention temperature variations, which can cause thermal shocks in structures. With temperature variations, concrete can shrink and contract its mass, consequently causing microcracks and thus promoting corrosion. Biological factors, such as microorganisms, can create corrosive environments in the reinforcement and concrete. An example of this is the environment created by sulfur-oxidizing or sulfide-oxidizing bacteria, which accelerate the oxidation of these substances into sulfuric acid. Chemical factors are related to the presence of chemicals in the environment surrounding the structure, whether in the soil, water, or atmosphere. Among the most aggressive substances are sulfuric acid and hydrochloric acid.

Cover

The concrete covering the reinforcement is referred to as the physical protection of the reinforcement, acting as a physical barrier against external agents, such as moisture and oxygen, and ensuring that the reinforcement has chemical protection. Cover concrete is one of the most important elements in combating corrosion. If there is no cover or if the cover thickness varies along the length of the piece, this can facilitate the onset or even accelerate the existing corrosion process. NBR 6118 stipulates the nominal cover thickness according to the aggressiveness of the environment, which varies from place to place. For example, a coastal city ( ) has a completely different thickness compared to a tropical city (CASCUDO, 1997).

Temperature

According to Cascudo (1997), temperature plays a dual role in deterioration processes. As the temperature rises, it promotes an increase in the speed of corrosion and ionic mobility, and on the other hand, as the temperature drops, it can lead to condensation, which can produce local increases in moisture content.

Types of Steel

In the corrosion process, the type of steel is of paramount importance, as the corrosion rate varies depending on the type of steel used in the reinforcement. Steels that

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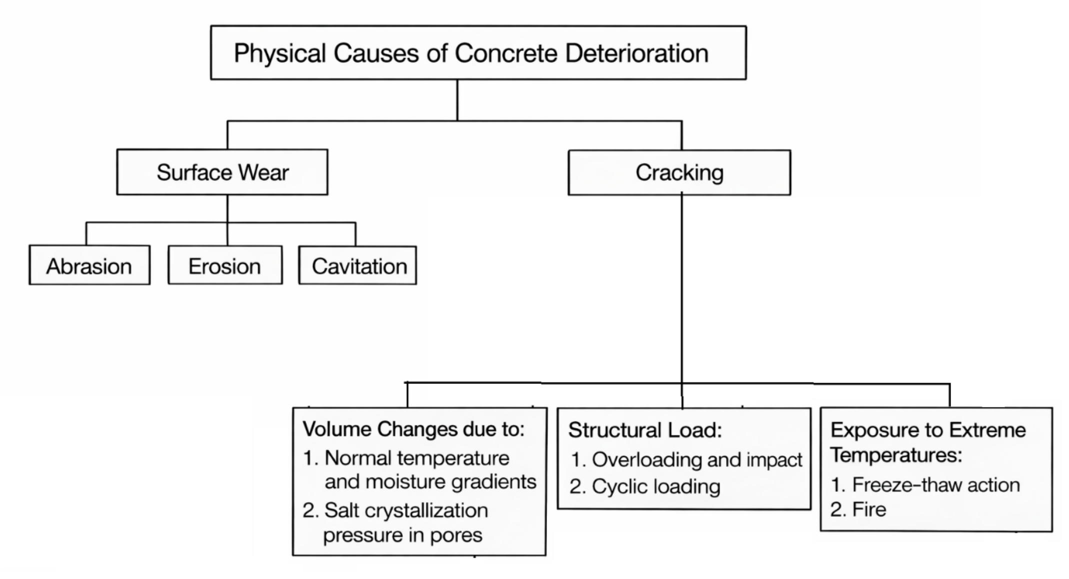

Figure 4 - Physical causes of concrete deterioration

Source: Ribeiro, Cunha (2014)

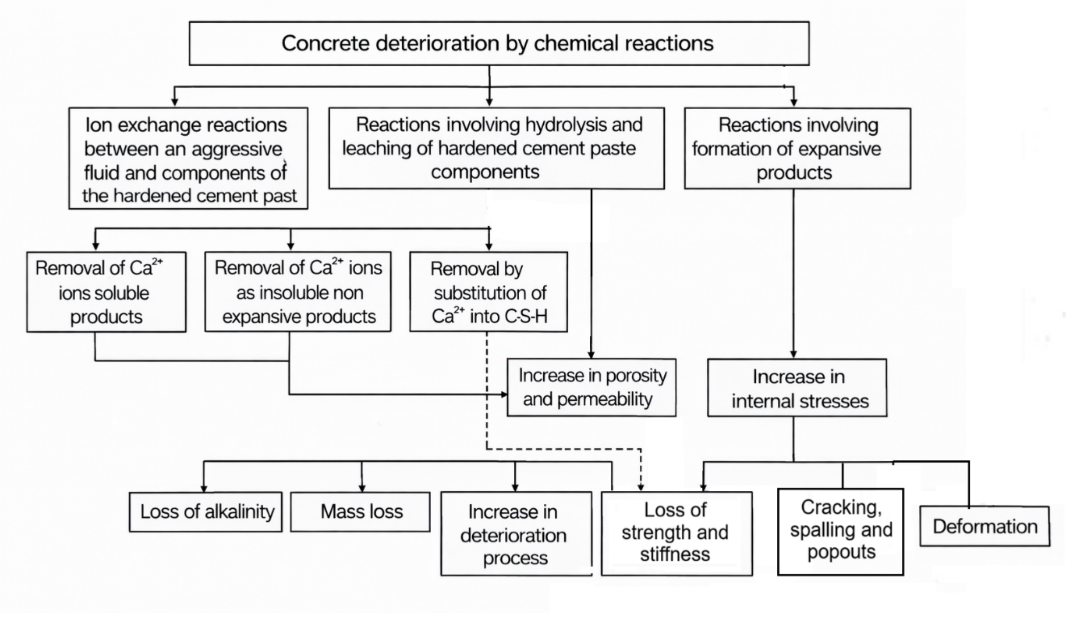

Figure 5 - Chemical causes of concrete deterioration

Source: Ribeiro, Cunha (2014)

Visual symptoms	Levels or degrees of deterioration				
	Initial-I	**Moderate-II**	**Severe-III**	**Strong-IV**	**Very severe -V**
Corrosion spots	Visible	Visible	Visible	Visible	Visible
Fissures	Few longitudinal cracks	Longitudinal and stirrups	Generalized	Generalized	Generalized
Detachment of concrete covering	–	Initial	Widespread	Even in areas where there is no reinforcement	Even in areas where there is no reinforcement
Reduction of the section	–	-5	-10	-25	Sectioned stirrups
Arrows	–	–	–	Possible	Visible
R/S new construction*	0.95	0.8	0.6	0.35	_
R/S new construction*	0.85	0.7	0.5	0.25	_

* estimate of the reduction in the structural component's resistance capacity based on the R/S ratio, where R = residual resistance capacity and S = maximum stress that the structure should withstand according to national standards. Under the most unfavorable load conditions

Table 1 - Classification of degrees of deterioration

Source: Helene (1993)

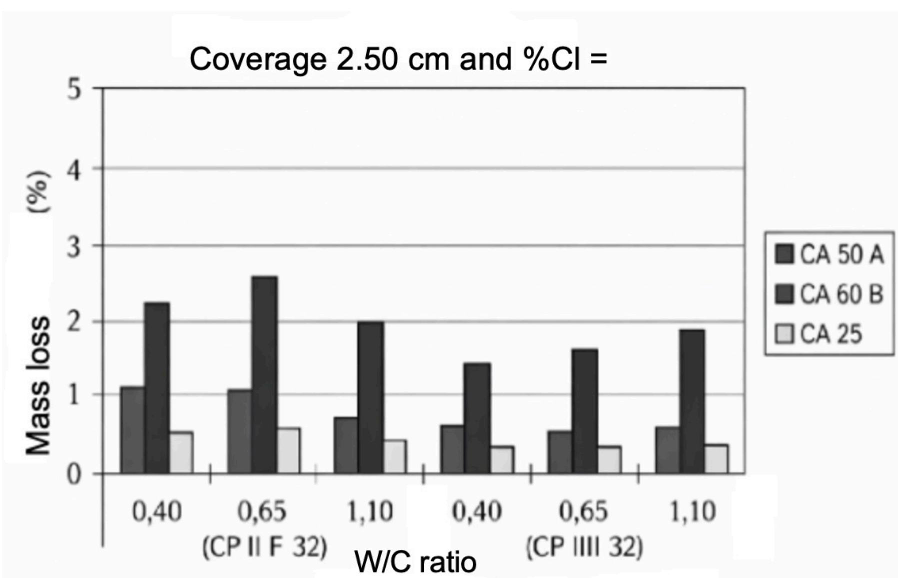

Figure 6 - Mass loss values for the three types of steel used, considering the variation in the water/cement ratio and cement type, with a 2.5 cm cover and 4% additive incorporated

Source: Cascudo (1997)

undergo cold treatment during manufacture, such as hardening or drawing, or steels with higher carbon content, are more susceptible to corrosion than other types of steel with lower hardness and low mechanical strength (CASCUDO, 1997).

According to the author, an experimental study conducted by the Federal University of Goiás evaluated the corrosion vulnerability of three types of steel (CA-25, CA-50, and CA-60), varying the water/cement ratio, cement type, cover thickness, and amount of $CaCl_2$ (calcium chloride), it was found that the variable types of steel was the one that most significantly influenced corrosion. In the experiment, the steel that showed the most susceptibility to corrosion was CA-60, which showed higher corrosion rates than CA-50 steel, which in comparison with CA-25 steel presented more relevant data. Figure 6 below shows the aforementioned research, presenting the difference in behavior of the three types of steel in terms of mass loss due to corrosion, and all data were based on a 2.5 cm cover layer and a $CaCl_2$ additive content equal to 4% in relation to the cement mass. These results prove that the type of steel is of paramount importance when it comes to corrosion.

Cracking of the Covering Concrete

Cracks in the concrete cover can interfere with the reinforcement depending on their width; the wider the cracks and the earlier they appear, the greater the intensity of the corrosion process (CASCUDO, 1997). According to Corsini (2010), cracks can reach up to 0.5 mm in width.

According to Cascudo (1997), cracks do not significantly interfere with the intensity of corrosion to the point of putting the useful life of structures at risk, but they can only anticipate the corrosive process in the reinforcement, because the larger these cracks are, the easier it is for aggressive agents to penetrate the concrete.

Water/Cement Ratio

When we talk about corrosion, the water/cement factor may not seem very important, but it is one of the parameters that must be taken into careful consideration. The water/cement ratio is one of the factors that determines the quality of your concrete, and the higher the quality, the greater the protection it will provide to the reinforcement.

In a mixture, a low water/cement ratio will slow down the diffusion of chlorides, carbon dioxide, and oxygen, thus hindering the entry of aggressive agents and moisture into your structural piece. By also decreasing the water/cement ratio, you will be limiting the number of pores, thus making the piece more impermeable. In view of this, we can say that the water/cement ratio has a major influence on corrosion (CASCUDO, 1997).

Permeability and Absorption

The water permeability and water absorption of a concrete piece are aspects that reflect the quality of the concrete, and it can be said that the concrete will be of low quality when its permeability and absorption are higher (CASCUDO, 1997).

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Electrical Resistivity of Concrete

Oswaldo Cascudo stated that the electrical resistivity of concrete is one of the factors that depends on the moisture content in the concrete, its permeability, and the degree of ionization. Resistivity is one of the factors that control the electrochemical function, and it can be said that corrosion occurs in places with high moisture content, but without pore saturation to hinder the arrival of oxygen.

Economic Importance and Structural Safety

According to Geho, cited by Helene (2014), a survey was conducted and concluded that corrosion is the third most common pathology, based on research carried out in 52 Spanish provinces. But when it comes to pathologies that affect structural safety, corrosion rises to a whole new level.

Helene (2014) writes that Magalhães et al. (1989) conducted an extensive survey of 145 viaducts in the capital of São Paulo, and 58% of the total had problems with corrosion of reinforcements.

The problem of corrosion in reinforced concrete reinforcement is, unfortunately, one of the most common cases, causing several accidents such as the collapse of marquees, cantilever slabs, and overpasses, leaving several victims, many of them fatal. To prevent corrosion from occurring in construction projects, professionals in the field must have up-to-date and comprehensive technical knowledge, both for assessing corroded structures and for treating them. It can be said that the study of corrosion in reinforced concrete structures is a topic of enormous importance for the evolution of engineering (HELENE, 2014).

Types of corrosion

Principles of Electrochemical Corrosion

As mentioned earlier, corrosion is a process of material deterioration due to chemical and electrochemical actions, causing the material to lose part of its mass. Most metals are found in nature in the form of compounds, such as oxides and hydroxides, and have a minimum energy state. The main component of steel reinforcement used in reinforced concrete structures, known as iron, begins to exhibit a lower energy state when it comes into contact with the environment, transforming into hydrated Fe_2O_3, better known as rust (SOUSA, 2014).

According to Cascudo (1997), the deterioration of the material by chemical actions, also known as dry corrosion or oxidation, occurs through a gas-metal reaction forming an oxide film, which is a slow process and does not cause major deterioration on the surface of metals, unless extremely aggressive gases are involved. Electrochemical corrosion, on the other hand, is the most problematic for civil construction works, as it is an electrochemical attack occurring in an aqueous environment.

Corrosion that occurs in steel reinforcement in reinforced concrete, like most corrosive processes, is known as the transfer of electrons and ions between two distinct regions of the metal, a process known as electrochemical corrosion. Corrosion in reinforcement can be localized by pitting and under tension or uniform, with uni-

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form corrosion occurring throughout the entire length of the bar, localized pitting occurring at a specific point in the reinforcement, and under tension corrosion being a type of localized corrosion that occurs with tensile stress in the reinforcement, which can lead to the propagation of cracks in the steel structure. Pitting corrosion is considered the most serious, as this process involves the presence of chloride ions, resulting in a cavity that spreads rapidly and causes the reinforcement to lose its mechanical properties with significant deterioration (SOUSA, 2014).

Black corrosion (absence of oxygen)

When a reinforced concrete part is immersed in water, the pores of the concrete are completely filled with water and in this case there is a lack of oxygen in the area. In this scenario, an even more complex corrosive process than usual may occur, due to the increased speed of the corrosive process and mainly due to the absence of corrosion symptoms, i.e., the absence of external signs proving the existence of corrosion in the part. With the absence of oxygen in the pores, the species resulting from the dissolution of steel in water, Fe^{2+} ions, will remain in solution, thus not forming any expansive oxide, even though the part is undergoing corrosion (RIBEIRO; CUNHA, 2014).

According to the author, the name black corrosion comes from the fact that when the part is immersed for some reason, whether for repair or inspection, it is exposed to air, and the solution surrounding it turns black or dark green.

Bacterial corrosion

The presence of aerobic bacteria such as *Thiobacillus thiooxidans* in soil or water is one of the main causes of deterioration in concrete structures and the onset of cor-

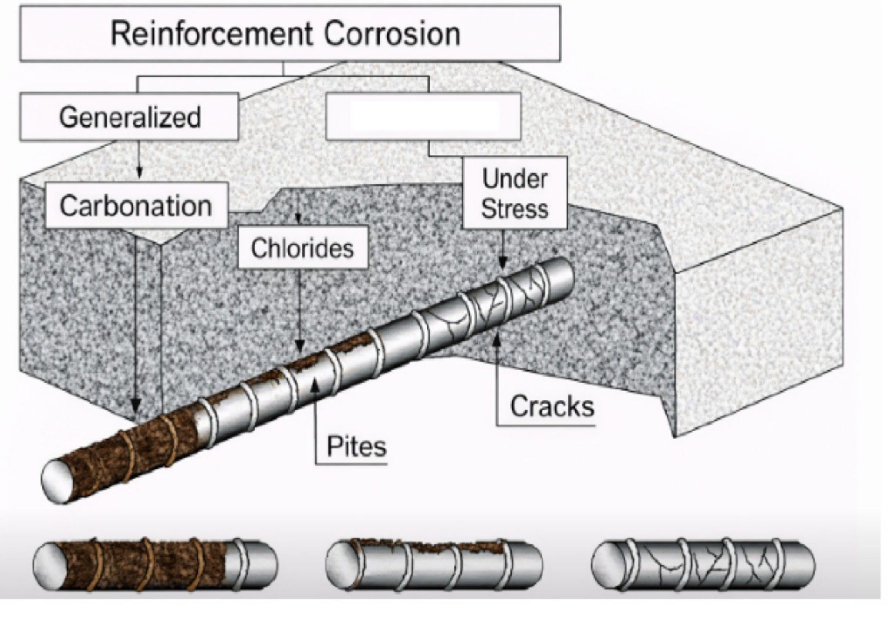

Figure 7 - Types of corrosion and factors that cause them

Source: Adapted from Cascudo (1997)

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rosion. This type of corrosion is common in water and sewage treatment plants, or in industrial effluent pipes (RIBEIRO; CUNHA, 2014).

According to Ribeiro and Cunha (2014), the corrosive mechanism is simple: bacteria produce sulfuric acid through the oxidation of sulfites or sulfur compounds, thus causing a decrease in the hydrogen ion potential (pH) of the concrete and the consequent depassivation of the steel. At the same time, sulfuric acid reacts with free calcium hydroxide or tricalcium aluminate, both present in concrete, producing calcium sulfoaluminate crystals that expand and consequently cause cracks in the concrete structure, thus exposing the reinforcement to aggressive substances.

Anaerobic bacteria, such as *Desulfovibrio desulfuricans* present in sewers, reduce the sulfur-rich organic and inorganic compounds present in water to sulfides. In many cases, this process produces H_2S, causing depolarization of the cathodic reaction and the formation of FeS, thus increasing the corrosive process (RIBEIRO; CUNHA, 2014).

Corrosion by "stray currents"

Corrosion due to the influence of "stray currents" or "Faraday currents" is a phenomenon that occurs when structures are very close to high-power direct current (DC) sources, such as structures on train and subway lines. It is generally accepted that this corrosive process in concrete is very rare when the voltage source is alternating current (AC) (RIBEIRO; CUNHA, 2014).

According to the author, the mechanism of the corrosive process caused by stray currents can be described as follows: due to poor insulation, the return current escapes through the concrete, through the reinforcement, to the ground. Along this path, the current always chooses the path of least electrical resistance, and can jump from bar to bar, either by electronic conduction or ionic conduction. In the areas where the currents exit to the ground or from one bar to another, corrosive phenomena originate in the reinforcement, which can be at high speeds. The current exit area becomes electrically more positive, functioning as an anode.

Acid attack on concrete structures

Concrete is a very sensitive material when it comes to acidic substances. Aqueous solutions of acids such as sulfuric, hydrochloric, acetic, and nitric acids are very aggressive substances for concrete structures. The aggressiveness of these acidic solutions on the structure depends on their ionic so-

Relationship between pH and the degree of attack on concrete	
Degree of attack on concrete	Acid pH
WEAK	6.5 to 5.5
STRONG	5.5 to 4.5
VERY STRONG	< 4.5

Table 2 - Relationship between pH and the degree of attack on concrete

Source: DIN Standard - 4030

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lubility and the salts formed, with greater solubility resulting in greater aggressiveness of the acidic solution. These solutions result in the disintegration of the cementitious matrix. The reason for the change is that the acid attack results from a change in the chemical balance within the pores of the concrete due to reactions with the acidic substances. These reactions result in other salts, such as calcium chloride or calcium sulfate (RIBEIRO; CUNHA, 2014).

According to DIN standard 4030 (Deutsches Institut Fur Normung), it is possible to relate the pH of acids to the degree of attack on concrete, as shown in Table 1.

Service life of concrete structures as a function of the corrosive process

Because reinforced concrete is exposed to the environment and subject to various interactions, its durability and service life are subject to various changes, which can compromise the properties and functionality of structures.

> According to ABNT NBR 15.575 - Part 1 - General Requirements, 2013 (p. 10), the concept of useful life is the period of time during which a building and/or its systems are suitable for the activities for which they were designed and built, considering the frequency and correct execution of the maintenance processes specified in the respective Use, Operation, and Maintenance Manual (the useful life should not be confused with the legal and certified warranty period).

> Antonoff 2016 (p. 20) defines service life as the period of time during which the performance of a material, system, component, or product is achieved or exceeded. Thus, different performance expectations for the same product can lead to different service life periods.

> In ISO 15868-1, service life is defined as "the period of time after installation during which the building or its components achieve or exceed the required performance."

In terms of structures, reinforced concrete structures are currently the most widely used, compared to steel and wood structures. This choice was made because of their greater durability. Like any structure, if maintenance is lacking, its durability decreases. Concrete structures are no different; there are numerous pathologies that are found in concrete structures, and all of them, if left untreated, will compromise the structures.

In a structure affected by corrosion in the reinforcement, especially if the corrosion process is at an advanced stage, several questions arise regarding the severity of the problem, whether repairs or reinforcements are necessary, and to what extent it may affect the useful life of the structures. These questions will be addressed in this paper.

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Loss of load-bearing capacity

For a material to lose its load-bearing capacity, the structure or reinforcement must suffer widespread deterioration. Cracks and spalling are good indicators of deterioration in the structure. Longitudinal cracks, parallel to the reinforcement, are signs of corrosion in the reinforcement, and with advanced corrosion, another symptom will appear, called spalling, which is caused by increased internal stresses due to expansive corrosion products. Cracking and spalling are not necessarily caused by corrosion, because if the corrosive process is occurring in a piece where the concrete is wet, the products developed by corrosion are dissolved and infiltrated into the porous networks, causing stains on the concrete surface (CASCUDO, 1997).

Therefore, if the concrete spalls, you automatically lose section in the part, and consequently the part will lose its load-bearing capacity. This is no different from steel: if there is a reduction in the diameter of the bar or a reduction in the section of the bar due to the penetration of corrosion, the reinforcement will lose its previous load-bearing capacity.

Effect of the environment on concrete structures

The durability of a concrete structure depends on its ability to withstand the aggressions to which it is exposed by the surrounding environment. The effects of the environment on structures depend on several factors, such as the macroclimate, which is the general climate covering large regions, and the microclimate, which are the climatic variations that occur around the structure. A real example of the interference of climate on structures is the presence of chlorides and sulfates contained in seawater, which can reach the structure through the air (ALMEIDA; SALES, 2014).

According to Bertolini (2010), cited by Almeida and Sales (2014), he classifies the local microclimatic conditions that concrete structures can create or are exposed to into four categories. These are:

- Dry concrete conditions: this is a case where the environment is not aggressive, as the occurrence of structural degradation and the corrosive process will require moisture to manifest itself.
- Conditions of total and permanent concrete saturation: in this case, the environment is not highly aggressive in terms of corrosion, as oxygen cannot reach the surface. However, the concrete may be subject to attacks by substances such as sulfates and be subject to freeze-thaw actions.
- Conditions of intermediate concrete moisture: in this climate, structures begin to suffer more, as there is a high possibility of corrosion and concrete degradation. The degradation process increases as the temperature rises and the moisture content of the concrete increases.
- Conditions in which concrete undergoes a cycle of wetting and drying: this is the condition in which concrete suffers the most and presents a critical level of corrosion, as water easily pene-

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trates the pores of the concrete and comes into contact with the reinforcement.

Helene, also cited by Almeida and Sales (2014), presents another classification of environmental aggressiveness according to the macroclimate, which are:

- Rural atmosphere: this is a region where aggressiveness towards the structure is considered low, as it generally has clean air, free from aggressive agents. It is a climate in which, if the structural element is perfectly executed , the probability of corrosion in the structure's reinforcement will be minimal.
- Urban atmosphere: this is an atmosphere that contains several aggressive agents, such as sulfur oxides, CO_2, NO_x, H_2S, acid soot, among many others. Another important factor in this environment is air humidity, which is extremely important when it comes to corrosion, as relative air humidity in urban centers varies around 75%, which is considered critical in terms of corrosion. Taking these two factors into account, their combination greatly accelerates the corrosive process.
- Marine atmosphere: considering outdoor regions, over the sea and on slopes, this is a region that poses serious risks to concrete structures, because in these environments the atmosphere contains large proportions of Cl^- (chlorides) and SO_4^{2-} (sulfates), which are extremely aggressive agents to concrete structures and can increase corrosion even if they are small in size.
- Industrial atmosphere: considering the relative humidity and the presence of various aggressive agents in this type of atmosphere, it can be said that it is an environment extremely conducive to corrosion in concrete reinforcement. Compared to the rural environment, the industrial atmosphere accelerates the corrosive process by around 60 to 80 times.
- Stale atmosphere: these are closed environments with little air circulation. A place conducive to the generation of gases that are aggressive to concrete reinforcement, such as hydrogen sulfide (H_2S), which is the decomposition of organic material caused by bacterial action.

When executing a structural project, the aggressiveness of the environment surrounding the structure must be taken into account to ensure its safety and stability. A well-calculated, well-executed project with preventive maintenance indicates a structure with greater durability. NBR 6118 (2014) presents a classification and suggests an assessment of the type of environment to which the structure will be exposed, as shown in Table 3.

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Classes of environmental aggressiveness			
Class of aggressiveness aggressiveness	Aggressiveness	General classification of the type of environment for design purposes	Risk of deterioration of the structure
I	Poor	Rural	Insignificant
		Submerged	
II	Moderate	Urban i) ii)	Small
III	Strong	Marine i) ii)	Large
		Industrial i) ii)	
IV	Very strong	Industrial i) iii)	High
		Tidal splashes	

i) A microclimate with a milder aggressiveness class (one level above) may be accepted for dry indoor environments (rooms, bedrooms, bathrooms, kitchens, and service areas in residential apartments and commercial complexes, or environments with concrete coated with mortar and paint).

ii) A milder aggressiveness class (one level above) may be accepted in: construction projects in dry climate regions, with relative humidity less than or equal to 65%, parts of the structure protected from rain in predominantly dry environments, or regions where it rarely rains.

iii) Chemically aggressive environments, industrial tanks, electroplating, bleaching in pulp and paper industries, fertilizer warehouses, chemical industries.

Table 3 - Environmental aggressiveness classes according to NBR 6118

Source: ABNT (2014)

Correspondence between aggressiveness class and concrete quality					
Concrete	Type	Aggressiveness class (Table 3)			
		I	II	III	IV
Water/cement ratio in mass	CA	≤ 0.65	≤ 0.60	≤ 0.55	≤ 0.45
	CP	≤ 0.60	≤ 0.55	≤ 0.50	≤ 0.45
Concrete class (ABNT NBR 8953)	CA	≥ C20	≥ C25	≥ C30	≥ C40
	CP	≥ C25	≥ C30	≥ C35	≥ C40

NOTES

1- The concrete used in the construction of the structures must comply with the requirements established in ABNT NBR 12655.

2- CA corresponds to reinforced concrete components and structural elements.

3- CP corresponds to prestressed concrete components and structural elements.

Table 4 - Correspondence between aggressiveness class and concrete quality according to NBR 6118

Source: ABNT (2014)

Correspondence between environmental aggressiveness class and nominal cover for Δc = 10 mm					
Type of structure	Component or element	Environmental aggressiveness class (Table 3)			
		I	II	III	IV
		Nominal cover (mm)			
Reinforced concrete	Slab[ii]	20	25	35	45
	Beam/Pillar	25	30	40	50
Prestressed concrete [i]	All	30	35	45	55

i) Nominal coverage of the passive reinforcement surrounding the sheath or wires, cables, and strands, always greater than that specified for the reinforced concrete element, due to the risks of stress corrosion cracking.

ii) For the upper face of slabs and beams that will be covered with screed mortar, with dry final coatings such as carpet and wood, with coating and finishing mortar such as high-performance floors, ceramic floors, asphalt floors, and many others, the requirements of this table may be replaced by a Δc=5mm, respecting a nominal cover ≥ 15 mm

iii) On the undersides of slabs and beams in reservoirs, water and sewage treatment plants, sewage pipes, effluent channels, and other works in chemically and intensely aggressive environments, the reinforcement must have a nominal cover ≥ 45 mm.

Table 5 - Correspondence between environmental aggressiveness class and nominal cover for Δc = 10 mm according to NBR 6118

Source: ABNT 2014

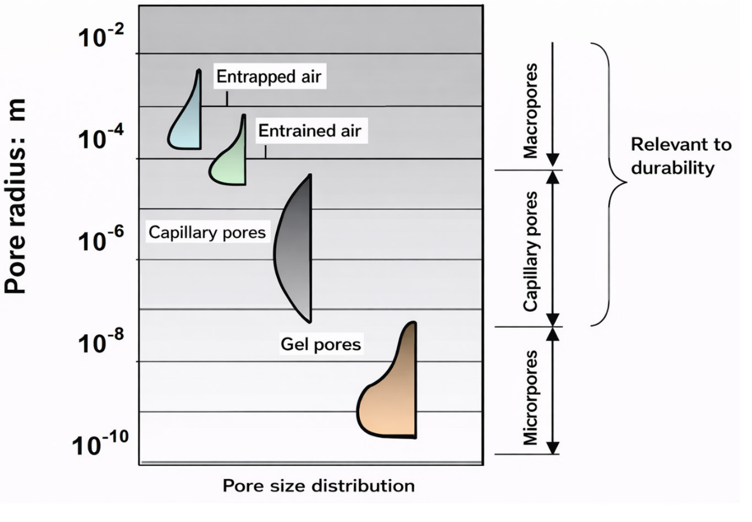

Figure 8 - Diagram of pore size distribution in hardened cement paste

Source: Adapted from Cascudo (1997)

To ensure high durability for concrete, tests must be carried out on the performance of the structure in relation to its surrounding environment. In the absence of these tests, NBR 6118 (2014) presents a table with some minimum requirements to be adopted, shown in Table 4, considering the water/cement ratio and the Fck of the concrete (Characteristic Compressive Strength of Concrete).

To ensure perfect reinforcement coverage, the appropriate covering concrete must be used according to its aggressiveness classes, and NBR 6118 also provides a table with the minimum reinforcement coverage dimensions, as shown in Table 4.

Pore structure

In concrete, pores are formed by using more water than necessary in the mix, and this excess adversely affects the final result of the concrete because, when this excess water evaporates from the concrete, it will leave voids. Such pores can also occur with poorly vibrated concrete during its execution, and the incorporation of air into the concrete mix is also inevitable. These voids or pores form a channel from the inside to the outside, allowing the transport of aggressive substances and gases, which can lead to the deterioration of the concrete and, consequently, to the corrosive process in the reinforcement (RIBEIRO, 2014).

According to Siebeert apud Freire (2005), cited by Ribeiro (2014), pore sizes are classified into several orders of magnitude, namely: Trapped air pores (resulting from concrete compaction processes), compressed air pores (obtained through the use of air-entraining additives), capillary pores (resulting from the release of free water in the concrete), and gel pores (due to gel water). The first three types have the greatest influence on the durability of concrete, as shown in Figure 11.

Capillary pores are primarily responsible for the penetration of aggressive agents into the interior of concrete, as they are interconnected and facilitate the entry of aggressive agents, and the speed at which such aggressive agents penetrate the concrete is determined by the size of the pores (RIBEIRO, 2014).

Transport mechanisms in concrete

When it comes to corrosion, the most influential mechanisms in the transport of liquids and gases in concrete are: permeability, capillary absorption, diffusion, and ion migration.

Permeability

Permeability is defined as the flow of a fluid due to pressure, which is characterized by the ability of a fluid to pass through a porous solid due to a pressure difference. To achieve good permeability in the covering concrete, the water/cement ratio and the degree of hydration must be taken into account. If the water/cement ratio is not within the correct proportions, there will be parts with higher permeability rates. Gas permeability in concrete structures is reduced in humid environments and with wetting and drying cycles, because the presence of water in the pores of the concrete makes it more difficult for gases to circulate (RIBEIRO, 2014).

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Capillary absorption

Capillary absorption is defined as the flow of a fluid due to a moisture gradient, or the transport of liquids due to surface tension acting on the capillary pores of concrete. Water absorption is one of the most difficult problems to control, because the larger the diameter of the capillaries, the greater the capillary pressures and, consequently, the greater and faster the absorption. Taking into account the saturation of concrete, it is correct to say that in saturated concrete there is no water absorption (RIBEIRO, 2014). According to Helene (1999) cited by Ribeiro (2014), if there is a reduction in the water/cement ratio, there will be a reduction in water absorption.

Diffusion

Diffusion is the process of transporting substances from one medium to another due to a difference in chemical potential, often concentration, or as a process of transporting masses from one medium to another by concentration gradients. This process can help control the entry of the two most aggressive agents when it comes to corrosion, chloride ions and carbon dioxide (CO_2). It is a process that can also occur in liquid media (RIBEIRO, 2014).

Ion migration

Ionic migration is a transport process that occurs when there is an electrical potential, which enables the movement of ions to neutralize the effect of the potential difference Ribeiro (2014). According to Nepomuceno apud Santos (2006) cited by Ribeiro (2014), this phenomenon can occur in structures that use electric current for their movement (subway sleepers), in concrete structures with cathodic protection by impressed current, or in structures subjected to chloride extraction and realkalization by the application of a potential difference.

Methods of protection and increasing the durability of concrete

To protect the reinforcement against corrosion, it is essential to have concrete of excellent quality, obtain a suitable mix, maintain a thickness within the standards established, and above all, execute them well. Even if the covering layer has all these qualities, aggressive agents can still penetrate the concrete through pores and cracks that the piece may develop over time. Therefore, in environments considered aggressive in terms of corrosion, or when subject to cracks due to mechanical stress, it is recommended to use additional measures to protect the reinforcement against corrosion (LOURENÇO; SOUZA, 2014).

According to Lourenço and Souza (2014), such additional measures to protect the reinforcement against corrosion may include: the use of corrosion inhibitor additives; cathodic protection of the reinforcement; coating the reinforcement with a zinc-based deposit or a polymer layer; replacing carbon steel reinforcement with corrosion-resistant materials, such as stainless steel, glass fiber reinforced polymer composites, and a protective coating on the concrete cover layer.

Such measures will increase the initial cost of the project, but it is worth noting that the use of these measures will result in lower maintenance costs and less downtime for repairs. Some examples that can cause disruption to the company and even to

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society are: the interruption of port works due t r maintenance of reinforced concrete structures, the interruption of water supply stations due t r maintenance of their tanks, and the interruption of transport systems such as bridges and viaducts for necessary repairs (LOURENÇO; SOUZA, 2014).

Use of inhibitors

Corrosion inhibitors are chemicals that, when present in a corrosion system in the correct concentration, slow down the rate of corrosion and thus increase the service life of concrete structures. In addition to protecting against corrosion, these inhibitors must be able to diffuse through the concrete to the location of the reinforcement, and, most importantly, they must not alter the physical and chemical properties of the concrete or its mechanical strength (LOURENÇO; SOUSA, 2014).

There are different ways to apply the products to concrete structures, either in new structures or in already completed structures. In new structures, these inhibitors can be added to the original mixture of fresh concrete, thus preventing or slowing down the corrosive process. In finished structures, inhibitors may appear in the presence of coating mortars, in repair concrete, being applied to the concrete surface or in holes or grooves made in the concrete surface. Inhibitors applied to the concrete surface are usually liquid products that, when applied, pass through the concrete layer by capillarity and reach the reinforcement. An example is monofluorophosphate, which is not widely used in Brazil (LOURENÇO; SOUSA, 2014).

According to Lourenço and Sousa (2014), inhibitors can be divided into anodic, cathodic, or mixed, acting to reduce the anodic reaction, the cathodic reaction, or both.

Elsener (2001/2002), cited by Lourenço and Sousa (2014), states that inhibitors used in reinforced concrete can be classified as:

- Adsorption, whether anodic, cathodic, or mixed
- Passive film formation, when they act by blocking the metal surface,
- Passivation, favoring the stability of the passivation film.

Examples of inhibitors used in reinforced concrete structures

According to Lourenço and Sousa (2014), the most commonly used corrosion inhibitors in reinforced concrete structures are nitrites and mixtures of amines and alkanolamines. The inhibitors used directly in the addition to the fresh concrete mixture are nitrite-based. Sodium nitrite was tested, but it was found that when mixed with fresh concrete, this inhibitor caused it to lose compressive strength and increased the risk of alkali-silica reactions (ASR) in the concrete.

Calcium nitrite ($Ca(NO_2)_2$) was one of the first inhibitors to be tested and has been used in epoxy coating reinforcements to protect against chloride-induced corrosion in bridge decks and substructures. It is an inhibitor that acts essentially on the anodic reaction, and its effectiveness depends on a critical value between the concentration of chlorides and the concentration of nitrites in the concrete at the reinforcement level (Cl^-/NO_2^-). However, these types of inhibitors are not in high demand because

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they are considered toxic substances, and there is an increase in interest in non-toxic inhibitors (LOURENÇO; SOUSA, 2014).

Organic inhibitors based on amines and alkanolamines have been developed, and these act as cathodic inhibitors. The amine is adsorbed on the metal surface, forming a protective layer that prevents contact between the metal surface and the corrosive environment. Amines also have a detergent effect, removing dirt that causes corrosion from the metal surface, thus allowing direct contact between the inhibitor and the surface layer of the metal, ensuring efficient protection (LOURENÇO; SOUSA, 2014).

In addition to nitrite and organic inhibitors, we can include inorganic inhibitors, such as phosphates and red mud (a residue from bauxite processing), and inhibitors consisting of mixtures of organic and inorganic compounds (LOURENÇO; SOUSA, 2014).

Studies have shown that sodium monofluorophosphate (Na_2PO_3F) is an inhibitor that, when in contact with the steel reinforcement inserted in the concrete, attempts to delay the onset of the corrosion process and reduce the rate of corrosion already existing in the reinforcement. It is an inhibitor that, when added to the cement mixing water, increases the corrosion resistance of steel reinforcement in chloride-containing environments when the ratio between the concentration of the inhibitor and chloride ions is greater than 1.0. The mechanism by which Na_2PO_3F inhibits corrosion of steel reinforcement is related to the formation of phosphate. Na_2PO_3F undergoes hydrolysis in an aqueous and neutral environment, forming orthophosphate and fluoride. The phosphate formed reacts with the corrosion products, thus causing the formation of protective films of Fe_3O_4, ɣ-Fe_2O_3, and $FePO_4.H_2O$ (LOURENÇO; SOUSA, 2014).

According to the authors, another inhibitor known as red mud, which is a residue generated in the processing of bauxite during the aluminum production process, is a product that, when added to the concrete mixture, increases the corrosion resistance of the reinforcement bars in the concrete, mixed at around 20% to 30% in relation to the cement mass. This increase in corrosion resistance in the reinforcement provided by red mud may be related to three isolated factors or a combination of them:

a) Increased alkalinity in the region near the steel/concrete interface;

b) Greater fixation of chloride ions due to the presence of sodium aluminates, preventing them from being free and available to initiate the corrosion process;

c) Increased pore width in the concrete, which promotes water loss.

The inhibitors sodium ß-glycerophosphate (0.05M) and saturated dicyclohexylammonium nitrite, mixed with cement mortars, have a satisfactory inhibition efficiency of around 80% to 90%. It was found that the mixture of sodium ß-glycerophosphate (0.05M) and saturated sodium N-phenyl-2-aminobenzoate is effective in inhibiting corrosion in a sodium chloride (NaCl) environment of steel reinforcement inserted into mortar in the absence or presence of ash. Studies were conducted and it was found that the inhibitors were more effective in mortars with ash, with inhibition efficiency in mortar test specimens with ash ranging from 50% to 70%, and inhibition efficiency in mortar test specimens without ash ranging from 30% to 60% (LOURENÇO; SOUSA, 2014).

Cathodic prevention

This method uses cathodic protection to prevent corrosion of reinforcement in reinforced concrete during the construction process. It is widely used in aggressive environments, such as marine environments, to prevent deterioration of structures, thereby increasing their service life (LOURENÇO; SOUSA, 2014).

There are two methods for applying cathodic protection: the galvanic method (with sacrificial anodes) and the impressed current method (CASCUDO, 1997).

The materials used in cathodic prevention are similar to those used in cathodic protection, but the installation methods for both are different. The installation of cathodic prevention during the construction phase of the concrete structure is considered simpler than the installation of cathodic protection. When installing cathodic prevention, it is essential that the anode has a long service life and is easy to install during the construction process of the structure. Titanium-based anodes (Ti/MMO) are generally used, in the form of meshes or strips, fixed to the reinforcement using appropriate spacers before concreting (LOURENÇO; SOUSA, 2014).

Cascudo (1997) states that cathodic protection is the only means capable of solving the problem of corrosion in reinforced concrete structures in a highly chloride-contaminated environment, because the potential of the steel in the concrete reaches the corrosion immunity domain, and even with the presence of chlorides, the reinforcement remains protected.

When used in existing structures, this method has several limitations, that is, when prevention is not carried out during the construction of the structures. Issues such as ensuring electrical continuity in the reinforcement inside the concrete, rigidity within the limits required for cover thicknesses, and adjustments to some architectural details are considered to be of great importance for the application of the method in existing structures, as these requirements have a major impact on the success of the protection.

For the implementation of the system in already constructed concrete structures, it is advisable to repair the damaged parts, with the aim of restoring the original characteristics of the structure. If there is a coating on the structure, whether plaster or any type of mortar, it is advisable to remove it for the application of the cathodic protection method. For such a system, a recommended procedure is to use a system with mesh-shaped anodes covering the entire surface of the concrete to be protected, which can be fixed in place by spraying concrete or even plastering the mesh (CASCUDO, 1997).

Final considerations

Solving the numerous corrosion problems in reinforced concrete structures is very complex for the technicians responsible, as it is a disease that affects the reinforcement of structural elements and is difficult to reach. This pathology progresses increasingly and, depending on the environment exposed, its corrosion speed is even greater.

Even with the complexity of this pathology, there is a certain recurrence of the errors that lead to this disease. Some builders seek speed in their work and forget about errors and flaws in execution, which will later leave buildings susceptible to the proliferation of pathologies, especially corrosion.

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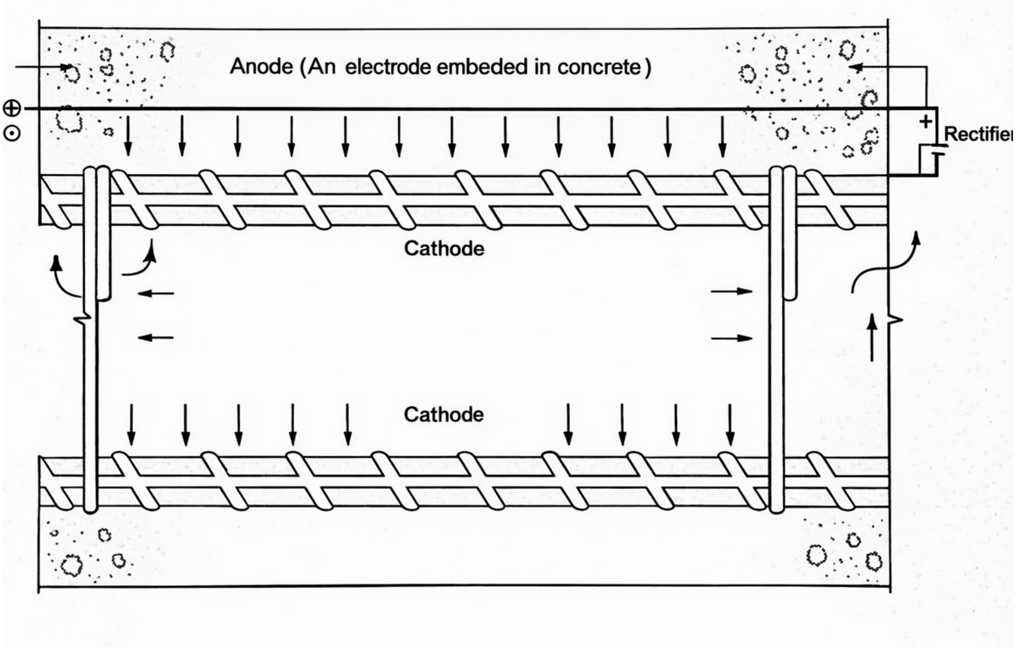

Figure 9 - Diagram of the cathodic protection mechanism for concrete reinforcement, with the direct current system

Source: Cascudo 1997

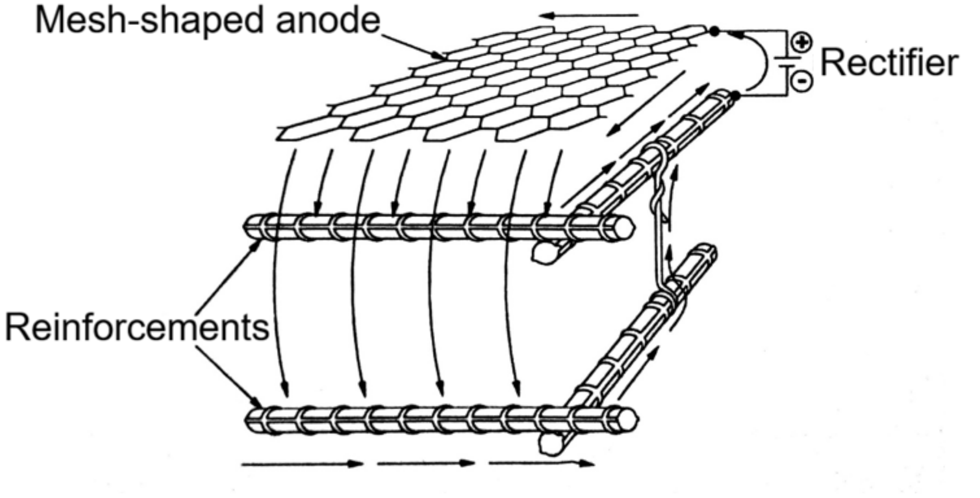

Figure 10 - Operation of the impressed current cathodic protection system, with mesh anodes

Source: Cascudo 1997

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