About concrete and reinforced concrete corrosion

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Abstract. This review article provides general information about reinforced concrete corrosion and types of corrosion. The most dangerous consequence of corrosion processes in reinforced concrete is a decrease in the load-bearing capacity of the structure. Corrosion of reinforcing steel is one of the most common damages to reinforced concrete structures. The most dangerous type of rebar corrosion is chloride corrosion, since at a certain concentration of chlorides, the concrete immediately loses its protective properties in relation to the rebar, the corrosion develops locally and deep into the rod, leading to significant losses of its cross-section, often without visible damage to the concrete surface. Types of corrosion: physical corrosion, chemical corrosion, leaching corrosion, magnesian corrosion, carbon dioxide corrosion, sulphate corrosion, hydrogen sulfide corrosion, biological corrosion, electrochemical and electroosmotic corrosion, the destruction of cement stone.

The article provides an overview of the mechanism of reinforcement corrosion, its initiation, progress and factors that expedite the process of reinforcement corrosion. Once the reinforcement corrosion is initiated, it shortens the service life of the structures by cracks initiation, propagation and subsequently spalling of the cover concrete due to expansion of corrosion steel. Corrosion of the embedded reinforcing steel is the most frequent cause for degradation.

Key words: reinforced concrete, reinforcement, corrosion, concrete, anti-corrosion protection, destruction.

1 Introduction

One of the great advantages of reinforced concrete in comparison with metals and other materials is its high corrosion resistance.

The durability and reliability of concrete structures and their elements are determined not only by the perfection of the project, the correct choice of materials (rebar, reinforced concrete), subject to the production technology, given the operating conditions, but the correct solution to corrosion problems, minimization or exception during design, construction, operation [1-5].

When operating reinforced concrete structures in aggressive environment it is necessary to assess their stress-strain state due to corrosion damage, assess their remaining service life, and take into account the reduction in the cross-section area of the reinforcement. Corrosion of elements of reinforced concrete structures can lead to changes in the strength characteristics of materials, design schemes and redistribution of forces in the sections of the structure, violation of the joint work of concrete and reinforcement. The most dangerous consequences of corrosion processes in reinforced concrete is a decrease in the load-bearing capacity of the structure.

Corrosion of reinforcing steel is one of the most common damages to reinforced concrete structures. Initially, the corrosion process of rebar in alkaline environment of the concrete is impossible and, as a rule, caused by the violation of operating conditions, such as an effect of
aggressive environment, it reduces the protective properties of concrete. In this case, the service life of structures can be significantly reduced. The most dangerous type of rebar corrosion is chloride corrosion, since at the certain concentration of chlorides, concrete immediately loses its protective properties in relation to the rebar, the corrosion develops locally and deep into the rod, leading to significant losses of its cross-section, often without visible damage to the concrete surface. Structures of swimming pools, parking lots, bridges, as well as structures operated in aggressive waters containing chlorides are subject to the action of chlorides. The study of reinforced concrete corrosion issues is also relevant when assessing the residual life of structures with corrosion damage, as it requires knowledge about the development of corrosion processes and their prediction [6-10].

The main causes of damage to reinforced concrete structures:
- violation of the rules of operation;
- abrasion and wear;
- freezing and thawing;
- influence of the gas-air environment;
- corrosion of reinforcement;
leaching corrosion of the I-th species;
- chemical effects of compounds dissolved in water or in contact with concrete-corrosion of types II and III;
- internal corrosion-reaction of cement compounds with aggregate;
- incompatibility of concrete components-differences in deformative properties, thermal incompatibility, etc.

2 Materials and methods

2.1 Physical corrosion
It results from the freezing of water that enters the pores of the concrete with liquids, freezes and expands upon release, destroying the structure and provoking the appearance of cracks.

2.2 Chemical corrosion
All acids and many salts are aggressive towards cement stone. This type of corrosion occurs more often than all however, the destruction is most intense. The most vulnerable substance in cement stone is lime. However, the binding lime (say, due to SiO₂-CaO + SiO₂) does not yet exclude corrosion – ZII, since it can be restored by retreating from the hydrates of calcium.

Acids and some salts react with Ca(OH)₂ and form new compounds, either easily soluble in water, or not-strong loose, or crystallizing with significant change-no more volume. Sometimes it all happens at the same time. All acids destroy Portland cement stone.

2.3 Leaching corrosion
Crystalline (hydro silicates, aluminates and ferrites calcium) formed by interaction with water clinker minerals and components together with fillers cement and they have significant equilibrium solubility in water. This this means that they remain stable in contact with water only if there is a sufficient concentration of Ca(OH)₂ in the water.

If the concentration of Ca(OH)₂ in water is lower than the equilibrium, then the hydrate the lime molecules will break off and the concentration will rise- pour to the equilibrium.

Hydrosilicates and calcium hydroaluminate have the more equilibrium solubility, the higher their basicity. Investigator- however, the separation of hydrates first occurs from the high-base ones, their basicity is reduced, and the stability in the Dan – the noise level increases.

If the concentration of calcium oxide hydrate in the future is not if it goes down, the process will stop there. If the end-the lime fraction will continue to fall and will become lower – in the spring for the newly formed hydrate, then the hydrate cleavage the calcium oxide will continue until complete decomposition Twenty seven hydrosilicates and hydroaluminations, with the formation of amorphous
silica and alumina. Although the latter are poorly soluble in water, however, they do not have astringent properties—strength and mono-the integrity of the stone is violated.

These processes can be observed if the cement stone is formed with continuously renewed water or salt solutions, having a low concentration of Ca(OH)$_2$, or if Ca(OH)$_2$ bound contained in the solution substances in solid Malory-created or low-dissociating chemical compounds.

The higher the concentration of lime in the pores of the cement stone, the higher leaching rate. Low-base calcium hydrates they have lower equilibrium solubility. The lime associated, and basicity is reduced in cases when the cement is introduced into the asset-silica additives, and at high temperatures and quartz the new sand.

Thus, the most corrosion-resistant in filtration is cement with a weak base.

The solubility of lime increases in the presence of chlorine since the sodium. So mineralized reservoir waters in principle all are aggressive to cement stone. The solubility of Ca(OH)$_2$ increase increases with temperature. So these are the conditions that require advantages of using low-base cements.

The filtering rate is highly dependent on the diffusion efficiency. This will be facilitated by a reduction from the carrier content of the filling liquid, Additions are high-particle detectors (hypan, K-4, CMC, etc.).

Lightweight cements are less resistant to leaching, with the exception of the key to those that have as a facilitating component of the IP any active silica additive was used.

2.4 Magnesian corrosion
If the environment surrounding the cement stone contains more amino acid formation with low soluble Ca(OH)$_2$ compounds, that is, the lime concentration will be maintained at a very low level.

For example, if there is MgSO$_4$ in reservoir waters, it enters in interaction with Ca(OH)$_2$ by reaction Ca(OH)$_2$ + MgSO$_4$ + 2H$_2$O → Mg(OH)$_2$ + CaSO$_4$·2H$_2$O.

2.5 Carbon dioxide corrosion
In reservoir waters, as a rule, there is a certain amount of carbon dioxide. It acts destructively, because it lowers the content of Ca(OH)$_2$, first oxidizing it to CaCO$_3$, which it is slightly soluble, which will cause a decrease in the basicity of hydrates cement’s. With the arrival of new portions of CO$_2$, CaCO$_3$ is oxidized to bicarbonate Ca(HCO$_3$)$_2$, which is highly soluble. If there is a small concentration of Ca$^{2+}$ in the water, the process can be damped. However if the acid is contained in the reservoir gas, then due to the large permeation, diffusion and osmosis are possible quickly destruction of the stone.

2.6 Sulphate corrosion
This is a type of corrosion that is associated with the formation of compounds crystallizing with the increase in volume. An example of such corrosion is the interaction with calcium and sodium sulfates. It is known that hydroaluminate calcium can attach the plaster to form hydrosulphuret. The latter crystallizes with increase in volume, which causes internal stress and destruction of the cement stone.

2.7 Hydrogen sulfide corrosion
This is one of the most common corrosion types on oil and gas sites. In the case of hydrogen sulfide corrosion in the tank, the composition of calcium and aluminum is poorly soluble. This leads to a decrease in the equilibrium concentration Ca(OH)$_2$, Al(OH)$_3$, Fe(OH)$_3$, which in turn causes destruction hydrates of calcium.

Iron sulfide is formed most energetically, so to increase the resistance against hydrogen sulfide corrosion should limit the content of iron, manganese and other oxides in cements other heavy metals. Silicates, carbonates, alkalis and their salts are harmless to cement stone. However, strong alkalis act on aluminates.

Oil and petroleum products are not dangerous, but if they contain naphthenic acids and sulfates, they also destroy the cement stone.
2.8 Biological corrosion
This type of corrosion has been little studied. However, at the end it is reduced to some chemical form. So, there are many bacteria that secrete carbon dioxide, which will cause carbon dioxide corrosion. Some bacteria can oxidize sulfates first to hydrogen sulfide, and then to sulfuric acid. Hence the nature of the stone’s destruction is revealed.

2.9 Electrochemical and electroosmotic corrosion
The source is stray currents (industrial networks). System: casing string, cement stone, the earth is a conductor. In this system, it is always possible to transfer ions, hence there is the possibility of electrochemical and electroosmotic corrosion. It should be noted that cement stones and concrete (foundations) have, as a rule, a certain electrical potential in relation to ground.

2.10 Destruction of cement stone
The destruction of cement stone can occur under the influence of physical factors (water saturation, alternate freezing and thawing, wetting and drying, etc.), as well as when the chemical interaction of stone components with aggressive substances contained in the environment takes place. The frost resistance of cement stone depends on the mineral content clinker composition, cement fineness and water requirements, it is necessary to obtain the laid mixture. Fineness of grinding can be considered in the range of 3000 to 4000 cm$^2$/g, and it is important to have in the cement, along with thin fractions of relatively large grains, which provide a «clinker Fund» for self-healing of defects that occur when alternating environmental impacts. Increasing the water demand of cement reduces frost resistance of cement stone, as it increases its capillary porosity (water in the gel pores does not turn into ice even in severe frosts). Therefore, in frost-resistant concrete, the value of V/C (V/C – water-cement ratio, i.e. the proportion of water and cement in the concrete mix), should be maintained no more than 0.4-0.55.

3 Results
In the article [11] authors provide an overview of the mechanism of reinforcement corrosion, its initiation, progress and factors that expedite the process of reinforcement corrosion. Since the desirable requirement of high electric resistivity of concrete and high alkalinity of the pre solution is not achieved in practice, a monitoring system of the structures becomes essential to assess the damage of the structure over time due to reinforcement corrosion. Once the reinforcement corrosion is initiated, it shortens the service life of the structures by cracks initiation, propagation and subsequently spalling of the cover concrete due to expansion of corrosion steel. Hence prediction of the remaining service life of the structure becomes essential in the assessment of the stability of structures. The prediction of the remaining service life of a corroded structure may be carried out with the help of various available prediction models on experimental techniques with the utilization of the data through monitoring.

The most common causes of reinforcement corrosion are chlorite ions and carbonation by atmospheric carbon dioxide. In wet and cold climates, reinforced concrete for roads, bridges, parking structures and other structures that may be exposed to deicing salt may benefit from the use of epoxy coating, hot dip galvanized or stainless steel rebar. A good structural design, detailing and a well-chosen cement mix that makes durable concrete may provide sufficient protection for many applications. Use of fly ash also delays the effect of chlorite and carbon dioxide.

In the article [12] Pitting corrosion and susceptibility to chloride attacks are the shortfalls of reinforcement steel used in concrete structures. The present work proposes the deposition of electroless nickel coatings to provide barrier protection due to their proven corrosion resistance. The effect of deposition of Ni–P, Ni–P–W and Ni–P–Cu coatings on the corrosion behavior of Fe – 600 grade rebars in 3.5 % NaCl has been investigated with the aid of potentiodynamic polarization and electrochemical impedance spectroscopy.

The corrosion potential of bare rebar was observed to be $-653$ mV while that of electroless Ni–P, Ni–P–Wand Ni–P–Cu coatings was $-436$, $-391$ and $-356$ mV respectively. The corrosion current density of the rebars also decreased significantly by the application of electroless nickel coatings.
Nyquist plots also revealed a bigger semicircular loop for the coated rebar. The chloride attack was severe on the bare uncoated rebar and scanning electron micrograph revealed severe cracking. On the other hand, the vulnerability of the electroless coated rebar to pitting corrosion decreased greatly.

In the article [13] the aging of reinforced concrete infrastructure in developed countries imposes an urgent need for methods to reliably assess the condition of these structures. Corrosion of the embedded reinforcing steel is the most frequent cause for degradation. While it is well known that the ability of a structure to withstand corrosion depends strongly on factors such as the materials used or the age, it is common practice to rely on threshold values stipulated in standards or textbooks. These threshold values for corrosion initiation ($C_{\text{crit}}$) are independent of the actual properties of a certain structure, which clearly limits the accuracy of condition assessments and service life predictions. The practice of using tabulated values can be traced to the lack of reliable methods to determine $C_{\text{crit}}$ on-site and in the laboratory. Here, an experimental protocol to determine $C_{\text{crit}}$ for individual engineering structures or structural members is presented. A number of reinforced concrete samples are taken from structures and laboratory corrosion testing is performed. The main advantage of this method is that it ensures real conditions concerning parameters that are well known to greatly influence $C_{\text{crit}}$, such as the steel-concrete interface, which cannot be representatively mimicked in laboratory-produced samples. At the same time, the accelerated corrosion test in the laboratory permits the reliable determination of $C_{\text{crit}}$ prior to corrosion initiation on the tested structure; this is a major advantage over all common condition assessment methods that only permit estimating the conditions for corrosion after initiation, i.e., when the structure is already damaged. The protocol yields the statistical distribution of $C_{\text{crit}}$ for the tested structure. This serves as a basis for probabilistic prediction models for the remaining time to corrosion, which is needed for maintenance planning. This method can potentially be used in material testing of civil infrastructures, similar to established methods used for mechanical testing.

In the paper [14], the effects of potassium-chromate ($\text{K}_2\text{CrO}_4$) and sodium-nitrite ($\text{NaNO}_2$) on concrete steel-rebar degradation in sulphuric-acid and in sodium-chloride media were studied. Electrochemical monitoring of open circuit potential and compressive strength effect of the different concentrations of these admixtures in steel-reinforced concretes immersed in the acidic/marine-simulating environments were analysed for detailing admixture performance. Results subjected to ASTM C876 interpretations showed that concrete admixed with 0.145 M potassium-chromate exhibited optimum inhibition effectiveness with good compressive strength improvement in the acidic medium. In the saline medium, the concrete admixed with 0.679 M sodium-nitrite exhibited optimal inhibition performance, but with reduction in concrete compressive strength.

The paper [15] reports results of a study conducted to investigate the effect of dust, contributed by the coarse aggregates, on the corrosion of reinforcing steel in concrete. The concrete specimens were prepared with up to 10% dust in the coarse aggregates. Two other batches of reinforced concrete specimens were also prepared. In one batch of specimens the aggregates were washed with raw water (total dissolved solids: 3338 ppm) while the dust in the second batch was removed by vacuum suction. Reinforcement corrosion was monitored by measuring corrosion potentials and corrosion current density. The results indicated that up to 10% dust in the coarse aggregates did not cause any corrosion of the reinforcing steel. Similarly, reinforcement corrosion was not noted in the concrete specimens prepared with coarse aggregates washed with raw water or cleaned with vacuum suction.

The use of cathodic protection in reinforced concrete is becoming increasingly common with such systems being installed on a number of structures throughout the United Kingdom and Ireland [16]. However, the prescribed design lives (or service life) of each cathodic protection system vary widely. The aim of this project was to assess the effectiveness of a sacrificial anode cathodic protection system and to predict its design life through a series of laboratory based experiments. The experimental plan involved casting a number of slabs which represented a common road bridge structure. The corrosion of the steel within the experimental slabs was then accelerated prior to installation of a cathodic protection system. During the experiment corrosion potential of the steel reinforcement was monitored using half-cell measurement. Additionally, the current flow between the cathodic protection system and the steel reinforcement was recorded to assess the degree of protection. A combination of
theoretical calculations and experimental results were then collated to determine the design life of this cathodic protection system. It can be concluded that this sacrificial anode based cathodic protection system was effective in halting the corrosion of steel reinforcement in the concrete slabs studied. Both the corrosion current and half-cell potentials indicated a change in passivity for the steel reinforcement once sacrificial anodes were introduced. The corrosion current was observed to be sensitive to the changes to the exposure environment. Based on the experimental variables studied the design life of this sacrificial anode can be taken as 26 to 30 years.

The research [17] represents the comprehensive experimental studies conducted on the identification of corrosion mechanism. The study is made in two different types of samples taken from reinforced concrete containing class–F Fly ash and steel bar with different fine aggregates such as river sand and manufactured sand. It also reports the study under different curing conditions to find out corrosion attack on fly ash concrete structure. Cement placed by means of Fly ash, concrete mixes prepared with 20%, 30%, 40% weight of cement and using16mm diameter steel bar 100 mm length with 25 mm clear cover were used as samples. Corrosion process was investigated in embedded steel bar by using Tafel polarization and AC Impedance methods by using ACM Instruments (UK). This study will help in identifying the level of corrosion between the usage of river sand and the manufactured sand.

In [18] a detailed research program was undertaken to explore the possibility of using zinc to enhance the repair of corroded concrete. The variables studied were the water–cement ratio, chloride content, and amount of zinc coverage in the repair area. The results confirmed that using dense repair mortar alone can move the corrosion damage to adjacent un repaired zones and that the presence of zinc can mitigate this problem. However, the engineering solution is complex since the effectiveness of zinc in the prevention of further corrosion may be influenced by various factors, such as leaking joint, zinc-steel contact area.

In the paper [19] reinforced concretes were corroded to varying degrees by exposing to cyclic NaCl spray and 40°C drying. The amount of corrosion products and induced damage were measured using image analysis. We found that corrosion products can accumulate at steel-concrete interface as well as penetrate cement paste and deposit within hydration products, relicts of reacted slag, and air voids. As corrosion increases, the products tend to accumulate at the steel-concrete interface, while the amount penetrating cement paste remains relatively constant. Only a small amount of corrosion is needed to induce visible cover cracking. Implications of cracking coverage are discussed.

Concentration CO$_2$ will aggravate the degradation process of reinforced concrete (RC) structures, leading to the decrease of durability, safety and serviceability [20]. Regarding the durability of concrete structures, carbonation-induced corrosion is definitely a significant and costly source of degradation, directly related to climatic parameters such as CO$_2$, temperature and relative humidity.

In [21] paper authors build a platform of triple poro-mechanical coupling model for micro and meso-scale events of ASR, FTC and steel corrosion in consideration of the mutually interacting processes. The proposed model attempts to cover the most essential aspects, from thermo-chemo coupling at micro-scale to the poromechanical coupling at meso-scale, and finally leads to the coupled fracture of structural concrete at macroscale. Several simulation examples are presented for both single and coupled deteriorations of structural concrete, and it is clarified that the combined deformation and damage of concrete are not the simple compilation of each sole effect, but it is highly path-dependent on both crack patterns and deformation levels. This triple coupling model can provide a platform, on which the coupled complex damages to structural concrete are consistently dealt with for damage assessment of structural concrete.

4 Discussions
In accordance with regulatory documents, primary and secondary protection measures are provided for protecting concrete and reinforced concrete from corrosion.

Primary protection provides optimal choice of design and construction solutions for reinforced concrete structures in terms of corrosion factors, the use of methods and materials for the manufacture of corrosion-resistant concrete and reinforced concrete structures at the design and construction stages.
These include:
- selection of design solutions for optimal dimensions, shape of cross-sections of the structure that reduce the impact of corrosion factors;
- rational design solutions that reduce the contact surface of reinforced concrete elements with an aggressive environment, as well as the development of effective bridge structures (without solid barrier barriers) that ensure the destruction of ice crust due to the deformation of superstructures under temporary load and the removal of ice crust destruction products by sweeping them off the roadway by the wind;
- development of effective strategies for the operation of reinforced concrete structures that reduce the use of chloride-containing deicing agents;
- rational choice of reinforcing steels;
- selection of the necessary concrete compositions that provide the necessary level of protection;
- reduced concrete permeability;
- use of additives that improve the physical and technical characteristics of concrete (inhibiting, plasticizing, regulating pH, reducing the crack resistance of concrete, reducing the tendency to corrosion cracking, etc.);
- technological measures that improve the quality of concrete and reinforced concrete;
- use of effective anticorrosive additives in concrete.

Secondary protection involves the use of protective equipment and materials immediately after commissioning and during operation. The methods of secondary protection are:
- application of paint and varnish materials;
- use of rolled and sheet materials;
- use of coating, covering and lining materials;
- application of the sealing impregnation, impregnating-bridging formulations, cementation, silication, etc.;
- use of biocidal materials.

5 Conclusions
Thus, we suggest using high-density, low-porous concrete to prevent the diffusion of water into concrete surfaces [22]. The concrete surface problems that are occurring due to various environmental factors can cause severe damage. The corrosions including peeling process is an example of such damage that often is notrepairable.

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