Cathodic prevention and cathodic protection of reinforced concrete structures

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Summary

Despite the natural protection given to the carbon steel reinforcement by the alkaline environment produced during the hydration reactions of the cement components, the rebar may be corroded for different reasons. The buried pipelines may suffer from corrosion due to the aggressive agents present in the soil, while the aerial pipelines may be attacked both by carbon dioxide and by marine or industrial pollutants.
There are several preventative measures that can be taken in order to delay the corrosion initiation: use of stainless steel, galvanized steel, mixed-in inhibitors. In case of existing structures with corrosion problems, maintenance may be performed by means of electrochemical techniques, such as chloride removal and realkalization, or with conventional repair methods. However, only cathodic prevention for new structures and cathodic protection for existing structures are considered a suitable and reliable means for ensuring the non corrodibility of the carbon steel in all circumstances.
The most important difference existing between the two techniques relies in the potential range suitable for the protection of the steel in concrete. In the case of the prevention the potential which must be fixed is not as negative as in the case of the protection. Too negative potentials may be very dangerous, because there may be the problem of hydrogen embrittlement, especially in the case of prestressed concrete.
The paper describes the modern solutions, as concerns materials and design, for the installation of cathodic protection systems for concrete structures.

1. Introduction

Carbon steel reinforcement, even with the protection given by the alkaline environment, does not provide sufficient resistance to corrosion, in particularly aggressive conditions (marine environment, corrosive soils, etc.).

When the reinforced concrete was first used, it was generally thought that it could be almost eternal, as it was a material similar to that made by the Romans. The problem is that the Roman concrete (concretum) did not host the steel, and therefore there was no possibility of corrosion but only the occasional deterioration mainly due to human intervention (conflicts, vandalism, etc.) or to natural events (earthquakes, winds, etc.).

The engineers of the last century sincerely thought that the reinforced concrete, which is still one of the major construction materials, could last forever, due to the very protective environment supplied by the reaction of the cement with the water: in fact, the alkalinity present in the pores, where the pH is usually higher than 12.5, offers to the steel the best situation for the self-protection [1].

However, civil engineers did not, and actually hardly do, imagine that whenever the steel reinforcement is no more protected by the environment, created by the hydration reactions of the cement components, for several reasons (bad quality of the concrete, thin cover, very aggressive environment, etc.), carbon steel corrodes and the corrosion products, which have a volume 6-7 times that of the steel which is oxidized, push very strongly against the concrete and cause the formation of cracks growing in width, with consequent accelerated ingress of aggressive agents and loss of section of the bars.

The service life of a reinforced concrete structure, as described by Tuutti [2] (Fig. 1), consists of two phases: the first phase corresponds to the initiation time t_o, taken for chlorides, carbon dioxide, or other aggressive agents to penetrate the concrete cover in sufficient quantities to destroy the passive film; the second phase covers the period of active corrosion from t_o to the time t_b at which the durability of the structure is compromised. The length of this period is determined by the corrosion rate, governed by the oxygen availability, chloride content, pH, humidity and temperature.

It has been demonstrated [3] that a diameter loss of 2%, corresponding approximately to a section loss of 5%, can cause spalling. Therefore, knowing the average corrosion rate of the reinforcement after the initiation of corrosion, it is roughly possible to predict the time for maintenance.

The estimated annual cost of repair of reinforced concrete structures is over 5 billion Euro in Western Europe.

In order to drastically reduce the amount of money requested for the repair, supplementary preventative measures suitable for prolonging the service life of the new structures have been thoroughly investigated.

Besides, as concerns the existing structures (buildings, piers, bridges, etc.), it is actually necessary to intervene with modern techniques, which, contrary to the conventional repair, can ensure a suitable residual life.

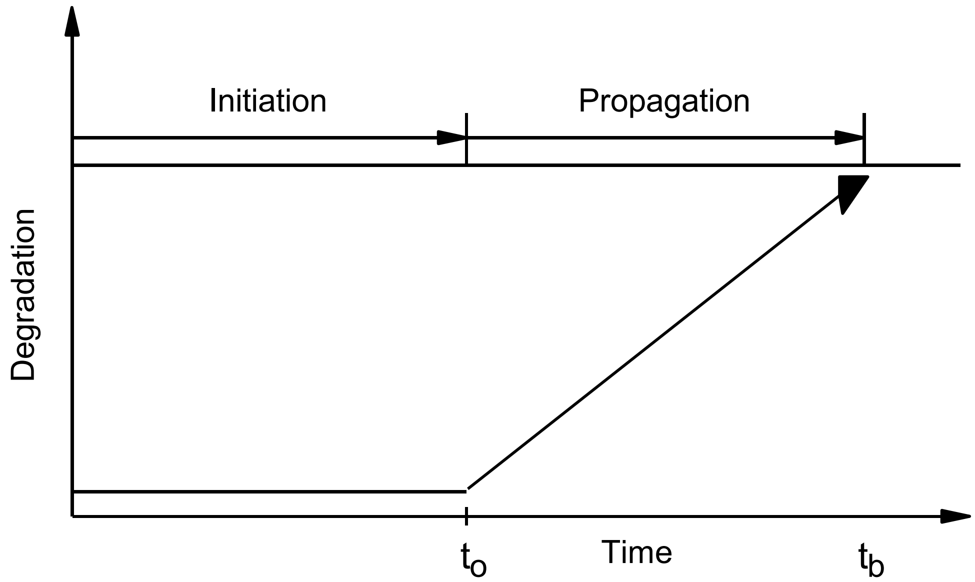

Figure 1 – Tuutti model of the service life of a reinforced concrete structure

Provided that whenever good rules for the mix design and casting are followed, the reinforced concrete should really last for very long times, unfortunately this is very rarely achieved. Therefore, several additional preventative measures have been investigated and proposed: some of them, e.g. epoxy coating of the bars, have actually been discarded, after some evident failure of the structures in which they have been employed. Some others, as the use of stainless steel bars and the cathodic prevention, seem to be at the moment rather expensive, although very effective. Further measures, as the use of mixed-in inhibitors and galvanized steel, are still debated.

2. Cathodic protection and cathodic prevention

Concrete pipelines, either buried or aerial, are frequently used for water transportation, and are subject to attack from the soil or from the atmosphere and this is the reason why since several years they are most often provided with the possibility of being connected to a cathodic protection system. This means that whenever during the service life a corrosion problem arises for the steel reinforcement, it will be very easy to use auxiliary electrodes and a power supplier.

When the concrete structure is buried, the cathodic protection system is the same as for the metallic structures: the only difference is that the electrolyte is composed by the sum of the soil and the concrete cover (Fig. 2).

When the concrete structure is aerial, as columns, piles, bridge decks and in some cases pipelines, the problem arises of which

type of counter-electrode can be used and where it has to be positioned.
When one wishes to use this technique in order to prevent the corrosion of the reinforcement, even if the circuit is almost the same, the protection principle is rather different and the protection technique must be nominated as “cathodic prevention”.

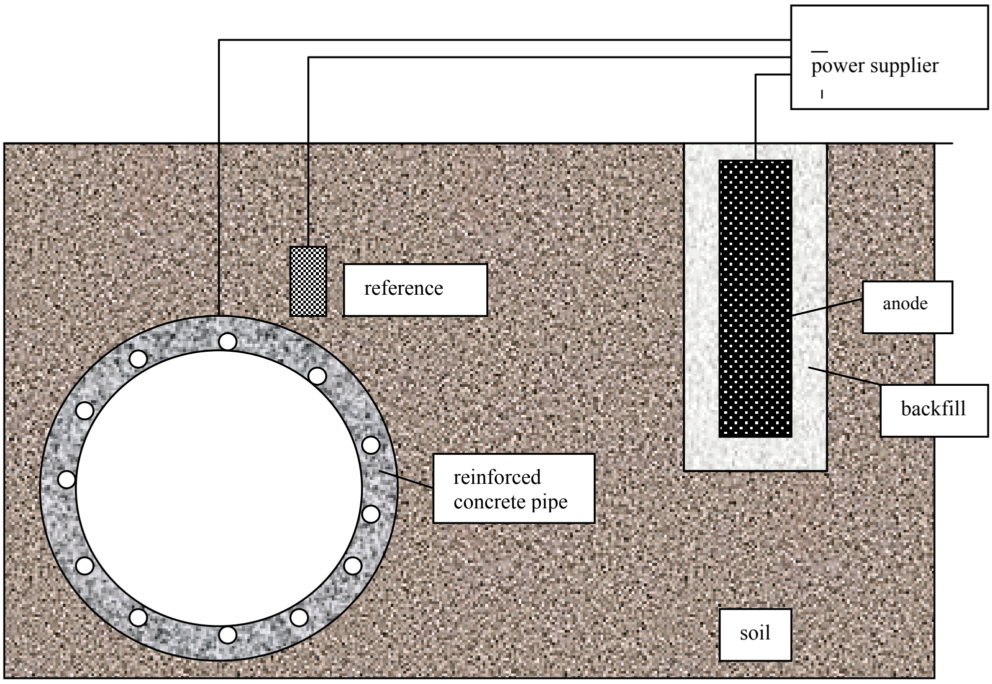

Figure 2 – Schematic illustration of a cathodically protected buried concrete structure

Cathodic prevention is a term invented by Pedeferri many years ago [4] in order to distinguish the use of the principle of application of a cathodic polarisation to the reinforcement of new structures (prevention of corrosion) from the rather traditional use of the cathodic protection, firstly proposed by Stratfull in 1959 [5], applied to deteriorated structures (stopping of corrosion in action).
The most important difference existing between the two techniques relies in the potential range suitable for the protection of the steel in concrete.
Since it is easier to prevent pitting corrosion than it is to suppress pitting corrosion in action, a lower current density is required; cathodic prevention systems are therefore cheaper in this case because less anode material is needed.

The cathodic polarisation makes the potential of the rebar less negative than the pitting potential, that is, the potential above which corrosion pits may develop. This is the main effect relevant for cathodic prevention, as illustrated in Figures 3 and 4.

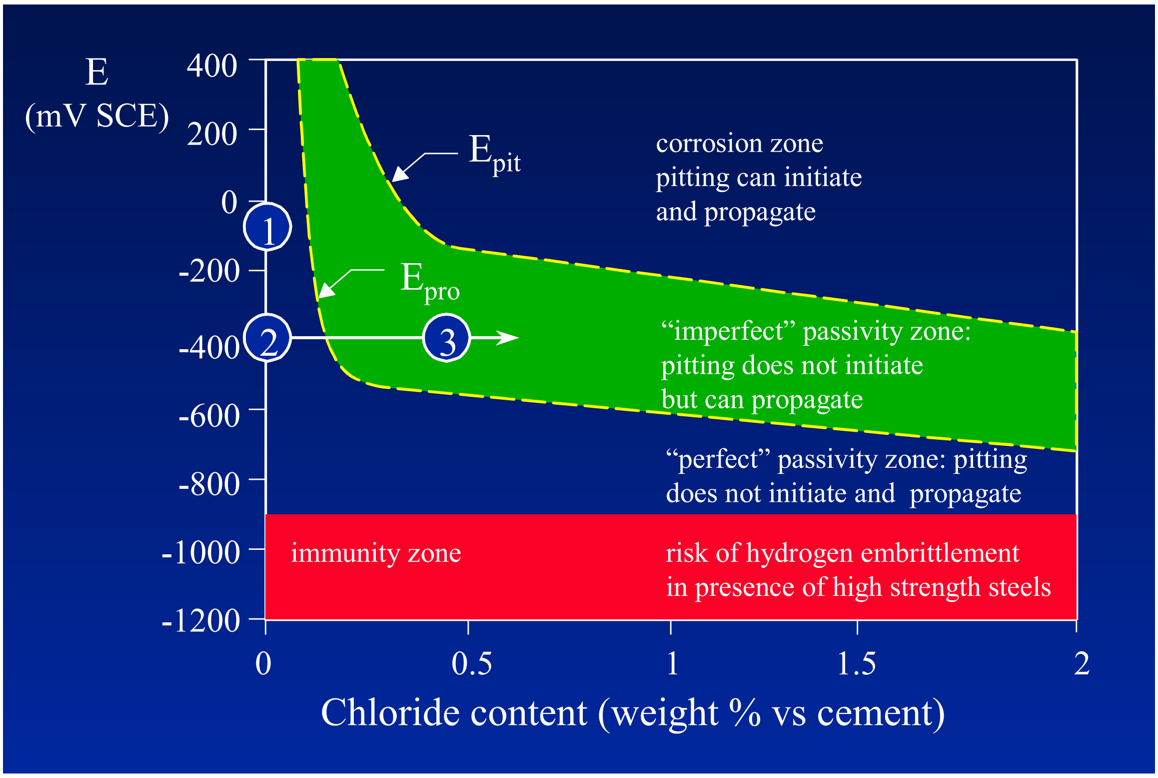

Figure 3 - Schematic illustration of pitting corrosion of steel in concrete as a function of steel potential and chloride content. Path 1→2→3→ shows the role of cathodic prevention in increasing the critical chloride threshold [6].

Provided that the spontaneous corrosion potential of the steel in concrete in normal conditions is in the range 0÷-200mV vs. CSE (point 1 of Figs. 3 and 4), it can be observed that the corrosion will initiate as soon as the chloride concentration will reach a value in the range 0.3÷0.6% by weight of cement (point 2 going to point 4 in Fig. 4). In marine environments this can happen, with a fairly good concrete, in 18-22 years and when it happens, the potential of point 3 in Fig. 4, or lower, must be reached in order to have a complete protection of the reinforcement.

If from the beginning, i.e. at the construction stage, the potential of the reinforcement is maintained 200 mV, or more, lower than the range of the spontaneous values (point 2 of Fig. 3), it can be seen that the chloride concentration that it can be born is much higher, increasing until 1.5% and more, which means that the corrosion will initiate at least tens years later.

Moreover, electrolysis produces hydroxyl ions at the steel surface, improving the resistance to chloride ions attack.

Finally, a further advantage of the use of cathodic prevention is the fact that, since a lower current density is needed and a less negative potential has to be reached, the risk of hydrogen evolution is much lower and it will be easier to safely apply cathodic prevention to prestressed structures [7].

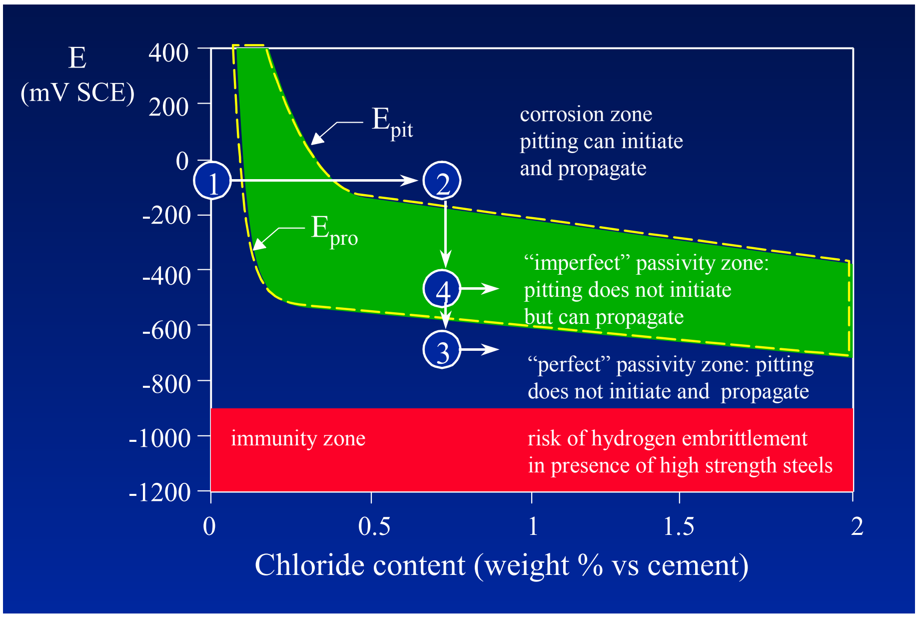

Figure 4 - Schematic illustration of the principle of cathodic protection in concrete

3. Design of cathodic prevention and cathodic protection

3.1. Electrical continuity

The electrical continuity of the whole reinforcement must be preliminary checked: if there is not electrical continuity, it must be provided, otherwise the non-connected parts of the reinforcement will not be protected and, in presence of aggressive agents, will suffer very strong additional corrosion due to the possible ingress and exit of the protection current.

3.2. Current density

Following the CEN Standards [8], typical cathodic prevention currents range between 0.2 and 2 mA/m^2, compared with 2-20 mA/m^2 for cathodic protection.

Due to the spread of the current, the steel surface area considered in the design should include all reinforcement including steel in deeper parts up to 0.5 m or more.

3.3. Monitoring sensors

The reference electrodes suggested by CEN to be permanently embedded in concrete in order to allow the measurement of the potential of the rebar are double junction silver/silver chloride and manganese dioxide. Graphite and activated titanium are also suitable, mainly for the measurement of the potential decay, which is one of the possible means of control of the cathodic protection efficacy.

For the buried structures, the traditional copper/copper sulphate electrode may be used.

3.4. Anode system

For buried reinforced concrete structures, both new and existing, the anode will be the same as for the usual cathodic protection systems for metallic buried structures.

For aerial structures, different solutions are possible. The types of anodes are the same for new and existing structures, but their amount, in terms of surface, and location may be very different in the two cases.

The materials which have been successfully tested in the field are the conductive organic coatings and the activated titanium strips or mesh.

The conductive organic coatings are solvent based or water borne products containing graphite particles to provide electrical conduction. The connection to the positive pole of the power supplier must be ensured by embedding, at suitable intervals, distribution metallic ribbons over the conductive coating (Fig. 5). A further coating is suggested for the protection of the anodic material and also for aesthetic reasons.

The conductive coating anode can bear up to 100 mA/m^2, but usually it works at a value of 20 mA/m^2 in order to provide a service life of over 15 years.

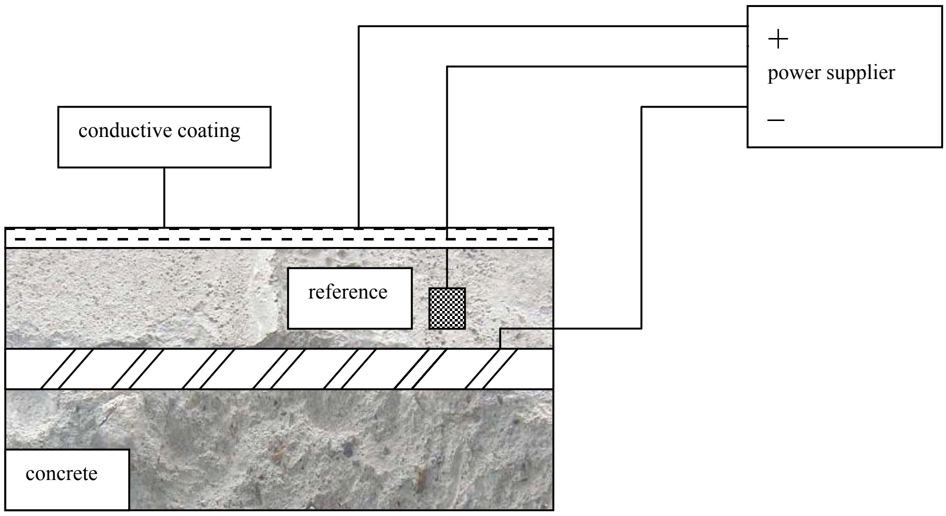

Figure 5 – Schematic illustration of a conductive coating system for cathodic protection and prevention of aerial reinforced concrete structures

The activated titanium mesh is at present the most widely anodic system for the protection of reinforced concrete: it bears up to 100 mA/m^2 current densities and it has a service life up to 100 years; it needs a cementitious overlay, which may be shotcrete or cast concrete. For new structures, on order to avoid the overlay a different solution may be adopted, using activated titanium strips positioned at a certain depth under the bars, as illustrated in Fig. 6.

Small portions of titanium strips may also be used as "single anodes" to be located into holes drilled into concrete components and then injected with cementitious grout or mortar. [9] (Fig. 7).

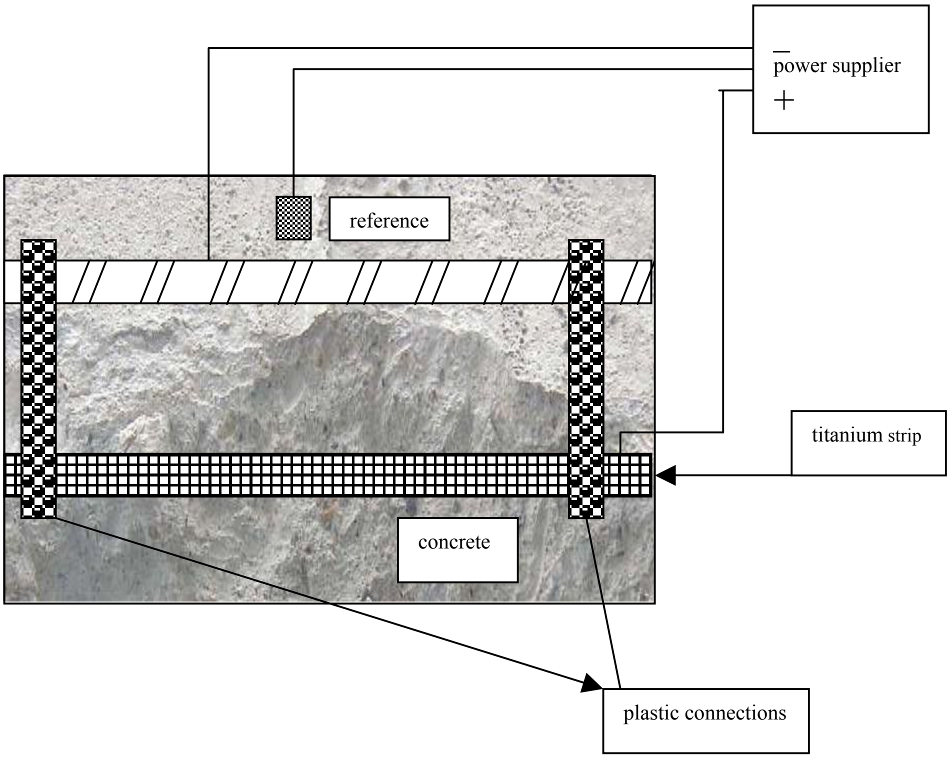

Figure 6 – Titanium strips for cathodic prevention

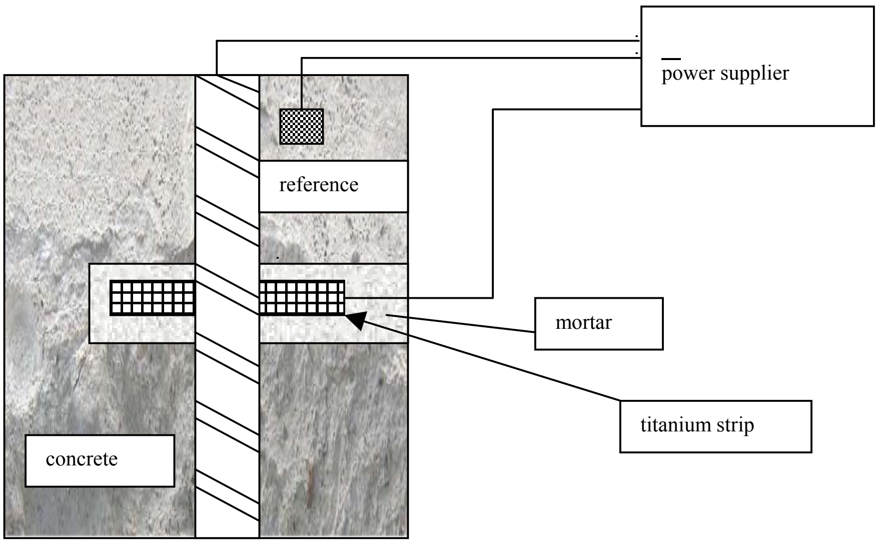

Figure 7 – Single anode titanium strips

4. Conclusions

Cathodic prevention is a reliable method for making sure that corrosion of reinforcement will not occur in corrosive environments. The design and execution of the cathodic prevention system will involve specialist technicians and will slightly interfere with design and execution procedures for the concrete structure (electrical continuity, location of the anodes, cabling). Since controls will be made in time, the owner will be continuously informed on the state of protection of the structure.
Cathodic protection has proved to have important advantages compared to conventional repairs: besides the improved reliability of corrosion protection and the much longer service life of the repaired structure (conventional repairs rarely last more than 5-

10 years), it implies less noise, dust and disruption of the use of the structure during execution, needs a shorter execution time, and has lower cost at long term.

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