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ENVIRONMENTAL AND ECONOMIC ASPECTS OF ANTICORROSION PROTECTION BY HOT-DIP GALVANIZED METHOD REBARS IN CONCRETE

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ABSTRACT:

The implementation of the sustainable development concept is nowadays a key issue in almost all human activities. For the constructions domain an European strategy has already been elaborated. Among its goals are also the use of long lasting materials and the reduction of repair costs. This paper presents an interdisciplinary study concerning the efficiency of the use of hot-dip galvanized rebar for concrete structures. Experimental results about corrosion kinetics of coated and usual steel reinforcement embedded in concrete, subjected to chlorine ions attack, are analyzed. Electrochemical methods as chronoamperometry and linear polarization have been used. Corrosion potential values recorded for galvanized steel embedded in concrete indicate an uncertain corrosion activation process up to a rate of 2.5 % calcium chloride relative to concrete. For rates of 5% $CaCl_2$ and more the corrosion process is activated. For unprotected steel bars embedded in concrete the corrosion activation process started at all calcium chloride studied rates and higher corrosion potential values has been registered than for the hot-dip galvanized ones, at the same rates. Economical assessments have been done using entire lifetime cost analysis of the reinforced concrete structures. Despite that the hot-dip galvanization is a rather expansive procedure, when taking into account the whole expected life span, the use of zinc coating proves to be efficient both from structural and financial approaches.

1. INTRODUCTIONS

Building sector is one of the domains which uses a huge quantity of materials and energy, and is also responsible for more than 8% of the CO_2 emissions in Europe, (after http://epp.eurostat.ec.europa.eu/statistics_explained).

For the manufacturing of classical building materials important amounts of energy is necessary. An average of 40MJ/kg is spent to obtain steel from raw materials and about 18MJ/kg, when used recycled materials (Sullivan and Hu, 1995). As energy production is mostly based on traditional fuels, it is associated with CO_2 emissions. European Union has to reduce 20% of the primary energy consumption till 2020, according to 2006/32/CE Directive. Thus, the extension of life span of rebar is one of the ways of mitigation the primary energy consumption. The use of corrosion protection of concrete reinforcement is an option to increase the lifespan of steel embedded in carbonated concrete and also when moderate concentration of chlorine ions are present.

According to R. E. Wilmot (2006), and other researchers as S. R. Yeomans (1987, 1991, 1994, 2002, 2004), Andrade (Andrade and Alonso ,1996, Andrade, Gulikers et al., 2003, Andrade and Alonzo, 2004), Sistonen (Sistonen, 2009, Sistonen, Cwirzen and Puttonen, 2008, Sistonen and Peltola, 2005, Sistonen, Tukiainen et al., 2006) have concluded that the use of hot-dip galvanization of rebar's, almost double the lifespan of a reinforced concrete structure (an average of 70 years), when a proper concrete is used, with an increase of the costs of the real estate only up to 3%. Z. Q. Tan (2007) determined the variation of corrosion potential and corrosion current with time for thermally galvanized reinforcement embedded in concrete. Based on experimental results, the author showed that of the hot dip galvanized reinforcement corrodes the first 9-10 hours of the embedding in concrete, during which there is a current maximum of 90 µA/cm2 corrosion and corrosion potential ranging from - 1.4 V to -0.7 V vs. SCE then passivation.

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2. MAIN OBJECTIVES AND RESEARCH METHODS

Literature indicates that the quality, the degree of carbonation of concrete, environmental temperature and humidity have a large influence on the minimum level of chlorine (%) initiating concrete corrosion. Thus, for a poor quality concrete, carbonated, placed in high humidity environment (85%) is sufficient chlorine concentration of 0.4% (relative to the amount of cement) to be initiated reinforcement corrosion (Sistonen, 2009, Sistonen, Cwirzen and Puttonen, 2008, Sistonen and Peltola, 2005, Sistonen, Tukiainen et al., 2006, Yeomans, 1987, 1991, 1994, 2002, 2004).

The main goal of this study is to verify the efficiency of hot-dip galvanized rebar's versus common steel reinforcement when the embedment concrete contains chlorine ions in different concentrations. A comparative financial analysis of the use of black steel and corrosion protected reinforcement embedded in concrete considering the entire lifespan of the buildings is the other principal objective.

The study is based on both technical regulations and literature documentation, and experimental investigations and data analysis done by authors.

3. EXPERIMENTAL STUDY

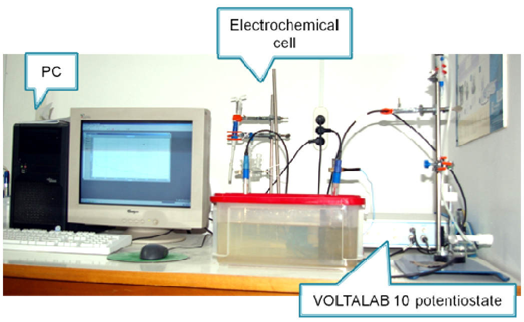
The experimental behavior of usual and hot-dip galvanized steel embedded in concrete has been studied in laboratories of Technical University of Cluj Napoca and URBAN INCERC Institute, Cluj Napoca Branch.

The main goal of the study has been the corrosion development in hot-dip galvanized reinforcement embedded in concrete which contain Chlorine ions from the fresh state. The Cl ions effect has been amplified by diffusion of supplementary Cl ions from the NaCl electrolyte solution in the electrochemical cell.

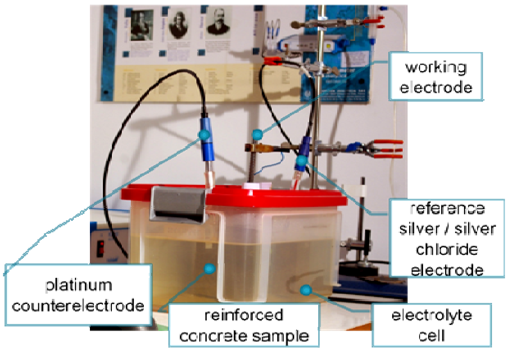
The chronoamperometry method has been used to obtain qualitative information regarding the corrosion process kinetics and linear polarization method has been performed for quantitative data acquisition.

3.1. Test program

3.1.1. Test set up: The test stand is shown in Figure 1a and 1b.



a)



b)

Figure 1. Chronoamperometry method. Experimental stand (a) and Electrochemical cell (b)

The tests have been performed using the VOLTALAB 10 potentiostat, and the data have been recorded on a computer hard disk.

The electrochemical cell has been made in a container with electrolyte, a 3% NaCl solution, where the concrete specimen and the electrodes have been submerged (Figure 1). The used electrodes are:
- working electrode made of the steel rebar embedded in concrete;
- reference electrode made of Ag/AgCl;
- counter electrode made of Pt.

The potential of 500 mV has been applied to the working electrode vs. the Ag/AgCl one, for the chronoamperometry tests. The electric current density has been recorded for 24 hours. The variation of the current density vs. elapsed time reveals important qualitative information about the corrosion momentary speed.

At the linear polarization tests, the potential of the working electrode has been scrolled in the interval between ±300 mV, with respect to the open circuit potential value, at the temperature of 20±2^{0}C. Based on the experimental diagrams, using Tafel interpretation, the main kinetics parameters have been determined (corrosion potential, corrosion current and corrosion speed).

3.1.2. Rebar: All the tests have been performed using the S355 steel of 8mm diameter as rebars. Some specimens have been embedded in concrete as manufactured (N) and others have been previously hot dip galvanized (ZT). The galvanization temperature has been 450°C and the zinc layer has been 140 μm depth. The measurement of the zinc layer has been done by electromagnetic method using a PHINIX device and by the dissolution method, according to ISO 1460 and respectively to EN ISO 2178.

3.1.3. Concrete: The class for the witness concrete has been C20/25, using CEM I 42.5N type cement, natural aggregates up to 8mm, and a water cement ratio of 0.4. The concrete with induced chlorides has been obtained by adding $CaCl_2$ in the fresh admixture in different ratios relative to the amount of cement, as follows 0,8%; 2,5%; 5,0%; 7,5% (percentage by mass).

3.1.4. Specimens: The prismatic shaped specimens have been made out of reinforced concrete. The rebar's ends have been coated with epoxy resin on a length of 10 mm. The rebar's cover and the reinforcement diameter are the same for all the specimens. All the specimens have been maintained 28 days in laboratory conditions. The testing specimens were submerged in a water solution of 3%, NaCl for 24 hours, before the beginning of the experiments.

The electrochemical systems have been encoded with respect to the reinforcement type and the amount of $CaCl_2$ used at the concrete mixture, as follows:
N – unprotected steel;
ZT - hot dip galvanized steel;
x – percentage by mass of $CaCl_2$ / cement amount.

3.1.5. Mode of expression of the results: The protection level of hot dip galvanization (EP) is calculated as:

$$EP = \frac{i_{cor}^{N} - i_{cor}^{ZT}}{i_{cor}^{N}} * 100 \ [\%] \qquad (1)$$

where:
i^{N}_{cor} corrosion current of unprotected steel [µA/cm^2]
i^{ZT}_{cor} corrosion current of protected steel [µA/cm^2]

3.2. Test results

Chronoamperometry method test results are expressed as a time dependent function of current density and are shown in Figure 2.

As can be seen from the diagrams in Figure 2, for the unprotected steel the current density increases continuously and depends proportional to the $CaCl_2$ amount in concrete. This means a continuous evolution of corrosion process. The fluctuation of the current density curves can be explained by a succession of antagonistic processes developing rapidly at steel surface, the former is formation of a passivation layer (oxides and hydroxides, of iron respectively of zinc, which form a layer on the surface of reinforcement) and the latter is its almost instant destruction.

For the galvanized steel the current density also depends proportional to the $CaCl_2$ amount in concrete, but a downward trend of the curves is observed. This means that a layer of corrosion products is formed at the reinforcement surface which is slowing down the corrosion process.

Comparing the current density magnitude for plain and hot-dip steel, for the same elapsed time and $CaCl_2$ concentrations, it can be seen that for the galvanized steel lower values are registered, for $CaCl_2$ rates up to 5%. One exception is the hot-dip steel embedded in concrete with 7.5% of $CaCl_2$, where the current density is higher than that of plain steel. In the first 200 minutes the current density increases, but afterward decreases under the value for the unprotected steel, at 900 minutes being even and at 24 hours being half relative to plain steel. This means that initially a rapid developing corrosion process takes place and corrosion products are formed. When the layer of corrosion products is thick enough the chlorine diffusion is more difficult and hence the process is slowed down.

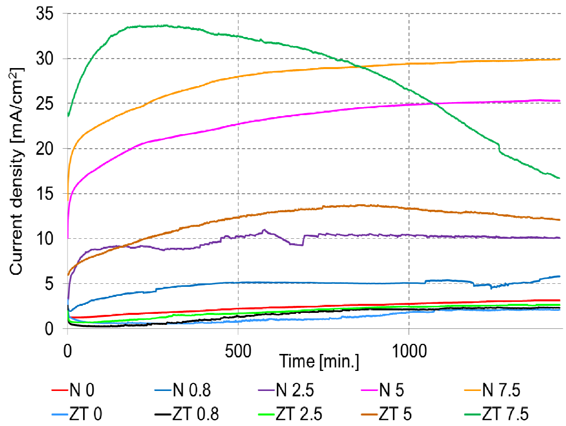


Figure 2. Time evolution of current density

As can be seen in Figure 3 the curves for galvanized steel (ZT) embedded in up to 2.5% $CaCl_2$ containing concrete are below the one of unprotected steel embedded in usual concrete, meaning that the corrosion speed is higher for the unprotected steel. Thus the use of galvanized steel is recommended when moderate concentration of Cl ions in concrete cannot be avoided.

The results of linear polarization tests, using Tafel polarization diagram are presented in Figure 4.

Analyzing the curves shape it can be observed that for small potentials, the process kinetics is controlled by the chemical reactions which occur. As the potential gets higher values, the influence of the diffusive aspect of the corrosions products layer formed on the metal surface. It can also be observed the formation of a passivation layer and followed by its almost instant destruction, the corrosion process evolving.

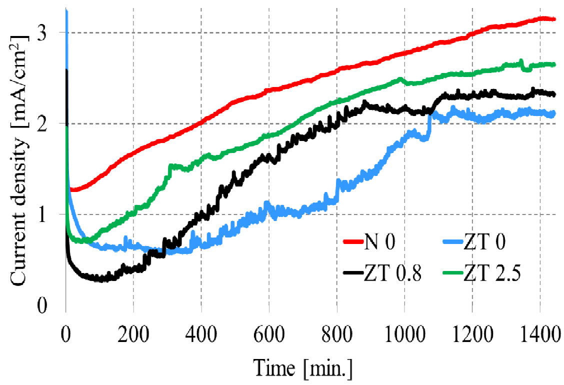


Figure 3. Current density of galvanized steel (ZT) embedded in 0%, 0.8% and 2.5% $CaCl_2$ containing concrete vs. plain steel (N) embedded in usual concrete

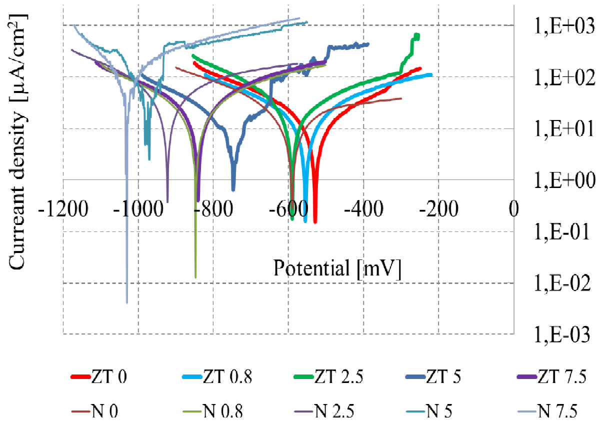


Figure 4. Tafel curves for galvanized steel (ZT) and usual steel (N) embedded in concrete containing 0%, 0.8% and 2.5%, 5% and 7.5% $CaCl_2$

In Figure 5 are represented the amount of the corrosion potential recorded during the test for hot-dip galvanized rebars and respectively for unprotected ones.

In Figure 6 are represented the amount of the corrosion current recorded during the test for hot-dip galvanized rebars and respectively for unprotected ones.

In Figure 7 are represented the amount of the corrosion speed recorded during the test for hot-dip galvanized rebars and respectively for unprotected ones.

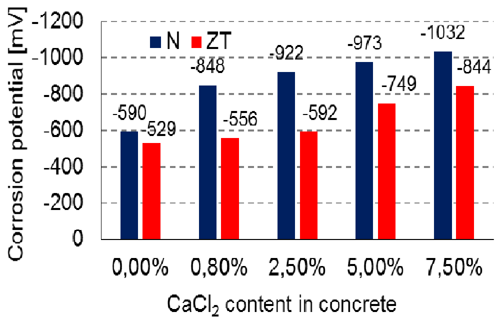


Figure 5. Corrosion potential for galvanized steel (ZT) and usual steel (N) embedded in concrete containing 0%, 0.8% and 2.5%, 5% and 7.5% $CaCl_2$

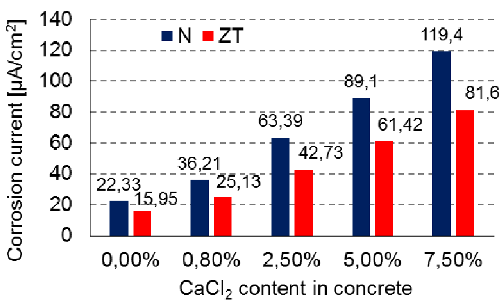


Figure 6. Current density for galvanized steel (ZT) and usual steel (N) embedded in concrete containing 0%, 0.8% and 2.5%, 5% and 7.5% $CaCl_2$

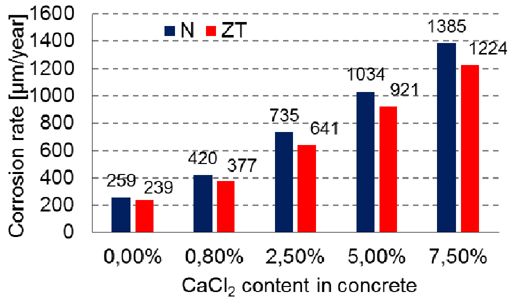


Figure 7. Corrosion rate for galvanized steel (ZT) and usual steel (N) embedded in concrete containing 0%, 0.8% and 2.5%, 5% and 7.5% $CaCl_2$

The increase of the Cl ions content in concrete determinates the corrosion intensification of both unprotected or galvanized embedded steel.

Function of the increase of $CaCl_2$ content of concrete it is revealed the followings:
- the corrosion potential of unprotected and hot-dip galvanized steel has moved towards negative values, indicating the increase of the probability of the corrosion process initiation;
- the corrosion current is also increasing;
- the corrosion speed follows the same ascending trend.

For the same chlorine content in concrete the galvanized steel has a corrosion potential displaced towards positive values and the corrosion current and speed are lower than those recorded for unprotected steel, this facts indicating a lower rebar corossion rate. From point of view of the kinetic of process, the corrosion potential shifted to more positive values, indicate, generaly, a lower rebars corrosion.

The concrete-unprotected rebars systems have higher values of corrosion potential than the concrete-galvanized rebar systems. The corrosion activation state of unprotected rebars occurs for all the $CaCl_2$ studied contents.

In Table 1 are shown the results of the calculated efficiency (EP) of hot-dip galvanization versus unprotected steel.

$CaCl_2$ content in concrete [% by mass relative to cement]	0	0.8	2.5	5	7.5
Efficiency of hot-dip galvanization of rebars [%]	28.58	30.59	32.60	31.07	31.66

Table 1. Hot-dip galvanization efficiency

Regardless of Cl ions content the hot-dip galvanization protection method for steel embedded in concrete has a good efficiency.

4. ENVIRONMENTAL IMPACT

It is estimated that corrosion costs around 4-5% of GDP in the high developed countries (Fratesi, 2002, Manzini, Noci et al., 2004, Yeomans, 2004).

Hot-dip galvanizing is probably the most environmentally friendly process available to prevent corrosion of steel and iron, and complies with the environment protection demands, having a reduced impact on environment, saving energy and resources. It does not imply the use of solvents (volatile compounds) dangerous for the environment and human health, as it is the case of the painting and repainting systems. Also, as opposed to the paint layer, the zinc layer is not flammable.

In the hot dip galvanizing process iron or steel articles are dipped into a bath containing molten zinc just above the melting point (450°C). Zinc that does not form a coating on the metal, remains in the bath for further re-use. Three residual products are formed during the process; a zinc/iron mix called dross (96% zinc + 4% iron), zinc ash (around 80% zinc) and flux skimming's (Marder, 2000, Zhang, 2012). All of these contain valuable zinc and are recovered and recycled and the recycled zinc is often returned to the galvanizer. Zinc oxide is recovered from galvanizers' ashes and used in pharmaceutical/beauty products.

Hot dip galvanized steel can be recycled easily with other steel scrap in the steel production process due to the different melting temperatures of the two metals.

Improvement in gas burner technology has also greatly improved energy efficiency in heating the hot dip galvanizing bath. Exhaust heat is not wasted and is used to heat pre-treatment chemicals or dry work prior to immersion.

According with Integrated Pollution Prevention and Control (IPPC) Reference Document on Best Available Techniques in the Ferrous Metals Processing Industry, December 2001, emissions from the galvanizing processes are very low. Aqueous discharge - all waste liquids - which consist mainly of spent acids used to prepare the steel, are removed by licensed waste management companies, in accordance with mandatory procedures, thus protecting surface and ground water. Spent acid is also increasingly used to neutralise other wastes and in the manufacture of water treatment chemicals. Emissions to the atmosphere are inherently very low and are strictly governed by the Industrial Emissions Directive 2010/75/EU (Cook, 2006, after Galvanizing and Sustainable Construction – A Specifier's Guide, EGGA, 2008).

5. ECONOMICAL ASSESSMENTS

Viewing the costs involved by buildings as the amount of the expenses generated by their design, errection, operation, maintenance, repair and post-utilization, based on whole-life cost analysis, the use of galvanized steel as rebars may be economically efficient.

Recent studies established, based on information provided by Turner and Townsend, Construction and Management Consultants, that up to 80% of whole-life costs of buildings, are the operation, maintenance and repair expenses, both capital and current ones (Galvanizing and Sustainable Construction – A Specifier's Guide, EGGA, 2008).

Material quality, anti-corrosive protection of construction elements are key factors which govern the level of maintenance and repair costs during the span of the buildings life time as well as the increase of their operational life.

A case study done by Turner and Townsend, Construction and Management Consultants which data have been analysed by EGGA and ANAZ (after Galvanizing and Sustainable Construction – A Specifier's Guide, EGGA, 2008), shown that for a steel structure, the initial 8-10 years from the commissioning, the repair and maintenance costs are neglectable. After this period of time the first peak in repair costs occurs and then the intervals are repeating at each 3 to 5 years, as can be seen in Figure 8.

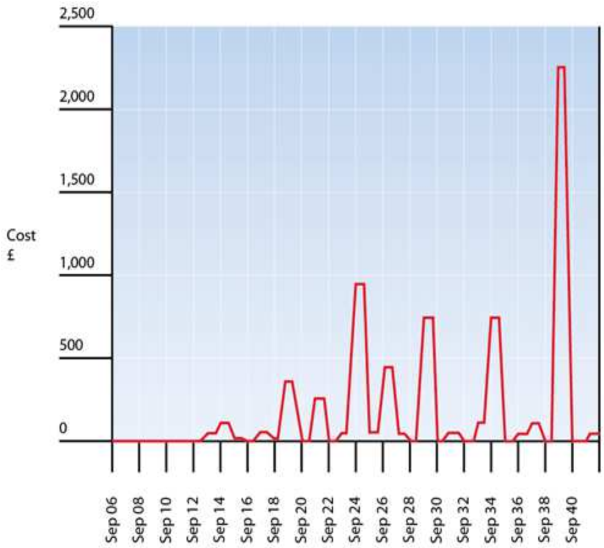


Figure 8. Life cycle expenditure for buildings/Structures (Galvanizing and Sustainable Construction – A Specifier's Guide, EGGA, 2008)

An economical assessment on the comparative costs of using unprotected and hot dip galvanized steel use, at a reinforced concrete building is done, considering an average life span of 100 years.

The whole – life cost analisys details are presented in Figure 9.

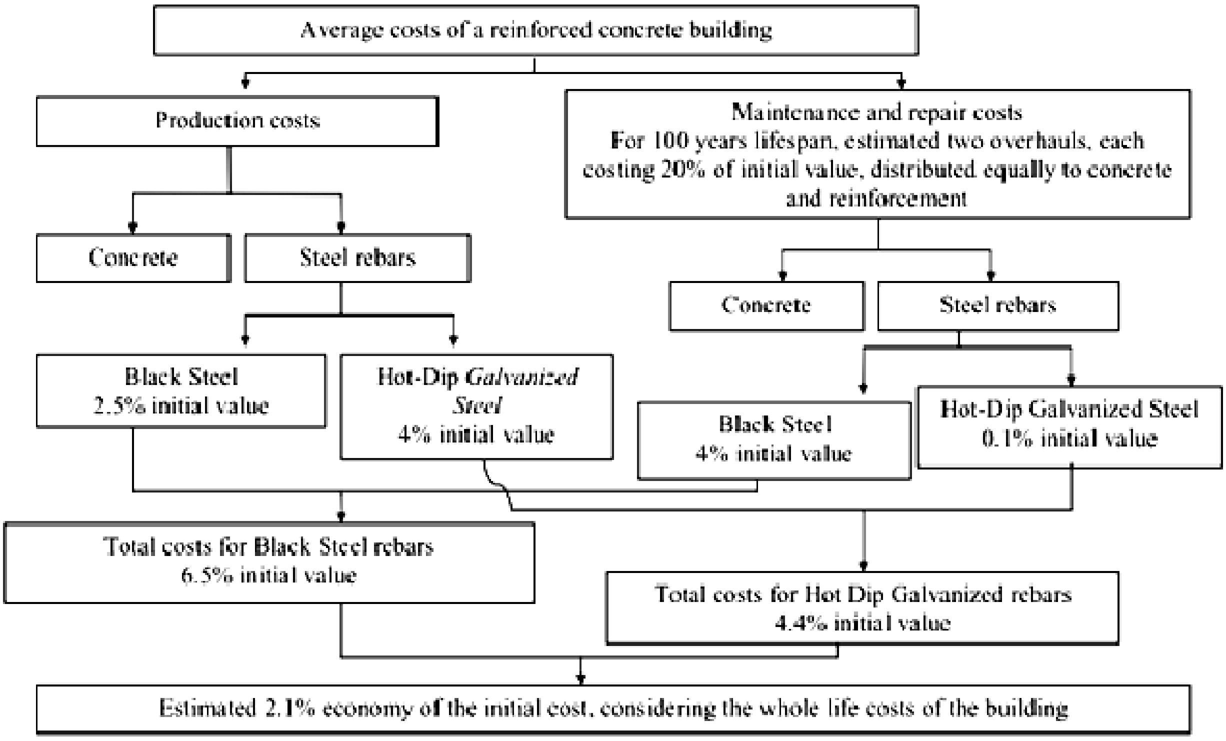


Figure 9. Assessment of whole life comparative costs of RC buildings when using black or hot-dip galvanized rebars

As can be seen in Figure 9, the costs are about 2% less, relative to the whole expenses, when hot-dip galvanized rebars are used instead of black reinforcement, although the initial investment is 1.5% higher.

This assessment does not take into account of the costs involved by the safety measures, which are associated with implementation, operating and administrating of the safety measures. Risk control measures have different levels of risk mitigation, benefits but also adverse effects and costs. As majority costs may be expressed in terms of monetary values, the risk control measures have to be treated in the same manner (Nukina, 2012).

6. CONCLUSIONS

Based on the performed study, the main conclusions are:

- the chronoamperometry tests have revealed lower momentary corrosion rates for the hot dip galvanized reinforcement compared with unprotected steel rebars, in similar environmental conditions (same concentration of $CaCl_2$ in concrete). An exception is present by hot dip galvanized reinforcement in concrete with 7.5% $CaCl_2$ added, to approximately 900 minutes of the 24 hours of the experiment show higher values of current density compared with unprotected steel reinforcement. This behaviour indicated a high corrosion of hot dip galvanized rebars, with formatting a thick layer of corrosion products. Once this layer is thick, chlorine diffusion is strongly hindered and is slowed down the corrosion process; highlighted by the strong downward trend recorded chronoamperometry curve.

- from the allure of Tafel polarization curves was found that at low overpotential, the kinetics of the process is controlled by chemical reactions that occur. If the potential tends to higher values, is observed the influence of the diffuse nature of the products of corrosion layer formed on the metal surface.

- increase in chloride content in concrete leading to an increase of corrosion both for hot dip galvanized steel and for the unprotected steel, but for the same content of chloride ions in concrete, galvanized reinforcement always presented corrosion potential shifted to positive values, the current and corrosion rate of less than unprotected reinforcement.

- the corrosion potential values registered for systems concrete - hot dip galvanized reinforcement showed a uncertain activation of corrosion for up to 2.5% calcium chloride in the concrete. For systems in which calcium chloride is 5% and 7.5%, the corrosion potential values indicate an activation of the corrosion for hot dip galvanized rebars. Systems concrete - unprotected reinforcement had higher levels of corrosion potential, indicating the activation state of the corrosion for all the chloride ions concentrations in the concrete studied.

- corrosion rate of galvanized steel in concrete with 2.5% addition of $CaCl_2$ is lower than the maximum corrosion rate of unprotected steel in concrete no added chlorides and can be considered the threshold concentration chlorides maximum acceptable concrete is much higher if the embedded reinforcement was galvanized.

- calculating the corrosion protection efficiency obtained by galvanizing it was observed that, regardless of the concentration of chloride ions in concrete, this indicator is positive, indicating efficient of corrosion protection by galvanizing, even in the presence of high concentrations of chloride ions.

- the economic analysis indicated that although seemingly the hot dip galvanization is an expensive protection method, using the "whole-life cost method" it is observed that, in fact, is an effective and convenient in terms of costs.

- although apparently galvanizing technology is not a friendly environment technology, by adopting the up-mentioned appropriate measures as well as the recycling and reusing of the materials, the hot dip galvanizing process may accomplish the requirements of EU regulations.

- the efficiency of corrosion protection by hot dip galvanization of reinforcement embedded in concrete, in the analysed circumstances, has been revealed from both technical and economical points of view.

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