

ΤΕΧΝΟΛΟΓΙΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΚΥΠΡΟΥ
ΣΧΟΛΗ ΜΗΧΑΝΙΚΗΣ ΚΑΙ ΤΕΧΝΟΛΟΓΙΑΣ



Μεταπτυχιακή διατριβή

ΜΗ ΚΑΤΑΣΤΡΕΠΤΙΚΗ ΜΕΤΡΗΣΗ ΤΗΣ
ΔΙΑΒΡΩΣΗΣ & ΑΞΙΟΛΟΓΗΣΗ ΤΗΣ ΚΑΤΑΣΤΑΣΗΣ
ΟΞΕΙΔΩΣΗΣ

Παναγιώτης Ηλία

Λεμεσός 2015

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Λεμεσός 2015

Πνευματικά δικαιώματα

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Η έγκριση της μεταπτυχιακής διατριβής από το Τμήμα Πολιτικών Μηχανικών και Μηχανικών Γεωπληροφορικής του Τεχνολογικού Πανεπιστημίου Κύπρου δεν υποδηλώνει απαραίτητως και αποδοχή των απόψεων του συγγραφέα εκ μέρους του Τμήματος.

Σημειώνεται ότι η εν λόγω διπλωματική εργασία εντάσσεται μέσα στις ερευνητικές δραστηριότητες της Δρ. Έλια Α. Ταντελέ στο οποίο συμμετέχει η ερευνητική ομάδα infrastructure² του Τμήματος ΠΟΜΗΓΕ του ΤΕΠΑΚ.

Θα ήθελα να ευχαριστήσω ιδιαίτερα τον την καθηγήτρια μου Δρ. Έλια Ταντελέ, για την σωστή καθοδήγηση και την άμεση ουσιαστική βοήθεια που μου παρείχε κατά τη διάρκεια της εκπόνησης της παρούσας μεταπτυχιακής διατριβής. Επίσης θα ήθελα να ευχαριστήσω τον Δρ. Ρένο Βότση, για την πολύτιμη βοήθεια του στο εργαστηριακό μέρος της μελέτης. Τέλος θα ήθελα να ευχαριστήσω την οικογένεια μου και τους φίλους μου, για την στήριξη και την κατανόηση τους κατά τη διάρκεια του μεταπτυχιακού προγράμματος σπουδών, και συγκεκριμένα κατά τη διάρκεια διεκπεραίωσης της μεταπτυχιακής μου διατριβής.

ΠΕΡΙΛΗΨΗ

Η παρούσα μεταπτυχιακή διατριβή αναλύει το φαινόμενο της διάβρωσης του οπλισμού του σκυροδέματος και τα αναμενόμενα αποτελέσματα και ενδείξεις στα κτίρια από οπλισμένο σκυρόδεμα. Τα κύρια μέρη αυτής της διατριβής αποτελούνται από το θεωρητικό υπόβαθρο καθώς επίσης και από την πειραματική προσέγγιση στο εργαστήριο του Τεχνολογικού Πανεπιστημίου Κύπρου.

Όσον αφορά το θεωρητικό μέρος της εργασίας, έχει επισημανθεί μια γενική ανασκόπηση του μπετόν και του χάλυβα, ως δομικά υλικά τα οποία χρησιμοποιούνται για την κατασκευή κτιρίων. Έχει γίνει μια εκτενέστερη ανασκόπηση και ανάλυση της διαδικασίας διάβρωσης του χάλυβα. Έχουν αναλυθεί θέματα όπως οι παράγοντες της διάβρωσης, λύσεις για τους μηχανισμούς διάβρωσης, τις διαδικασίες ανάπτυξης της διάβρωσης, οι περιβαλλοντικές συνθήκες στις οποίες δημιουργείται διάβρωση και οι συνέπειες της μακροχρόνιας διάβρωσης, βάσει βιβλιογραφικής ανασκόπησης.

Όσον αφορά το πειραματικό μέρος της εργασίας, επτά διαφορετικά δοκίμια δοκών από οπλισμένο σκυρόδεμα έχουν κατασκευαστεί. Τα δοκίμια περιείχαν διαφορετικές ποσότητες χλωριούχου νατρίου (κοινό αλάτι), από το πρώτο μέχρι το έβδομο, με αυξανόμενη πορεία. Η αύξηση του χλωριούχου νατρίου δείχνει αύξηση της οξειδωσης, όπως αυτό βρέθηκε από την βιβλιογραφία και διαπιστώθηκε αργότερα από τις εργαστηριακές μετρήσεις. Η οξειδωση των δοκών μετρήθηκε με τη βοήθεια του οργάνου “Gecor6 Corrosion Rate Meter for steel in concrete”. Το συγκεκριμένο όργανο επιτρέπει την μη – καταστρεπτική μέτρηση και παρακολούθηση της διάβρωσης με τρεις τρόπους ταυτόχρονα. Αυτές οι μέθοδοι είναι οι εξής: corrosion rate, half – cell potential, concrete resistivity. Οι καταγραφές αυτών των μεθόδων παρουσιάζονται σε πίνακες όπως επίσης και τα αποτελέσματα παρουσιάζονται σε ανάλογα διαγράμματα. Η κατάσταση της διάβρωσης για καθεμιά από τις δοκούς φαίνεται σε πίνακες όπως επίσης και οι βαθμοί οξειδωσης με διαφορετικά χρώματα. Τα μέτρα τα οποία πρέπει να ληφθούν αναφέρονται στο τέλος του κειμένου.

Λέξεις κλειδιά: Διάβρωση οπλισμού; Συγκέντρωση χλωρίων; Ενανθράκωση; Corrosion rate; Half – cell potential; Concrete resistivity; Βαθμοί οξειδωσης

ABSTRACT

The current master thesis examines the corrosion aspect of steel reinforcement and the proposed effects in reinforced concrete structures. The main parts of this research project consist of the theoretical background as well as the experimental approach in the laboratory of the Cyprus University of Technology.

Regarding the theoretical part of the project, an overall review of the concrete and steel as construction materials used for building structures has been carried out. Furthermore, an extensive review and analysis for the corrosion process of steel was done. Issues like the factors of corrosion, solutions to corrosion mechanisms, the corrosion development processes, the environmental conditions in which the corrosion is experienced and the consequences of long term corrosion were analyzed on the basis of a literature review.

As far as the experimental part of the thesis, seven different reinforced concrete beam specimens were constructed. The specimens contained different amounts of sodium chloride with an increasing pattern, beginning from the first to the seventh. The increase of sodium chloride would show increase of the corrosion as this confirmed from the literature. The corrosion of the beam specimens was measured with the aid of the “Gecor6 Corrosion Rate Meter for steel in concrete”. The specific apparatus enables the non – destructive measurement and monitoring of corrosion with three methods simultaneously. These three methods are: corrosion rate (linear polarization), half – cell potential, concrete resistivity. The collected data of the aforementioned methods, are presented on tables as well as the results are presented on charts. The condition of each corrosion method for each of the specimens is shown on tables as well as the degree of corrosion with different colors. The measures that should be taken are referred in the text.

Keywords: Steel reinforcement corrosion; Chloride concentration; Carbonation; Corrosion rate; Half – cell potential; Concrete resistivity; Corrosion state classification

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1. INTRODUCTION

Reinforced concrete is one of the most widely used construction materials in the world. Many concrete structures are exposed to various ambient conditions, as well as large amounts and concentrations of deicing salts in regions with snowfall. Exposure to chloride is present, in which chlorides accelerate corrosion on the reinforcement surface. A rust formation appears, which has greater volume than the original steel. Stresses induce the concrete and cracking occurs, in turn making it an even more open structure and through crevices, chlorides pass towards the steel. In parallel, the diameter of the steel reduces, so the part of the steel which acts and serving the concrete structure properties, is just the core of the bar whole body. The surface and external rust has passed away with no benefit at all.

The phenomenon of corrosion of steel reinforcement has compared to cancer disease in the human body. Research carried out by the U.S Bureau of Standards in 1913 and concluded that the addition of a small amount of salt into concrete mixture significantly increased the corrosion occurrence (Husock 1982). The corrosion mechanism occurs on structures exposed to various environmental conditions, so the recipe that should be found in order to avoid greatly that process depends on the location of the existing structure. That will determine accordingly the degree of corrosion and the specific recipe to apply. The matter of cost is embedded, because repairs are estimated for extremely high values of money needed for recovery of the building. The latter is taken into consideration for the new buildings which have been designed with the new codes, in order to prevent premature corrosion in a period with a dominating crisis.

Despite the fact that the structural elements suffer cracking with pitting points and regions of non-continuity, those members lead to lack of serviceability and inelegant state. The size of the extent that a structural element will be subjected to unfavorable loading and how this loading will determine the scale of the crevices, are going to ensure the spread of corrosion along or in-situ points of steel reinforcement bars. When is referred the term reinforcement bars, undoubtedly the stirrups are included in corrosion process because they are in touch confined together. The corrosion process acts relating to continuity of the steel, as the steel is a good conductor. So it transfers current to any good conductor material, and the corrosion is developed through the whole system.

1.1 RESEARCH OBJECTIVES

The objective of this research project is to investigate the deterioration of steel embedded in concrete, by mixing different amounts of sodium chloride (NaCl) or salt commonly, under laboratory ambient conditions. The corrosion rate of each of the specimens is expected to getting higher, as the percentage of salt increases. This happens because as the literature suggests, the salts deteriorate the concrete and consequently the state of the steel to corrosion.

2. LITERATURE REVIEW

2.1. Corrosion process

Corrosion is the process by which an extracted metal returns to chemical compounds that are similar to those found in surrounding environment nature. This is the destructive result of chemical reactions between a metal or metal alloy and its environment. So the corrosion is present.

2.1.1. Factors responsible for corrosion

One of the main parameters of contributing to corrosion of steel reinforcement in building's structural elements is the hydrophilic property of the concrete surface and body; hydrophilic because it contains infinite number of pores due to itself distribution and mixing of the materials during the manufacturing. The likelihood of permeability of hardened concrete consists of the amount of cement, the water to cement ratio (W/C), adequate compaction, consolidation and microcracking of the concrete surface. The porosity depends upon other factors, such as the age of concrete, degree of compactness, the size and grading of aggregate, type of cement. For example high strength concrete is a dense concrete which is impervious to a large degree, so the corrosion process is difficult to occur in short – term period mainly.

As that is embedded in the corrosion process of the steel bars, directly stems in parallel with the opening of crevices of the structural element. Because the structural elements are taking loads and are considered the primary elements resisting the worst combinations of actions, favorable or unfavorable, are easily subjected to a huge number of possibilities to obtain deformations and stresses which affect the integrity of the building. Those cracks of the body or surface of the structural elements (e.g. beams, columns, retaining walls) as aforementioned, coming from various sources, mainly from the continuous loadings (creep) or the transient loadings (earthquake hit).

The concrete surface cover comes into play as well. This is the thickness of the concrete between the external surface of concrete and the steel reinforcement. The cover is determined, as the relevant Standards suggest, based on the atmospheric conditions and the country of building the structure. Above the cover of a structural element, plastering is applied as well as traditional layers of finishes, which the plastering is approximately ranging from 2 to 2.5 cm, but in its turn has negligible contribution to the opening of crevices and resistance to loadings. This stands based on the concept of yielding of the steel and after the yielding of concrete which is brittle in tensile forces. As the reinforced concrete opens in crevices, the plaster is directly opening due to the transfer of that force to the outermost material. The strength of materials Mohr's Circle applies for this happening of shears and tension combination. The scale of how the crevices are going to behave and in how many years will appear is predicted by the design in front-end when the building is shown in drawings, when the static and dynamic designs take place. But of course the limitation of damages due to crevices could be addressed, whilst the null crevice number could not be achieved.

Chemicals either from environmental or from within the concrete making materials are the main sources of deterioration process. Due to attack of chemicals, the concrete develops cracks, which is the first sign of deterioration. The effect of chemicals is mainly due to presence of salt, carbonation, chloride attack and reaction of sulphates with tricalcium aluminate (C3A) present in cement.

Concrete is a mixture of cement, aggregate and water which is highly alkaline. The hydration of cement develops calcium hydroxide which increases the pH value up to 12.5. In such alkaline conditions, the reinforcing steel is covered with a film of oxide which protects the steel.

The surface condition of the steel reinforcement, at the time of its placing in concrete, affects its corrosion rate. If the reinforcement is contaminated with salt or badly corroded, the corrosive action on reinforcement after placement in concrete is promoted rapidly.

The effect of high thermal stresses is present as a corrosion factor. Normal concrete can withstand temperature up to 100 ° C. Beyond this temperature the deterioration of concrete starts. The concrete in industrial plants requires special protective measures otherwise the

concrete may develop thermal cracks. Cracked concrete structures are consequently affected by the environmental chemical.

Freezing and thawing actions should contribute to development of cracks in concrete. In cold regions, the moisture in the pores of concrete freezes. The ice formation gives rise to volumetric expansion which may exceed bursting pressure of surrounding concrete mass.

2.1.2. Corrosion prevention strategies

Therefore the corrosion mechanisms could be addressed by means of protection solutions; and in this way to increase the service life of a structure. Such solutions include:

- Epoxy coatings (before the casting of concrete or when maintenance in order to inhibit corrosion in order to decrease the corrosion rate and become cost-effective)
- Stainless reinforcing steel
- Hydrophobic treatment of the concrete surface (isolation of the reinforced concrete sections using synthetic elastic coatings e.g. spatula coatings etc.)
- Pozzolanic additives to concrete mixture
- Minimum slope of exposed surfaces (for water flow out)
- Efficient drainage systems
- Corrosion inhibitors
- Cathodic protection
- Another method applied for the unavoidable penetration of the cover layer of concrete by corrosion agents, is the optimum selection of the grain size of the concrete constituents in order to obtain a compact structure with reduced porosity

The sizes of the cracks during the life of structure is not constant because it varies and depends on the loads, dynamic actions, variation of temperature, expansion, contraction, shrinkage,

creeping, reinforcement strain relief etc. The coatings that could be used for such conditions are the creep-resistant coatings; polyethylene paints (wear resistant), elastomer -based varnishes, oil or bitumen-based varnishes, silicone resins. For example ED-20 epoxy resin, zinc coating. In relation to the solution to prevent the corrosion by coatings, it is commonly known that the epoxy layer has brittle behavior and it could easily scratch from abrasion between bars and concrete during life. So, because several studies (Vaca – Cortes 1998) demonstrated that epoxy-coated bars experienced uniform corrosion with shallow pitting and of course decrease of cross sectional areas of bars, instead of no-coating application to steel bars and eventually extensive corrosion with moderate to severe pitting, further studies should be done in order to determine the optimum reinforcement coating. But the latter should not be pointed out in that research project.

As far as the stainless reinforcing steel, selection of stainless steel is based on its corrosion resistance, strength, and long life. When selected, the overall increase in project installed costs, ranges from one to fifteen percent. When Life Cycle Costs (LCC) are calculated using stainless steel rebar of up to 125 years this product becomes very cost effective as repair work becomes necessary for carbon steel reinforced structures earlier in the cycle.

2.1.3. Corrosion mechanisms in concrete

Corrosion of reinforcing steel embedded in concrete is an electrochemical process that requires an anode, a cathode, an electrolyte, and an electrical connection between the anode and cathode for the transfer of electrons. Coupled anodic and cathodic reactions take place on the surface of the reinforcing steel. Concrete pore water acts as the electrolyte and the body of reinforcement provides the electrical connection between the anode and cathode. Cathodes and anodes may be located on the same rebar or on different bars that are electrically connected through metallic ties or chairs.

The oxidation and reduction reactions that take place at the anode and cathode are called half-cell reactions. At the anode, iron is oxidized and goes into solution as ferrous ions releasing its electrons as it is shown in Eq. (3) below.



Depending on the availability of oxygen and the pH of the environment, different reduction reactions can take place at the cathode. In the highly alkaline concrete pore solution where oxygen is available, the most likely reaction is shown in Eq. (4) below, which produces hydroxyl ions.

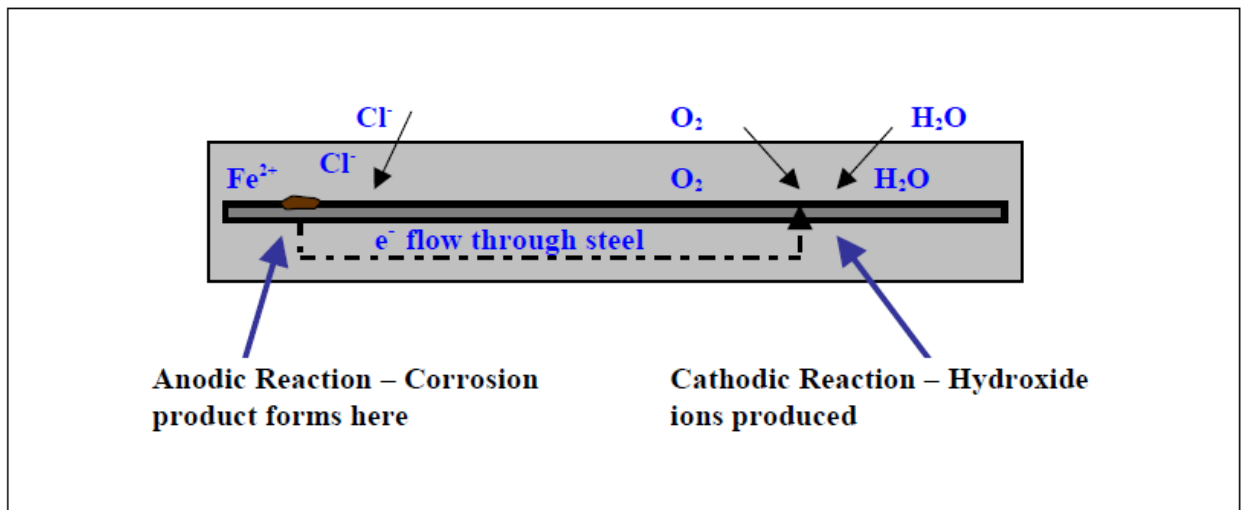
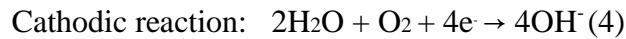


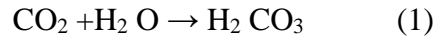
Figure 1: Corrosion reaction at the cathodic and anodic sites

Source: <http://www.odot.state.or.us/tddresearch/epoxyv.pdf>

There are two general processes occurring in concrete that cause the corrosion. The first one is the *carbonation* and the second one is the *chloride ingress* corrosion.

Carbonation occurs when carbon dioxide from the ambient air reacts with the hydroxides in the pore solutions to form carbonates and water. These reactions cause the alkalinity to drop from pH values of 12,5 or 14 to 8 or 9. The reduced pH values of the concrete allow the oxide film to become unstable and the reinforcing bars change from a passive corrosion state to an active state. The rate of carbonation penetration into hardened concrete is slow and the effects of carbonation can be minimized easily through proper design and detailing of the structure.

Atmospheric carbon dioxide diffuses into the concrete and dissolves in pore solution to form carbonic acid Eq. (1), which neutralizes the alkalis in the concrete pore solution and combines with calcium hydroxide to form calcium carbonate Eq. (2).



Due to the neutralization of alkalis, carbonation and diffusion of other acidic gases, such as SO_2 and NO_2 , cause a decrease in the pH of concrete pore solution, which is typically between 12,5 and 13,6. A reduction of pH to a lower level may cause loss of passivity and initiate corrosion of reinforcement. Different studies stated different limits of pH for the stability of passive film. Berkely and Pathmanaban (1990) stated that a pH level lower than 9,5 would commence corrosion of steel reinforcement as shown on Table 1. Later Metha and Monteiro (1993) stated that the protective film tends to be stable in the absence of chloride ions as long as the pH of concrete pore solution stays above 11,5.

Table 1: State of reinforcement corrosion at various pH levels

pH of concrete	State of reinforcement corrosion
Below 9,5	Commencement of steel corrosion
At 8,0	Passive film on the steel surface diassapears
Below 7	Corrosion occurs

Source: <http://d2dtl5nmlpfr0r.cloudfront.net/tti.tamu.edu/documents/0-4825-1.pdf>

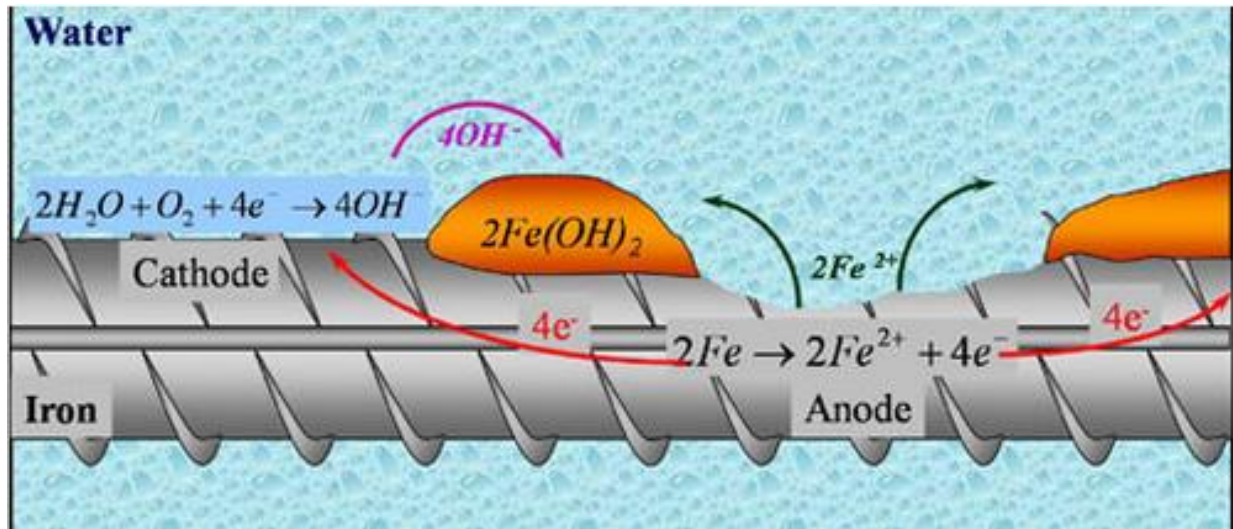


Figure 2: Detailed corrosion reactions on steel reinforcement

Source: http://www.cement.org/images/default-source/contech/corrosion_water_graphic.jpg?sfvrsn=2

The other one corrosion mechanism in concrete is the *chloride ingress*. $Fe(OH)_2$ is a weak base formed during the reaction and is unstable. In the presence of oxygen, another reduction reaction occurs and $Fe(OH)_2$ is converted into $Fe(OH)_3$, or rust, which precipitates out of solution.

An electrolyte is an aqueous medium through which electric current flows. In this instance, the electrolyte is the concrete itself. Chlorides, permeating into hardened concrete, act as a double-edged sword. Not only do chlorides break down the protective oxide film of the reinforcement, but chlorides also increase the conductivity of the concrete, allowing more current to flow.

The requirement of an electrical circuit is always satisfied in a concrete structure. Columns and beams are reinforced with steel cages, and slabs are reinforced with one or two mats of reinforcement. Metal ties, mechanical connectors, and chairs, which are used to facilitate construction, create electrical connections among virtually all of the reinforcing bars in a reinforced concrete member.

The primary cause of the electrochemical process in concrete is the presence of free chloride ions in solution. It is speculated that chloride ions penetrate through pores or defects and break down the oxide film more easily than do other ions. There are many potential sources for chlorides, including proximity to salt water environments, industrial brines, deicing salts, and even chlorides that are cast in during construction. Small chloride levels in concrete are not sufficient to initiate corrosion. Test results to determine a more exact concentration level

threshold have had significant variations and are subject to debate. One report stated that corrosion is not likely when chloride levels are at or below 0,15%, based on weight of cement, and that corrosion is likely when chloride levels are above 0,30%, based on weight of cement. Under atmospheric conditions, the corrosion of mild steel occurs. But the mild steel in sound concrete comes in contact with highly-alkaline concrete pore solution and eventually is protected against corrosion. A thin layer is formed which provides a noble reinforcement behavior (stainless steel likened), as it is shown on Figure 3. This layer breaks down when chloride concentration increases or the carbon dioxide diffusing and the carbonation in the concrete occurs. The latter causes decrease in the pH level. Chloride induced corrosion is very important for structures exposed to chloride-containing environments (e.g. deicing salt occurrence, marine climate, salt-contaminated aggregates). The latter is the type of aggregates (rounded) that have been used in the past when the selection of aggregates was performed from the sea and directly poured in the concrete mixture with no any separation of chemical substances, like salt. An example of severe chloride exposure is on parking decks.

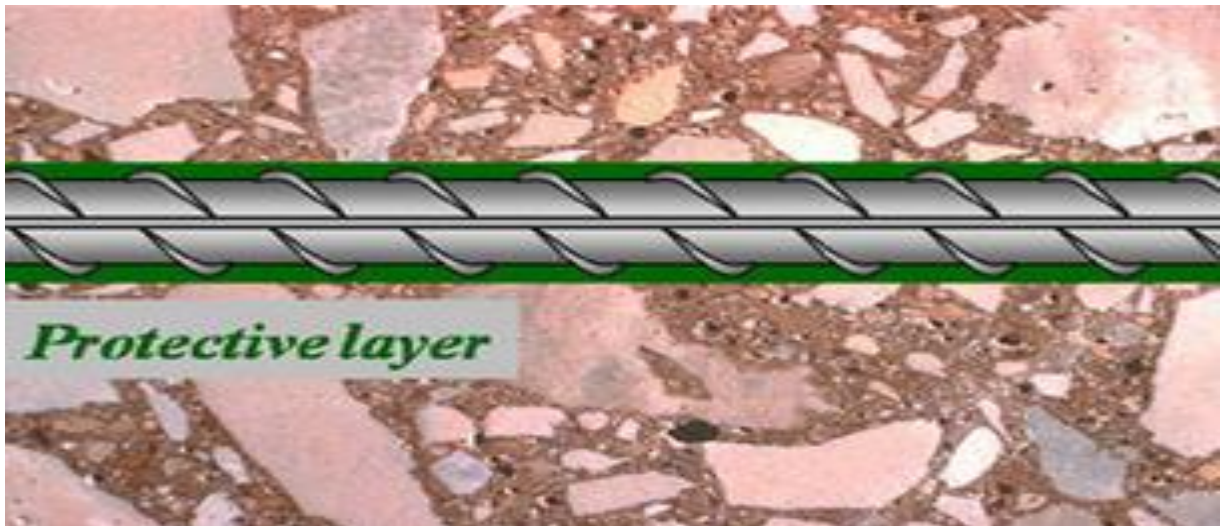


Figure 3: Formation of a thin protective layer around the steel bar

Source: http://www.cement.org/images/default-source/contech/corrosion_graphic2.jpg?sfvrsn=2

2.1.4 Exposures to different environments

As discussed before, corrosion degree depends in a certain extend to the environmental conditions encountered. The environments are classified to three, having as source the outdoor exposure. Outdoor exposure could be the immersion, atmospheric and splash. What each exposure is analytically could be explained as follow.

Immersion: The immersion takes place in the case of structures immersed into the water (seawater or fresh) or buried into soil (for example the foundation of a building or a bridge foundation). A combined effect of temperature, salinity, pH, dissolved gases (e.g. oxygen) define the degree of corrosion whether certainly the element developed crevices caused by creep or other form of loading during its life. The type of soil, humidity, salts, bacteria, oxygen and pH determine the long-term behavior of the coating. The type of dissolved salts and oxygen define a lot the structures exposed to freshwater. Sea water has dissolved salts (sodium chloride mainly). Immersed into water or buried in soil may be affected negatively by gravel, sand and stones.

Atmospheric: Atmospheric exposure of reinforced concrete structures leads to subjection to heat, moisture, ultraviolet radiation, and salt and gas concentrations. The level of pollution as well determines the degree of corrosion of a structure. The buildings located in rural environments are less subjected to corrosion in comparison to the buildings located in industrial and marine area conditions.

Splash: Structures exposed to sea (e.g. offshore plants and foundations of wind turbines) are located in the so-called “splash-zone”. Extremely aggressive environments dominate because of combination of oxygen-rich atmosphere and splashing of electrolytes from the sea. The degradation of coatings is likely to be accelerated further by exposure to ultraviolet radiation.

2.1.5 Consequences of long – term corrosion

As a result of the aforementioned, the corrosion process leads to different consequences for the structure such as:

-Decrease of cross-sectional area of reinforcement (callipered in the laboratory): The cross – sectional area of the steel reinforcement is reduced due to the deterioration of the steel material due to corrosion phenomenon. As a result the tensile strength to be reduced and the structure to be subjected to various undesirable stresses. The calibration of the diameter of the steel is performed with the aid of the caliber apparatus, but in such case, the steel bar should be taken out from the body of concrete and cleaned out.

-Delamination of the concrete cover: Because of the fact that the corroded steel is expanded in diameter (corroded stuff), the concrete cover is delaminated and it needs specified treatment to become to the initial state. Corrosion byproducts occupy a much larger volume than does the original reinforcing steel. This increase in volume creates high pressures and tensile forces between steel and concrete material.

-Loss of bond strength between steel and concrete due to corrosion: Due to the fact that the concrete has different properties relating to the corroded steel, the bond between is decreased to zero.

-Cracking and spalling of the concrete cover: Because the concrete cover has been delaminated from the existing structure, it has no bond to the active body of the structural element. Eventually it suffers from itself cracks.

-Loss of strength of the structure: This should be done with models in order to specify the initial strength of structure and compare with the existing strength after long – term corrosion of structural elements.

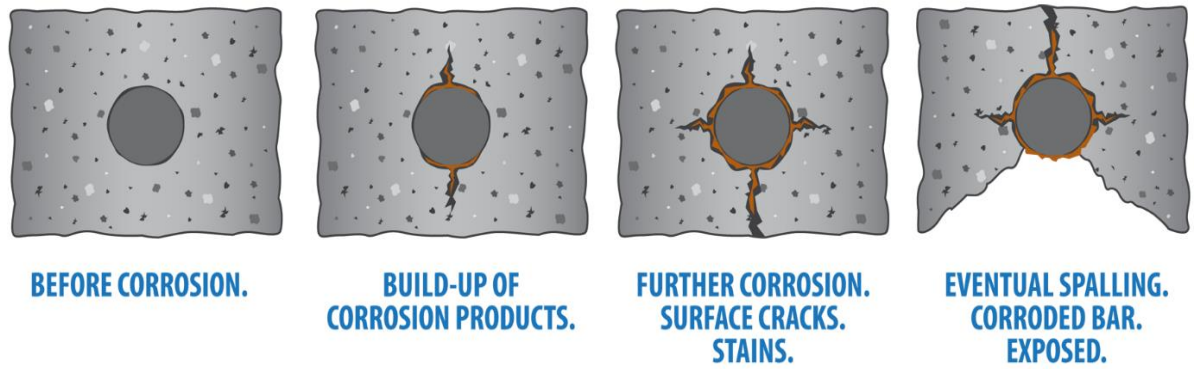


Figure 4: Deterioration of reinforcing steel and concrete due to corrosion intrusion

Source: http://www.bpcomposites.com/wp-content/uploads/2012/08/FRP_chart_crossioneffect.png



Figure 5: Corroded steel of a slab and delamination of concrete cover

Source: <https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRc5i3uqsX2dM39psbWzWsB6Mh7bhZV5-P6ekk5jfFmNRWh5ZA>



Figure 6: Corroded steel and delamination of the cover layer on a basement

Source: <http://www.nordicgalvanizers.com/foretag/images/Fig-10-14.gif>



Figure 7: Corrosion of the whole system of reinforcing bars (longitudinal and stirrups) on a concrete beam

Source:

http://www.msdp.com/images/projects/for1_Forensic_Investigation_Concrete_Beam_Corrosion_01_large.jpg



Figure 8: Severe corrosion condition of a column

Source: <http://www.testconsult.co.uk/images/stock750/Condition03.JPG>

2.2. CORROSION MONITORING – METHODS

The field of corrosion measurement, control, and prevention covers a spectrum of technical activities. Regarding corrosion control and prevention, there are technical options such as cathodic and anodic protection, materials selection, chemical dosing and the application of internal and external coatings. Corrosion measurement determines how corrosive the environment is and at what rate metal loss is being experienced. Corrosion measurement is the quantitative method by which the effectiveness of corrosion control and prevention techniques can be evaluated and provides the feedback to enable corrosion control and prevention methods to be optimized.

2.2.1. Half – cell potential

The method of half – cell potential gives values and interprets information about the probability of corrosion and not about the rate of corrosion. It is well known that the probability of corrosion in concrete structures depends on specific factors. Provided that the corrosion conditions are equal (chloride content or carbonation of the concrete at the steel surface), the main influences are: the ionic conductivity of the concrete electrolyte, the humidity, the temperature, and the quality of the concrete cover and its thickness.

As far as the humidity, it has a large effect on the measured potential leading to more negative values.

As far as the temperature, measurements below the freezing point is not suggested as incorrect readings should occur. The measurements for the current research project were done under laboratory conditions.

As far as the concrete cover thickness, some aspects should be present. The potential measured at the surface becomes more positive as the concrete cover increases. Deviations should be caused due to the variations of concrete cover. Thinner concrete cover leads to more negative values of potential which would indicate high corrosion values.

As far as the oxygen content at the reinforcement, the decreasing oxygen concentration and increasing pH-value at a steel surface its potential becomes more negative. High values of water saturation, low porosity and/or very high concrete cover and thus oxygen supply, the steel surface potential may be very negative even though no active corrosion is taking place.

It should be noted that in the literature there are only a few papers in which the probability of corrosion is determined using both concrete resistivity measurements and half-cell potential mapping.

Table 2: Application limits for the half – cell potential

Potential (E_{corr})	Probability of corrosion
$E_{\text{corr}} < -500 \text{ mV}$	Severe corrosion
$-500 \text{ mV} < E_{\text{corr}} < -350 \text{ mV}$	High. Greater than 90 % probability that reinforcing steel corrosion is occurring in that area at the time of measurement
$-350 \text{ mV} \leq E_{\text{corr}} \leq -200 \text{ mV}$	Intermediate. Corrosion activity is uncertain
$E_{\text{corr}} > -200 \text{ mV}$	Low. 90 % probability that no reinforcing steel corrosion is occurring in that area at the time of measurement (10 % risk of corrosion)

Source: <http://dx.doi.org/10.1155/2013/714501>

2.2.2. Concrete resistivity

Empirical studies have shown that there is a direct relationship between the corrosion rate and the electrical resistivity. The readings of corrosion rate are of limited value as the rebar corrosion rate varies considerably with time.

The electrical resistivity of the concrete cover layer decreases due to increasing concrete porosity, increasing concrete water content, increasing temperature, increasing chloride content and decreasing carbonation depth. Based on empirical research studies, when the electrical

resistivity of the concrete is low, the rate of corrosion increases. As the electrical resistivity is getting higher, then the corrosion rate decreases e.g. for the case of dry and carbonated concrete.

The ionic conductivity is measured quantitatively as the resistivity of the concrete. Concrete resistivity ρ ranges widely from 10^1 to $10^6 \Omega\text{m}$, depending on mainly the moisture content and the material of the concrete. Concrete resistivity ρ is inversely proportional to the corrosion rate. This was confirmed by Glass who showed that the effect of mortar resistivity is strongly dependent on the relative humidity of the environment, while L'opez et al. showed that the amount of pores in concrete determines its resistivity ρ and corrosion rate. Morris et al. found that reinforcing bars undergo active corrosion when concrete resistivity ρ is below $10 \text{ k}\Omega\text{cm}$, whereas at concrete resistivity ρ above $30 \text{ k}\Omega\text{cm}$ the probability of their corrosion is low. Extensive research on the resistivity technique, covering experimental analyses and an analysis of the effects of geometry and material properties, was done by Zhang et al.

The electrical resistivity measurements are disturbed because of the presence of rebars. The reason is because they conduct current better than the surrounding concrete. Particularly, this is the case when the cover depth is less than 30 mm.

Low electrical resistivity leads to more negative potentials that can be measured on the surface and the potential gradients become flatter. In this case, the grid under measurement of potential may be coarser, as the risky undetected anodic areas with flat gradients is getting lower. As the resolution between corroding and passive areas is reduced, this may lead to an overestimation of the active corrosion surface area. High electrical resistivity is leading to more positive potentials that may be measured on the surface and potential gradients become steeper.

The following table shows the application limits for resistivity:

Table 3: Application limits for the resistivity

Resistivity ρ	Corrosion condition
When $\rho < 5 \text{ K}\Omega.\text{cm}$	Very high
When $\rho = 5 \text{ to } 10 \text{ K}\Omega.\text{cm}$	High
When $\rho = 10 \text{ to } 20 \text{ K}\Omega.\text{cm}$	Low to moderate
When $\rho > 20$	Negligible

Source: www.electrochemsci.org

2.2.3. Corrosion rate or linear polarization

Table 4: Correlation between changes in current with the corrosion condition (application limits)

I_{corr} ($\mu\text{A} / \text{cm}^2$)	Corrosion condition
$< 0,1$	Passive
$0,1 < I_{\text{corr}} < 0,5$	Low to moderate
$0,5 < I_{\text{corr}} < 1,0$	Moderate to high
$> 1,0$	High

3. EXPERIMENTAL APPROACH

3.1. Specimen construction – sodium chloride mixing – quantities of constituents

For the scope of the laboratory part of this research project, 14 small RC beam specimens were constructed. The specimens had dimensions 0.5 x 0.1 x 0.06 m.



Figure 9: Beam specimens in the laboratory

For each corrosion measurement, two beams were constructed. So seven measurements sets were done, of which each one included different quantity of sodium chloride (NaCl). The proportion of the sodium chloride was determined as a percentage of the weight of cement. The percentages of sodium chloride mixed in the concrete were as follows: 0%, 1%, 2%, 3%, 5%, 10%, and 15%. The total volume of the small beams was calculated as:

$$(\text{Length} * \text{Width} * \text{Height}) * \text{Number of beams} = (0.5 * 0.1 * 0.06) * 14 = 0.042 \text{ m}^3$$

Based on the constituent amounts for the construction of 1 m³ of concrete class C30, all the constituents were calculated as these presented on Table 5 below.

Table 5: Analytical table with the amounts of each constituent

Constituents	Quantity per 1 m³ (kg)	Quantity per 0.042 m³ (kg)
Cement	400	16,8
Sand	700	29,4
Aggregates	1000	42
Water	-	Depending on the mixing
Reinforcement	-	14 bars (10 mm diameter and 600 mm length)
Sodium chloride (NaCl)	-	Depending on the specimen

The following table shows analytically the materials that have been used, for both specimens for each measurement, including the sodium chloride.

Table 6: Amounts of NaCl and constituents for each of the specimens

NaCl (%)	NaCl (Kg)	Cement (Kg)	Sand (Kg)	Aggregates (Kg)	Water (Kg)
0 %	0	2.4	4.8	6	1.55
1%	0.024	2.4	4.9	6	1.35
2%	0.048	2.4	4.9	6	1.35
3%	0.072	2.4	5.26	6.33	1.35
5%	0.12	2.4	5.26	6.33	1.35
10%	0.24	2.4	5.26	6.33	1.35
15%	0.36	2.4	5.26	6.33	1.35

After the construction of the beam specimens, they have been submerged into water for a period of 28 days as shown on figure 10 below.



Figure 10: Beam specimens submerged into a water tank for 28 days

3.2. Testing procedure (GECOR6 Corrosion Rate Meter apparatus)

The corrosion measurement was performed with the aid of the “GECOR6 Corrosion Rate Meter for steel in concrete”. GECOR6 was developed to measure the corrosion rate of steel in concrete by the “polarization resistance” or “linear polarization” technique. It enables the measurement of corrosion and the loss of cross – sectional area of the steel reinforcement in the concrete, in mm/year based on a relationship from the literature. A small current is applied to the reinforcing bar and measuring the change in the half-cell potential.

The apparatus was developed by GEOCISA in collaboration with two leading Spanish Research Centres under EUREKA/EUROCARE project EU-401 with the involvement of the Swedish Cement and Concrete Research Institute (CBI). Also evaluated by SHARP.

GECOR6 has three components, the rate meter and two separate sensors. The LG-ECM-06 meter controls the system, collects the measurements and processes the data. The meter and the sensor A measure the corrosion rate, in $\mu\text{A}/\text{cm}^2$ over a defined area of rebar, the corrosion potential E_{corr} , measured relative to a copper / copper sulfate half-cell (CSE), and the electrical resistance of the concrete for the calculation of I_{corr} . The sensor B measures the concrete resistivity, the relative humidity and temperature.



Figure 11: GECOR6 Corrosion Rate Meter apparatus

As far as the unit conversion from $\mu\text{A}/\text{cm}^2$ to mm/year is done based on equation retrieved from the literature. The rationale was retrieved from the Report 19: Considerations for Use in Managing the Aging of Nuclear Power Plant Concrete Structures: State-of-the-Art Report of RILEM Technical Committee 160-MLN. The latter method represents the actual loss of the cross – sectional area. There are two other methods that the apparatus measures. The measurements of those methods are not referred to actual loss, but they show probability percentage.

Having as reference background, Andrade modeled corrosion currents for estimating the remaining service life. Her model considers reduction in steel section as a corrosion important matter.

The corrosion current was converted to reductions in the diameter of the reinforcing steel by the relationship of Eq. (5):

$$\Theta(t) = \theta_i - 0,023 * i_{\text{corr}} * t \quad (5)$$

$\Theta(t)$ = rebar diameter at time t (mm)

θ_i = initial diameter of the rebar (mm)

i_{corr} = corrosion rate ($\mu\text{A}/\text{cm}^2$)

t = the time after the beginning of the propagation period (years)

0.023 = 2 * (the conversion factor of $\mu\text{A}/\text{cm}^2$ into mm/year)

The method of measuring the corrosion is a non-destructive method, since the apparatus consists of a sensor which is applied on concrete surface along the rebar.

The polarization resistance R_p is the change in potential. The GECOR6 obtains the corrosion rate I_{corr} from the polarization resistance R_p by the relationship $I_{\text{corr}} = \frac{B}{R_p}$

where

B = constant relating to the electrochemical characteristics of steel in concrete

I_{corr} = change in current

R_p = polarization resistance expressed as (change in potential) / (applied current)

3.2.1 Setup procedure

3.2.1.1 Filling the Cu / CuSO₄ reservoir

A syringe was provided along with the equipment of the GECOR6, in order to be used to fill the Cu / CuSO₄ reservoirs in sensor A. The syringe was filled with solution. The 3 reservoirs of the sensor A have been opened, so as to gain access to holes in the inserted copper tubing. The reservoirs have been filled each with 15 ml capacity of the solution, by squirting the solution into the holes, until the reservoirs have been completely full. The 'O' Ring was replaced and plugged.



Figure 12: Filling the A sensor with solution liquid

3.2.1.2 Selection of location points for measurement

Prior to the survey of corrosion rate, the selection of the number and location of points where corrosion rates will be calibrated is obtained. The number of points will be determined based on the size of structure in order to provide consistency of the results. Strategic locations should be selected for measurements, such as construction joints, sources of water and chloride, near the ground and depending on the water level submerged. For instance, the base of a column the

corrosion is higher because of the contact with ground. Measurements should be taken along a line, in order to get reliable results if corrosion condition varies. Chloride concentration, staining, cover and carbonation depths can also be used where appropriate.

3.2.1.3 Connection between equipment and structure

For a complete circuit, a connection must be made to the reinforcement bars. A piece of reinforcement is exposed at the edge of the specimens, since the casting of the beams has been made. The exposed steel is bonded to the reinforcement and a cable attached. The steel is clean, without any substances, for ensuring a good electrical contact. Ensuring electrical continuity should provide accurate results. Discontinuity is attributable to construction joints with separated rebar cages, excessive corrosion and light reinforcement content. Performing the measurements of that research project, no discontinuities occurred.



Figure 13: Attached cable to the exposed steel to create a circuit

3.2.1.4 Check for the correct function of the instrument

Before the beginning of a real test, a functional test is recommended. The instrument should be ready to measure the corrosion correctly, by checking a specified area of measurement twice. A good idea is to make comparison measurements on areas that are damaged more against areas damaged less. This means that the specimens with higher amount of sodium chloride should present higher corrosion records, in comparison with specimens having less amount of sodium chloride.

3.2.1.5 Surface preparation

A correct grid should be marked out, corresponding to the grid to be used. In that research laboratory project, a black marker has been used on the concrete surface along the rebar. The preferred location for the application of the A sensor, was directly over the single rebar into the specimens. The rebar diameter is equal to 10 mm. Complete electrical (ionic) contact between the half-cells in the sensor and the concrete surface should be present. Deformations and uneven surfaces should be avoided by grinding or pressing the sponge pad until full confinement obtained.

Concrete surface has been wetted (but not saturated) prior to applying the sensor. The surface of each specimen was moistened 10 minutes before carrying out the measurement, in order to ensure water absorption and reaching until the point in which the reinforcement is located. This was done using a sponge.



Figure 14: Wetting of the specimen surface using a sponge

3.2.1.6 Taking a measurement

A sponge pad was wetted. After the wetting of the sponge pad, it was mounted on the concrete surface on the first point of measurement, which was the left hand side of the specimen. Onto the sponge pad, the sensor A was mounted. The first parameter that the operator must input is the area of steel to be measured (in cm^2). The diameter (D) of the steel was given by the instructor. The specimens were constructed on December 2014 and remained in the laboratory of Civil Engineers at the Cyprus University of Technology. The diameter (D) of bars was 10 mm or 1 cm for all the specimens. The area measured corresponded to the top rebar below a 105 mm diameter circle centered on the sensor. For the case of the specific specimens, a single rebar crosses the concrete, so the general form of area of steel will be:

$$A = 3.142 * D * 10.5 \text{ cm}^2 \quad (6)$$

Thus, the area of steel reinforcement crossing the concrete beams is equal to

$$A = 3.142 * 1 * 10.5 \text{ cm}^2 = 32.991 \approx 33 \text{ cm}^2 \quad (7)$$

The corrosion current I_{corr} , the corrosion potential E_{corr} and the concrete electrical resistance and resistivity were measured. The same procedure obtained also for the other locations of measurement. For each of the beam specimen, 3 locations were selected to measure (at the 2 edges and in the middle). The reason of measuring 3 locations is because the final value should be calculated based on the average of the same 2 specimens' records. The sensor should be maintained flat against the surface with the half cells and with full contact. This should be achieved by pressing the sensor lightly by hand. When the contact face cannot be in full contact with the concrete, then the sensor should be rotated so that the three reference electrodes (half cells) are perpendicular to the edge.

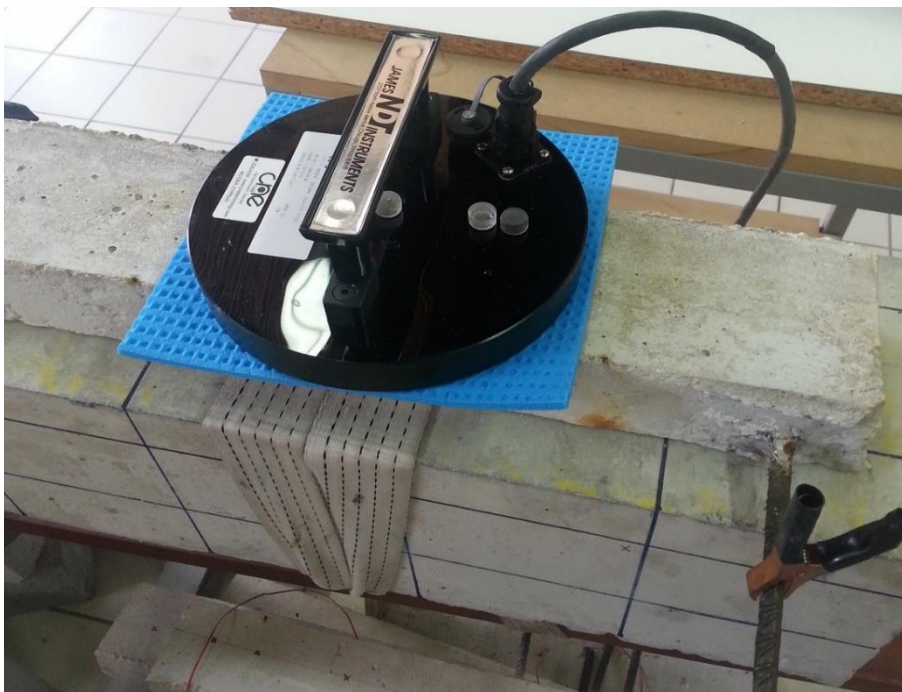


Figure 15: Taking a measurement with sensor A

3.2.1.7 Environmental conditions

Extreme conditions of temperature and humidity should not be present, for the measurement of corrosion rate. The ambient conditions that dominate for the case of that research project consisting of laboratory conditions.

4. RESULTS AND DATA ANALYSIS

4.1 Acquired data

4.1.1 Half – cell potential data

Table 7: Results for the half – cell potential

NaCl (%)	Beam specimen No	Average of specimen (a) [mV]	Average of specimen (b) [mV]	Total average [mV]
0 %	1	-305.8333333	-164.8	-235.317
1%	2	-275.885	-302.6	-289.243
2%	3	-333.2	-276.05	-304.625
3%	4	-334.3666667	-360.3	-347.333
5%	5	-422.3666667	-382.4666667	-402.417
10%	6	-424.7666667	-473.0666667	-448.917
15%	7	-470.6	-475	-472.8

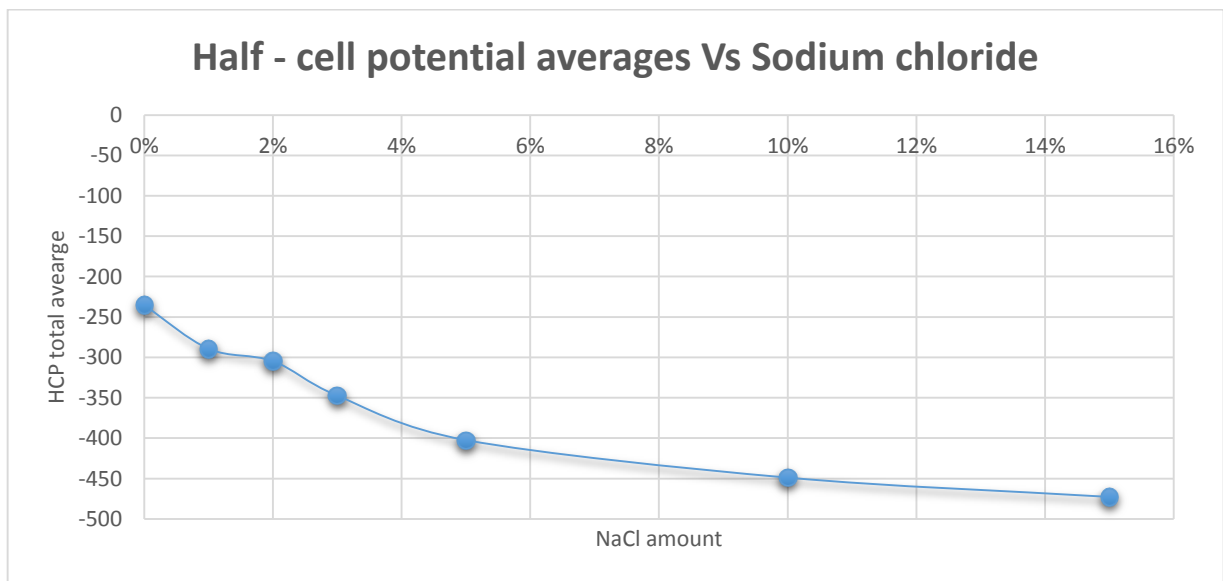


Figure 16: Graph showing the half – cell potential total average values on y-axis Vs the amounts of sodium chloride on x-axis

4.1.2 Concrete resistivity data

Table 8: Results for the concrete resistivity

NaCl (%)	Beam specimen No	Average of specimen (a) [KΩ.cm]	Average of specimen (b) [KΩ.cm]	Total average [KΩ.cm]
0 %	1	10.305	9.958333	10.13
1%	2	8.37	7.51	7.94
2%	3	7.135	6.2	6.67
3%	4	5.816667	5.8	5.81
5%	5	5.5075	5.133333	5.32
10%	6	3.183333	2.416667	2.8
15%	7	2.091667	1.5875	1.84

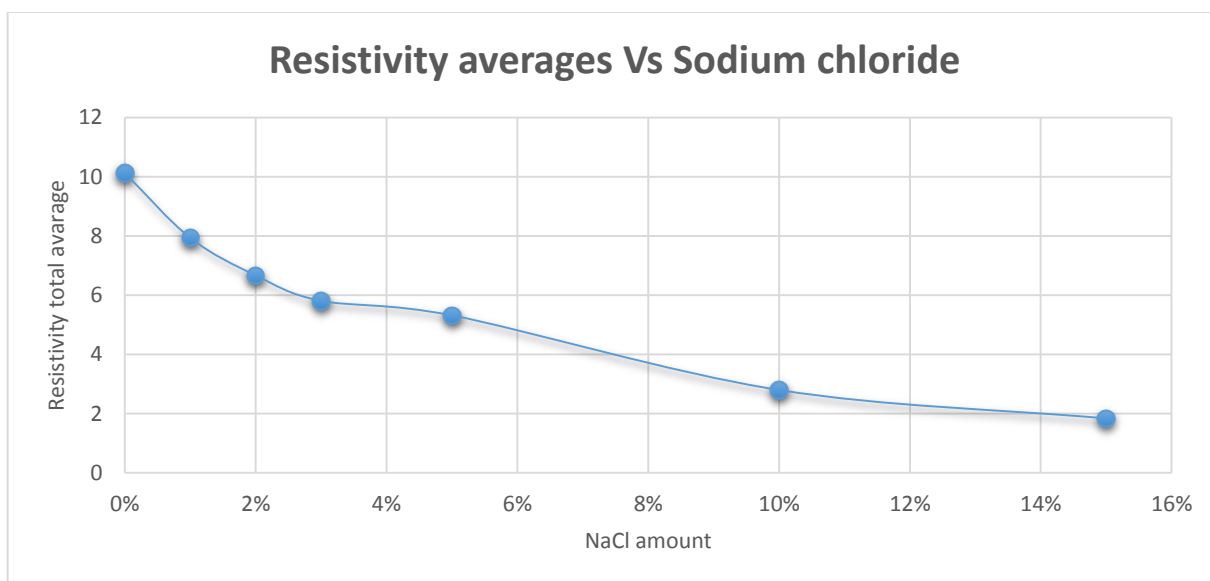


Figure 17: Graph showing the resistivity total average values on y-axis Vs the amounts of sodium chloride on x-axis

4.1.3 Corrosion rate data

Table 9: Results for the corrosion rate

NaCl (%)	Beam specimen	Average of specimen (a) [$\mu\text{A} / \text{cm}^2$]	Average of specimen (b) [$\mu\text{A} / \text{cm}^2$]	Total average [$\mu\text{A} / \text{cm}^2$]
0 %	1	0.414	0.415	0.4145
1%	2	0.7355	0.508	0.62175
2%	3	0.582	0.693	0.6375
3%	4	0.5633333333	0.742	0.652667
5%	5	1.1773333333	0.9463333333	1.061833
10%	6	2.638666667	3.0073333333	2.823
15%	7	3.428666667	2.337666667	2.883167

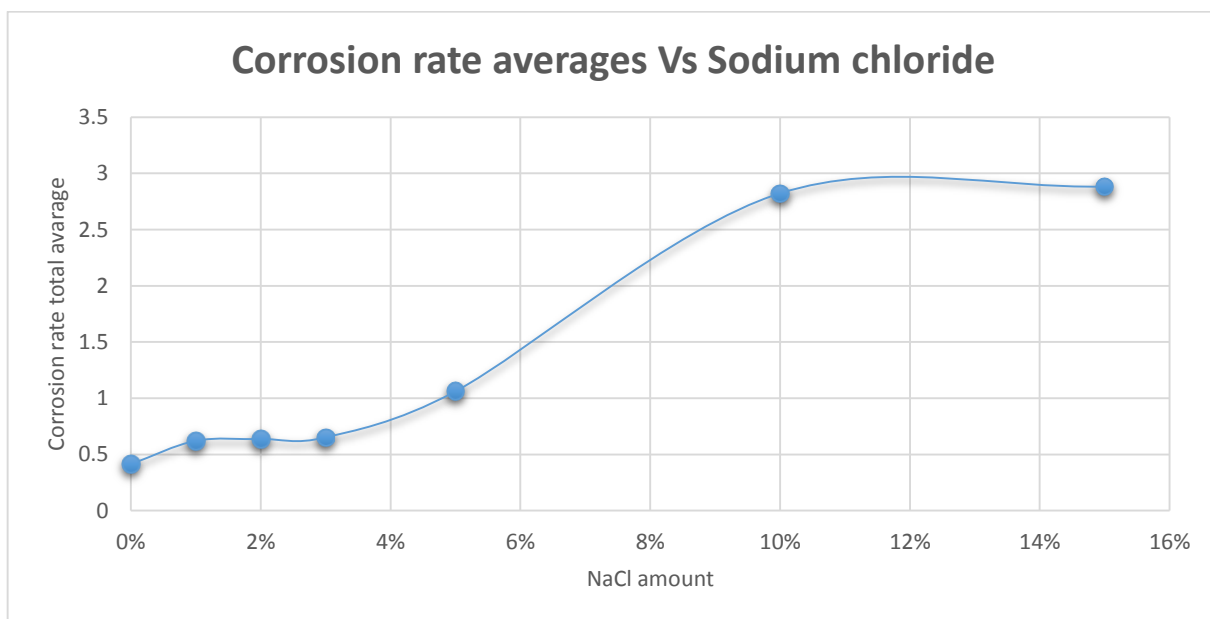


Figure 18: Graph showing the corrosion rate total average values on y-axis Vs the amounts of sodium chloride on x-axis

In order to convert the corrosion rate values in mm/year a specific manner is applied on the basis of the Eq. 5 and the literature. An indicative process is shown. For example, for the first beam specimen the following equation applies:

$$\frac{\text{Corrosion rate}}{2} * 0.023 = \quad (8)$$

$$\frac{0.4145}{2} * 0.023 = 0.00477 \text{ mm/year}$$

Thus, the converted currents are shown on Table 10 below:

Table 10: Converted currents into mm/year

NaCl (%)	Beam specimen <u>No</u>	Total average [$\mu\text{A} / \text{cm}^2$]	Converted total average loss of diameter [mm/year]
0 %	1	0.4145	0.00477
1%	2	0.62175	0.00715
2%	3	0.6375	0.00733
3%	4	0.652667	0.0075
5%	5	1.061833	0.0122
10%	6	2.823	0.0324
15%	7	2.883167	0.033

4.2 Data interpretation

4.2.1 Corrosion risk for the half – cell potential

Based on the limits range of half – cell potential shown on Table 2, the following table shows the corrosion risk for each of the beam specimens.

Table 11: Corrosion risk

NaCl (%)	Beam specimen <u>No</u>	Total average [mV]	Corrosion risk
0 %	1	-235.317	Intermediate
1%	2	-289.243	Intermediate
2%	3	-304.625	Intermediate
3%	4	-347.333	Intermediate
5%	5	-402.417	High
10%	6	-448.917	High
15%	7	-472.8	High

4.2.2 Corrosion risk for concrete resistivity

Based on the limits range of resistivity shown on Table 3, the following table shows the corrosion risk for each of the beam specimens.

Table 12: Corrosion risk

NaCl (%)	Beam specimen <u>No</u>	Total average [KΩ.cm]	Corrosion risk
0 %	1	10.13	Low to moderate
1%	2	7.94	High
2%	3	6.67	High
3%	4	5.81	High
5%	5	5.32	High
10%	6	2.8	Very high
15%	7	1.84	Very high

4.2.3 Corrosion risk for the corrosion rate (linear polarization)

Based on the limits range of corrosion rate shown on Table 4, the following table shows the corrosion condition for each of the beam specimens.

Table 13: Corrosion risk

NaCl (%)	Beam specimen No	Total average [$\mu\text{A} / \text{cm}^2$]	Corrosion condition
0 %	1	0.4145	Low to moderate
1%	2	0.62175	Moderate to high
2%	3	0.6375	Moderate to high
3%	4	0.652667	Moderate to high
5%	5	1.061833	High
10%	6	2.823	High
15%	7	2.883167	High

4.3 Data integration

4.3.1 Condition assessment ranges

For each one method, an indicative fraction value has been given with an increasing rate depending on the corrosion risk, as shown on Table 14. Each method's fraction value is then multiplied by an impact value. As it is shown, the impact value for the corrosion rate is equal to 2, because the specific method is the actual representation of the degree of corrosion and it is taken into account more than the other methods. The impact value for the other two methods is equal to 1. On Table 14 below, the condition assessment range is shown, as calculated from the three methods.

Table 14: Condition assessment range multiplying by the impact value of each method

Half – cell potential Impact=1	Resistivity Impact=1	Corrosion rate Impact=2	Condition Assessment Range
LOW (1/6)	LOW (1/6)	LOW (1/6)	$1/6 + 1/6 + 2 * 1/6 = 4/6$
LOW TO MOD (2/6)	LOW TO MOD (2/6)	LOW TO MOD (2/6)	8/6
MOD (3/6)	MOD (3/6)	MOD (3/6)	12/6
MOD TO HIGH (4/6)	MOD TO HIGH (4/6)	MOD TO HIGH (4/6)	16/6
HIGH (5/6)	HIGH (5/6)	HIGH (5/6)	20/6
VERY HIGH (6/6)	VERY HIGH (6/6)	VERY HIGH (6/6)	24/6

*MOD-Moderate

The Table 14 above, shows the condition assessment range for all the methods. The corrosion risk is interpreted by colors. The low corrosion risk is green colored, the moderate corrosion risk is yellow to orange and the high corrosion risk is red.

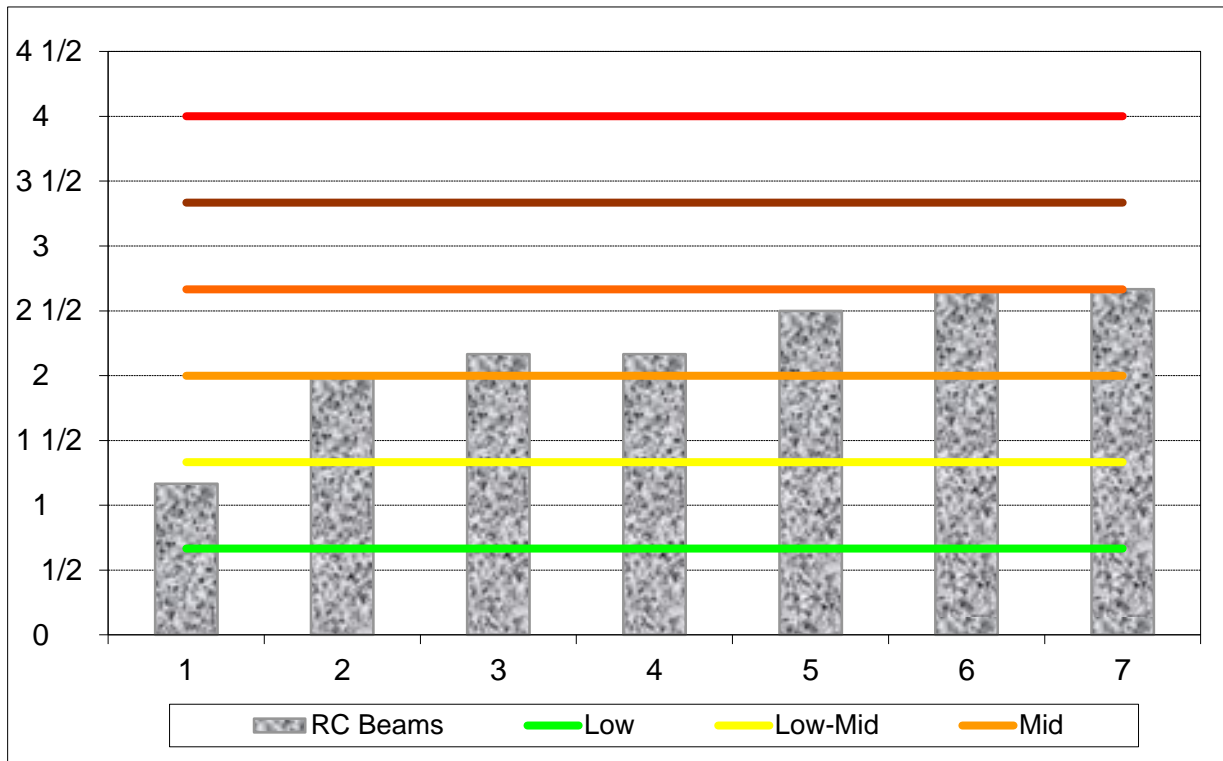
4.3.2 Results and corrosion state classification

In order to have an overall conception for combination and correlation of the three methods, the simple math calculations are shown below. The results of the calculations below may subject to approximations, but this would not be a problem because there are ranges. Depending on the corrosion risk for each method, the correlated results arise as the final stage of this thesis. As shown on Table 15 below, the total condition value arising from the summation of the three methods condition values e.g. $2/6 + 2/6 + 3/6 = 7/6$

Table 15: Results

Beam specimen No	Corrosion rate condition	Resistivity condition	Half – cell potential condition	Total condition
1	2/6	2/6	3/6	7/6
2	4/6	5/6	3/6	12/6
3	4/6	5/6	4/6	13/6
4	4/6	5/6	4/6	13/6
5	5/6	5/6	5/6	15/6
6	5/6	6/6	5/6	16/6
7	5/6	6/6	5/6	16/6

Table 16: Histogram showing the condition of steel reinforcement corrosion – corrosion state classification of specimens



DISCUSSION OF THE RESULTS

As shown on tables, graphs and diagrams, the corrosion rate increases as the amount of sodium chloride increases. The potential decreases as the sodium chloride increases, as well as the resistivity decreases as the sodium chloride increases. When the electrical resistivity of the concrete is low, the rate of corrosion increases. As the electrical resistivity is getting higher, then the corrosion rate decreases. Low electrical resistivity leads to more negative potentials. High electrical resistivity is leading to more positive potentials. The latter two, show similar curve on diagrams and the curves of the measurements for each method show non – linear pattern.

However, the findings of this research project verify the findings of previous related work. The diagrams show clear results, as these found in the literature.

Based on the colors classification, when the condition is on the green line the corrosion has not commenced so it does not need any maintenance, when it is on the yellow to orange line the corrosion is intermediate so it needs preventive maintenance and when it is on the red line then it needs immediate maintenance against corrosion.

EPILOGUE

For an absolute decision of the civil engineer, an overall and complete status of the corrosion process should be present. The decision of the engineer is critical because depending on the corrosion overall analysis, protection measures for maintenance of a reinforced concrete structure should be taken urgently.

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