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LOCAL STRESS-STRAIN BEHAVIOR AND CORROSION OF ALTERNATIVE REINFORCING BARS

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ABSTRACT. *Premature deterioration of concrete buildings and infrastructure due to corrosion of reinforcement is a severe challenge, both technically and economically. It has been estimated that Western Europe spends 5 billion Euros yearly for repair of corroding concrete infrastructures. Repair-work on the public transportation infrastructure are causing significant inconveniences and delays for both the industry and the general public, and are now recognized as a substantial cost for the society.*

Set of experiments were conducted in order to produce a description among bars of different types to assist engineers to better comprehend the relative corrosion resistance of those bars. The bars were degreased with solvent, rinsed with de-ionized water and air-dried. After that they were exposed to 5 % NaCl salt spray at 35°C for up to 3 weeks. The exposure condition followed the ASTM B117 test protocol. During the test the following steps were conducted:

☐ *Collection rate of salt spray flow was 3 ml/hr*

pH adjustment or monitoring was not performed

Visual inspection of the samples was performed after 10, 60, 120, 180, 360 hours and 3 weeks of exposure.

During the last three visual inspections, one bar per test condition was removed from the chamber and cleaned following ASTM G1-03 Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens methods.

☐ *The bars were then weighed to obtain weight loss data which was used to calculate average corrosion rates.*

Stainless steel 316LN and 2205 bars were largely free of corrosion except some minor corrosion product near to cut ends. The coating applied to the cut ends may have generated crevices which are at least partially responsible for the observed corrosion. These two types of stainless bars exhibited phenomenal low corrosion rates, approximately 0.2 % of conventional steel.

INTRODUCTION

In recent years there has been an increasing interest in applying stainless steel reinforcement in concrete structures to combat the durability problems associated with chloride ingress. However, the use of stainless steel reinforcement has so far been limited mainly due to high costs and lack of design guides and standards. The behavior of constructional stainless steels differs from mild steels in that these stainless steels do not exhibit a well defined yield point when representative test pieces are submitted to tensile load. A true yield point is obtained in mild steel when plastic deformation starts to occur without any increase in loading. The stress in the test piece at the yield point is known as the yield strength of the material. Constructional grades of stainless steel show early plastic deformation in test, but continue to sustain increasing load with increasing strain. In order to characterize the useful design strength of such materials, proof strengths are used and are determined as the stress (R_p) at which plastic extension equals a specified strain. For stainless steels this is commonly at 0.2% strain and the proof strength for a particular grade of steel is based on the (R_p) 0.2% proof stress.

Carbon steel reinforcement embedded in concrete will not normally corrode due to the formation of a protective iron-oxide film, which passivates the steel in the strong alkaline conditions of the concrete pore water. However, this passivity may be destroyed by chlorides penetrating through the concrete, or due to carbonation, reaching the surface of the reinforcement. As a result of corrosion reaction, rust forms and

occupies a volume of up to 6-7 times that of the original metal, hence generating bursting forces. These forces might exceed the tensile strength of concrete, causing cracking and spalling of the concrete leading to further corrosion and loss of bond between the concrete and the steel. Hazardous situations might occur when pieces of spalled concrete fall and threaten the user or passer-by, or when the structural member loses cross-sectional area and thereby experiences increased stress on the remaining section, which potentially could lead to structural failure.

METHOD OF CORROSION RESISTANCE OF BARS

The question of interest in the use of steel is not whether this process will occur (it will!) but how fast it will occur in practice. Fortunately, only the surface atoms of the steel are exposed to the atmosphere and, therefore, are available to react. In the case of a 15 mm diameter bar, this amounts to only about 1 in every 40 million atoms. Any coating on the steel will reduce this number even further. For steel embedded in concrete, the concrete itself provides a coating limiting the access of water and oxygen to the steel surface. A second beneficial aspect of concrete is that the solution in the pores of the cement paste has a very high alkalinity and, as indicated in the Pourbaix diagram in Figure 1, at the pH levels typical of concrete, the corrosion products which do form are insoluble. They produce a very thin (~ few nm) protective coating on the steel (a passive film) which limits the metal loss from the steel surface due to corrosion to about 0.1 - 1.0 $\mu\text{m}/\text{year}$.

The passive film does not form immediately but starts as soon as the pH of the mixing water rises in the concrete when the cement begins to hydrate and stabilizes over the first week to protect the steel from active corrosion.

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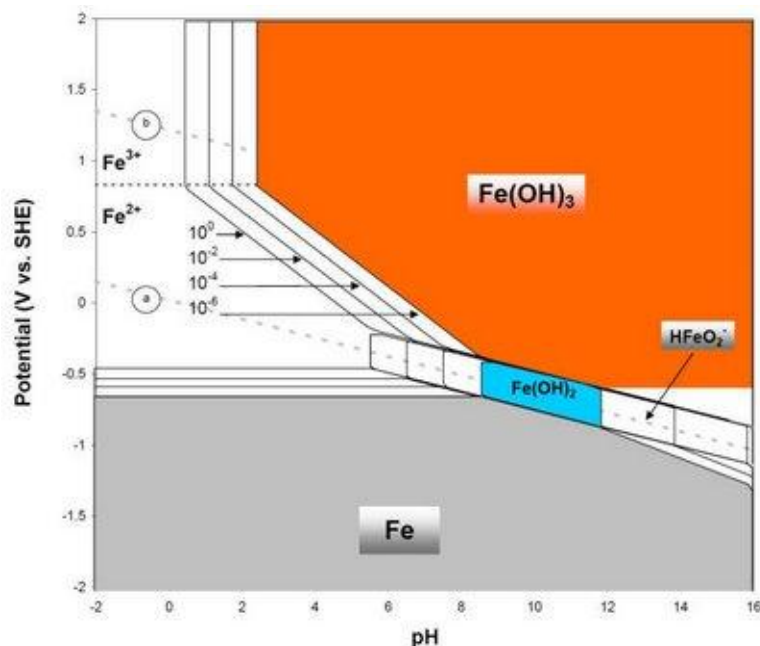
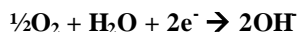


Figure 1 The Pourbaix diagram for iron showing regions of electrochemical potential and pH where metallic iron is stable (grey region); where active corrosion occurs (white areas) and where the metal is passivated (green and orange areas)

Corrosion, whether at the negligible passive rate or the damaging active rate, is an electrochemical process, involving the establishment of anodic and cathodic half-cell reactions on the microscopic and/or macroscopic levels. In high pH solutions and in the absence of chloride ions, the anodic dissolution reaction of iron:



is balanced by the cathodic reaction:



and the Fe^{2+} ions combine with the OH^- ions to produce the stable passive film. The electrochemical process is illustrated schematically in the figure below. One of the major problems associated with reinforcement corrosion is that its initiation and early stages of propagation cannot be detected visibly. Yet early detection of corrosion in a reinforced concrete structures can provide the opportunity to schedule appropriate maintenance procedures, thereby ensuring the safety of the structure. If corrosion remains undetected until cracking and spalling occur, then the costs of repair are significantly higher because all of the concrete cover and much of the reinforcement must be replaced. The most commonly used techniques for evaluating the condition of embedded reinforcement are based on the electrochemical nature of the process. The electrons released by the iron as it corrodes and consumed by the dissolved oxygen constitute a current, illustrated before, which can be indirectly measured. This current, representing dissolution of one iron atom for each two electrons in the current, can be converted to thickness of steel dissolved by the equation:

$$1\text{mA/m}^2 = 1.16 \text{ mm/year} = 0.0456 \text{ mils/year (mpy)}$$

The currently available electrochemical monitoring techniques are described below. Unfortunately only a few of these can be readily used in the field.

A two-fold approach to corrosion resistant structures includes:

The use of high performance concrete (HPC) to lower concrete's permeability and reduce the rate of ingress of chlorides or carbonation and, thereby, increase the effectiveness of the physical barrier.

The use of more resistant reinforcing bar materials to provide better chemical resistance. In those parts of structures exposed to very severe chloride environments, stainless steel is recommended. Despite the initial expense, it is a cost effective solution in these circumstances when both direct and indirect costs (such as user costs) are taken into account. In the somewhat less severe chloride environments, corrosion resistant alloys such as MMFX or 2101LDX, which are more resistant to chlorides than black steel - but less corrosion resistant and much less costly than stainless steel - should be considered. Galvanized reinforcement is recognized as having greater resistance to chlorides than black steel and is significantly more resistant to carbonation-induced corrosion or combinations of chlorides and carbonation than black steel.

MATERIALS AND EXPERIMENTAL SET-UP

For the experiment of corrosion of alternative reinforcing bars we tested three types with various surface conditions, Table 1.

Table 1 Description of bars materials

<u>Material</u>	<u>Test Condition</u>	<u>Nomenclature</u>	<u>Source</u>
Stainless steel 2205	As received	2205-as received	Salit Specialty Rebar, Inc
Stainless steel 316LN	As received	316LN-as received	Salit Specialty Rebar, Inc
Carbon Steel	As received	A615-as received	Stock
Carbon Steel	Sandblasted	A615-sandblasted	Stock

Bars were sealed with epoxy, exposing approximately 15 cm of bar length. For epoxy-coated, as-received specimens and specimens with intentional small damaged areas were tested. The damage was introduced with a single drill hole, resulting in a damaged area of ~0.06 %. For solid bars, as-received specimens were tested when possible. Among them, as-received A-615 bars had as-rolled mill scales while stainless steel 316-LN and 2205 were pickled by the manufacturer. This important process achieves the removal mill scales with chemical reactions. A615 bars were also tested in sandblasted condition for compaction.

The bars were degreased with solvent, rinsed with deionized water and air-dried. After that they were exposed to 5 percent NaCl salt spray at 35°C for up to 3 weeks in a Q-Fog apparatus. The exposure condition followed the ASTM B117 test protocol. During the test the following steps were conducted:

Collection rate of salt spray flow was 3 ml/hr
pH adjustment or monitoring was not performed

Visual inspection of the samples was performed after 10, 60, 120, 180, 360 hours and 3 weeks of exposure. During the last three visual inspections, one bar per test condition was removed from the chamber and cleaned following ASTM G1-03 Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens methods.

The bars were then weighed to obtain weight loss data which was used to calculate average corrosion rates. The salt spray test is the oldest 'corrosion test' and the most widely used for highly corrosion-resistant materials. It is defined as an universal test. This is due to the salt spray test which offers many advantages:

The test is suitable for various materials.

The duration of the test is much shorter than the natural environment.

The cost is limited.

We use a standardized material

The test can be combined with testing of surface finish, due to the roughness and wettability which play a considerable role on the final result.

RESULTS AND DISCUSSIONS

Two important causes for corrosion of rebar are chloride attack due to de-icing salts and seawater and carbonation of concrete due to carbonic acid from carbon dioxide. While chloride-induced corrosion is generally more pernicious and expensive to repair, carbonation-induced corrosion of reinforcement may affect a far wider range of reinforced concrete structures. Solid stainless steel is a promising solution to address these issues because of its superior corrosion resistance compared to carbon steel and surface treated corrosion resistant steel such as epoxy coated rebar, galvanized rebar, and stainless clad rebar. The expected lower life cycle cost associated with a corrosion resistant structure is undoubtedly the reason for the ascending trend.

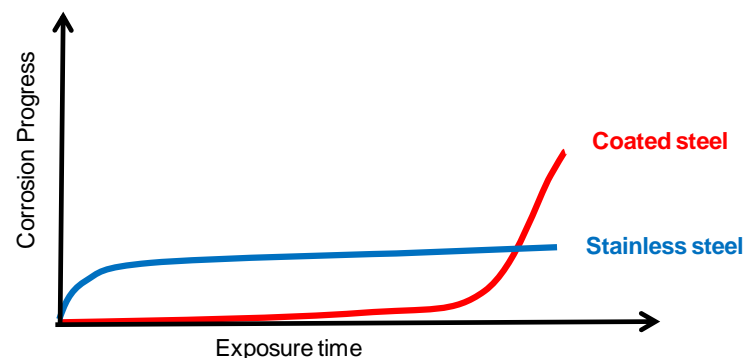


Figure 2. Diagram of the corrosion progress of stainless steel (blue) and coated steel (red) when exposed to the salt spray test.

In figure 3 summarized the weight loss and estimated corrosion rate data. The corrosion rate ratios compared to the least corroded bars (316LN) are also included in this table. The bars can be divided into 4 groups based on their average corrosion rates:

A615 and galvanized bars- high corrosion rates (915 to 1558 $\mu\text{m}/\text{year}$)

All 2205-minor corrosion rates. (less than 2 $\mu\text{m}/\text{year}$)

Corrosion rate of sandblasted A615: 1557.6 $\mu\text{m}/\text{year}$

The testing condition employed in this research is very aggressive and the corrosion rates are not typical of bars in a concrete environment. For example, the average corrosion rate of A615 black bars was about 900 $\mu\text{m}/\text{year}$ in this test and about two orders of magnitude higher than typical corrosion rates of black bars in concrete. Nevertheless, this test program was able to provide a quick comparison of various reinforcing bars both qualitatively (visually) and *quantitatively* (weight loss). While a number of studies have reported that other bars or galvanized bars provide improved corrosion resistance than conventional ASTM A615 bars, this

test program demonstrated that compared to the data of previous studies these bars can corrode rapidly when subjected to salt spray. Further for galvanized bars, we know that its corrosion resistance comes from the zinc coating of limited thickness (typically approximately 100 μm).

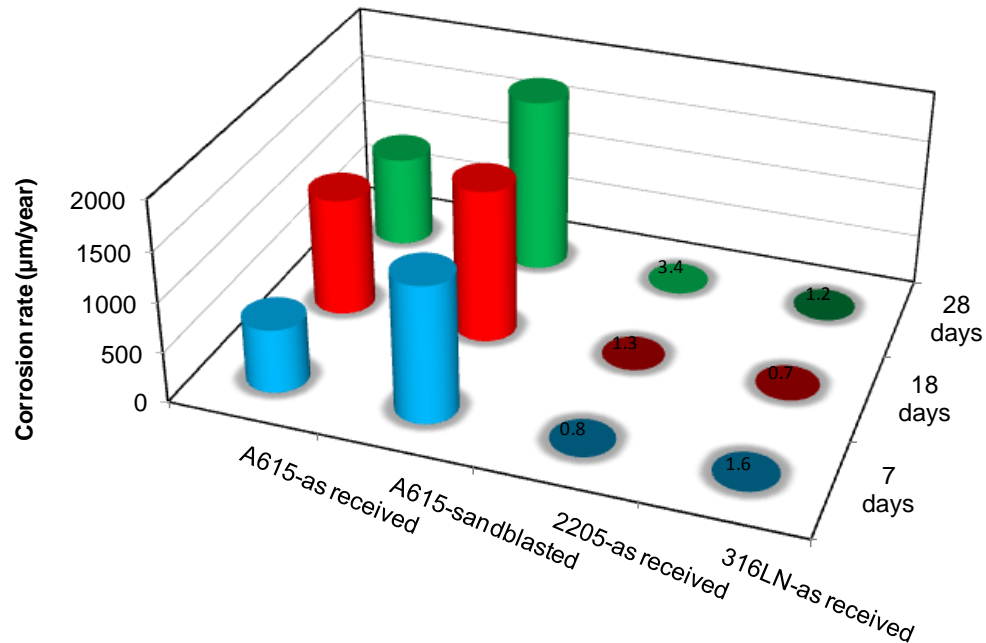


Figure 3. Corrosion rate ($\mu\text{m/year}$), measured after 7 days, 18 days, 28 days

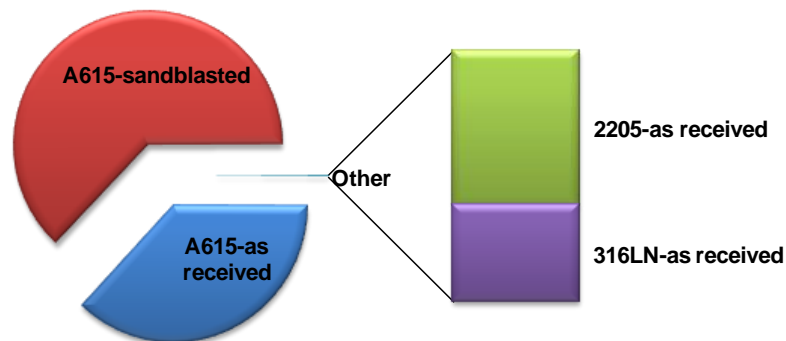


Figure 4. Average corrosion rate ($\mu\text{m/year}$)

Stainless steel 316LN and 2205 bars were largely free of corrosion except some minor corrosion product near to cut ends. The coating applied to the cut ends may have generated crevices which are at least partially responsible for the observed corrosion. These two types of stainless bars exhibited phenomenal low corrosion rates, approximately 0.1 percent of conventional steel. All the epoxy coated bars performed very well in this test program, and corrosion only took place at drilled holes and at other existing defects.



Figure 5. Appearance of stainless steel 316LN after three weeks of exposure.



Figure 6. Appearance of stainless steel 2205 after three weeks of exposure.



Figure 7. Appearance of carbon steel after three weeks of exposure.

CONCLUSIONS

Reinforcing bar corrosion is a major cause of the degradation of reinforced concrete structures, because of the high quantities of chloride de-icing salts used. In addition the increase in construction near coastal marine environments may increase the potential for corrosion deterioration in these areas. As a result, some structures of ordinary portland cement concrete with black steel reinforcement are requiring repair and remediation long before their current specified service lives (typically 40 – 50 years) are reached. Therefore, easier, faster and more reliable condition analysis techniques are required than those currently available, and described above, to allow corrosion detection at an earlier stage and, thus, permit remedial action to be taken before major repairs are required. At the same time, with the current emphasis on sustainability, building codes are now requiring longer service lives, of the order of 75 to 100 years. Consequently, for new structures, there must be a greater understanding of the reinforcement corrosion process and of materials and structural designs aimed at minimizing the risk of corrosion

A615 bars, both as-received and sandblasted condition, corroded at high corrosion rates. The sandblasted bars had corrosion rates even higher than the as-received bars. Pitting corrosion was noted.

Stainless steel 316LN stainless bars had very high corrosion resistance and only experienced minor corrosion likely due to presence of crevices or steel contamination.

While the zinc offered protection to the underlying steel, the galvanized bars corroded extensively. Within 2 weeks, the zinc layer was essentially consumed and underlying steel corrosion was observed.

Type A epoxy-coated bars (recently produced) performed very well, corrosion was only observed at drilled holes.

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