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Assessment of stainless steel reinforcement for concrete structures rehabilitation

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ABSTRACT

The aim of this study was to revise the factors influencing the service life of galvanic coupling between carbon steel and stainless steel reinforcements in simulated concrete pore solution, simulating the condition of a damaged structure repaired with stainless steel reinforcing bars. Numerous investigations have reported that austenitic stainless steel rebar, compared to carbon steel, when embedded in concrete, offer superior corrosion resistance in aggressive environments, especially chloride contaminated concrete. In concrete, contact with other metals should be avoided because of the risk of galvanic corrosion. When passive, both carbon steel and stainless steel have comparable corrosion potentials and the coupling of the two materials is of little effect on the corrosion behavior of either material. Galvanic current values measured between carbon and stainless steel are negligible.

1. Introduction

Corrosion is the main cause of deterioration of traditional carbon-steel-reinforced concrete structures. Due to the high maintenance costs involved in infrastructure preservation, a strategy of designing concrete structures with improved corrosion resistance in aggressive environments is highly desirable.

Theoretically, carbon steel rebar is immune to corrosion when embedded in concrete due the high alkalinity created by the concrete environment. Unfortunately, this is not always the case due to surrounding environmental conditions. Typically, passivity of the embedded rebar is lost due to sufficient accumulation of chloride ions and dissolved oxygen introduced from the surrounding environment. These conditions are encountered in tropical environments due to exposure to seawater and areas where deicing salts are used heavily to prevent adverse driving conditions in the winter. The critical chloride concentration that enables corrosion initiation is known as the chloride threshold and is typically expressed as weight per volume of concrete (kg/m^3) or chloride to hydroxide ion ratio (Cl^-/OH^-) in pore solution [1].

Corrosion of conventional carbon steel rebar in reinforced concrete has become a major concern for the Federal Highway Administration, FHWA, due to the resulting decrease in lifetime of concrete structures and cost associated with repair [2]. Repair costs associated with the corrosion of reinforcing steel are estimated at over $8 billion [2]. In this study, carried out between 1999 and 2001 and published in 2002 [2], the annual direct cost of corrosion for infrastructure in the category of highway bridges can be estimated in the order of $8.3 billion, consisting of $3.8 billion to replace structurally deficient bridges over the next ten years, $2.0 billion for maintenance and cost of capital for concrete bridge decks, $2.0 billion for maintenance and cost of capital for concrete substructures (minus decks), and $0.5 billion for maintenance painting of steel bridges.

Mexico is no exception to this world problem. An evaluation performed by the Mexican Institute of Transportation [3] estimated that there are 10,000 bridges in Mexico. Of this total of bridges, Fig. 1,

(a) 330 bridges require a detailed inspection for their susceptibility to present corrosion damage,
(b) 65 bridges require urgent and immediate inspection,

Life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at more than ten times the direct cost of corrosion maintenance, repair and rehabilitation.

Located in Puerto Progreso port, in the Yucatan Peninsula, Mexico, a dock constructed between 1937 and 1941 is an interesting case to study due to the fact that 304 stainless steel was used as reinforcing bars. Until now no rehabilitation has been necessary, contrasting strongly with another dock constructed in 1960 in the same place, but with carbon steel reinforcing bars, which is completely destroyed, Fig. 2 [4].

One example of the costs related with maintenance, repair and rehabilitation of a Mexican bridge is presented in Table 1. This bridge opened in 1982. The cost associated with its maintenance, repair and rehabilitation was, at the end of 2004, of the order of approximately $5 million. From Table 1 it is clear that after

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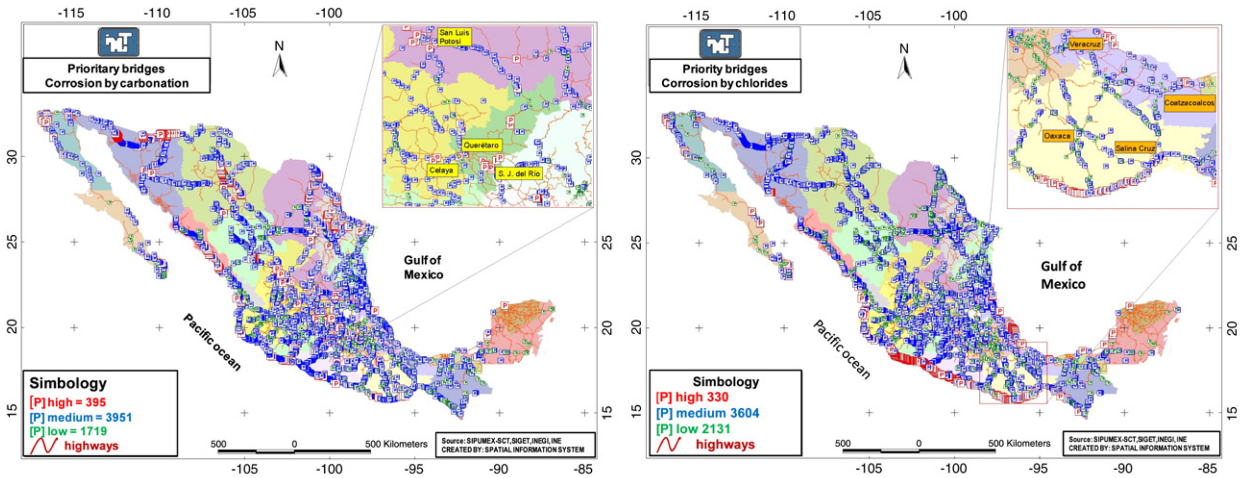

Fig. 1. Mexican bridges localization. Corrosion by carbonation (left) and corrosion by chlorides (right).

Fig. 2. View of the dock constructed with stainless steel (right) and carbon steel (left) [4].

only 4 years of operation, repairs were required costing 8 million Mexican pesos (approximately $0.8 million). This bridge was designed in principle for a life-cycle of 50 years. Since total investment in the nation's highway infrastructure amounts to millions of dollars, it is extremely important that all possible methods applicable to controlling corrosion in existing concrete bridges be developed so that these structures do not deteriorate prematurely.

Different technical practices have been developed in recent years to solve problems that could affect both old and new structures subjected to corrosion damage. Some of these are:

- Cathodic protection of rehabilitated structures.
- Rehabilitation of reinforced carbon steel structures + unprotected.
- Rehabilitation of reinforced carbon steel structures + corrosion inhibitors.
- Rehabilitation of reinforced carbon steel structures + coatings.

Some of these technical solutions involve changes in the local concrete environment surrounding the reinforcing steel bar. From a corrosion engineering point of view, the best solution is to chose the correct material for the reinforcing bar. A material with inherent corrosion resistance in the working media seems to be an intelligent engineering solution. In this sense, stainless steel reinforcing bars (rebar) seems to be an interesting alternative. Stainless rebar can provide long-term corrosion resistance when concrete is exposed to aggressive media, such as chloride containing environments. Stainless steels have been used successfully as rebar to minimize the problems of reinforcement corrosion in many structures in the last 20 years, especially in highway bridges.

Some Mexican institutions organized extensive corrosion testing [5] to find rebar materials that could extent the lifetime of reinforced concrete bridges to 75–100 years, when the concrete was contaminated with chlorides. Studies carried out in Mexico [6] demonstrate the influence of chloride environment on rebar corrosion. Carpio et al. [6] found chloride concentration in the range 0.4%–2.9% by weight. At the mentioned Progreso dock [7] the chloride concentration at a depth of 7.8 cm was of the order of 1.2% while in the area surrounding the rebars was of 0.6–0.8 wt% [8].

In recent years, several research projects have been conducted to compare corrosion properties of stainless steel and stainless steel clad reinforcement to conventional steel. Limited investigations have been published, but the results and conclusions are controversial. Some reports on the use of stainless steel as reinforcing bars in concrete structures are summarized below.

Treadaway et al. [9] carried out some studies with stainless steel rebars (304 and 316) in chloride contaminated concrete of medium and high porosity. After 10 years of exposure, no corrosion was observed when the chloride content is as high as 1%. This Cl^- content is similar to that reported by Carpio et al. [6] and Castro et al. [8] in Mexico.

Sorensen et al. [10] compared the corrosion performance of type 304 and 316 stainless steels with that of conventional steel. The electrochemical investigation found that the Cl^- content threshold for corrosion to occur for reinforcing bars embedded in mortar with admixed chloride was more that 10 times higher for stainless than for conventional steel. The critical chloride content by weight of cement was less than 0.5 percent of admixed chloride for the conventional steel, while the critical chloride content for grade 304 stainless steel was 5%–8% and greater than 8% for type 316 stainless steel.

The major drawback regarding employing stainless steel rebar in construction applications is the increased cost over carbon steel. The projected increase in materials costs of stainless steel rebar is approximately 4–8 times greater than carbon steel rebar depending on stainless steel grade [11]. However, the projected lifetime costs of using stainless steel are likely to be lower than carbon steel rebar, due to the extended lifetime of the structure without the need for costly repair and rehabilitation projects [11]. However, the actual degree of extension of lifetimes must be established and baseline properties must be established in order to do this.

In 1998, McDonald et al. [12] reported the results of a five-year study on the corrosion performance of solid 304 and 316 stainless steels. In that study, the lowest corrosion rates of the 304 stainless steel bars were obtained when the stainless bars acted as both the anode and cathode. The test results indicated that the 304 stainless steel bars were about 1500 times less corrosive than