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## Corrosion of coupled steels with different microstructures in concrete environment

H. Torbati-Sarraf<sup>a,\*</sup>, A. Poursaei<sup>b</sup><sup>a</sup> Glenn Department of Civil Engineering, Clemson University, Clemson, SC, United States<sup>b</sup> Glenn Department of Civil Engineering, Department of Materials Science and Engineering, Clemson University, Clemson, SC, United States

### HIGHLIGHTS

- The galvanic connection between TMT and conventional reinforcement steel in chloride-contaminated concrete pore solution led to significant increase in the corrosion of steel reinforcement.
- Individual TMT steel specimens showed superior corrosion resistance compared to the conventional steel specimens.
- When coupled, the conventional steel showed better passivation compared to the TMT steel in chloride-free pore solution. When chloride added, the TMT steel became the anode and their corrosion activity increased compared to the conventional steel.

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### ABSTRACT

This study investigated the electrochemical behavior of two carbon steels with different microstructures, i.e. thermomechanical treated (TMT) steel and conventional steel, and the influence of galvanic coupling between them on their corrosion performance in simulated concrete pore solution. The specimens were immersed in the chloride-free pore solution for 30 days and then 3% by weight of NaCl was added to the solution. The specimens were then kept in the chloride-contaminated solution for 50 days. The corrosion resistance of the specimens were assessed by different electrochemical measurement techniques. An increase in the overall corrosion was observed in the coupled specimens compared to the individual specimens. The results of the electrochemical experiments showed that while the individual thermomechanical treated steel specimens showed superior corrosion resistance compared to the conventional steel specimens when coupled, they became the anode and their corrosion activity increased compared to the conventional steel.

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## 1. Introduction

In the alkaline environment of concrete, a protective passive film forms on the surface of the embedded steel bar which makes it resistant to corrosion. Many studies have been focused on determining the growth mechanism of this passive film, its structure, and composition in alkaline solution [1–6]. However, this passive film damages and leads to localized corrosion when pH or the chloride concentration of environment reach the critical values [7–9]. Steel composition and microstructure can affect the formation and breakdown of this the passive film, consequently the corrosion and mechanical properties of the steel [10–13]. Steel reinforcing bars are produced through the different manufacturing process. Conventionally, hot rolled and air-cooled mild steel have been used

in this industry. However, recently, high strength bars are becoming more popular [14–16]. Thermomechanical treated steel bars are in this category. These steel bars generally have an outer layer consisted of tempered martensite<sup>1</sup> phase and an inner core made of ferrite<sup>2</sup>-pearlite<sup>3</sup> phases. The combination of different phases in these steel bars improves the load-bearing and ductility of these steels compare to the single-phase bars [10,12,15]. Unless specifically mentioned, both of the above-mentioned bars can be embed-

<sup>1</sup> Martensite is a phase that forms as the result of diffusion less solid-state transformation due to rapid cooling and most commonly has a very hard form of crystalline structure. In carbon steels, tempering alters the size and distribution of carbides in the martensite, forming a microstructure called tempered martensite. When martensite is tempered, it partially decomposes into ferrite and iron carbide.

<sup>2</sup> Ferrite ( $\alpha$ -ferrite) is interstitial solid solution of carbon in iron with BCC crystal structure.

<sup>3</sup> Pearlite has Layered structure composed of alternating layers of  $\alpha$ -ferrite and iron carbide.

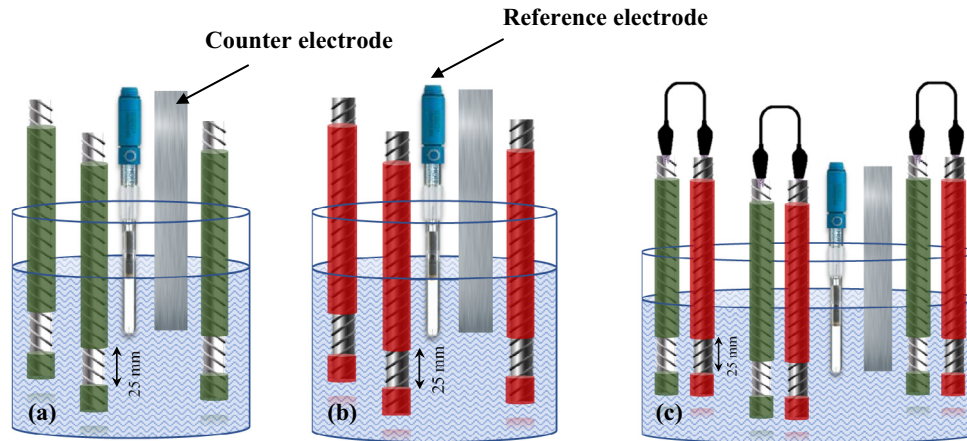
\* Corresponding author.

E-mail address: [storbat@g.clemson.edu](mailto:storbat@g.clemson.edu) (H. Torbati-Sarraf).

**Table 1**

The main alloying elements in the steel specimens used in this study.

Alloying element (%)	C	Mn	P	S	Si	Cu	Ni	Mo	V
A	0.31	1.23	0.018	0.024	0.29	0.23	0.08	0.016	0.002
B	0.39	1.37	0.03	0.011	0.15	–	–	–	–

**Fig. 1.** Schematic illustration of the measurement cells with (a) three specimens made with steel A bars; (b) three specimens made with steel B bars; and (c) coupled bars.**Table 2**

The chemical composition of the concrete simulated pore solution.

Compound	Mol/L
NaOH	0.1
KOH	0.3
Ca(OH) <sub>2</sub>	0.03
CaSO <sub>4</sub> ·H <sub>2</sub> O	0.002

ded in concrete [17,18], thus; in practice, both types of steels may be connected and used together. Since these steels have different phases and microstructures, this connection could lead to corrosion, particularly in the joints, due to galvanic effect. The objective of this work was to evaluate and compare the passivation and corrosion behavior of steel bars with different microstructures, individually and when they were connected.

## 2. Materials and experimental procedures

#4 steel bars from two different suppliers, satisfying the ASTM A615 standard [18], with the chemical composition given in Table 1 were used in this investigation. Microscopic analysis revealed (Section 3) that steel A had tempered martensitic microstructure on its surface while steel B had ferrite-pearlite microstructure.

For microstructure analyses, 10-mm-long pieces of each type of the steel were cut and mounted in two-part cold epoxy. Then, the specimens were ground, polished and etched in 4% Nital<sup>4</sup> solution. For electrochemical measurement, 100-mm-long pieces of each bar were cut, and then slightly wire brushed and cleaned by alcohol and dried with a hairdryer. Each specimen was coated with three layers of UV cure vinyl ester epoxy resin, except 25 mm of the mid-section, the exposed area, and 10 mm of one end of each specimen for electrical connection.

Three cells with three bars in each one were used in this experiment. One cell contained three bar of steel A, one cell contained

three bars of steel B, and the last cell had three coupled bars of A and B. Fig. 1, schematically shows the measurement cells.

Concrete simulated pore solution, with the composition given in Table 2, was used as the electrolyte in each cell to simulate the concrete environment [5].

The advantage of performing the experiments in the solution rather than in concrete is that the surface of the steel bars can be visually examined during the test period and the results can be obtained in a reasonable time frame. All specimens were immersed in pore solution for 30 days and then 3 wt% of laboratory grade NaCl was added to each cell. The pH of the solution was periodically measured during the experiment to ascertain the pH remained around 13.2. A three-electrode measurement setup, including a specimen as the working electrode, an SCE (saturated calomel electrode) as the reference electrode, and a 316L stainless-steel sheet as the counter electrode, was used for the LPR (linear polarization resistance), CP (cyclic polarization) and CV (cyclic voltammetry) tests.

All electrochemical measurements were conducted at ambient temperature and cells were sealed during the experiment to minimize atmospheric carbonation effect.

Corrosion potentials were measured every 24 h. To determine the corrosion current density of the specimens, LPR within the range of  $\pm 10$  mV vs. corrosion potential with the scan rate of 0.166 mV/s [19] was conducted on all specimens every 2–3 days. ZRA (zero resistant amperometry) was used to determine galvanic current flow between two types of steel in the cell with coupled steel bars (Fig. 1c). The test was carried out for 1 h during each measurement. CP technique was carried out every week on one of the specimens in each cell to analysis the protectiveness of the passive film and pitting susceptibility of the specimens. This test started at  $-100$  mV below the corrosion potential to  $+500$  mV vs. SCE and then decreased to  $-100$  mV below the corrosion potential with the scan rate of 0.166 mV/s.  $\beta_c$  and  $\beta_a$  (Tafel slopes) were extracted from CP results to calculated Stern-Geary values and subsequently corrosion current densities. CV was conducted to study oxidation and reduction behaviors of each specimen. The voltammograms were obtained between voltage limits of  $-1.4$  V and  $+0.4$  V vs. SCE at a linear sweep rate of 20 mV/s.

<sup>4</sup> Nital is an oxidizing etchant solution composed of aqueous nitric acid and ethanol. 4% Nital has 4% nitric acid.

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