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A CORROSION COMPARISON OF HISTORICAL AND MODERN REINFORCING BARS

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Abstract: Ransome bars are one of the oldest reinforcing types used in concrete construction and date back to 1894. They were generally made by cold-twisting a plain square bar a given number of turns per length, thus altering the material's microstructure and mechanical properties. While this increases the yield and tensile strength of the bars, it is unclear whether the corrosion properties of Ransome bars differ from other types of steel reinforcement. Understanding the corrosion rate of Ransome bars is required to properly assess and plan for the rehabilitation of concrete members reinforced with these bars. This paper presents the results of an experimental program used to evaluate the corrosion potential of these bars compared to modern reinforcement. Differences in corrosion potential and rate between modern reinforcing bar types and historical Ransome bars were measured. Both polished and sandblasted surface preparation techniques were used in two different solutions: one to simulate fresh non-carbonate concrete, and the second to simulate carbonated concrete. Potentiodynamic scans and linear polarization resistance tests were conducted. Diffusion barriers (i.e. rust) formed quickly on all samples regardless of which solution was being used. The results of the experimental program showed that there were no significant differences between the corrosion rates of historical Ransome bars and modern deformed bars. Similarly, there was no indication that the cold twisting required to form a Ransome bar from a plain square bar affects its corrosion properties.

1. INTRODUCTION

Reinforced concrete is one of the most popular building materials on the market today. Its life cycle, however, can be dramatically shortened by corrosion of the reinforcing steel, which can have very costly results. The cost of corrosion in highway bridges is an estimated $13.6 billion in the US annually (National Association of Corrosion Engineers 2016). Corrosion products have a higher volume than the original reinforcing steel. If the corrosion continues, the concrete will develop cracks and spalls. These can be exacerbated by freeze-thaw cycles. If the corrosion becomes severe, the cross-section of the original reinforcing bars will decrease and can ultimately reduce the resistance of the structural member to a level that is less than the demand. A structural failure can potentially result.

In 1911 the International Correspondence School considered Ransome bars the superior choice over other types of reinforcing steel of the day (Rabun 2000). Differences between Ransome bars and modern deformed reinforcing bars include the quality of metals and additives used, and differences in the manufacturing technique. This paper therefore presents the results of an experimental program used: to evaluate the corrosion potential of historical Ransome bars as compared to modern deformed reinforcement, and to determine whether the process of twisting a plain square bar into Ransome bar affects its corrosion potential.

2. EXPERIMENTAL PROCEDURE

2.1 Sample Description

This experimental program used samples of the same length cut from the reinforcing bars. Table 1 provides information related to the samples tested. All bars that the samples were to be cut from were first sandblasted (200 grit aluminum oxide, nozzle pressure: 698 kPa, distance: approximately 100 mm). Then all individual samples were machine cut to a length of 1.75 cm, with a hole drilled 1.5 cm deep in the center of the sample on one of the cut sides then tapped to ¼" fine thread. Half the samples needed to be polished, which was completed on a buffing wheel achieving a mirror finish. One hundred and fifty millimeter long rods, cut from ¼" stock, were threaded a length of 15 mm on one end and affixed to the sample. The non-cut surfaces of the samples were then masked for painting, so that they ultimately were exposed on the test surface only to the solutions that they were submerged in. The completed sample apparatus was then painted with enamel, and cured for seventy-two hours in an oven at 105°C and lastly the masking was removed.

Table 1: Reinforcing Steel Sample Properties

	Standard	Grade	Size (mm)	Hot/Cold Turned	Pitch (mm/rev)
Historical Ransome Bar	Unknown	Unknown	19	Cold	305
Square Bar	CSA G40.21	300W	25	N/A	N/A
Modern Ransome Bar	CSA G40.21`*	300W	25	Cold	305
Modern Deformed Bar	CSA G30.18	400	10	N/A	N/A

*Square bar conforming to CSA G40.21 twisted cold into Ransome bar

2.2 Solution Preparation

Two solutions were used in the experiments:

Solution 1: 0.2M NaCl+ 0.6M KCl + 0.002M $Ca(OH)_2$
Solution 2: 0.05M $NaHCO_3$

As per Mohamed's work (2009), Solution 1 was used to simulate fresh (non-carbonated) concrete pore solution, and solution 2 was used to simulate carbonated concrete pore solution. Both chemicals were made using Reverse Osmosis Water and certified chemicals. It was necessary to compare how the corrosion rates would respond in a new concrete environment compared to an old concrete environment simulating an older structure. Solution 1 was made by mixing 11.68 g of NaCl, 44.73 g of KCl and 0.148 g of $Ca(OH)_2$. The pH of this solution was 11.74. Solution 2 was made with 4.2 g of $NaHCO_3$, and had a pH of 8.74.

2.3 Corrosion Cell and Corrosion Measurement Techniques (LPR and Potentiodynamic Scan)

Two corrosion measurement techniques were used in this study: linear polarization resistance (LPR) tests, and potentiodynamic (PD) scans. A PD scan is an electrochemical test that uses a wider voltage scanning range that may be destructive to the metal and is used to find the corrosion rate of the sample, as well as the anodic and cathodic Tafel Slopes which are needed to calculate the corrosion rate and polarization resistance in the LPR test. The LPR test is a non-destructive test used to determine the corrosion rate and polarization resistance of a material. The LPR test relies on the Stern-Geary equation to calculate the corrosion rate from the experimental data (Mohamed 2009). The change in potential as obtained for a given sample divided by the change in current is used as input to the Stern-Geary equation along with the Tafel slopes as determined from the PD scans.

A Gamry Interface 1000 was used for both the LPR tests and PD scans. The electrochemical cell consisted of a saturated calomel electrode (SCE) (reference electrode), a graphite electrode (counter electrode) and, finally, the sample, which served as the working electrode. The Gamry system measures current density (A/cm^2) and the resulting corrosion rate is calculated from this value and is independent of surface area. During each seven-day period the working electrode remained completely submerged; however, the reference and counter electrodes were only submerged in the solution at the time of testing.

3. RESULTS AND DISCUSSION

3.1 Potentiodynamic Scan Results

Figure 1 shows the corrosion rate of all samples over the total exposure time and Figure 2 shows the corrosion potential for all samples with a polished finish. Figure 1 presents the corrosion rate determined from the PD tests for all five samples in a non-carbonated environment. It can be seen that the corrosion rates of all samples increased as the freshly polished samples started to corrode and form a corrosion product on the surface. The subsequent reduction in the corrosion rate corresponds to corrosion product formation that reduces the mass transport of cathodic reactants to the surface producing a corresponding decrease in the rate of electrochemical reaction, i.e., rust formation. All samples show a relative low corrosion rate after a period of 168 hours with the modern deformed bar and modern Ransome bars showing a slightly lower corrosion rate that is likely due to the formation of a thicker oxide film. It appears that the corrosion product on these two samples formed much more rapidly than on the other materials. The corrosion rates ranged from 0.0087 mm/yr to 0.0594 mm/yr overall. The corrosion rates at twenty four hours ranged from 0.0369 mm/yr to 0.1226 mm/yr and the 168 hour rates were 0.0009 mm/yr to 0.0595 mm/yr. Figure 2 shows the corresponding corrosion potentials that show a decrease as the rust film forms on the surfaces.

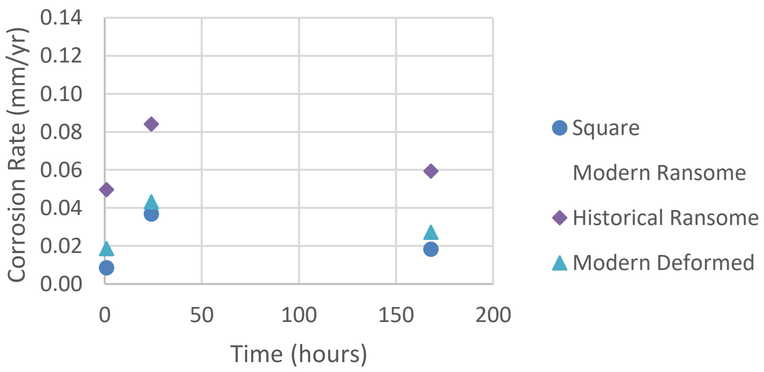

Figure 1: Corrosion rate measurements from the potentiodynamic scan tests on polished samples immersed in simulated fresh (non-carbonated) concrete pore solution

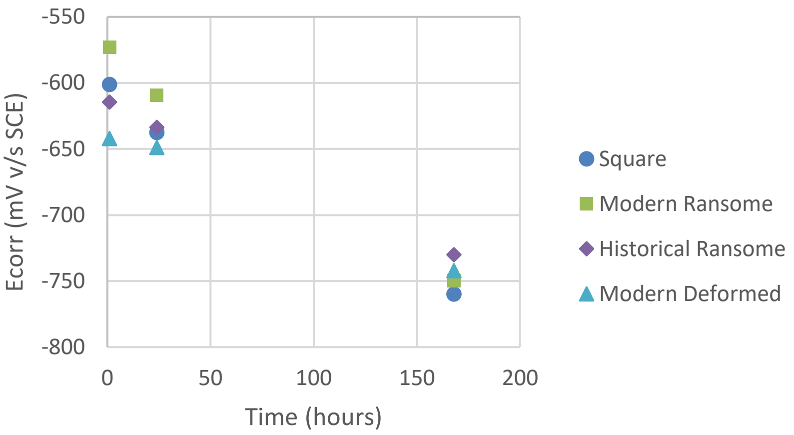

Figure 2: Corrosion potential for all polished samples in simulated fresh (non-carbonated) concrete pore solution

Figures 3 and 4 show the Potentiodynamic scan results for all unpolished bar samples in Solution 1 with an unpolished finish. Figure 3 shows the corrosion rate of all samples over the total exposure time, while Figure 4 shows the corrosion potential, Ecorr, for all the unpolished samples in Solution 1.The corrosion rates are close to those of the polished samples albeit slightly higher for most samples, especially the modern Ransome and modern deformed reinforcement samples. The corrosion rate of the modern Ransome bar rapidly increased rapidly during the first day of immersion but then reduced to a value that was only slightly higher than that of the other samples.

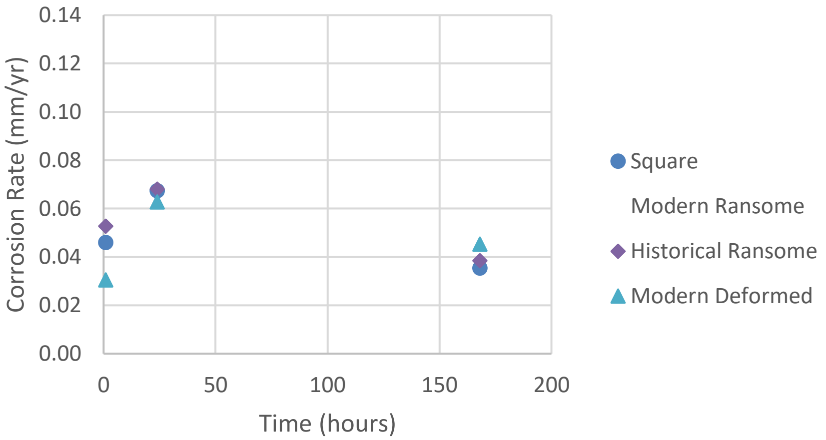

Figure 3: Corrosion rate measurements from the potentiodynamic scan tests on unpolished samples immersed in simulated fresh (non-carbonated) concrete pore solution

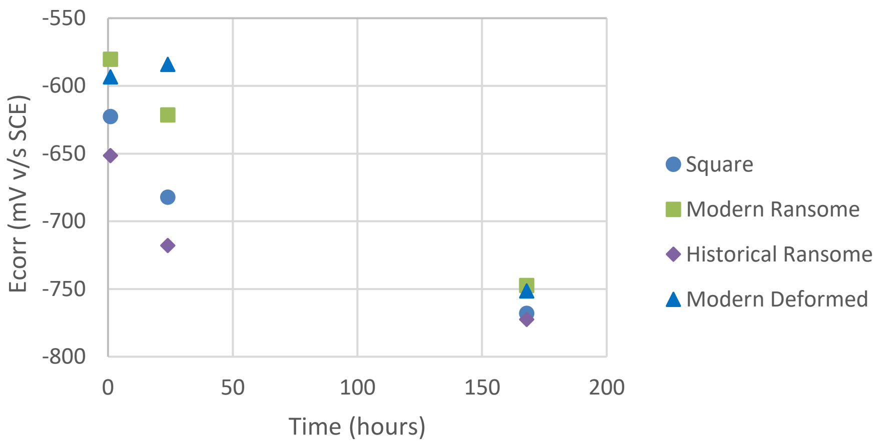

Figure 4: Corrosion potential for all unpolished samples in simulated fresh (non-carbonated) concrete pore solution

Figures 5 and 6 show the corrosion rate and Ecorr of all the polished samples in Solution 2, respectively. Figures 5 to 8 show the results of the PD scans for carbonated solutions for both polished and unpolished samples. The corrosion rate peaked at a higher value than those immersed in the non-carbonated solutions for both polished and unpolished samples, but then decreased rapidly to values that were as least as low as those in the latter solution. In fact, for the polished samples in a non-carbonated environment, the corrosion rate approached zero due to the formation of a thick film of corrosion products that acts as a diffusion barrier for oxygen mass transfer to the metal surface. However, in all cases the value of the corrosion potential increased with time suggesting an increase in the driving force for corrosion. The effect of this increase in the corrosion potential was mitigated by the corrosion product film that reduced the limiting current density of the cathodic reaction and the corresponding corrosion rate.

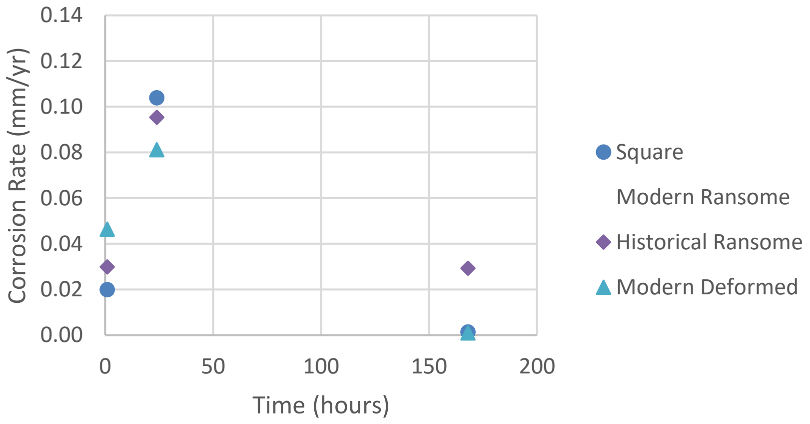

Figure 5: Corrosion rate measurements from the potentiodynamic scan tests on polished samples immersed in simulated carbonated concrete pore solution

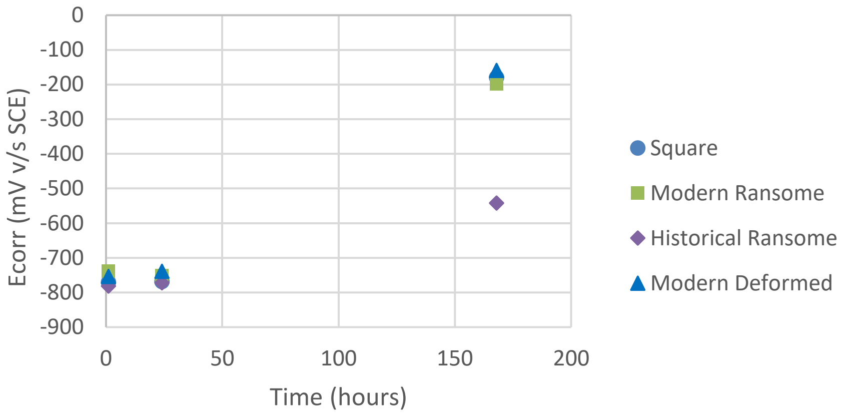

Figure 6: Corrosion potential for all polished samples in simulated carbonated concrete pore solution, demonstrating initially low corrosion potential then rising as time progressed

The potentiodynamic scan results of the unpolished samples submerged in Solution 2 are shown in Figures 7 and 8. Figure 7 shows the corrosion rate over the entire exposure time while Figure 8 shows the Ecorr values for all the unpolished samples in solution 2. Figure 7 shows that modern deformed reinforcing bars have a higher corrosion rate at the 24 hour mark, which contradicts the trend in the other experiments in this study. This phenomenon is attributed to experimental error.

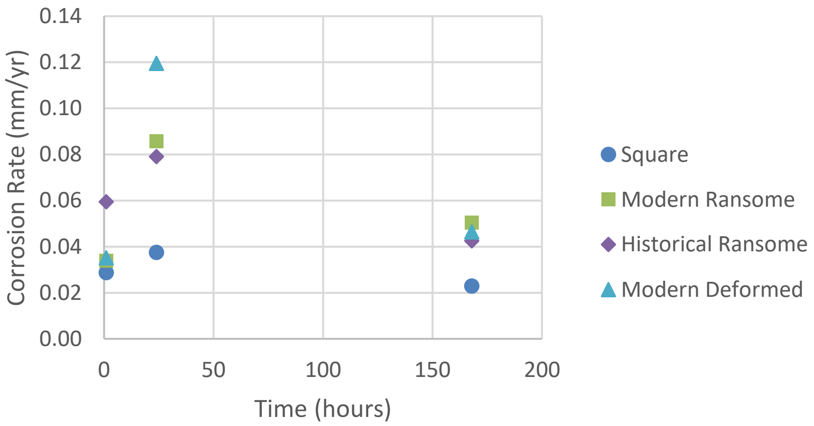

Figure 7: Corrosion rate measurements from the potentiodynamic scan tests on unpolished samples immersed in simulated carbonated concrete pore solution

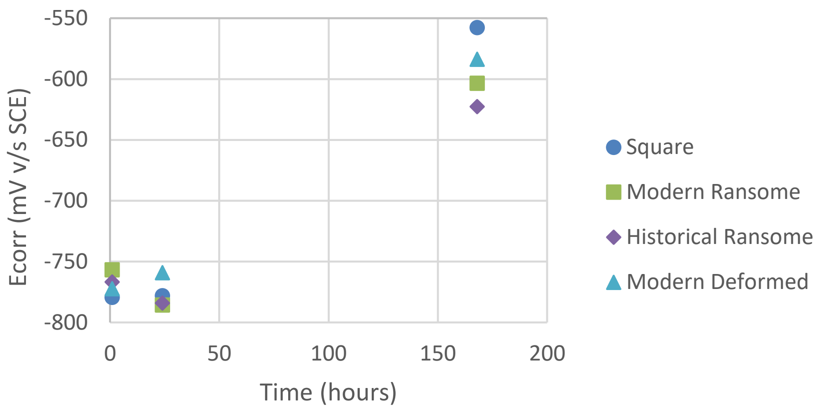

Figure 8: Corrosion potential for all unpolished samples in simulated carbonated concrete pore solution

3.2 Linear Polarization Resistance Results

The corrosion rates upon completion of the linear polarization tests ranged from 0.0119 mm/yr to 0.1235 mm/yr at one hour, 0.0545 mm/yr then 0.2254 mm/yr at twenty-four hours, and 0.0012 mm/yr to 0.2143 to 168 hours. In this study, the anodic Tafel slopes range from 0.01264 V/decade to 0.36970 V/decade, while the cathodic Tafel slopes range from 0.01230 V/decade to 0.64060 V/decade. In all cases the corrosion rates are close to those obtained potentiodynamically, and once the system's Tafel slopes are known, linear polarization can be an effective non-destructive test for the corrosion rate measurement of deformed bar in synthetic pore solutions. Insignificant differences in the corrosion rate for all samples was once a protective oxide film had formed. As described in Section 2.3, Tafel slopes are interpreted from the Potentiodynamic Curve Plot which can introduce experimental error. There can also be error associated with linear polarization tests if the conditions, including: the solution composition; metal surface condition, including films, oxide layer, and localized corrosion occurrence; and material batch are not identical.

Figure 9 shows the corrosion rate as determined from linear polarization scan tests for all polished samples at all exposure times for Solution 1. The corrosion rates for unpolished samples immersed in Solution 1 are shown in Figure 10.

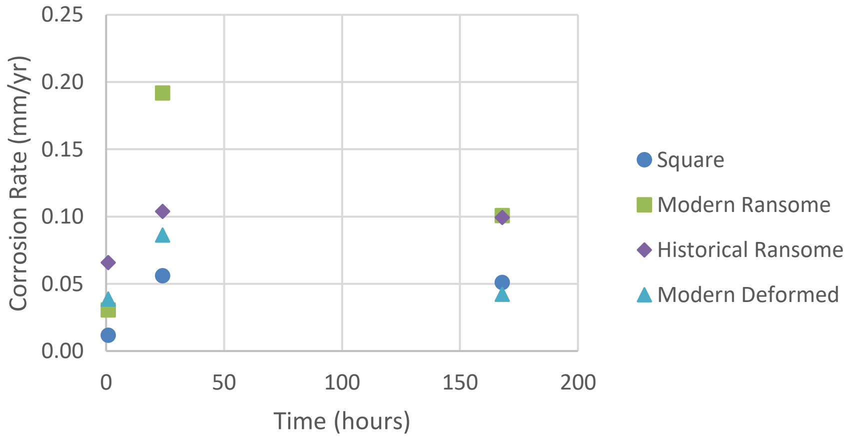

Figure 9: Linear Polarization Corrosion Rate – Polished samples in simulated fresh (non-carbonated) concrete pore solution

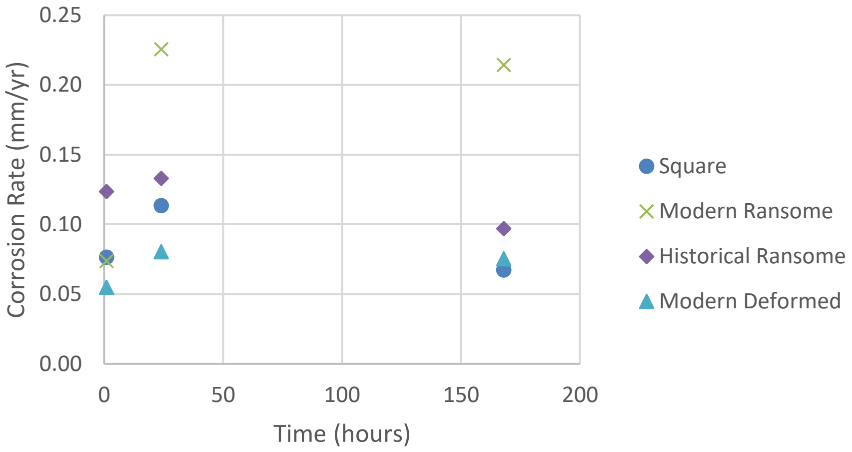

Figure 10: Linear Polarization Corrosion Rate – Unpolished samples in simulated fresh (non-carbonated) concrete pore solution

Figures 9 to 12 show the corrosion rates calculated from the linear polarization tests. Figure 10 shows that the modern Ransome bar corrosion rate is much higher than all the other bars at 168 hours. This would be attributed to experimental error and further tests should be performed, including those for replicate specimens, to confirm this. Therefore, a corrosion rate of 0.21 mm/yr for modern Ransome bar at 168 hours is relatively insignificant. All the corrosion rates in Figure 10 are relatively low. This is caused by diffusion barriers and are likely within the experimental error of each other. However, more replicates should be performed to confirm this.

The corrosion rate results for Solution 2 are shown in Figure 11 for the polished samples and Figure 12 for the unpolished samples. A review of Figure 12 suggests that it is notable that the square bar, modern Ransome bar, and modern deformed bar corrosion rates are approaching zero due to the formation of a thick diffusion barrier.

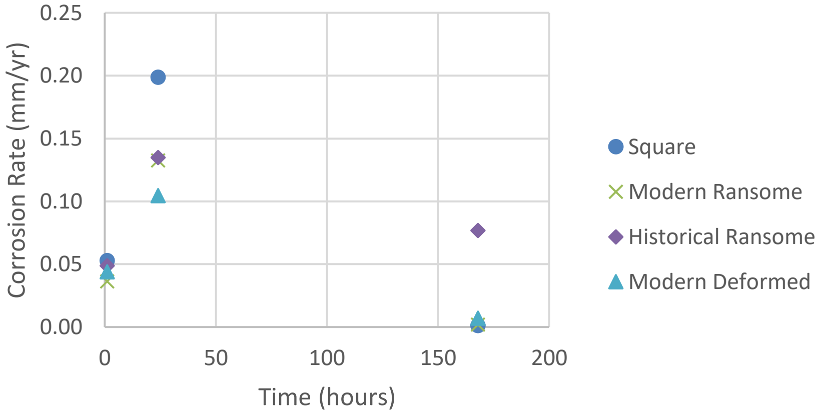

Figure 11: Linear Polarization Corrosion Rate – Polished samples in simulated carbonated concrete pore solution

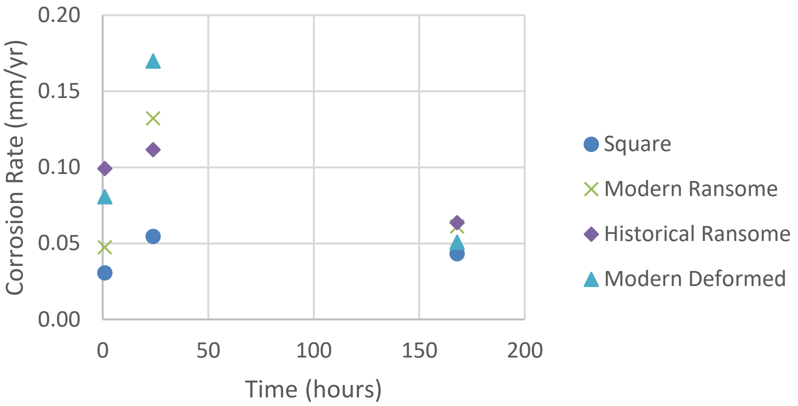

Figure 12: Linear Polarization Corrosion Rate – Unpolished samples in simulated carbonated concrete pore solution

4. SUMMARY AND CONCLUSIONS

The results of an experimental program used to evaluate the corrosion potential of historical Ransome bars compared to modern deformed reinforcement was performed. The study included four different reinforcing bar types: historical Ransome bar, plain square bar, modern Ransome bar, and modern deformed bar. Two samples of each reinforcing type were tested: one sand blasted and one polished. The samples were then tested in two different solutions: one represented fresh concrete, while the other represented older concrete as would be seen in a historical structure. Linear polarization and potentiodynamic scans were conducted on all samples and the results were compared.

The corrosion rates for potentiodynamic scans at one hour range from 0.0087 mm/yr to 0.0594 mm/yr depending on the type of solution used and whether the sample was polished or unpolished. The PD corrosion rates at twenty-four hours range from 0.0369 mm/yr to 0.1226 mm/yr. The 168-hour rates span the range of 0.0009 mm/yr to 0.0595 mm/yr. The samples immersed in the simulated carbonated concrete pore solution began with higher corrosion rates at one hour, but then decreased towards hour 168.

Linear polarization tests showed that corrosion rates between solutions and samples ranged from 0.0119 mm/yr to 0.1235 mm/yr at one hour, 0.0545 mm/yr to 0.2254 mm/yr at twenty-four hours, and 0.0012 mm/yr to 0.2143 to 168 hours. Linear polarization tests are non-destructive, and provide a good measure of corrosion rates if the Tafel slopes are known for the sample in question.

No significant differences were noted between the corrosion rates in the samples aside from those previously mentioned. It was also apparent that diffusion barriers (i.e. rust) formed quickly on all samples regardless of the solution used, which reduced the corrosion rates to the low values expressed in the study.

No discernible differences between the corrosion properties of Ransome bars or the other types of reinforcing bars evaluated in the study were observed. Therefore, it was concluded that the process of twisting a plain square bar into a Ransome bar does not affect the corrosion properties. From a corrosion perspective, concrete members and structures reinforced with Ransome bars will behave similarly to those reinforced with modern deformed bars.

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