11th Canadian Masonry Symposium, Toronto, Ontario, May 31- June 3, 2009

VALIDATING A SERVICE LIFE MODEL OF METAL TIES EMBEDDED IN THE MORTAR JOINTS OF BRICK VENEER WALLS WITH THE USE OF THE LINEAR POLARIZATION TECHNIQUE

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ABSTRACT

The Linear Polarization Resistance (LPR) technique has been successfully used to obtain the instantaneous corrosion rates of steel reinforcement embedded in concrete. To date, this technique has not been used in brick veneer wall systems to obtain the corrosion rate of metal ties embedded in the mortar joints of the brick veneer where corrosion is typically found to occur first. Successful tests were conducted using the LPR technique, where the results obtained were used to validate an ISO corrosion rate model called ISOCORRAG. The LPR tests agreed well with the one-year ISOCORRAG predicted corrosion rates indicating that the ISOCORRAG formula is quite accurate at least in predicting the instantaneous corrosion rate within the first year. In one test, the corrosion rate obtained from the LPR test produced an instantaneous corrosion rate of 2.24 μm/year while ISOCORRAG predicted a rate of 2.57 μm/year. This ISOCORRAG model uses time of wetness TOW (hrs/year), sulphur dioxide concentration (μg/m^3), and chloride deposition rates (mg/m^2/day) to estimate the annual corrosion rate for atmospheric corrosion of flat metal coupons of various types. The service life model proposed is a stochastic model that randomizes the TOW, chloride, and sulphur deposition rate inputs on a monthly basis. TOW of the surrounding mortar was modeled using hygIRC-1D to obtain the temperature and humidity for several locations across Canada for four types of brick veneer wall systems. In Canada, the corrosion rate of ties in masonry veneer wall systems have not been correlated to external environmental parameters. Thus, a service life model that correlates the external environment to the tie life is an improvement to the current state-of-the-art model.

KEYWORDS: Tie Corrosion, Brick Veneer, Linear Polarization Resistance, Stochastic Corrosion, Service Life

INTRODUCTION

The Linear Polarization Resistance (LPR) technique has been successfully used to obtain the instantaneous corrosion rates of steel reinforcement embedded in concrete. This technique was used to obtain the instantaneous corrosion rate of metal ties embedded in the mortar joints of nine brick prism specimens and one brick veneer wall specimen, as corrosion typically occurs first on the portion of the tie embedded in the mortar joint. The LPR technique required the use of a potentiostat. The potentiostat used was a Petrolite Potentiodyne IIB scanning potentiostat. A corrosion probe was developed to obtain corrosion rates from ties embedded in the wall specimens. The results from these experiments validated the assumption that the ISOCORRAG equation [1] could be used to model the corrosion rate of ties embedded in the mortar joints of brick veneer walls when the mortar surrounding the tie was treated as the tie's atmosphere. The ISOCORRAG equation formed the foundation of the stochastic tie life model used to estimate the service life of ties embedded in the mortar joints of brick veneer walls in eleven cities, representing a spectrum of Canadian environments. The stochastic tie life model and the experimental program are discussed in the following sections.

THE STOCHASTIC TIE SERVICE LIFE MODEL

A stochastic tie service life model based on the ISOCORRAG equation was created using a Monte Carlo simulation programmed in Visual Basic for Excel. In this simulation, the user specifies the wall location (from 11 cities in Canada), the wall orientation (north, south, east, or west), the tie type (wire or corrugated strip tie), and the zinc coating thickness (g/m^2) and steel substrate thickness/diameter (mm). The result is a tie service life yielding a minimum, maximum, and mean expected tie service life for one of eleven Canadian city locations. The ISOCORRAG equation was developed to predict the annual corrosion rate resulting from atmospheric corrosion for several metals. The equation was created by the multiple linear regression of corrosion data from several sites around the globe. Treating the mortar surrounding the tie as the tie's atmosphere, ISOCORRAG was used to estimate the monthly corrosion loss of the ties embedded in mortar. With ISOCORRAG, the annual corrosion rate is expressed as [1]:

$$CR = a_1 + B_1 \cdot [SO_2] + B_2 [ToW] + B_3 [Cl^-] \tag{1}$$

In Equation 1, the constants a_1, B_1, B_2, and B_3 differ according to the type of metal, shape of the specimen, and exposure conditions. These constants for flat metal coupons (rectangular cross-sections) were obtained from the literature for zinc and steel, the two metals that are used to fabricate zinc-galvanized ties [1]. In the equation, the deposit of sulphur dioxide [SO$_2$] in μg/m^3, the deposit of chloride pollutants [Cl$^-$] in mg/m^2/day, and time of wetness [TOW] in hours per year, for the mortar surrounding the tie were used to obtain a resulting annual corrosion rate in μm per year. This value was converted to a monthly corrosion rate by dividing the annual corrosion loss by 12. In order to create a stochastic model, the values for [TOW], [SO$_2$] and [Cl$^-$] were transformed into Gaussian random variables. The TOW for the mortar joint for eleven cities in Canada was obtained using a 1D hygrothermal finite element model called hygIRC-1D. The mean and covariance of the TOW was estimated from the data of several runs corresponding to the weather profiles for different years at each city location. The mean and covariance of the [SO$_2$] and [Cl$^-$] at the level of the mortar embedded tie, were estimated using methods described in the following sections. A number of factors were also applied to Equation 1 to account for increased corrosion due to carbonation of the mortar surrounding the tie, temperature fluctuations, age, and pitting (in the case of the steel substrate). These factors are discussed below. The randomly generated corrosion loss at monthly time steps is subtracted from the original zinc-coating thickness or steel substrate thickness/diameter to yield the number of months required to consume the zinc-coating and steel substrate. This is repeated for 100 iterations to produce the maximum, minimum, and average tie service life in years.

The sulphur dioxide concentration at the level of the mortar embedded tie was estimated from Annex of the CSA-A370-04 [2] for the 11 cities modelled by the stochastic tie life model. This value was used as the mean at the level of the tie, but does not start contributing as a variable until carbonation of the mortar has commenced. Carbonation occurs when carbon dioxide from the atmosphere diffuses into the capillary pores and reacts with the water and hydrants (alkalis) in the mortar to form carbonic acid [3]. Carbonation was estimated with a root function frequently used when modelling the carbonation of concrete [3]. This model suggests that the carbonation is a diffusion-controlled process. Given that mortar initially protects the steel, no corrosion occurs on the portion of the tie embedded in the mortar until carbonation reaches a sufficient depth of the mortar joint surrounding the tie. This depth was also randomized according to a uniform distribution between 0 and 40 mm of mortar cover. This depth range was assumed because carbon dioxide and sulphur dioxide can diffuse through the interior face (cavity side) of the mortar joint which does not provide the same depth of mortar cover that the exterior face provides. Once carbonation reaches this randomly generated depth, corrosion begins and includes the sulphur dioxide and TOW factor in ISOCORRAG, as well as the corrosion rate increase for carbonation.

In Canada, chloride ion deposition can occur on the surface of brick veneers with proximity to a saltwater body or due to the secondary transfer from de-icing salts on sidewalks and roads during winter. These salts are transported to the embedded tie by diffusion and capillary action. Often diffusion is considered the dominant process. Using Fick’s law of diffusion, randomly generated chloride deposition rates (mg/m^2/day) were used to determine the chloride-induced-corrosion (CIC) of embedded steel initiation time. For the randomized deposition rate, the mean deposition rate was 900 mg/m^2/day for coastal cities and 180 mg/m^2/day for non-coastal cities according to CSA-S478-95 [4]. The embedment depth was also randomized; however it was randomized according to a uniform distribution between 40 and 50 mm as ties must be embedded at least 50 mm [2] into the bed joint leaving 40 and 50 mm of mortar cover to the veneer exterior. As a result, the CIC initiation time became a random variable. For non-coastal cities, a periodic function was created to express the chloride ion deposition on the veneer surface as a periodic function because deposition from these locations occurs from de-icing salts that are only used for approximately 6 months per year. The periodic function was based on a Fourier series approximation because its approximation enables a non-periodic function to be expressed periodically as long as the Fourier series converges. In the case of a square wave function (deposition for six months, then no deposition for six months), the Fourier series’ approximation of the function converges (although non-uniformly). Once the randomly generated CIC initiation time is reached, the ISOCORRAG equation begins to include randomly generated [Cl^-] deposition values in the calculation of the monthly corrosion rate at each time step.

The stochastic ISOCORRAG model required adjustment factors for tie shape, temperature, pitting, carbonation, and age. Beginning with tie shape, where strip ties have rectangular cross-sections and wire ties have circular cross-sections, the adjustment factor for shape of the tie was determined using drag coefficients from fluid mechanics. The ratio of the drag coefficient in laminar flow around a circular cross-section to that of a rectangular plate cross-section was determined to be 0.67. For wire ties, this meant that the corrosion rate was only 67% of the corrosion rate experienced by a rectangular plate, and accounted for wire ties trapping less pollutant and moisture than strip ties. The next factor was temperature. This adjustment factor was calculated according to Arrhenius's Law, which accounts for an increase in the rate of an electro-chemical reaction due to an increase in thermal energy. Using the observation that the corrosion rate of steel in concrete doubles for an increase in temperature of 10°C [5], the factor could be generated at monthly time steps by estimating the average monthly temperature from sine approximated temperature functions at each location. The temporally dependent temperature sine function was used to generate the temperature input into the Arrhenius equation, calibrated as described above. A factor accounting for an increase due to pitting was a randomly generated, uniformly distributed variable between 2 and 6 [6]. Carbonation was accounted for by an increase to the monthly corrosion rate. This uniformly distributed variable depended on the type of metal experiencing corrosion from a lower pH of carbonated mortar around the tie. For zinc, the carbonation factor was uniformly distributed between 0.01 and 0.93 μm/month, while for black steel the values were uniformly distributed between 0.042 and 0.067 μm /month [3]. The age factor accounted for a decrease in corrosion rate with time due to the accumulation of corrosion products. This was modelled using a bilogarithmic function with an exponent of 0.97. This value allowed for a conservative reduction to the corrosion rate with age (time).

Table 1: Comparison Between Empirical Tie Coating Life Corrosion Rate and Predicted Minimum Coating Life and Corrosion Rate

City	Building	Tie Type	Empirical Tie Coating Life (yrs)	Stochastic ISOCORRAG Model			
				Minimum Tie Coating Life (yrs)	Maximum Tie Coating Life (yrs)	Assumed Wall Orientation	% Error b/w Empirical and Best Estimate (%)
St John's	Apart. #1	Strip	7.5	6.4	8.3	South	14.7
Montreal	Apart. #1	Strip	9.0	8.3	17.6	East	8.43
	Apart. #2	Strip	4.0	9.4	17.7	East	135
	Apart. #3	Dovetail	8.0	6.7	15.4	East	16.3
Toronto	Apart. #1	Wire	7.5	5.7	13.4	East	24.0
	Apart. #2	Wire	11.5	5.7	13.4	East	16.5
Nepean (Ottawa)	Swim Pool	Wire	7.0	10.6	19.0	East	51.4
Ottawa	House	Strip	8.0	5.5	14.3	East	31.3
Winnipeg	Build. #1**	Strip	21.0	12.3	24.3	North	15.7
Calgary	Apart. #1	Strip	8.5	15.3	26.6	North	80.0
	Hotel*	Strip	30.0	21.1	33.3	West	10.0
	Low-rise#1*	Strip	33.0	19.9	36.4	West	10.3
	Low-rise#2*	Strip	40.0	28.3	42.7	West	6.75

*Results from field research in Calgary between Sept 2005 to Dec 2006

**Result from Crosier Kilgour Structural/Building Enclosure Engineers in Winnipeg

The service lives of ties embedded in the mortar, predicted by the stochastic ISOCORRAG model, were compared with the limited number of empirical results found in the literature [5], and the empirical results for Calgary supplemented by field investigation, during the course of this project. Table 1 above contains this comparison. As can be seen in Table 1, the stochastic ISOCORRAG tie service life model performed fairly well. The error between the actual service life and the predicted life (the minimum or maximum coating life depending on which produced the best estimate) was frequently less than 25% and as low as 6.75% in one case. Additionally, the minimum tie coating life predicted by the stochastic model generally underestimated the tie coating life. Underestimating the tie coating life is conservative and thus desirable.

EXPERIMENTAL PROGRAM

The program was conducted with the intention of developing an experimental procedure in the laboratory that could eventually be applied to the field for obtaining instantaneous corrosion rates of ties in brick veneer walls, in-situ in a non-destructive manner. This procedure was also required to validate the effectiveness of the ISOCORRAG model in predicting instantaneous corrosion rates of ties embedded in mortar assuming the mortar acted as the tie environment. The Linear Polarization Resistance (LPR) measurement procedure was selected for this purpose. LPR is a potentiostatic electrochemical technique that has many applications in corrosion engineering and requires the use of a potentiostat. A potentiostat has three electrodes: a Counter Electrode (C.E.), Reference Electrode (R.E.) and Working Electrode (W.E.). LPR measurements are made using the potentiostat which has the ability to impose small amplitude perturbations of potential through the CE to polarize the corroding specimen (connected to the W.E) while the current necessary to attain such perturbations is measured (Figure 1a). These LPR experiments were performed on several small brick prisms and a brick veneer concrete unit wall (BVCU) specimen. Each prism was four bricks high and had two structural ties of the same type placed in two of the bed joints. Both the prism specimens and the BVCU wall specimen were placed in a room, held at 100% RH and 22°C, called the "Fog Room".

For the LPR experiments on both the prism and the wall specimens, a programmable scanning potentiostat designed and fabricated by PETROLITE was used. The PETROLITE Potentiodyne IIB^{TM} potentiostat (Figure 1b) was designed to perform electrochemical corrosion tests in the field or the laboratory. It consists of a potentiostatic instrument that provides measurement and control of the corrosion cell, and a Toshiba T3100/20 computer that provides data acquisition, storage, manipulation, and graphing functions. In the case of the PETROLITE Potentiodyne IIB^{TM} potentiostat, the current and voltage are recorded with a 16 bit Data Acquisition Circuit (DAC) with a minimum sweep rate of 2 mV/min, a maximum sweep rate of 3000 mV/min, and a current measurement with 12 bit ADC for each 7 decades. The input impedance of the R.E. is 1000 MΩ or greater and a current compliance isolation of +/- 1.0 Amps. The corrosion cell circuit is swept between the user defined start and set points. The set point corresponds to an action, such as END the experiment, NEXT, make the next pass without delay, PAUSE, or HOLD. As the voltage is swept, the difference in potential between the R.E. and W.E. is maintained at zero by the application of current through the C.E. The current required to maintain the zeroed potential difference is recorded and plotted on the Toshiba computer to produce anodic and cathodic polarization curves.

The brick prism specimens were tested by immersing the prisms in a salt water bath and connecting the specimens to the PETROLITE Potentiodyne IIB^{TM} potentiostat according to Figure 1a. This method [7] was used to ensure a good electrical contact and conductivity through the mortar. For the LPR experiments, the potentiostat was set at a sweep rate of 100 mV/min, with a start point of 0.5 V, and an end point of -0.5V. The brick prisms were subjected to this LPR technique several times throughout the testing program and at different points in time to get an indication of the temporal variation in corrosion current density (instantaneous corrosion rate) as the corrosion progressed. As can be seen in Figure 1b, the PETROLITE Potentiodyne IIB^{TM} potentiostat was quite old and the output on to the monochrome LCD screen was difficult to see.

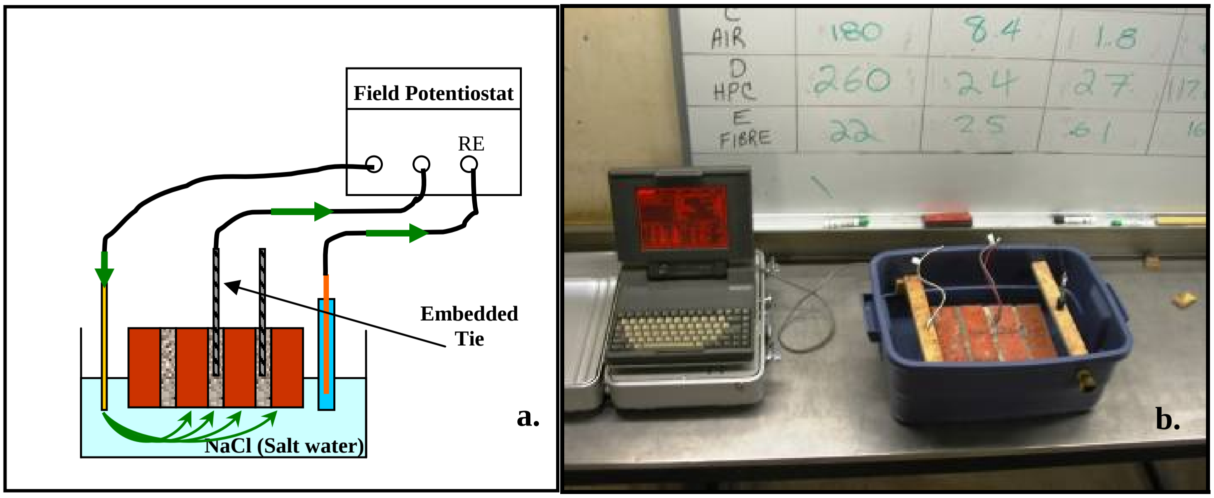

Figure 1: a) Brick Prism LPR Experiment Schematic b) FERO^{TM} wire V-ties in Brick Prism - LPR Experiment Set-up

Fortunately, the data used to generate the curves on the Toshiba T3100/20 computer screen could be converted to a text file. This text file was then plotted in EXCEL. According to the ASTM G3-89 [8] and ASTM G102-89 [9], the intersection point of the two Tafel slope lines and the open circuit potential (corrosion potential) provides both the corrosion potential (V) and the corrosion current density (μA/cm^2) directly from the graph. Once the figure was plotted, the anodic and cathodic Tafel slopes were estimated (represented by the sloped lines on the graph in Figure 2 below) and the corrosion current density obtained in μA/cm^2 was obtained by the intersection of the Tafel slopes and the line at the open circuit potential (horizontal intersecting line in Figure 2). The intersection of the three lines yielded the instantaneous corrosion current, i_{corr}. Figure 2 illustrates the typical results from an LPR experiment. This experiment, conducted on November 6, 2006, was on a FERO V-tie embedded in a brick prism. In the figure, the corrosion current density, i_{corr}, was determined to be 0.15 μA/cm^2. Using methods from the ASTM G102-89, the corrosion rate of the zinc-galvanized FERO wire tie was calculated. The resulting corrosion rate was equivalent to 2.24 μm/year (15.9 g/m^2/year). This value was close to the theoretical corrosion rate of 2.57 μm/year (18.2 g/m^2/year), determined using the ISOCORRAG equation with fog room parameters of: TOW of 8760 hours/year (100%/year), 0 μg/m^3 for the sulphur dioxide concentration, and 0 mg/m^2/day for the chloride ion concentration. In the event that the steel substrate is corroding, the ISOCORRAG equation with fog room conditions predicts a corrosion rate of 51.3 μm/year. Therefore, the lower corrosion rate results and the absence of red (iron) rust on the fully exposed portions of the tie support the theory that the zinc coating was corroding at the time of the LPR experiment. The percentage difference between the ISOCORRAG predicted corrosion rate and the measured corrosion rate was approximately 14.7%. The predicted corrosion rate was larger than the measured corrosion rate, which was expected because ISOCORRAG predicts corrosion rates for flat metal coupons (rectangular cross-sections) and the FERO^{TM} V-ties are wire ties with a circular cross-section.

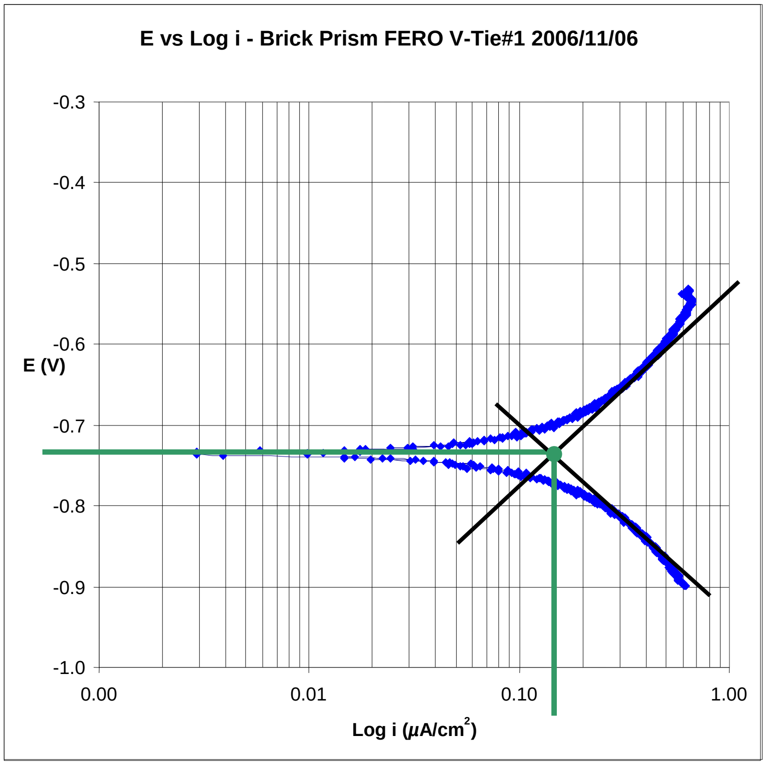

Figure 2: Results from an LPR experiment on a brick prism with FERO^{TM} V-ties

Some of the results from the LPR experiments on the brick prisms are provided in Table 2 below.

Table 2: Corrosion current density and rate of zinc-coated ties embedded in prisms

Tie Type	*Tie Type*	*Corrosion Current Density,* i_{corr} [μA/cm^2]	*Corrosion Rate,* r_{corr} [μm/year]
FERO V-tie	Wire	0.15	2.24
Corrugated strip tie	Wire	8.0	93.6*
FERO strip tie	Strip	4.4	65.4

*This rate assumes that the steel substrate is corroding, confirmed by the appearance of red rust and higher corrosion rate

The BVCU wall specimens could not be partially submerged in a saltwater bath due to their size. In this case, the potentiostat and a corrosion probe were used to measure the instantaneous corrosion rate. This was achieved by attaching the working electrode directly to the tie under investigation and then applying the corrosion probe normal to the face of the exterior wythe with the center of the probe concentric with the location of the center of the tie. The corrosion probe design was based on existing designs used for obtaining corrosion rates of steel reinforcement embedded in concrete [10, 11, 12]. Figure 3a illustrates the as-built corrosion probe. In the figure, the reference electrode used was a commercially available Tinker-Rasor Model 6B $Cu/CuSO_4$, the counter electrode was constructed using a brass ring, and the saltwater-soaked sponge was used to improve the electrical connection between the electrodes and the masonry. The apparatus and set-up used to obtain the instantaneous corrosion rates of ties embedded in the wall specimens is illustrated in Figure 3b. Using the same method to analyze the polarization curves, and to obtain the corrosion current densities as was used for the brick prisms, the corrosion rates of the ties embedded in the BVCU wall specimen were obtained. The results are presented in Table 3.

Table 3: Corrosion current density and rate of zinc-coated ties embedded in BVCU wall specimens

Tie Type	*Tie Type*	*Corrosion Current Density,* i_{corr} [μA/cm^2]	*Corrosion Rate,* r_{corr} [μm/year]
FERO V-tie	Wire	3.1	46.4
Corrugated strip tie	Wire	7.5	87.8*

*This rate assumes that the steel substrate is corroding, confirmed by the appearance of red rust

Figure 3: a) Corrosion Probe As-built; b) Apparatus/set-up use for wall specimen LPR experiments

The large corrosion current densities of 8.0 μA/cm^2 and 4.4 in Table 2 and 7.5 μA/cm^2 in Table 3 respectively, may be partially explained by the accelerated conditions of the Fog Room (22°C and 100% RH). However, the error is much greater than the expected increase factor of 3.5 obtained from using Arrhenius's Law [6] for estimating the effects of temperature on corrosion rate, assuming doubling of corrosion rate for every 10°C above 10°C [5]. Other possible sources of error could be the errors with LPR measurements discovered by Law et al. [13] which can be as large as a 340% overestimate for the corrosion rate of steel in carbonated concrete or as large as 523% for chloride contaminated concrete. In the case of the 4.4 μA/cm^2 in Table 2, for the zinc coated FERO tie in the BVCU wall specimen, another possible source of error could be a larger corrosion rate, generated if the corrosion has progressed to the level of the zinc-iron hybrid layer of the zinc coating formed during the hot-dip galvanizing process. This would result from the fact that steel has a much larger corrosion rate than zinc when experiencing atmospheric corrosion.

CONCLUSIONS

LPR experiments conducted on wire and corrugated strip ties, embedded in brick prisms and a BVCU wall specimen, correlated well with the corrosion rate predicted by an atmospheric corrosion model called ISOCORRAG. In several cases, the error between the ISOCORRAG prediction and the LPR experimentally obtained results was less than 15%. This validated the use of the ISOCORRAG equation as a corrosion model for predicting the service life of ties in the mortar joints of brick veneer walls when treating the mortar surrounding the tie as the tie's atmosphere. Randomizing the ISOCORRAG model and applying adjustment factors for tie shape, temperature, pitting, carbonation and age, the maximum, minimum, and average expected tie service life resulting from a Monte Carlo simulation were produced. The results from the simulation agreed well with the limited values from existing literature on tie service life of brick veneer walls in the Canadian environment. Errors between the predicted and literature values were typically between 0 and 25% with the predicted values underestimating the tie service-life.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Canada Masonry Design Centre and NSERC for their financial support, Dave Owen for donation of the Petrolite Potentiodyne IIB potentiostat, and FERO for the donation of the V-ties.

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