INSTANTANEOUS CORROSION RATES OF TIES EMBEDDED IN MORTAR JOINTS OF BRICK VENEER WALLS USING THE LINEAR POLARIZATION TECHNIQUE

M.D. HAGEL[1], S.L. LISSEL[2]

[1]PhD Candidate
Civil Engineering Department
Schulich School of Engineering
The University of Calgary
Calgary, AB Canada
mdhagel@ucalgary.ca

[2]Associate Professor
Civil Engineering Department
Schulich School of Engineering
The University of Calgary
Calgary, AB Canada
sllissel@ucalgary.ca

SUMMARY

The Linear Polarization Resistance (LPR) technique has been successfully used to obtain the corrosion rate of metal ties embedded in the mortar joints of 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 a corrosion rate model called ISOCORRAG [Knotkova et al., 1995]. ISOCORRAG is being used for stochastic corrosion modeling of ties embedded in mortar. In most cases, the LPR tests performed in the lab agreed well with the 1-year ISOCORRAG predicted corrosion rates.

INTRODUCTION

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 applied to brick veneer wall systems to obtain the corrosion rate of zinc-galvanized steel ties embedded in the mortar joints. Corrosion typically occurs first on the portion of the tie embedded in the mortar joint. Therefore, an experimental program was conducted with the intention of developing an instrument 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 instrument was also required to validate the effectiveness of the ISOCORRAG atmospheric corrosion model [Knotkova et al., 1995] in predicting instantaneous corrosion rates of ties embedded in mortar, assuming the mortar surrounding the tie behaves as the tie's atmosphere. The ISOCORRAG equation formed the foundation of a 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 the Canadian environment. To achieve these objectives, several small brick prisms and a brick veneer concrete unit wall (BVCU) specimen were built. These specimens contained two types of ties which were FERO™ V-ties (wire ties) and corrugated strip ties (strip ties). 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”. The ISOCORRAG predictions were tested against the results obtained from the LPR experiments on ties embedded in mortar. This paper documents the LPR experiments conducted to develop an instrument that can be used in the lab or field to obtain corrosion rates of tie in-situ in brick veneer walls, and to validate the ISOCORRAG equation as an effective tool for the stochastic tie life model.

STOCHASTIC TIE 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 exposure), the tie type (wire or corrugated strip tie) and the zinc coating thickness (g/m^2) and steel substrate thickness/diameter (mm). The results are the minimum, maximum, and mean expected tie service lives 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 [Knotkova et al., 1995]:

$$CR = a_1 + B_1 \cdot \left[SO_2\right] + B_2\left[ToW\right] + B_3\left[Cl^-\right] \quad (1)$$

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 [Knotkova et al., 1995]. In equation (1), the deposit of sulphur dioxide [SO_2] in $\mu g/m^3$, 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 rate by 12. In order to create a stochastic model, the values for [TOW], [SO_2], and [Cl^-] were transformed into Gaussian random variables. The mean and covariance of the TOW variables of the mortar joint for eleven cities in Canada were obtained using a 1D hygrothermal software called hygIRC-1D, while at the level of the mortar embedded tie, the mean and covariance for [SO_2] and [Cl^-] were estimated using other methods described elsewhere (Hagel and Lissel, 2005). 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). 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 50 iterations to yield the maximum, minimum, and average tie service life.

EXPERIMENTAL PROCEDURES

Nine brick prisms were built. Each prism was four bricks high and had two ties of the same type (wire or strip) embedded in two of the mortar joints. The BVCU wall specimen was built with 200 mm block, orange brick and contained several FERO™ V-ties and corrugated strip ties. Both the prism specimens and the BVCU wall specimen were placed in the fog room.

The Linear Polarization Resistance Technique

Linear Polarization Resistance (LPR) is a potentiostatic electrochemical technique that has many applications in corrosion engineering. It is capable of determining the instantaneous corrosion current density, i_{corr}, generated by metals in solution and is widely used under full immersion, aqueous conditions (Roberge, 2000). The technique requires the use of an instrument called a *potentiostat* that 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 to polarize the specimen while the current necessary to attain such perturbations is measured [Kelly et al. 2002]. For the LPR experiments on both the prisms and the wall specimen, a programmable scanning potentiostat, designed and constructed by PETROLITE, was used. The PETROLITE Potentiodyne IIB™ potentiostat (Figure 1b) was designed to perform electrochemical corrosion tests in the field or 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™ 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 of 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 makes 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 zero potential difference is recorded and plotted on the Toshiba computer to produce anodic and cathodic polarization curves. Once the corrosion current density was obtained from the LPR experiments, it was converted into an annual corrosion rate using the methods outlined in the ASTM G102-89. For zinc the expression for the corrosion rate as a function of the corrosion current density ($\mu A/cm^2$) from the ASTM G102-89 is CR = 14.96 i_{corr}, while for steel the expression is CR = 11.7 i_{corr}.

Brick Prism Tie Specimen Experiments

The brick prism specimens were tested by immersing the prisms in a salt water bath and connecting the specimens to a PETROLITE Potentiodyne IIB™ potentiostat according to

the diagram in Figure 1a [Bentur et al., 1997]. This method was used to ensure good electrical contact and conductivity through the mortar.

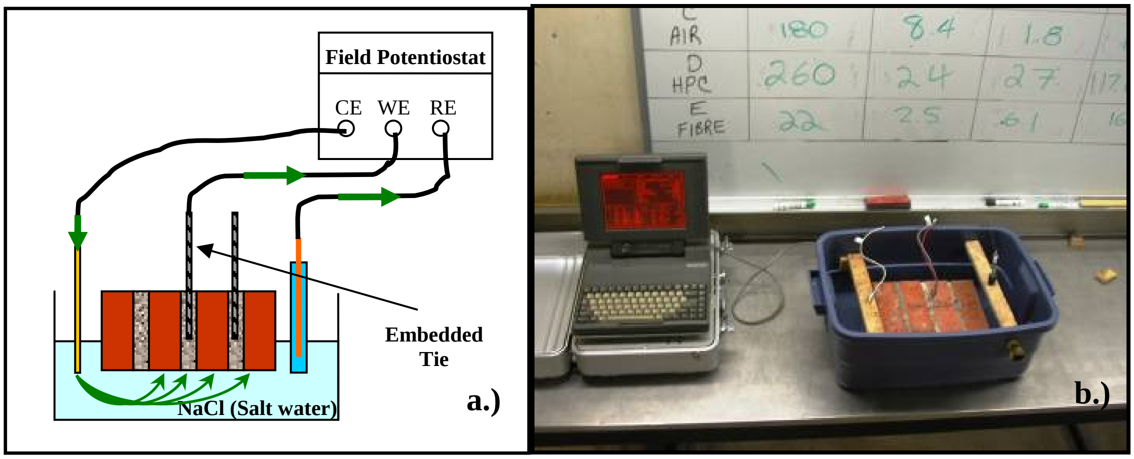

Figure 1 – a) Brick Prism LPR Experiment Schematic b) FERO™ wire V-ties in Brick Prism - LPR Experiment Set-up

In Figure 1a, the arrows represent the flow of electrical current emitted by the C.E. A brass wire 2 mm in diameter was used for the C.E., represented as the gold wire in Figure 1a. A copper/copper sulphate solution (Cu/CuSO4) was used for the reference electrode depicted by the blue and orange object in Figure 1a. An actual experiment set-up is illustrated in Figure 1b. As can be seen in Figure 1b, the PETROLITE Potentiodyne IIB™ potentiostat was quite old and the output onto the monochrome LCD screen was difficult to see. 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. Figure 2 illustrates the typical polarization curves that resulted from an LPR experiment conducted on November 6, 2006 on a FERO™ V-tie (wire tie) embedded in the mortar joints of a brick prism specimen. From the figure, the anodic and cathodic Tafel slopes were estimated. These Tafel slopes are represented by the black lines on the graph in Figure 2. According to the ASTM G3-89 the intersection point of the two Tafel slope lines and the open circuit potential (corrosion potential) provides both the corrosion potential and the corrosion current density (mA/cm^2) (green lines in Figure 2). For the case shown, the corrosion current density, i_{corr}, was determined to be 0.15 μA/cm^2. From the expression for the corrosion rate of zinc provided in the previous section, the corrosion rate of the zinc-galvanized FERO wire tie was calculated. The resulting corrosion rate was 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) - a difference of 14.7% - determined using the ISOCORRAG equation with a TOW of 8760 hours/year (100%/year), 0 ug/m^3 for the sulphur dioxide concentration, and 0 mg/m^2/day for the chloride ion concentration.

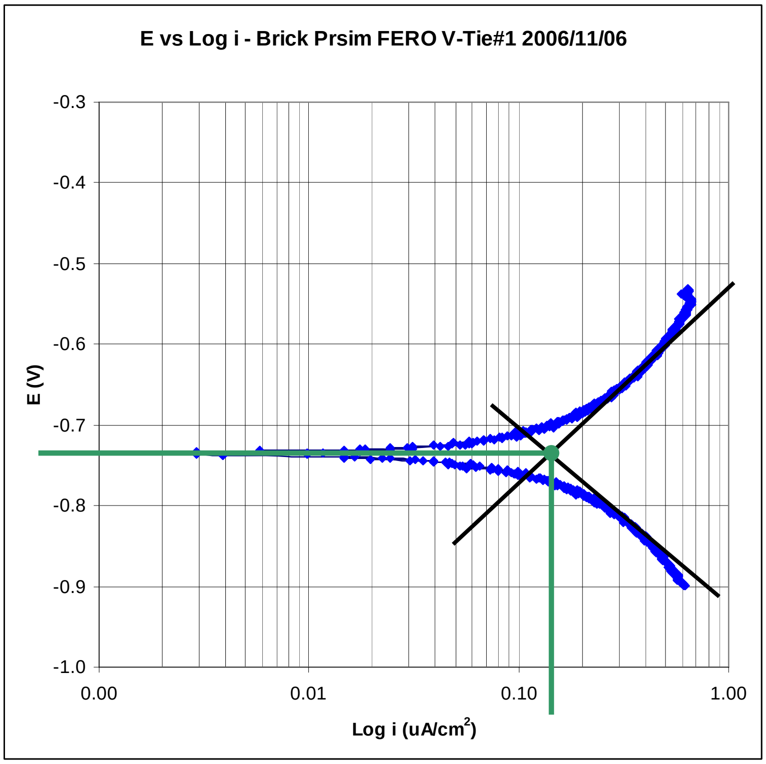

Figure 2 - Results from an LPR experiment on a Brick Prism with FERO V-tie

In the event that the steel substrate is corroding, the ISOCORRAG equation predicts a corrosion rate of 51.3 μm/year. Therefore, it is obvious that the results support the theory that the zinc coating was corroding at the time of the LPR experiment. 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 V-ties are wire ties with a circular cross-section. A circular cross-section traps less moisture and pollutants resulting in a smaller corrosion rate. Some of the results from the LPR experiments on the brick prisms are provided in Table 1 below.

Table 1. Experimental corrosion current density and rate of zinc-coated ties in prisms

Specimen	*Tie Type*	*Corrosion Current Density,* i_{corr} [uA/cm^2]	*Corrosion Rate,* r_{corr} [um/year]
FERO V-tie	Wire	0.15	2.24
Small corrugated strip tie	Strip	0.14	2.09
Large corrugated strip tie	Strip	8.0	93.6*
FERO strip tie	Strip	4.4	65.4

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

Wall Tie Specimens LPR Experiments

One of the main objectives of using the LPR technique to obtain the instantaneous corrosion rate for ties embedded in mortar was for application to non-destructive field measurements. Given that wall ties are embedded in walls, and walls cannot be submerged, a handheld field probe that mimicked the circuit created by the saltwater bath was developed. The field probe measured the instantaneous corrosion rate by attaching the W.E. directly to the tie under investigation. The probe was then applied normal to the face of the exterior wythe with the center of the probe concentric with the location of the center of the tie in a similar fashion to Figure 3.

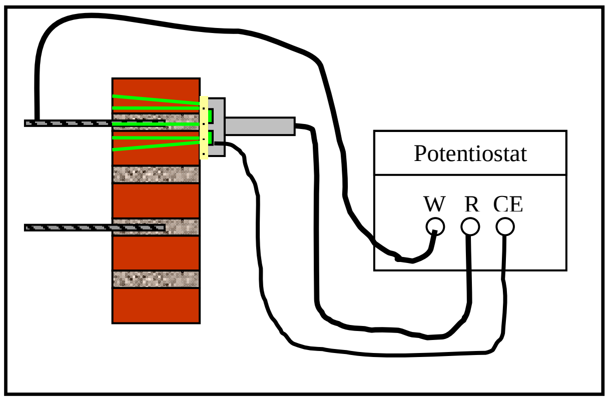

Figure 3 – BVCU Wall Specimen Experiment Schematic

The potentiostat is normally used to obtain corrosion rates of steel reinforcement embedded in concrete which lies in a plane perpendicular to the electrical field generated by the probe. However, a steel tie embedded in a mortar joint lies in a plane parallel to the electrical field generated by the probe (Figure 3). Furthermore, wall ties are much smaller than the steel reinforcement in concrete and distributed throughout the wall and mortar differently. The required tie spacing of 400 mm that governs this distribution is advantageous to the use of LPR, in that the area of corroding metal captured by the electrical field of the tie in the mortar is easily determined. Unlike steel reinforcement in concrete where the area of steel caught in the electrical field of the probe is difficult to determine even with a guard ring, the tie spacing means that if the probe is designed properly only one tie will be caught in the field of the probe. Given that the embedment lengths are typically 40 mm to 50 mm the area of the tie caught in the field is simply the width or circumference of the tie by the embedded length. The probe design was modelled on previously developed probes used for obtaining the instantaneous corrosion rate of steel embedded in concrete which were researched extensively [Escalante and Ito, 1990; Andrade et al, 1990; Law et al, 1999]. The probe is composed of five main components. These are the Reference Electrode (R.E.), the Counter Electrode (C.E.), the sponge, and the base. A standard copper/copper sulphate ($Cu/CuSO_4$) half-cell reference electrode was used for the probe's R.E. These electrodes are commercially available and the model purchased for the probe was the Tinker-Rasor Model 6B. The C.E. is generally fabricated from platinum, gold graphite, or another conducting, inert metal. In the interest of reducing costs, this counter electrode was fabricated from brass. Brass was

successfully used as a counter electrode in experiments conducted by [Law et al, 1999], and, as such, was deemed sufficient. The smallest diameter for the wire loop counter electrode was used in order to minimize the electrical field spread and to ensure the embedded steel would be captured in the field. This diameter was slightly larger than the size of the hole (25 mm) made in the probe base that was necessary for the reference electrode to have contact with the sponge. No guard ring to contain the spread of the electrical field was necessary because the tie layout was such that the ties were far enough apart that only one tie would be captured by the spreading field (Figure 3).The C.E. and R.E. were built into a single, hand-held probe. In this probe, the base was used to house the counter electrode and conducting sponge. The sponge was soaked with salt water to ensure good electrical contact between the probe and the masonry. The masonry was washed down after every experiment to remove any residual salt solution. These components formed the hand-held probe necessary to take the corrosion current measurements of the ties embedded in the mortar joints of brick veneer walls. Its design allows for easy adaptation to the field. The as-built photo of the corrosion probe is found in Figure 4a. In Figure 4b, the apparatus and set-up used to obtain the instantaneous corrosion rates of ties embedded in the BVCU wall specimen can be seen.

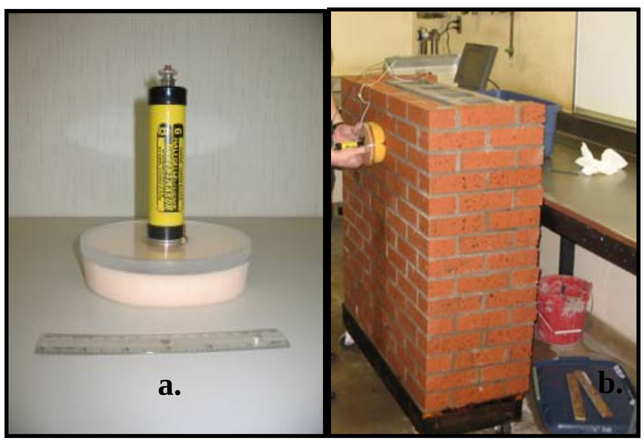

Figure 4 – a) Corrosion Probe as-built b) Apparatus and set-up use for wall experiments

The same procedure that was used for ties embedded in the brick prisms was used to analyze the polarization curves and obtain the instantaneous corrosion rate on the ties embedded in the BVCU wall specimen. To illustrate, the results from an experiment on a small corrugated strip tie in the BVCU wall specimen conducted on March 6, 2007 are explained in detail. In the case of the small strip tie in the BVCU wall specimen, it was initially assumed that the zinc coating was corroding at an experimentally determined corrosion current density of 5.1 $\mu A/cm^2$. If the zinc coating was assumed to be corroding, an experimental corrosion rate of 64.3 μm/year was the result. This value was much greater than the 2.57 μm/year predicted by ISOCORRAG. Therefore, it was assumed that the zinc had been consumed and the steel was now corroding. Repeating the procedure, but using the function for steel of $CR = 11.7 i_{corr}$, yielded an experimental corrosion rate of the steel substrate of 59.7μm/year. Using the ISOCORRAG equation with the coefficients for flat steel coupons [Knotkova et al., 1995] the ISOCORRAG predicted corrosion rate was 51.3 μm/year. The resulting percentage error between the experimentally determined

corrosion rate and the ISOCORRAG predicted corrosion rate was only 14.1%. Although the tie was not removed from the wall to prove that the steel was corroding, it was a well-educated assumption given that the tie was several years old and had very little of its mill-galvanized zinc coating at the time it was embedded into the BVCU wall. The same LPR experimental procedure applied in the lab could be applied in the field for testing corroding steel ties in-situ. However, it would require the use of acoustic emission, Ground Penetrating Radar, or X-rays to locate the ties in the wall. Furthermore, a small opening in the wall near the tie under investigation would be necessary in order to attach the working electrode to the tie. The removal of one brick proved sufficient (Figure 5a and 5b) to apply the W.E. clips to the corroding tie and obtain the corrosion rate of the FERO V-tie (Tie Specimen #3) on September 11, 2007.

Figure 5 - a) Removal of a brick from the BVCU specimen
b) LPR experiment on the BVCU specimen

Using the same method as was used for the brick prisms to analyze the polarization curves and obtain the corrosion current densities, the corrosion rates for the ties embedded in the BVCU wall specimen were obtained. These results are found in Table 2.

Table 2. Corrosion current density and rate of zinc-coated ties embedded in BVCU wall

Specimen	*Tie Type*	*Corrosion Current Density,* i_{corr} [uA/cm^2]	*Corrosion Rate,* r_{corr} [um/year]
FERO V-tie	Wire	3.1	46.4
Small corrugated strip tie	Strip	12.0	140.4*
Large Corrugated strip tie	Strip	7.5	87.8*

*This rate assumes that the steel is corroding confirmed by the observation of red rust

DISCUSSION

The high corrosion current densities of 8.0 and 4.4 μA/cm^2 in Table 1 and 12.0 and 7.5 μA/cm^2 in Table 2 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 increase that would be expected from using Arrhenius's Law [Wei, 2003]. When estimating the effects of temperature on corrosion rates, the rate is expected to double for every 10°C above 10°C [Maurenbrecher & Brousseau, 1993]. In this case the rate would be expected to increase by a factor of 3.5, less than that observed. Other possible sources of error could be the errors with LPR measurements suggested by Law et al. [2004], which can be overestimated by as much as 340% for the corrosion rate of steel in carbonated concrete or by as much as 523% for chloride contaminated concrete. In the case of the 4.4μA/cm^2 for the zinc coated FERO tie in the BVCU wall specimen, another possible source of error could be a higher 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.

CONCLUSIONS

LPR experiments were conducted on wire and corrugated strip ties that were embedded in brick prisms and a BVCU wall specimen placed in the Fog Room. These experiments were used to create an instrument that could be used in the lab or field to obtain the corrosion rates of ties embedded in the mortar joints of brick veneer. The results of the experiments 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. These values also accounted for the wall location and wall orientation of the embedded ties. Eleven Canadian city locations with a spectrum of temperature moisture and pollution exposure can be modelled where the user specifies the wall location, wall orientation, tie type, zinc-coating thickness, and steel substrate thickness/diameter. In most cases results from the simulation agreed fairly 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. These results support the use of ISOCORRAG as a modeling tool in the development of a stochastic tie service life model that randomizes the inputs into ISOCORRAG.

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