SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I11P104

Volume 12 Issue 11, 36-54, November 2025

Original Article

Assessment of Temperature Levels on the Probability of Corrosion for RC Decks Made of Various Percentages of Supplementary Cementitious Materials

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Received: 03 September 2025 Revised: 04 October 2025 Accepted: 02 November 2025 Published: 29 November 2025

Abstract - *This research aims to evaluate the Probability of Chloride-Induced corrosion initiation (PCI) due to chloride, utilizing the Monte Carlo simulation method across various percentages of Supplementary Cementitious Materials (SCMs), ranging from 10% to 50%, with the cement used in concrete mixes for uncracked Reinforced Concrete (RC) decks. Moreover, the RC decks are impacted by various maximum temperature scenarios. The maximum temperature values that affect the diffusion coefficient for chloride range from 25°C to 50°C, representing a different range of representative concentration pathways of the maximum temperature values in future years. The results show that the relationship between the impact of maximum temperature levels varying from 25°C to 50°C applied to the RC deck and the corresponding reliability index is a descending linear relationship across various percentages of SCMs used in the RC deck mixes. The impact of slag is more significant on the PCI compared to the fly ash used as an SCM in various mixes, when the percentages of both SCMs range from 10% to 30% for RC decks subjected to a maximum temperature value of 25°C, 35°C, and without the impact of maximum temperature. This study provides valuable insights into the assessment and management of RC bridges under climate change and offers a predictive model for assessing the risk of corrosion.*

Keywords - *Climate Change, Fly Ash, Maximum Temperature, Probability of Chloride-Induced Corrosion Initiation, Slag*.

1. Introduction

Reinforced Concrete (RC) bridges are essential for transportation infrastructure that provides safe and efficient mobility for people and goods between cities and suburbs in each country in the world. RC bridges are vital structures that are subjected to various environmental conditions and operational loads that may cause severe deterioration of the structural members. One of the most severe forms of deterioration for vital RC structures is chloride-induced corrosion of steel rebars, which affects the structural integrity, service life, and durability of RC members.

Chloride ions penetrate the concrete microstructure through different mechanisms [1-5]. The steel rebars in concrete are protected from corrosion due to the concrete's alkalinity (pH values around 12.5) [6, 7]. When the steel rebars inside the concrete members are exposed to several levels of chlorides due to deicing salts, this will lead to the breakage of the passive film layer around the steel rebars, making the rebars more susceptible to corrosion. The internal cracks also play a vital role inside the concrete section, allowing more chlorides, moisture, and oxygen to penetrate the concrete microstructure, which will lead to further accelerating the corrosion process.

The factors affecting chloride ion transmission inside concrete pores are as follows: the water-cement ratio, exposure time, the chloride ion binding effect of the maximum temperature, and relative humidity. The porosity and chloride diffusivity of concrete increase as the water-cement ratio in the concrete mix increases. The increase in the maximum temperature accelerates the chloride ion diffusivity inside the concrete microstructure. Relative humidity is also an important environmental factor.

Tuutti [8] introduced the mechanism of steel rebars corrosion in RC structures. Moreover, Tuutti [8] hypothesized it as a dual-stage process: an initiation stage and a propagation stage. In this research, the corrosion initiation stage for RC decks subjected to severe chloride concentration and maximum temperature levels is studied in detail. Various factors impact the duration of each stage, including the environmental conditions, concrete properties, exposure time, and chloride diffusion rates [8, 9]. As detailed by several studies [10-14], the consequences of chloride-induced corrosion in RC structures include loss of bond along the steel/concrete interface, reduction of the cross sections of the steel rebars, and loss of steel ductility.

To mitigate the impact of corrosion in structural members subjected to severe chloride ions or CO_2 concentration effects, the specific design codes must recommend reducing the water-to-cement ratio in the concrete mix to a particular limit to enhance the durability of concrete, using the Supplementary Cementitious Materials (SCMs) such as Fly Ash (FA), Ground-Granulated Blast Furnace Slag (GGBFS), Silica Fume (SF), etc. [15, 16] as a partial replacement with the total amount of cement used in the concrete mix, providing adequate concrete cover for the steel reinforcement that satisfies specific minimum requirements due to climate change according to the standard code. Geopolymer concrete is also recommended as a sustainable construction material, replacing ordinary Portland cement concrete, to inhibit steel reinforcement corrosion in extreme environmental conditions.

The IPCC [17] plays an important role in influencing variables that affect the durability of reinforced concrete structures. The primary environmental factors affecting chloride ion penetration, such as maximum temperature, freeze-thaw cycles, and relative humidity, govern the penetration of chloride species into concrete pores [18-24]. The Fifth Assessment Report from the IPCC [25] used four distinct greenhouse gas concentration trajectories, known as RCPs, to build its climate model. In this research paper, different RCPs, such as RCP2.6 (Low Emission Scenario), RCP4.5 (Intermediate Emission Scenario), and RCP8.5 (High Emission Scenario), are utilized to project the annual maximum temperatures for a City in Canada [21] and conclude their impact on the probability of chloride-induced corrosion for RC deck members having various percentages of SCMs (e.g., FA, Slag (SG)) concerning the total amount of cement used in their concrete mixes.

In concrete mix design, it is well known that the amount of water, cement, and the chemical composition of the cementing materials are the primary factors in developing concrete with high mechanical, physical, and thermal properties. It has been found that using mineral admixtures improves the pore structures of concrete. Mineral admixtures act as pozzolanic materials and fine fillers; therefore, the microstructure of the hardened cement matrix becomes denser and more resistant to environmental impact.

SCMs purify the cementitious microstructure by enhancing particle packing, developing more C-S-H gel through pozzolanic reactions, and densifying the interfacial transition zone. These changes result in reducing the porosity, increasing the strength, and enhancing the durability of concrete due to improved resistance against chloride ingress into the concrete microstructure. The addition of FA significantly reduced the penetration of chloride ions in the concrete pores. Moreover, as the amount of FA used in the concrete mix increased, the chloride ion diffusion coefficient decreased. Silica fumes were also found to have a significant effect on concrete mixes [26] and reduce the porosity (i.e., increasing the resistance to chloride diffusion into concrete microstructure) [27]. The proper usage of silica fume percentages results in a reduction in chloride penetration depth. Furthermore, it was found that replacing ordinary Portland cement with 10% silica fume would reduce the chloride diffusivity 15 times [27]. Hassan et al. [28] deduced that the porosity of concrete, including silica fume, was 25% lower than that of an ordinary Portland cement concrete specimen. The consumption of portlandite occurs by the pozzolanic reaction according to Zhao et al. [29] and Sisomphon and Franke [30]. Moreover, Black [31] showed that at a low level of replacement by 10% of GGBFS with the amount of cement in the concrete mix, the pozzolanic reaction reduces the permeability of the concrete. Using GGBFS improved the resistance of the chloride penetration depth inside concrete pores [29]. Moreover, the diffusion rate in concrete using ordinary Portland cement could be reduced to 2-5 times when using GGBFS as SCMs [32].

Different approaches for measuring chloride ion concentration in concrete depend on the application, i.e., determining the chloride ingress profile for quality control of new structures or chloride ion concentration in existing structures. The most routinely used technique is the leaching method, and subsequent analysis of the extracted solution is the potentiometry and the Volhard method, measuring the free and total chloride content, respectively [33]. Furthermore, the field methods are further divided into destructive and nondestructive measurements. The Volhard and potentiometric analysis methods are destructive and require extracted pore solutions. According to Castellote et al. [34], for measuring chloride ions inside concrete pores, their analyses are based on leaching and pore solution expression techniques of sampling [35]. Destructive sampling can result in significant measurement errors due to the concrete heterogeneity and the sample preparation, resulting in under- or over-estimations. Detections of cracks and chloride ion penetration were conducted using nondestructive methods such as linear and square inner electrical resistivity measurement. The nondestructive methods are characterized by their noninvasive nature. These techniques used external contactless measurements or embedded sensors inside concrete [36].

The problem for the current research is the increase in the maximum temperature levels due to climate change and the chloride concentration applied to the upper part of the RC deck, which will lead to a reduction in the concrete durability and service life of the vital RC structures in the future. The main objective of this research is to assess the reliability index obtained from the probability of corrosion across various temperature levels applied to the top part of the RC decks at a certain age. Moreover, the RC deck is composed of various percentages of either FA or SG. Furthermore, the time of corrosion initiation will be determined at different maximum temperature levels and percentages of SCMs.

The research gap of this study is to investigate climate change (i.e., maximum temperature and relative humidity) impacts on infrastructure, specifically focusing on the potential probability of corrosion initiation and their corresponding reliability index across diverse maximum temperature levels on infrastructure in a city in Ontario province in Canada. A detailed mechanistic model was conducted using the Monte Carlo simulation method across different percentages of SCMs, including (FA and SG), utilized in the concrete mixes for RC decks subjected to a wide range of maximum temperature levels. The RC deck is also subjected to a chloride concentration of 6 kg/m^3 on the upper part of the RC deck. The findings can inform urban planning, influence construction choices, and shape safety standards, potentially offering economic advantages by minimizing repair expenses and bolstering community safety. The importance of this study extends beyond this city, offering a model that can be applied globally and emphasizing the importance of robust urban infrastructure in the face of climate challenges.

1.1. Description of the RC Bridge Deck Used in the Probabilistic Chloride-Induced Corrosion Initiation Model

The proposed RC highway bridge deck structure is made of normal concrete with conventional carbon steel, subjected to deicing salt application. Moreover, the reinforcement ratio is 0.3%, and it is used for both top and bottom mats of reinforcement in the longitudinal and transverse directions, as noted by Saassouh and Lounis [37], with a yield strength of 400 MPa, as illustrated in Figure 1. The overall thickness of the RC deck is equal to 300 mm, with a clear concrete cover of 70 mm. The amount of ordinary Portland cement used in the concrete mix equals 460 kg/m^3. Moreover, the concrete compressive strength for the RC deck is equal to 40 MPa.

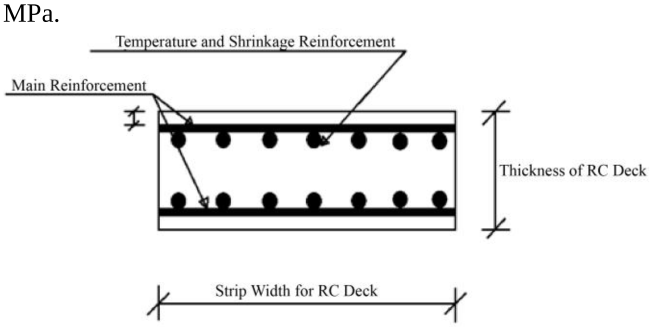


Fig. 1 Cross-section elevation for RC bridge deck showing details of steel rebars

2. Research Methodology

This methodology provides a comprehensive, data-driven, and statistically robust framework for determining and predicting the impact of maximum temperature on the structural integrity of RC structures, with a specific focus on Ontario City in the Canadian urban environment. This study utilizes a Monte-Carlo simulation method to determine the Probability of Corrosion Initiation (PCI) for RC decks across various maximum temperature values ranging from 25°C to 50°C at different SCMs used in the concrete mix for RC deck, which reflect potential future greenhouse gas emission scenarios, converging upon the envisioned climatic trajectory for the projected maximum temperature in the future for Toronto city. Focusing on two distinct RCPs (RCP2.6 and RCP8.5) and a concrete cover of 70 mm. In addition, the PCI will be conducted across various maximum temperature values ranging from 25°C to 50°C at different times, using the following steps:

- Data Collection: The study will collect data on the projected maximum temperature and the relative humidity for a City in Ontario province. The average chloride diffusion coefficient over various SCMs in different years will be calculated.
- Monte-Carlo Simulation Model Development: The Monte-Carlo simulation model will be developed to predict the PCI for RC deck members subjected to various maximum temperature levels. The model will consider the effect of maximum temperature and relative humidity on the corrected chloride diffusion coefficient at different SCMs used in concrete mixes for RC decks.
- Simulation Process and Iteration: The steps for the conduction of the Monte Carlo simulation process to generate the probability of chloride-induced corrosion initiation across various SCMs at different temperature levels are illustrated as shown in Figure 2.

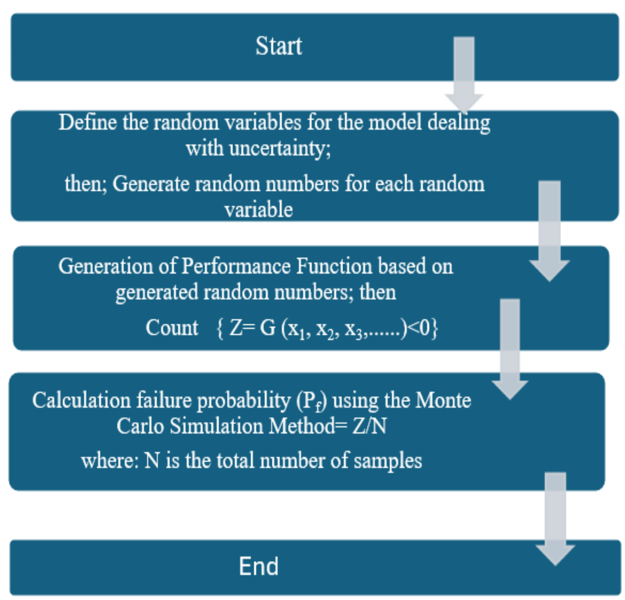


Fig. 2 Flowchart of the Monte Carlo simulation method process

- Analytical Evaluation: The results of the Monte-Carlo simulation will be analyzed to determine the PCI at each percentage of SCM across different temperature levels. The analysis will include statistical measures for each random variable defined in the probabilistic model, dealing with the uncertainty, such as the mean, standard deviation, coefficient of variation, and their distribution.
- Prediction and Comparison: Finally, the study will predict the corrosion initiation time across different SCMs (e.g., FA and SG), considering the effect of the maximum temperatures, and the other time, without considering its effect on the chloride diffusion coefficient. Furthermore, this comparative approach will clarify the differentiating impacts of different percentages of SCMs on the corrosion initiation time.

2.1. Calculation of the Average Chloride Diffusion Coefficient Over Time

Over time, the average chloride diffusion coefficient is an essential parameter for estimating the service life of RC structures exposed to severe environmental conditions. The reference chloride diffusion coefficient (D_{ref}) is a constant value, and it is calculated using Equation 1 according to Bentz and Thomas [38], who proposed a relationship between D_{ref} and the Water-to-Cement ratio (W/C) of concrete. Moreover, the values for D_{ref} with their corresponding W/C ratios are shown in Figure 3.

$$D_{ref}=10^{(-12.06+2.4\ W/C)} \quad (1)$$

Where: D_{ref} is the reference chloride diffusion coefficient (m^2/s), and W/C is the water-to-cement ratio used in the concrete mix.

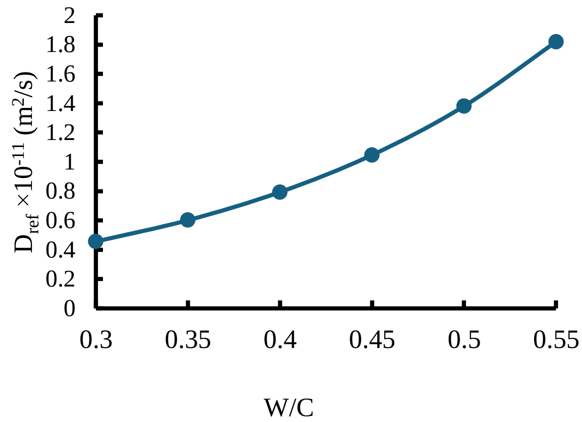


Fig. 3 Relationship between different values for W/C ratios and their corresponding reference chloride diffusion coefficients.

The formula used to account for the age factors (m) that describe the percentages of SCMs (e.g., specific percentages of FA up to 50% or SG up to 70%) used as a partial replacement with the total amount of cement used in the concrete mixes depending on mix proportions is expressed as in Equation 2 according to Bentz and Thomas, [38] and Kwon et al. [39]. Figure 4 and Table 1 show the relationship between various percentages of SCMs, whether FA or SG, used in the concrete mixes ranging from 5% to 50%, and their corresponding age factors are a linear function.

$$m = 0.2+0.4(\%FA/50 + \%SG/70) \quad (2)$$

Where m is a constant representing the age factor depending on the percentage of either FA (%FA) or SG (%SG), or a combination of both, used partially to replace the total cement used in the concrete mix.

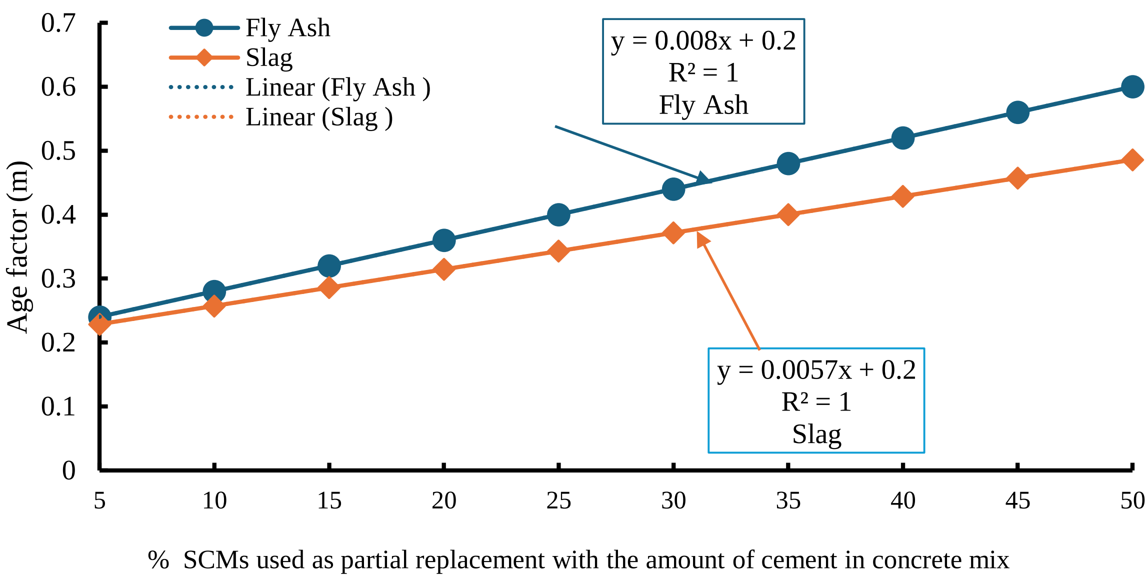


Fig. 4 The relationship between different values of age factors (m) and their corresponding percentages of SCMs is used as a partial replacement for the total amount of cement used in the concrete mixes

Table 1. Polynomial functions for predicting age factors for two types of SCMs used in concrete mixes for RC structures

Various SCMs	Age factor (m)
FA	(0.008×%FA)+0.2
SG	(0.0057×%SG)+0.2

Where % FA and % SG vary from 5 to 50.

The average chloride diffusion coefficient (D_m) at a particular time (t) (m^2/s) is calculated using Equations 3 and 4 [39].

$$D_m = \frac{D_{ref}}{1-m}\left(\frac{t_{ref}}{t}\right)^m \qquad t < t_R \tag{3}$$

$$D_m = D_{ref}\left[1 + \left(\frac{t_R}{t} \times \frac{m}{1-m}\right)\right]\left(\frac{t_{ref}}{t_R}\right)^m \qquad t \geq t_R \tag{4}$$

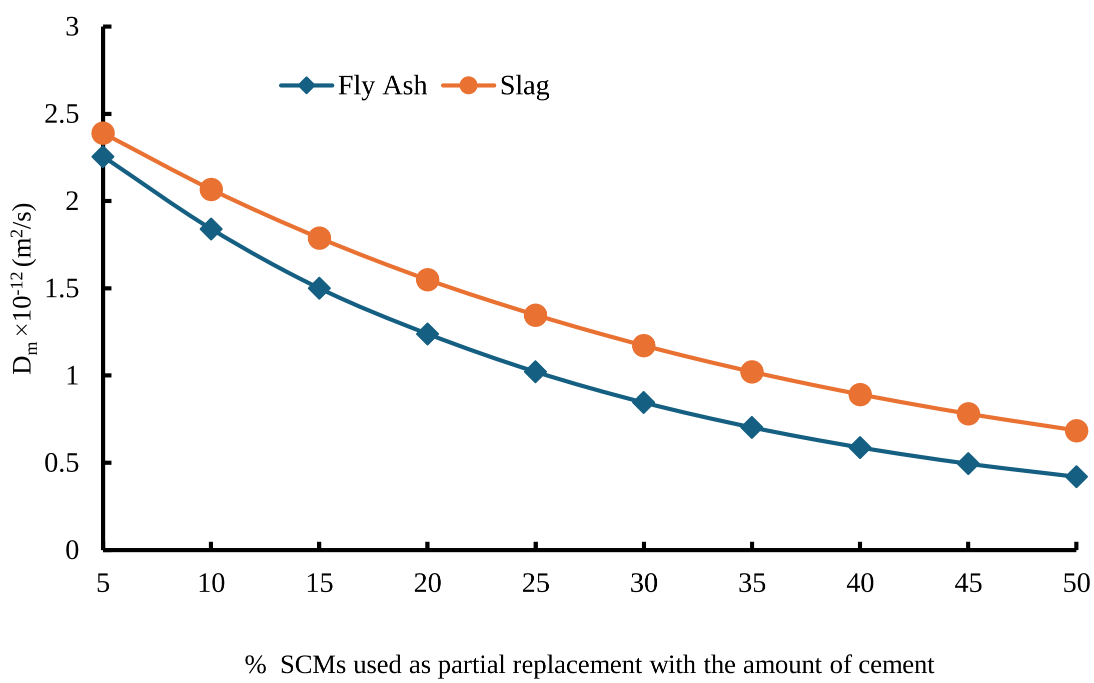
Where m is the age factor, t_R=30 years, t_{ref}=28 days, D_m is the average chloride diffusion coefficient at a particular time (m^2/s), and (t) is time (years).

The diffusion coefficient of chloride ions in geopolymer concrete can generally be described by Fick's second law for variable diffusion coefficients based on the percentages of precursor materials in the geopolymer concrete mix. Calculating the chloride diffusion coefficient over time is expressed in Equation (5).

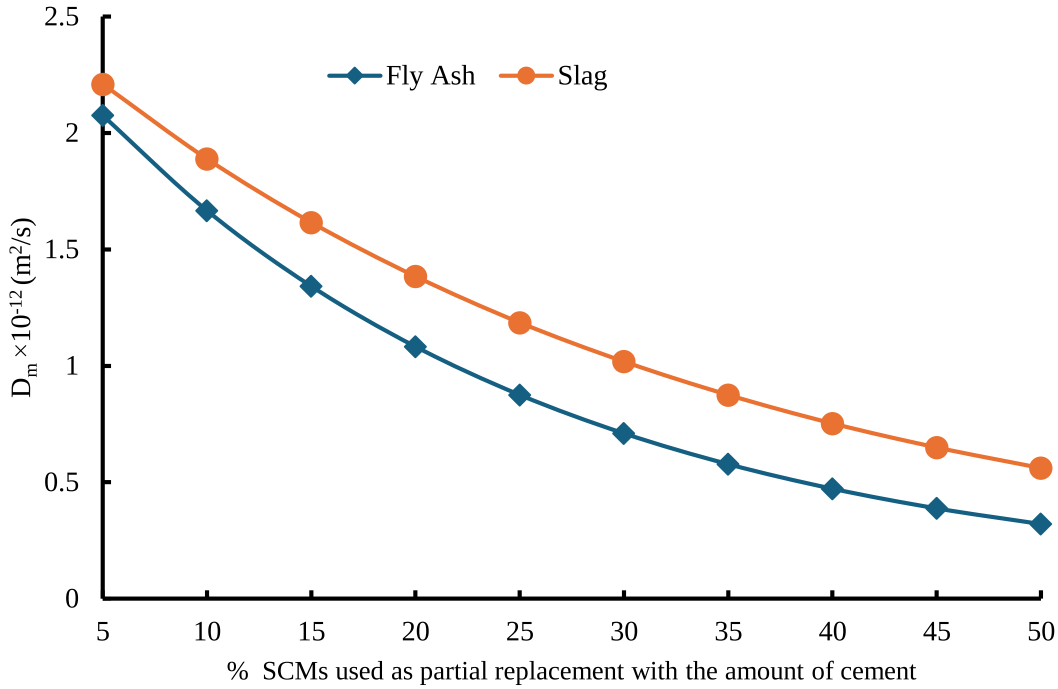
$$D(t) = D_o \times \left(\frac{t_o}{t}\right)^m \tag{5}$$

Where: (D_o) is the apparent chloride diffusion coefficient at reference time (t_o); (t_o) is the reference time (28 days, which is equivalent to 0.0767 years); (t) is the exposure time in years, and m is the age factor, and D(t) is the chloride diffusion coefficient dependent on time and material properties.

Figure 5 shows the decreasing trend of the average chloride diffusion coefficients versus the percentages of the FA or SG used in concrete mixes, in different years. FA significantly decreases the average chloride diffusion coefficient of chloride ions in concrete as the percentage of FA in the concrete blend increases compared to the SG, which acts as SCM with the total amount of cement used in the concrete mix in various years. According to Oh and Jang [40], the diffusion coefficient of chloride ions decreases by 15%–50% in the presence of FA in the concrete mix. This research sets the water-to-cement ratio at 0.4 for a concrete mix used in the RC deck to assess the probability of chloride-induced corrosion initiation due to the application of a certain amount of chloride concentration on the top part of the RC deck versus various percentages of FA or SG used as SCMs with the total amount of cement used in various concrete mixes. Finally, it was observed from Figure 5 and Table 2 that the relationship between various percentages of either FA or SG used as SCMs ranging from (5% to 50%) in the concrete mixes and the corresponding average chloride diffusion coefficients is a decreasing exponential function in different years, based on the coefficient of determination (R^2=0.99) between the data points plotted on x-axis and y-axis.



(a)



(b)

Fig. 5 Average chloride diffusion coefficient (D_m) values versus corresponding percentages of SCMs (e.g., FA, SG) are used as SCMs with the total amount of cement used in the concrete mixes in different years. (a) T =50 Years, and (b) T=100 Years.

Table 2. Exponential functions for predicting the average chloride diffusion coefficients across various FA and SG percentages used as SCMs in concrete mixes at different ages

SCMs	Average Chloride Diffusion Coefficient (D_m) (m^2/s)	
	T=50 Years	T=100 Years
FA	$D_m = 3 \times 10^{-12} \times e^{-0.037\times(\% FA)}$ (R^2=0.99)	$D_m = 3 \times 10^{-12} \times e^{-0.042\times(\% FA)}$ (R^2=0.99)
SG	$D_m = 3 \times 10^{-12} \times e^{-0.028\times(\% SG)}$ (R^2=0.99)	$D_m = 3 \times 10^{-12} \times e^{-0.03\times(\% SG)}$ (R^2=0.99)

Where: D_m: average chloride diffusion coefficient (m^2/s), %FA, and %SG vary from 5 to 50.

2.2. Performance Function for Chloride-Induced Corrosion Initiation Model

Methodology Approach: The MCS method is widely used for assessing the likelihood of either carbonation or chloride-induced corrosion due to its accuracy [37, 41]. Recognized for solving problems by defining random variables, the method generates large samples for each random variable, dealing with uncertainty, ensuring an accurate probability distribution for the phenomena under consideration [42-45]. This research uses 100,000 samples to simulate different scenarios, thereby determining the probability of chloride-induced corrosion initiation versus various percentages of FA or SG used as SCMs in concrete mixes subjected to various maximum temperature values at different times of chloride exposure.

Chloride Ingress Modeling: The chloride ingress into RC bridge decks due to deicing salts is transported by several mechanisms [46]. A modified version of Fick's 2nd law is utilized in modeling chloride transport to the steel rebars (ionic diffusion process).

Once the chlorides have penetrated the concrete cover and reached the steel rebars, and their concentration exceeds the threshold level, corrosion initiation begins. To predict the ingress of chlorides into a concrete member exposed to the periodic application of deicing salts, diffusion can be assumed to be the governing transport mechanism [47]. Using Fick's second law of diffusion for the chloride concentration profile.

Using Equation 6, one can calculate the chloride concentration at a certain steel level and time, [37, 48]. The chloride diffusion coefficient (D) used in this model is a constant value, as shown in Equation 6.

$$C(x,t) = C_o\left[1 - erf\left(\frac{x}{2\sqrt{D \times t}}\right)\right] \quad (6)$$

Where: C_o is the chloride concentration at the concrete surface (kg/m^3), and x is the depth of the concrete cover (m).

Performance Function Description: The performance function is generated by calculating the difference between a term equivalent to a resistance (C_{th}) and a term equivalent to the load effect ($C_{x,t}$). The parameter $C_{x,t}$ is a function of several variables.

Final Formulation: The corrosion initiation performance function comprises three random variables: concrete cover (x), surface chloride concentration (C_o), and chloride threshold (C_{th}), as shown in Equation 7. The allowable amount of chloride ions coming from the original mix ingredients is specified as a percentage of the total cement content used (C_{th}=0.15% weight of cement) according to CSA A23.1-94 and ACI 318-89, especially for RC structures. Moreover, the corrected diffusion coefficient D_c is considered to change over time, factoring in maximum temperature, equivalent maturation time of concrete, and relative humidity impacts, as shown in Equation 8.

$$G(C_o, x, C_{th}) = C_{th} - C_o\left[1 - erf\left(\frac{x}{2\sqrt{D_c \times t}}\right)\right] \quad (7)$$

Where: C_{th} is the chloride threshold (kg/m^3); C_o is the chloride concentration applied on the top surface of the concrete cover (kg/m^3); x is the concrete cover thickness (m); D_c is the corrected chloride diffusion coefficient including the effect of temperature, maturation time of concrete, and relative humidity (m^2/s); and t is time (years).

In this research, chloride diffusion coefficient values vary over time depending on the exposure conditions of maximum temperature levels and the properties of concrete that include various percentages of SCMs. Moreover, the impact of maximum temperature on the chloride diffusion coefficient is considered for the high- and low-emission scenarios based on the RCPs. Furthermore, relative humidity is assumed to be a constant value over time in this research, which affects the chloride diffusion coefficient by influencing the moisture content of concrete.

2.3. Determination of the Corrected Chloride Diffusion Coefficient (D_c)

Other scientists utilized the corrected chloride diffusion coefficient at a certain type of concrete based on the average chloride diffusion coefficient, considering several influential factors, such as maximum temperature, equivalent maturation time of concrete, and relative humidity in the probabilistic corrosion initiation model. However, in this research, the corrected chloride diffusion coefficient is illustrated in Equation 8 based on the average chloride diffusion coefficient conducted using Equations 3 and 4, as referenced by [23].

$$D_c = D_m \times f_1(T) \times f_2(te) \times f_3(RH) \quad (8)$$

Where D_m (m^2/s) and D_c (m^2/s) are the average chloride diffusion coefficient and the corrected chloride diffusion coefficient changing over time, respectively; $f_1(T)$ is the factor that represents the influence of temperature according to [49-52] on chloride diffusion coefficient; $f_2(t_e)$ is the factor that represents the influence of the equivalent maturation time based on the ξ factor which indicates how much diffusivity decreases over time, ranging from 0 to 1 (see Figure 6), the ξ parameter is assumed to equal to 1 for concrete with a low water-to-cement ratio in this research, and $f_3(RH)$ is the factor that represents the influence of relative humidity on chloride diffusion coefficient [53].

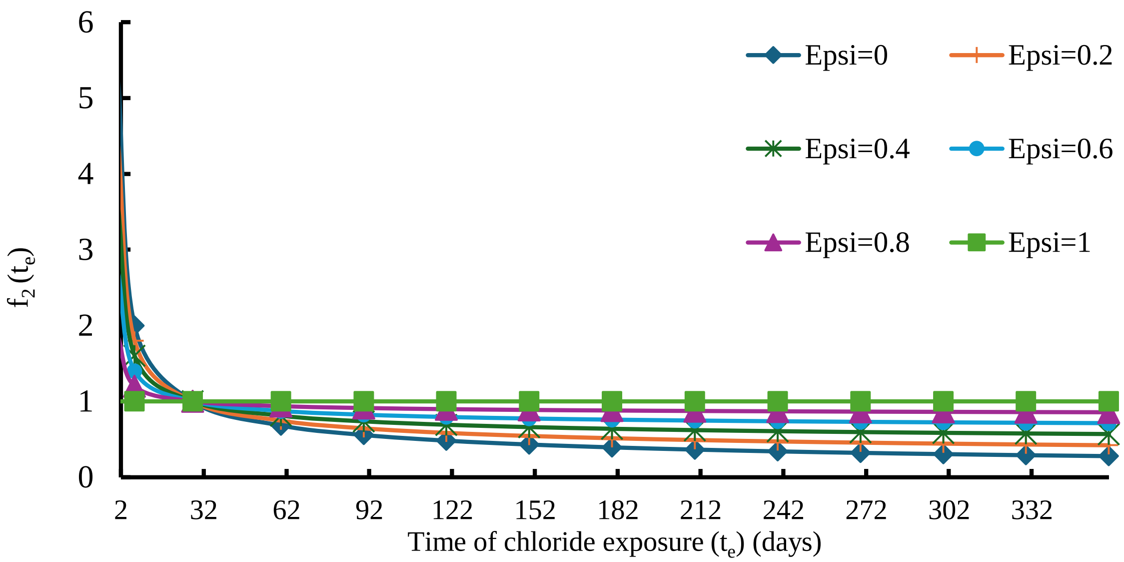


Fig. 6 Factors for the equivalent maturation time of concrete versus the corresponding time of chloride exposure

The corrosion initiates at the time (T_i) at which the concentration of chlorides at the steel level exceeds the chloride threshold (C_{th}), and it is calculated using Equation 9, where the average chloride diffusion coefficient does not consider the impact of any environmental factors.

$$T_i = \frac{x^2}{4 \times D_m \times \left[erf^{-1} \times \left(1 - \frac{C_{th}}{C_o}\right)\right]^2} \tag{9}$$

For RC members subjected to the impact of the maximum temperature, relative humidity levels, and varying chloride concentration, the corrosion initiation time can be calculated using Equation 10.

$$T_i = \frac{x^2}{4 \times D_m \times f_1(T) \times f_2(t_e) \times f_3(RH) \times \left[erf^{-1} \times \left(1 - \frac{C_{th}}{C_s}\right)\right]^2} \tag{10}$$

2.3.1. Maximum Temperature Impact

The impact of the maximum temperature, ranging from 25°C to 50°C, which represents the low, intermediate, and high emission scenarios for the temperature in current and future projections for Toronto City, on the probability of the chloride-induced corrosion initiation was evaluated in this research for an RC deck made of different percentages of SCMs. CCCR [54] deduced a comprehensive analysis for the projection of the maximum temperature for different cities in Canada at different RCPs. The CCCR presented forecasts for Toronto's maximum temperatures from 2010 to 2100. The factors of the maximum temperature were obtained in relation to the corresponding maximum temperature levels, which reflect the chloride diffusion coefficient for concrete used in RC decks containing SCMs at a particular time.

2.3.2. Relative Humidity's Impact

The factor that represents the effect of relative humidity on the chloride diffusion coefficient is illustrated in previous research [53]. Once the relative humidity (%) reaches a value of less than 50%, its corresponding factors diminish substantially compared to values within the 55% to 100% range. This research utilizes a current relative humidity value of 70% (RH=70%), combining its effect with various maximum temperature values applied on the top part of the RC deck in the probabilistic chloride-induced corrosion initiation model.

2.4. Validation of the Probabilistic Chloride-Induced Corrosion Initiation Model

The proposed probabilistic approach aims to predict the probability of chloride-induced corrosion initiation. Its application is demonstrated on a real RC deck exposed to deicing salts. The input parameters are adapted from field data, as documented by Saassouh and Lounis [37]. The log-normal mean (μ_{ln}) and standard deviation (σ_{ln}) can be calculated from the original mean and standard deviation [55, 56]. Saassouh and Lounis [37] conducted projections of the probability of corrosion initiation for the RC deck subjected to deicing salts using the Monte Carlo Simulation (MCS). Moreover, all the random variables follow a log-normal distribution function. Saassouh and Lounis [37] found that the probability of corrosion initiation at a specific time, especially at 23 years and 10 months, was around 45%. The MCS utilized consisted of 100,000 simulations at every interval of time. Finally, it was found that the results of the probabilistic corrosion model coincide with the results conducted by Saassouh and Lounis [37], which confirms the robustness and accuracy of the probabilistic model in predicting the probability of corrosion initiation across various maximum temperature levels, for concrete mixes including different percentages of SCMs, in this research.

3. Analysis of Results

3.1. Impact of Varying Maximum Temperature Values on the PCI across Diverse SCMs

The Monte Carlo Simulation, utilizing 100,000 simulations, provided a thorough analysis of the probability of chloride-induced corrosion initiation under varying conditions. The mean of the top concrete cover used for the RC deck equals 70 mm, and the coefficient of variation is 20%, following the log-normal distribution function. A relative humidity level is set at 70% in the analysis. For consistency, the average chloride diffusion coefficient (D_m) is considered to change over different percentages of SCMs used in concrete mixes in other years. The study examined the effect of various percentages of the SCMs used in the concrete mixes on the PCI for a concrete mixture containing 460 kg/m^3 of cement within the structural framework of reinforced concrete. With the W/C ratio set at 0.4, the average diffusion coefficient (D_m) was determined. The chloride threshold was capped at 0.15% of the weight of the cement in line with the CSA A23.1-14 standards, the statistical mean value for the C_{th} was set at 0.7 kg/m^{3,} and the coefficient of variation is 20%, following the log-normal distribution function. There is enormous variability in the surface chloride concentration applied on the deck of the RC bridge between one region and another. Weyers et al. [57] classified the corrosive environments surrounding decks into four categories according to the surface chloride concentration. Moreover, within the same structure, the coefficient of variation of the chloride concentrations could be equal to 30%, according to Bentz [58]. The mean chloride concentration (C_o) applied on the RC deck’s surface equals 6 kg/m^3, linked to deicing salts [59, 60], with a coefficient of variation of 30% following the log-normal distribution function. A constant relative humidity of 70% was maintained throughout the study.

The probability of corrosion initiation due to the effect of the chloride concentration of 6 kg/m^3 is determined using the MCS method versus the effect of the maximum temperature values ranging from 25°C to 50°C on the chloride diffusion coefficient at different percentages of FA. SG was used as SCMs, with the amount of cement used in the concrete mixes as shown in Figure 7. Moreover, the effect of the relative humidity (R=70%) was considered on the corrected chloride diffusion coefficient in this probabilistic model, and the concrete cover used in the model is assumed to be equal to 70 mm. When the maximum temperature changes from 25°C to 50°C, it was deduced that the PCI increased sharply from (0.57 to 0.99) and from (7.7×10^{-4} to 0.42) for concrete mixes including 10% FA and 50% FA, respectively, as illustrated in Figure 7 (a). Figure 7 (b) shows that the PCI also increased from (0.66 to 0.99) and from (0.021 to 0.80) for concrete mixes including 10% SG and 50% SG, respectively, when the maximum temperature rose from 25°C to 50°C.

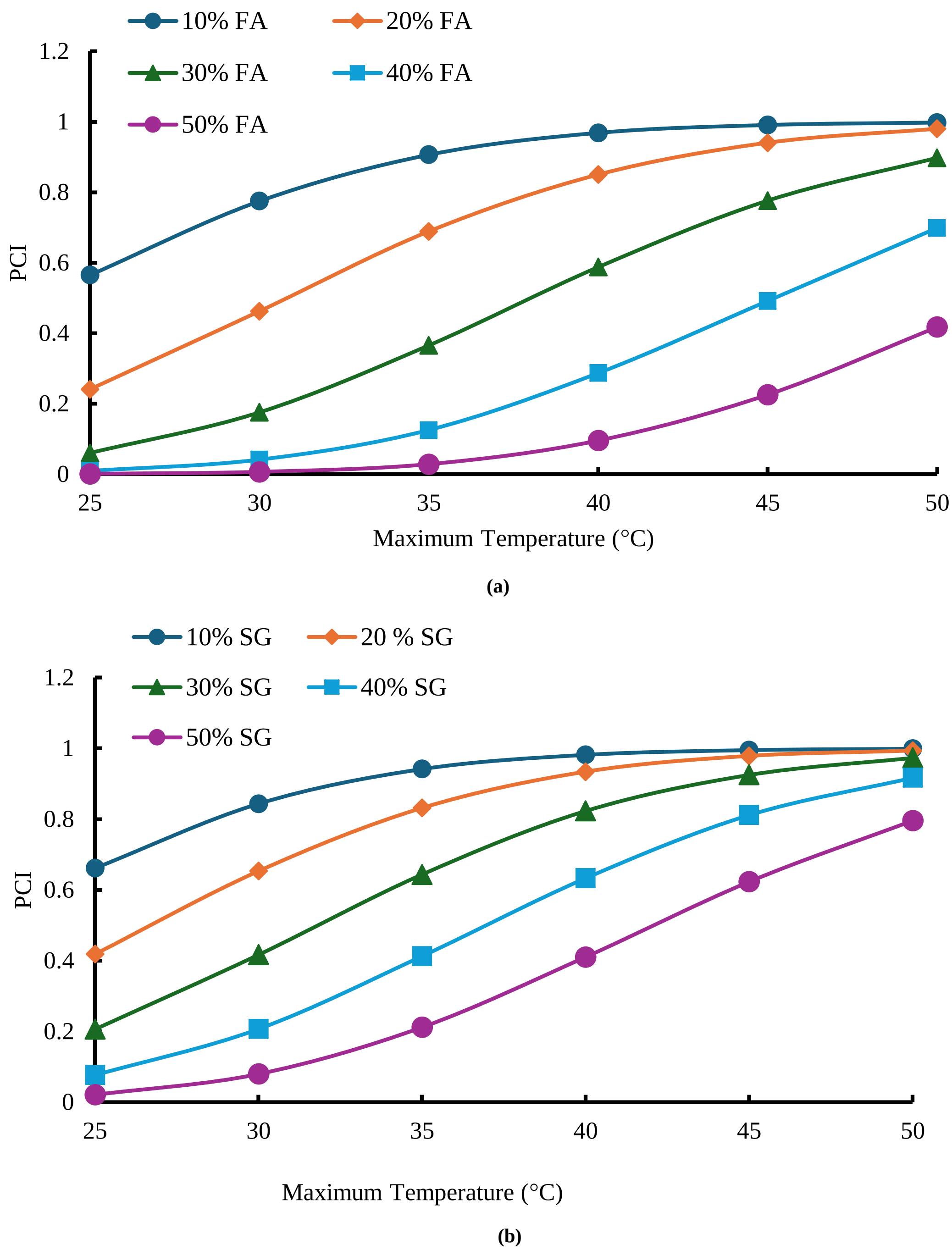


Fig. 7 Impact of various maximum temperatures on the probability of chloride-induced corrosion initiation at different SCMs used in concrete mixes for RC decks at T=50 years. (a) FA, and (b) SG.

The change in the PCI values from 10% to 50%, whether using FA or SG as SCMs in the concrete mixes for the RC decks, is significant when the RC deck is subjected to various maximum temperature values, as shown in Table 3.

Table 3. Change in the probability of corrosion initiation when the percentage of SCMs changed from 10% to 50% at various maximum temperature values at T 50 years

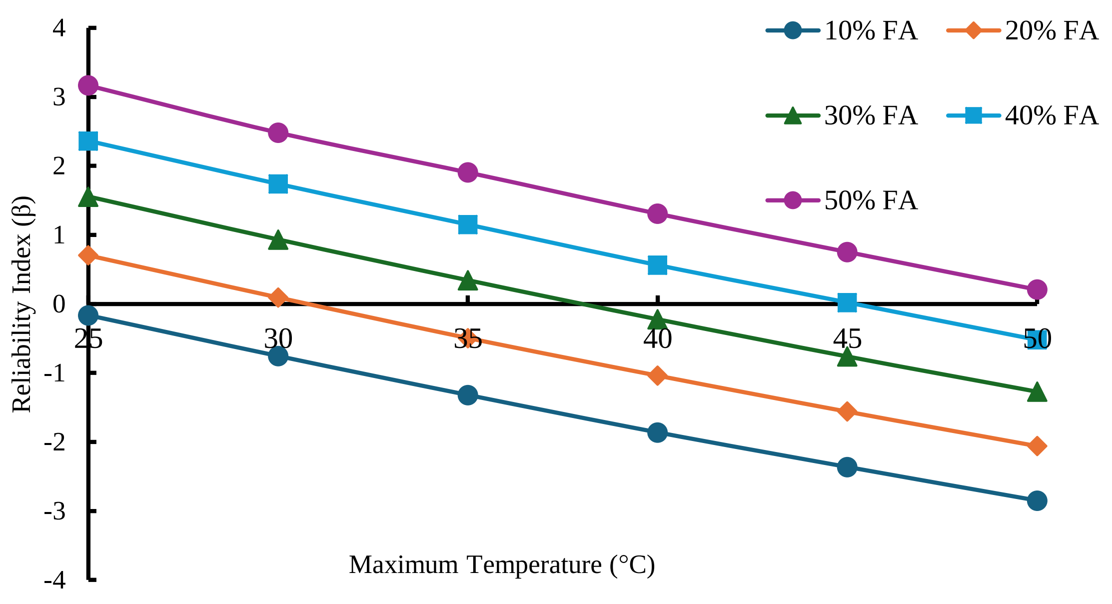
Maximum Temperature (°C)	Change in PCI from 10% FA to 50% FA	Change in PCI from 10% SG to 50% SG
25	0.57 to 7.7×10^{-4} Δ=0.56	0.66 to 0.02 Δ=0.64
30	0.78 to 6.5×10^{-3} Δ=0.77	0.84 to 0.08 Δ=0.76
35	0.91 to 0.03 Δ=0.88	0.94 to 0.21 Δ=0.73
40	0.97 to 0.10 Δ=0.87	0.98 to 0.41 Δ=0.57
45	1.0 to 0.23 Δ=0.77	1.0 to 0.62 Δ=0.37
50	1.0 to 0.42 Δ=0.58	1.0 to 0.80 Δ=0.20

Where Δ is the difference between the PCI that corresponds to 10% SCM and the PCI that corresponds to 50% SCM.

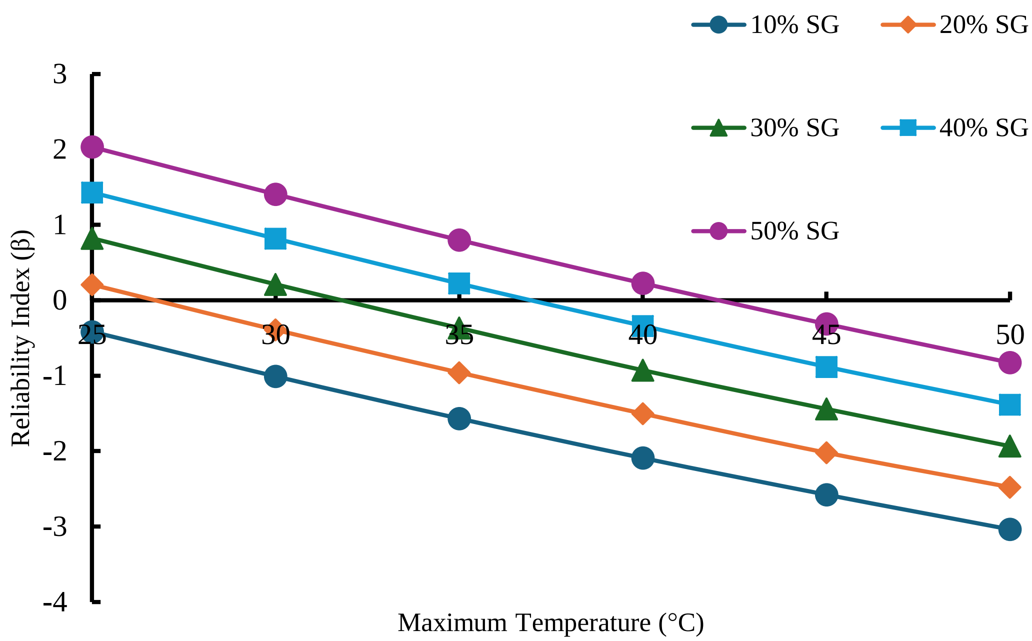
The reliability index was calculated from the probability of corrosion versus the effect of the maximum temperature values ranging from 25°C to 50°C applied on the RC deck at different percentages of FA and SG used as SCMs, with the amount of cement used in the concrete mixes, as shown in Figure 8. Moreover, the impact of the relative humidity (R=70%) was considered on the corrected chloride diffusion coefficient in this probabilistic model, and the top concrete cover used in the model is assumed to be equal to 70 mm.

It was observed that the relationship between the effect of the maximum temperature ranging from 25°C to 50°C applied on the RC deck and the corresponding reliability index is a descending linear relationship at various percentages of the SCMs (e.g., FA or SG) used in the concrete mixes, as shown in Figure 8 and Table 4.

Furthermore, linear polynomial functions were deduced as a function of the maximum temperature levels ranging from (25°C to 45°C) using the least squares method between the data points plotted on the x-axis (maximum temperature(T)) and the y-axis (reliability index(β)), as illustrated in Table 4.



(a)



(b)

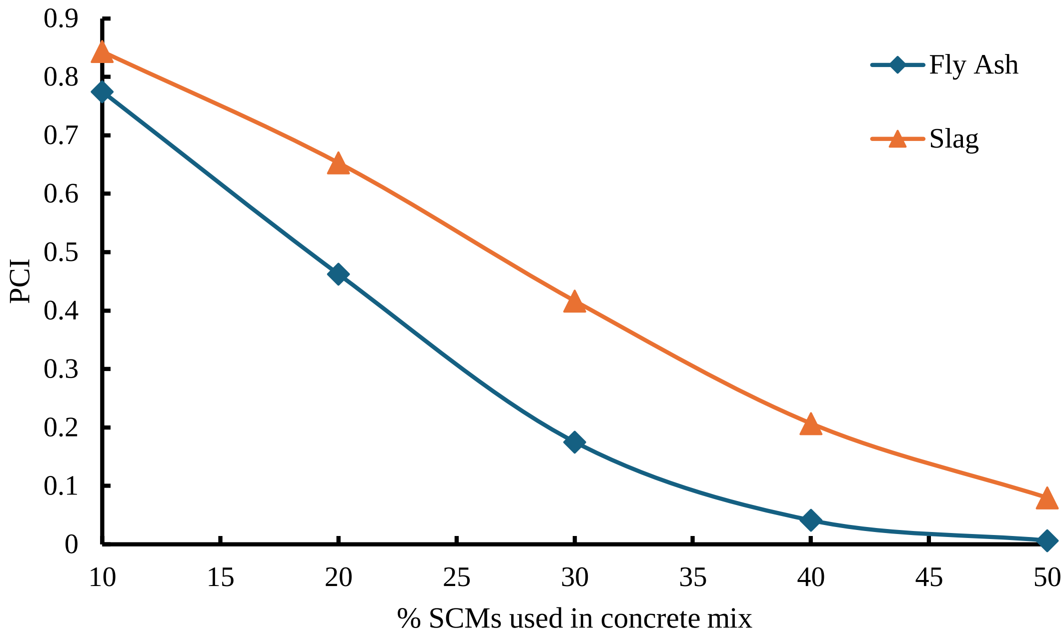
Fig. 8. Impact of various maximum temperatures on the reliability index at different SCMs used in concrete mixes for RC decks at T=50 years. (a) FA, and (b) SG.

Table 4. Prediction of the reliability index as a function of maximum temperature values ranging from 25°C to 50°C at various percentages of SCMs used in the RC deck

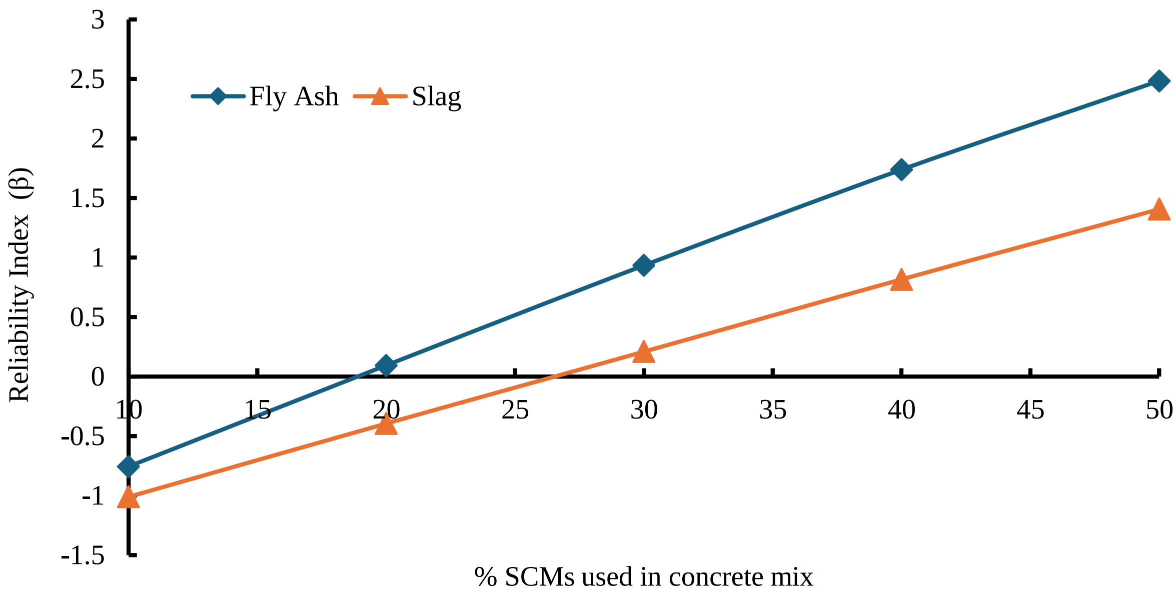
% SCMs	FA	SG
10%	β=(-0.1073×T) + 2.4729 (R^2 = 0.99)	β= (-0.1047× *T*)+2.143 (R^2 = 0.99)
20%	β= (-0.1104×T) + 3.4139 (R^2 = 0.99)	β= (-0.1077×T) + 2.8486 (R^2 = 0.99)
30%	β= (-0.113×T) + 4.3348 (R^2 = 0.99)	β= (-0.1102×T)+ 3.5256 (R^2 = 0.99)
40%	β= (-0.1151×T) + 5.2026 (R^2 = 0.99)	β= (-0.1127×T) + 4.2046 (R^2 = 0.99)
50%	β= (-0.1176×T) + 6.0487 (R^2 = 0.99)	β= (-0.1145×T)+ 4.8477 (R^2 = 0.99)

Where β is the reliability index, and T is the maximum temperature ranging from 25°C to 50°C.

For the RC deck subjected to a maximum temperature of 30°C affecting the chloride diffusion coefficient in the probabilistic model, it was observed that the PCI reached maximum values of 0.84 and 0.78 at 10% of SG and 10% of FA, respectively, as SCM in the concrete mix for the RC deck, as shown in Figure 9 (a). However, it was deduced that the PCI reached minimum values of 0.08 and 0.007 at 50% of SG and 50% of FA, respectively, as SCM in the concrete mix for the RC deck, as shown in Figure 9 (a). Figure 9 (b) shows the reliability index obtained from the MCS method across various percentages of SCMs (i.e., FA or SG) used in the concrete mixes for the RC decks subjected to a maximum temperature of 30°C at the age of 50 years.



(a)



(b)

Fig. 9 Impact of various percentages of SCMs used in concrete mixes for RC decks on the probability of corrosion initiation and reliability index at a maximum temperature of 30°C at the age of 50 years. (a) Probability of Corrosion Initiation, and (b) Reliability Index.

3.2. Estimating the Time to Corrosion Initiation (T_i) Due to Chloride Ingress

The prediction of the time of corrosion initiation, represented as (T_i), is conducted using Equation 9 according to Saassouh and Lounis [37] and Lounis and Amleh [61]. The concrete cover, chloride concentration, and chloride threshold used in this study were assumed to be equal to 70 mm, 6 kg/m^{3,} and 0.7 kg/m^3, respectively.

If the average diffusion coefficient does not consider the effect of the maximum temperature, the corrosion initiation time can be calculated using Equation 11, depending on the age factor corresponding to the percentages of SCM used in the concrete mix. However, in Equation 12, the average diffusion coefficient considers the effect of the maximum temperature on the corrosion initiation time.

$$T_i = \left[\frac{x^2}{4 \times \frac{D_{ref}}{1-m}\left(\frac{28}{365}\right)^m \times \left[erf^{-1}\left(1-\frac{C_{th}}{C_o}\right)\right]^2 \times 31536 \times 10^3}\right]^{\frac{1}{1-m}} \quad t < t_R \tag{11}$$

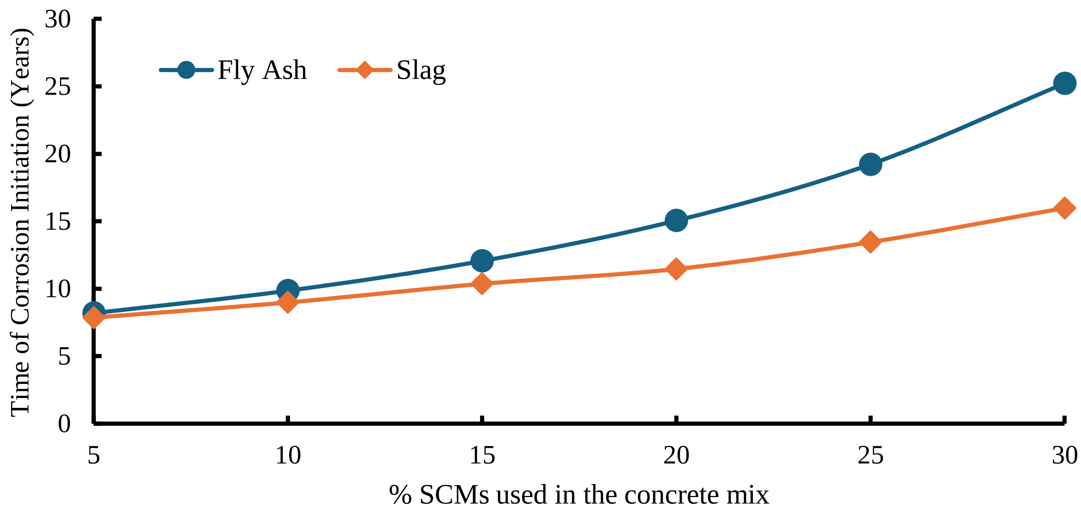
$$\mathbf{T_i} = \left[\frac{\mathbf{x^2}}{\mathbf{4} \times \frac{\mathbf{D_{ref}}}{\mathbf{1-m}}\left(\frac{\mathbf{28}}{\mathbf{365}}\right)^{\mathbf{m}} \times \mathbf{f_1(T)} \times \left[\mathbf{erf^{-1}}\left(\mathbf{1}-\frac{\mathbf{C_{th}}}{\mathbf{C_o}}\right)\right]^2 \times \mathbf{31536} \times \mathbf{10^3}}\right]^{\frac{1}{1-m}} \quad \mathbf{t < t_R} \tag{12}$$

The time of corrosion initiation was determined using Equation 12, considering the impact of the maximum temperature as shown in Figure 10 (a)-(c). At a maximum temperature of 25°C, when the ratio of SCMs increased from 5% to 30% in the concrete mix, it was deduced that the corrosion initiation time was delayed from 7.85 years to 15.97 years for SG. For FA used as SCMs, it was observed that the corrosion initiation time was delayed from 8.20 years to 25.22 years, as shown in Figure 10 (a). Furthermore, it was observed that adding 30% of SCMs, compared to 5% of SCMs, delayed the time of corrosion initiation by 8.1 years and 17 years for SG and FA, respectively, when the chloride diffusion coefficient considered the impact of the maximum temperature of 25°C and 6 kg/m^3 of external chloride concentration applied on the top part for RC deck.

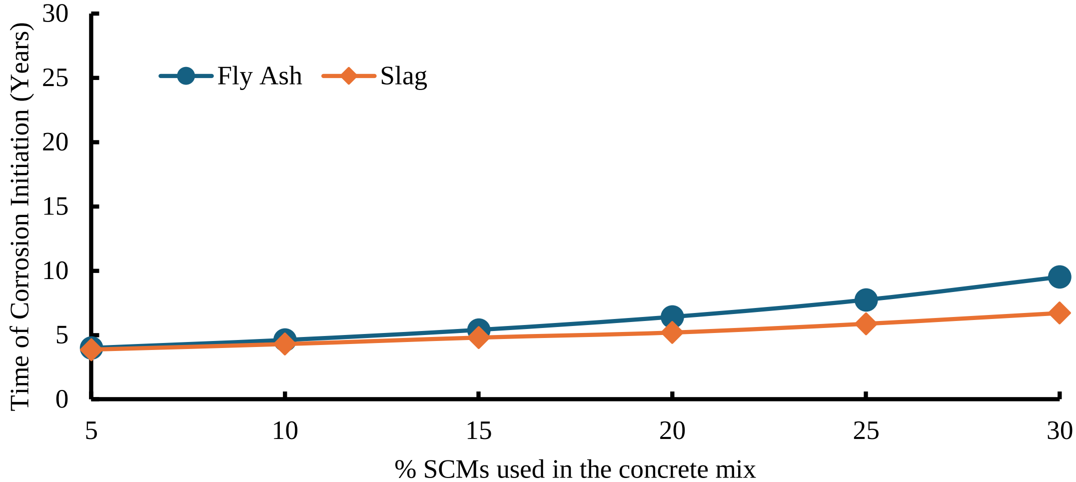
At a maximum temperature of 35°C, when the ratio of SCMs increased from 5% to 30% in the concrete mix, it was observed that the corrosion initiation time changed slightly from 4.0 to 9.52 years, respectively, for FA. For SG used as SCMs, it was deduced that the corrosion initiation time changed from 3.9 years to 6.72 years, as shown in Figure 10 (b). It was deduced that adding 30% of SCMs compared to 5% of SCMs delayed the time of corrosion initiation by 5.52 years and 2.82 years for FA and SG, respectively, when the chloride diffusion coefficient was considered, with the impact of the maximum temperature of 35°C and 6 kg/m^3 of external chloride concentration applied on the top part of the RC deck.

At a maximum temperature of 45°C, when the ratio of SCMs increased from 5% to 30% in the concrete mix, it was observed that the corrosion initiation time changed slightly from 2.0 to 3.80 years, respectively, for FA. For SG used as SCMs, it was deduced that the corrosion initiation time changed from 1.98 to 2.97 years, as shown in Figure 10 (c). It was deduced that adding 30% of SCM compared to 5% of SCM delayed the time of corrosion initiation by 1.80 years and 1 year for FA and SG, respectively, when the chloride diffusion coefficient was considered, with the impact of the maximum temperature of 45°C and 6 kg/m^3 of external chloride concentration applied on the top part of the RC deck.

For the chloride diffusion coefficient that does not consider the impact of the maximum temperature, and when the SCM's ratio increased from 5% to 30% in the concrete mix, it was observed that the time of corrosion initiation changed sharply from 9.63 to 31.40 years, respectively, for FA. For SG used as SCMs, it was deduced that the corrosion initiation time changed from 9.20 years to 19.40 years, as shown in Figure 10 (d). Finally, it was deduced that adding 30% of SCM compared to 5% of SCM delayed the time of corrosion initiation by 21.80 years and 10.20 years for both FA and SG, respectively.



(a)



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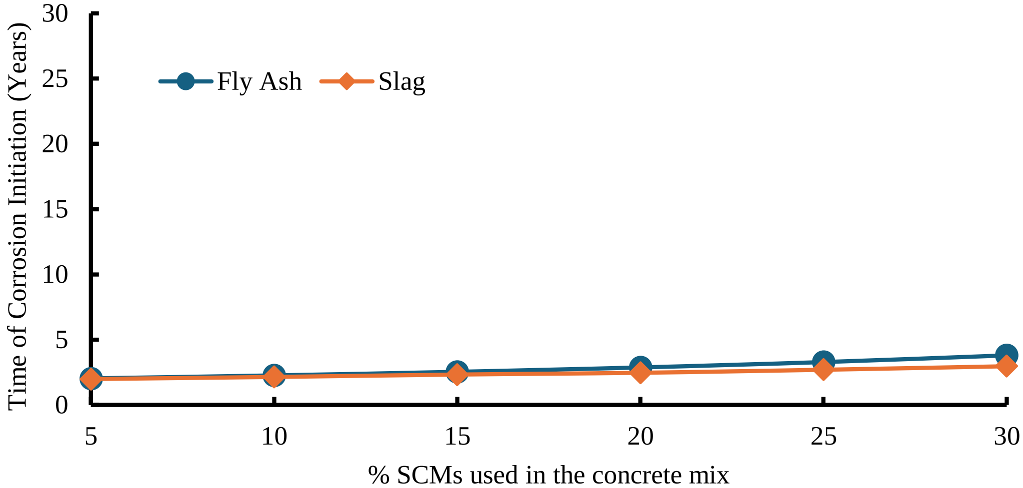
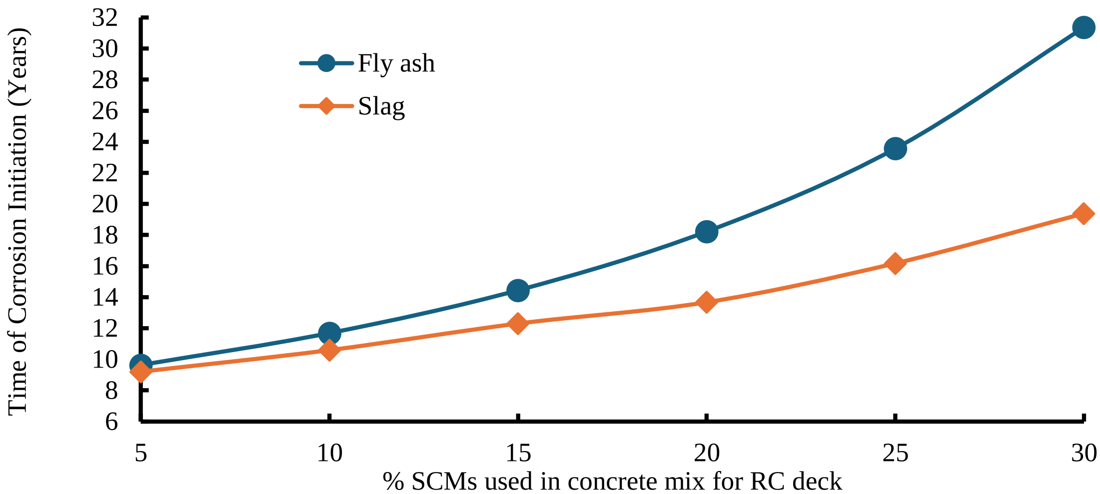


(c)



(d)

Fig. 10 Impact of various percentages of SCMs used in concrete mixes for RC decks on the corrosion initiation time at various maximum temperature values. (a) T 25 °C, (b) T= 35°C, (c) T 45 °C, and (d) Without the effect of the maximum temperature.

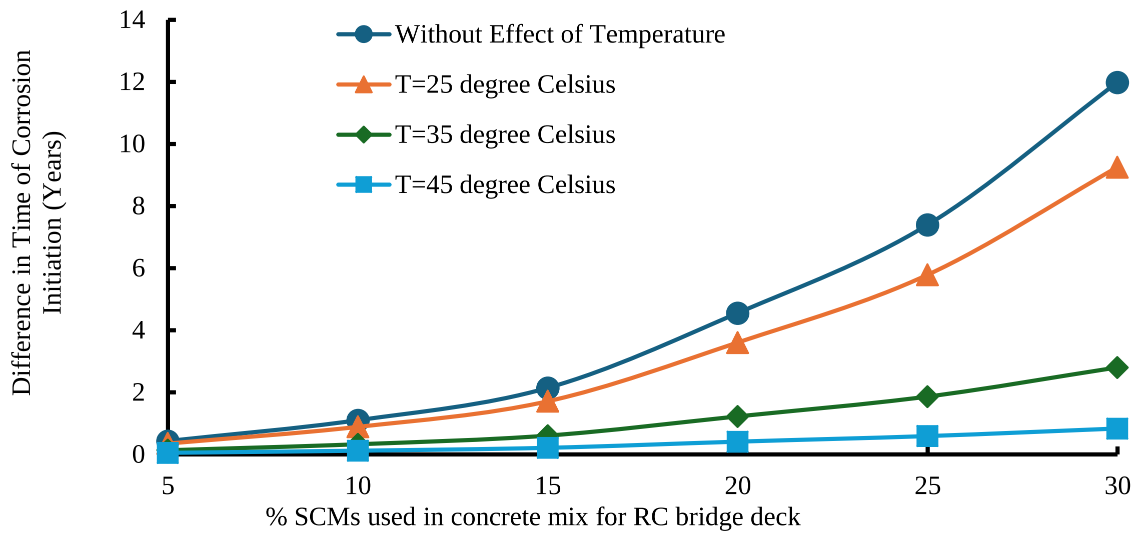


Fig. 11 The difference in corrosion initiation time between FA and SG across various corresponding percentages of SCMs used in concrete mixes for RC members at different maximum temperature values.

The difference in time of corrosion initiation between the same corresponding percentage of FA and SG is plotted at various maximum temperature values, as shown in Figure 11. The difference in time of corrosion initiation between FA and SG used as SCMs is maximum at a percentage of 30% for the model that does not consider the effect of the maximum temperature and the other model that considers the impact of a maximum temperature of 25°C on the chloride diffusion coefficient and minimum at a percentage of 5% at maximum temperature value of 45°C as shown in Figure 11.

4. Conclusion

The urban landscape of a North American city located in the province of Ontario, Canada, is susceptible to the severe forces of climate change and its varied impacts. Its location is ideal for this comprehensive time-dependent reliability study. This study examines the impact of climate change on concrete durability. Utilizing the Monte Carlo simulation method across diverse RCPs to gauge the consequences of severe maximum temperature levels due to climate change on the likelihood of chloride-induced corrosion initiation within the confines of Ontario City in Canada. The percentages of FA and SG used as SCM in the concrete mixes for the RC deck vary from 10% to 50%, with the total amount used in various mixes. Additionally, the water-to-binder ratio in the mix is adjusted to 0.4. Moreover, the corrected chloride diffusion coefficient used in the performance function considered only the impact of the maximum temperature on conducting PCI at various percentages of either FA or SG used in the concrete mixes for the RC decks.

The primary conclusions drawn from the analysis are:

- The relationship between average chloride diffusion coefficients across various percentages of either FA or SG, ranging from 5% to 50% used as SCMs in the concrete mixes, is a decreasing exponential function in different years.
- The relationship between the effect of the maximum temperature values ranging from 25°C to 50°C applied on the top part of the RC decks and the corresponding reliability index conducted from the MCS method is a descending linear relationship (1st-degree polynomial function) obtained from the least squares regression method, across various percentages of the SCM (e.g., FA or SG) used in the concrete mixes for RC decks.
- For the RC deck subjected to a maximum temperature value of 30°C affecting the chloride diffusion coefficient in the probabilistic corrosion initiation model, the PCI reached maximum values at 10% for either using SG or FA as SCM in the concrete mix for the RC deck. However, the PCI reached minimum values of 8% and 0.7% at 50% for SG and FA, respectively, which were utilized as SCM in the concrete mixes in the RC decks.
- The impact of 50% for either SG or FA utilized as SCMs in the concrete mixes for the RC deck has a negligible impact on the probability of chloride-induced corrosion initiation (PCI values are approximately equal to zero values) when the diffusion coefficient for chloride considered the impact of the maximum temperature value of 30°C at the age of 50 years of exposure.
- The optimum percentages of the FA and SG utilized separately in the concrete mixes for the RC decks having a mean concrete cover value of 70 mm must be equal to 40% and 47%, respectively, to resist the impact of a mean chloride concentration value less than or equal to 6 kg/m^3 and maximum temperature value ranges from 25°C to 30°C applied on the top part of the RC decks. However, the impact of percentages of SCMs ranges

from 10% to 30% for whether FA and SG are used in the mixes for the RC decks, have a severe impact on the PCI when the RC decks are subjected to a maximum temperature value equal to 30°C or above and a mean chloride concentration of more than or equal to 6 kg/m^3.

- The impact of SG is more significant on both the probability of chloride-induced corrosion initiation and time of corrosion initiation compared to the FA used as a SCM in various concrete mixes, especially when the percentages of SG vary from 10% to 30%, for RC decks subjected to a maximum temperature value of 25°C, 35°C and also without the influence of maximum temperatures.
- The corrosion initiation time versus different percentages of SCM used in the RC decks was deduced. The following conclusions are deduced from the analysis:
  - ✓ Substituting 30% of SCM with the total amount of cement used in the mix com-pared to another mix, including 5% of SCM used in the concrete mix, would lead to delay the time of corrosion initiation due to the application of chloride concentration of 6 kg/m^3 by 21.80 years, and 10.20 years for both FA and SG as SCM in concrete mixes, respectively, when the chloride diffusion coefficient does not consider the impact of the maximum temperature.
  - ✓ At a maximum temperature of 25°C, considering its impact on the chloride diffusion coefficient, substituting 30% of SCM with the amount of cement in the concrete mix compared to 5% would lead to a delay in the time of corrosion initiation by 17 years and 8.1 years for both FA and SG, respectively.
  - ✓ When considering the impact of a maximum temperature of 45°C reflected on the chloride diffusion coefficient, the variation in the time of corrosion initiation values is not highly significant (almost the same) when the percentages of either FA or SG changed from 5% to 30% as SCM in the concrete mixes.

4.1. Limitations and Recommendations

The chloride concentration applied on the external surface of the RC deck is equal to 6 kg/m^3, which is related to the use of deicing salts on the RC bridge deck in North America. Moreover, the mean for the concrete cover used in the probabilistic models is assumed to be 70 mm, following a log-normal distribution function. In addition, the maximum temperature values used in this research vary from 25°C to 50°C to observe their effect on the probability of corrosion initiation across various percentages of SCM used in the concrete mixes for the RC decks. The percentages of FA and SG used as SCM in the mix for the RC deck vary from 10% to 50%. The relative humidity is set at 70%, considering its impact on the chloride diffusion coefficient in most cases.

It is recommended that the percentages of the FA and SG used as SCMs in the mixes for the uncracked RC decks must be limited to 40% and 47% or beyond, respectively, to resist the impact of a mean chloride concentration value less than or equal to 6 kg/m^3 and maximum temperature level ranges from 25°C to 30°C applied on the RC decks having a statistical mean concrete cover value of 70 mm. Moreover, this research recommended not to use SCMs ranging from 10% to 30% for both FA and SG in the mixes for the uncracked RC decks, which would lead to a severe impact on the PCI and time of corrosion initiation when the RC decks are subjected to a maximum temperature value equal to 30°C or above and mean chloride concentration with more than 6 kg/m^3.

Various chloride concentration ranges and relative humidity levels will be studied in future work. Moreover, a typical maintenance optimization management system for the RC bridge decks, which is composed of various SCMs that are subjected to severe maximum temperature levels and chloride concentrations, should be considered in future work.

This research is a wake-up call for engineers and policymakers in North America, especially in some provinces in Ontario, Canada, and beyond. There is a pressing need to recalibrate construction standards, material choices, and maintenance regimes in alignment with the insights from such studies. The connection between climate change and materials science warrants a multidisciplinary approach, and this manuscript serves as a stepping stone in that overarching journey.

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