SENSITIVITY ANALYSIS OF CARBONATION MODELS IN REINFORCED CONCRETE UNDER THE EFFECT OF GLOBAL WARMING

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ABSTRACT

This paper studies and compares the sensitivity of carbonation models to climatic parameters including CO_2 concentration, temperature, and relative humidity. These climatic parameters are observed and projected based on various climate change scenarios proposed by the Intergovernmental Panel on Climate Change (IPCC). The sensitivity analysis is performed on two carbonation models as mentioned in the FIB Bulletin 34 as well as Vietnamese National Standard TCVN 12041:2017 in terms of predicting the carbonation depth of reinforced concrete structures during its service life. The results of our research indicate that the sensitivity of the model specified in TCVN is very low, as the model does not express a correlation with climatic parameters. Under the influence of climate change and global warming, this potentially can lead to inaccurate carbonation depth of reinforced concrete structures that affects its lifespan. Thus, the carbonation model presented in TCVN 12041:2017 needs to be optimized.

PHÂN TÍCH ĐỘ NHẠY CỦA CÁC MÔ HÌNH CACBONAT HÓA TRONG BÊ TÔNG CỐT THÉP DƯỚI ẢNH HƯỞNG CỦA VIỆC NÓNG LÊN TOÀN CẦU

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TỪ KHÓA

Bê tông cốt thép
Cacbonat hoá
Biến đổi khí hậu
Độ ẩm tương đối
Nhiệt độ
Mô phỏng Monte Carlo
Phân tích độ nhạy

TÓM TẮT

Bài báo này nghiên cứu và đánh giá độ nhạy của các mô hình cacbonat hóa đối với các tham số khí hậu, điển hình như nồng độ CO_2, nhiệt độ và độ ẩm tương đối. Các tham số khí hậu trên được đo đạc, dự đoán trên cơ sở các kịch bản biến đổi khí hậu được đề xuất bởi Ủy ban Liên chính phủ về Biến đổi Khí hậu IPCC. Bài báo này phân tích độ nhạy của hai mô hình cacbonat được quy định trong Tiêu chuẩn FIB và TCVN 12041:2017 thông qua việc xác định chiều sâu ăn mòn cacbonat theo thời gian đối với cấu kiện bê tông cốt thép. Kết quả nghiên cứu cho thấy độ nhạy của mô hình được quy định trong TCVN 12041:2017 rất thấp, không phản ánh được mối quan hệ giữa các tham số khí hậu, có thể dẫn đến việc đánh giá sai chiều sâu cacbonat hóa của các kết cấu bê tông cốt thép, ảnh hưởng đến tuổi thọ công trình, đặc biệt dưới ảnh hưởng của biến đổi khí hậu và nóng lên toàn cầu. Vì vậy, cần có những thay đổi phù hợp để tăng tính chính xác của mô hình cacbonat trong TCVN 12041:2017.

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1. Introduction

Reinforced concrete (RC) structures are extensively utilized in construction projects around the world given their high load carrying ability and long term durability; however, the durability and long-term performance of RC are commonly influenced by corrosion of the embedded steel reinforcement, the most important factor of which is carbonation [1]-[3]. Carbonation is caused by an atmospheric CO_2 influx into the cement mix as well as a reaction of CO_2 with calcium hydroxide to generate calcium carbonate, and this decrease in alkalinity from highly alkaline (pH > 12.5) pore solution to almost neutral levels is responsible for the depassivation of steel reinforcement. Carbonation, a slow process that can take a long time, can have strong effects on the structure such as (1) reduction of the steel cross-sectional area, (2) cracking and spalling of the concrete cover and (3) increase in maintenance cost [4], [5]. The carbonation response over natural environmental exposure depends on material properties (e.g. water-cement ratio and porosity) and environmental drivers [6]. Considering global warming, with the advent of climate-warming trends, certain important climate variables such as temperature (T), relative humidity (RH), and atmospheric CO_2 concentration, are projected to undergo substantial alterations of their levels. As a result, carbonation evolution and service-life prediction are increasingly uncertain [7], [8]. Thus for the long-term characterizations of carbonation process, the future scenario can contribute to its integration.

With the aim of effectively managing the degradation of RC structures and providing guidance on maintenance strategies, valid carbonation models that can adapt to real-world environmental changes are very much needed. Various international codes have proposed carbonation models for this. The International Federation for Structural Concrete's Model Code for Service Life Design (FIB Bulletin 34) [9] offers a comprehensive probabilistic framework for assessing service life of concrete structure and has already been applied to study the effects of climate change [1], [6], [10]. In Vietnam, the TCVN 12041:2017 [11] offers a simple and convenient way to calculate carbonation depth. While the carbonation model proposed in FIB Bulletin 34 has been extensively validated and widely applied in recent studies, the model specified in TCVN 12041:2017 remains limited in both application and critical evaluation. Moreover, its effectiveness for long-term predictions under climate change conditions has not been adequately assessed, despite recent studies examining climate impacts on RC durability in Vietnam [12], [13]. This gap raises concerns regarding the reliability and predictive capability of the Vietnamese standard model in evolving environmental conditions. Accordingly, this study addresses this research gap by evaluating the sensitivity of both carbonation models to variations in key environmental parameters associated with global warming. A probabilistic framework based on Monte Carlo simulation is employed to account for the variability of input parameters. The resulting outputs, expressed in terms of carbonation depth, are subsequently analysed to quantify their sensitivity to variations in climatic parameters, thereby enabling a systematic assessment of model responsiveness. This approach provides insight into the capability of each model to predict carbonation-induced service life of RC structures under future climate scenarios.

The paper is organized as follows. Section 2 describes the methodology, including climate change scenarios, environmental projections, and detailed descriptions of the TCVN 12041:2017 and FIB Bulletin 34 carbonation models. Section 3 presents the sensitivity analysis results through Monte Carlo simulations under different climate scenarios. Finally, Section 4 summarizes the findings and proposes recommendations for model improvement.

2. Research Methodology

2.1. Climate change scenarios - Shared Socioeconomic Pathways (SSPs)

In 2023, the IPCC Sixth Assessment Report (AR6) [14] released five Shared Socioeconomic Pathways (SSPs) reflecting different futures with thresholds on greenhouse gas emissions, fossil

fuel extraction and consumption, etc. These scenarios are projected with respect to CO_2, T, and RH - three of the pivotal factors that affect the degree to which carbonation dissolves concrete frames. To enable quantitative comparison of climate change scenarios, they are commonly classified according to radiative forcing levels projected for the year 2100. Radiative forcing represents the net change in energy flux within the Earth's atmosphere, expressed in W/m², and serves as an indicator of the additional energy retained in the climate system. It is formally defined by the IPCC as the change in energy flux at the tropopause, i.e., the boundary between the troposphere and the stratosphere. Based on this framework, four representative forcing pathways are typically considered. The SSP126 scenario corresponds to a low-emission pathway with a radiative forcing of 2.6 W/m². The SSP245 scenario represents an intermediate pathway at 4.5 W/m², while SSP370 reflects a higher-emission trajectory reaching 7.0 W/m². The SSP585 scenario corresponds to the most extreme pathway, with radiative forcing increasing to 8.5 W/m² by 2100. The primary SSP scenarios are included in Table 1.

Table 1. *Climate Scenarios and Radiative Forcing Levels*

Scenarios	Description	2100 Forcing Level (W/m^2)
SSP126	Sustainability	2.6
SSP245	Middle of the road	4.5
SSP370	Middle of the road	7.0
SSP585	Fossil fueled development	8.5

2.2. Projections of temperature, relative humidity, and atmospheric CO_2 concentration under climate change

How climate change might affect carbonation in RC structures is being studied by the three atmospheric parameters, including CO_2 concentration, temperature, and relative humidity. Global atmospheric CO_2 data were collected from 2000 to 2015 and projected through 2100 based on different SSP scenarios [14]. For T and RH, we focus on Hue where it is a typical location for central Vietnam's climate conditions. The projected annual mean temperature (T) and relative humidity (RH) for this city through 2100 were obtained from the World Bank Climate Change Knowledge Portal [15], based on downscaled multi-model ensemble outputs under four Shared Socioeconomic Pathway (SSP) scenarios.

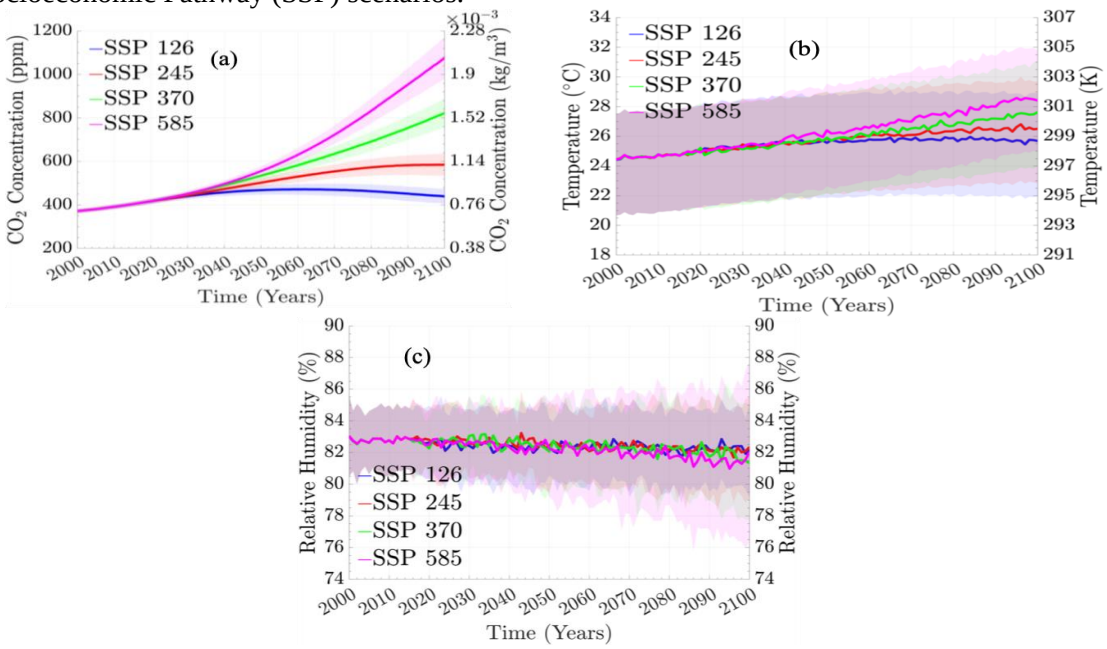

Figure 1. *(a) CO_2 concentration, (b) Temperature, (c) Relative humidity projection in Hue city from 2000-2100*

Figure 1a illustrates global atmospheric CO_2 projections across all four SSP scenarios, with concentrations expressed in two units: parts per million (ppm) on the left vertical axis and the corresponding values in kg/m³ on the right vertical axis. The use of both units ensures consistency with the formulations presented in Section 2.3. The conversion between these units can be expressed as follows: $1\ ppm = 0.0019 \times 10^{-3} kg/m^3$. The data show an increasing trend, but there are differences in magnitude between scenarios. The SSP126 scenario predicts a slight increase in CO_2, reaching approximately $0.85 \times 10^{-3}\ kg/m^3$ by 2100. In contrast, SSP585 projects a sharp increase to roughly $2 \times 10^{-3}\ kg/m^3$, about 2.5 times the 2015 baseline. The shaded bands represent the 5-95 percentiles of the observed values, indicating the uncertainty in these projections.

Local temperature data for Hue shows divergence patterns (Figure 1b). That is, SSP126 forecasts a moderate path of warming, with temperatures rising by only about 1°C above 2015 levels by 2100 and remaining stable thereafter. The more aggressive scenarios paint a different picture. SSP585 has the steepest temperature increase - potentially reaching nearly 29°C by century's end.

The RH trends for Hue show an inverse relationship with T: showing a declining tendency toward 2100 (Figure 1c). That sort of makes physical sense: warmer air can hold more moisture, so unless absolute humidity rises in a proportional way, RH falls. The scenario-based differentiations do not appear to show as clear as for T or CO_2, where clear demarcations could become evident around 2060–2070.

2.3. Carbonation models

Carbonation velocity is influenced by ambient conditions: temperature, relative humidity, and atmospheric carbon dioxide, alongside concrete characteristics including gas permeability, cement type and content, calcium oxide levels, and water-to-cement ratio [6], [13], [16]. Multiple modeling frameworks exist to represent this phenomenon, ranging from empirical correlations to advanced numerical methods [1], [2], [6], [17]. Given the strong dependence of carbonation on both material characteristics and environmental exposure, comprehensive model evaluation should account for the influence of these parameters. However, the present study specifically targets environmental variables, which inherently exhibit stochastic temporal variability. The effects of material property variability are therefore excluded from the current scope and will be investigated in future work. In this study, two representative approaches are examined: the Vietnamese standard TCVN 12041:2017 [11] and the FIB carbonation model [9]. The objective is to evaluate the responsiveness of each model to environmental changes projected under different climate scenarios.

2.3.1. Approach proposed in TCVN 12041:2017

The Vietnamese National Standard TCVN 12041:2017 [11] offers a relatively straightforward approach that can be applied for preliminary assessment of carbonation depth in reinforced concrete structures. Carbonation depth X_c at a given time t is determined through the following expression:

$$X_c = \alpha_1 \alpha_2 k \sqrt{t} \quad (2)$$

where: - α_1: is the rain or moisture exposure coefficient, $\alpha_1 = 0.95$ for potential exposure and $\alpha_1 = 1$ for no exposure condition.

- α_2: is the carbonation environment serverity factor, which is equal to 0.65; 0.85 and 1 corresponding to normal, moderate and intensive severity level respectively.

- k: is the carbonation depth coefficient, $k = 17.5 k_r W/C^3$ with k_r is the fly ash replacement ratio (depending on the class of fly ash [18]) and W/C is the water-to-cement ratio, depending on the surrounding environment (classification of each environment is presented in Table 1 of the TCVN 12041:2017 [11]). For the most representative exposure conditions in Vietnam which is moderate humidity conditions (XC3), the maximum W/C ratio is 0.5.

TCVN 12041:2017 adopts the classification diagram shown in Figure 2a, which defines carbonation severity as a function of CO_2 and RH. The diagram partitions environmental

conditions into three severity levels: Normal, Moderate, and Intensive, allowing the applicable exposure class to be identified at any time by plotting the corresponding CO_2 and RH values. A notable limitation of this approach is that temperature effects are not explicitly considered, which may reduce the accuracy of carbonation severity assessment under climate change scenarios characterized by significant warming.

Fly ash can partially replace Portland cement in concrete mixes, functioning as a pozzolanic material that reacts with calcium hydroxide during hydration [19]. This substitution influences carbonation rate, prompting TCVN 12041:2017 to introduce a correction coefficient k_r that varies with fly ash type and proportion (Figure 2b). In the FIB model, the influence of fly ash is not considered; accordingly, the TCVN model also assumes that fly ash is not used ($k_r = 1$). Both models are further defined under exposure class XC3 to ensure consistency. However, these assumptions do not affect the primary objective of this study, which is to evaluate the sensitivity of the models to time-varying climatic parameters.

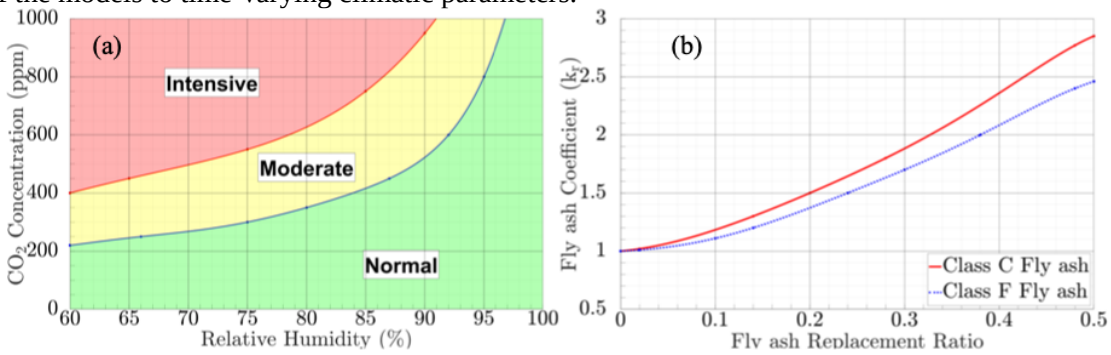

Figure 2. *(a) Classification of carbonation severity, and (b) fly ash replacement ratio*

2.3.2. Approach proposed in FIB Bulletin 34

The FIB Bulletin 34 proposed an empirical approach to predict the carbonation depth in RC structures, accounting for several material and environmental factors.

$$X_c(t) = \sqrt{2k_c R_{NAC,0}^{-1} k_{RH} k_T [CO_2]} \sqrt{t} W_f(t) \quad (3)$$

where:

- $k_c = \left(\frac{t_c}{7}\right)^{b_c}$ express the relationship between the curing duration and concrete CO_2 diffusivity (t_c is curing duration (in days) and b_c is the regression exponent).

-$R_{NAC,0} = \frac{a_{CO_2}}{D_{e,CO_2}}$ is the resistivity of concrete to carbonation in natural conditions, depending on the efficient CO_2 diffusion coefficient (D_{e,CO_2}), and the concrete properties (a_{CO_2}).

- $D_{e,CO_2} = D_1(t)^{-n_D}$, where:

  - D_1: is the diffusion coefficient at 1 year ($D_1 = 6 \times 10^{-4} cm^2/s$) [6], and
  - n_D: is the factor accounting for the degradation of diffusion coefficient over time ($n_D = 0.24$) [6]

- $a_{CO_2} = 0.75C[CaO]\alpha_H \frac{M_{CO_2}}{M_{CaO}}$, where:

  - $C(kg/m^3)$ is the cement content ($C = 300kg/m^3$ for XC3 condition [6], [11]),
  - $[CaO]$ is the amount of CaO per weight of cement,
  - α_H is the degree of hydration,
  - M_{CO_2} and M_{CaO} are the molar masses of CO_2 and CaO, respectively.

- k_{RH} and k_T are parameters describing the influence of relative humidity and temperature, which are determined by Eq (2) depending on the environmental parameters (T and RH) and their reference values ($T_{ref} = 293\ K$ and $RH_{ref} = 0.65$):

$$k_{RH} = \left(\frac{RH}{RH_{ref}}\right)^{2.6};\ k_T = exp\left[\frac{E_a}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (4)$$

- $[CO_2]$: is the atmospheric CO_2 concentration

- t is the exposure time and $W_f(t)$ is the weather function, which accounts for the microclimate conditions near the concrete surface, its formula can be found in [20].

2.4. Monte Carlo Simulation Approach

To address the inherent uncertainties in future climate projections, a Monte Carlo simulation approach was employed to generate probabilistic datasets for all three environmental parameters across the four SSPs. The simulation procedure follows a three-stage Generate-Filter-Evaluate (GFE) framework.

In the generation stage, climate parameters at each year were treated as normally distributed random variables, consistent with assumptions adopted in previous studies [6], [20]. For CO_2 concentration, the mean and standard deviation were extracted directly from the SSP ensemble data. Temperature and relative humidity projections for Hue utilized regional climate model outputs, with temperature adopting a coefficient of variation (CoV) of 0.1 to capture local variability, while RH standard deviations were derived from the regional bounds [21].

A total of 10^5 Monte Carlo simulations were performed for each scenario, with consistent random seeds ensuring reproducibility. In the filtering stage, generated datasets were extracted for the analysis period and converted to appropriate units. Finally, in the evaluation stage, environmental modification factors required by the carbonation models were computed. The resulting datasets, along with their 5th and 95th percentile bounds, provide the statistical foundation for the subsequent sensitivity analysis of carbonation models under climate change scenarios.

3. Results and Discussion

3.1. Carbonation Depth Predictions under Climate Change Scenarios

This section evaluates carbonation depths in reinforced concrete (RC) structures constructed in 2000, 2025, and 2050, each with an identical service life of 50 years. The predicted carbonation depths over these periods are analyzed for comparative purposes (Figure 3). All simulations were carried out for the XC3 exposure class, which reflects moderate humidity conditions typically associated with sheltered outdoor environments. This exposure category is widely adopted for urban RC buildings and provides a realistic and practical basis for evaluating carbonation-induced corrosion [1], [6].

Figure 3a shows the predicted carbonation depth of RC structures subjected to XC3 exposure by the TCVN 12041:2017 model over three construction periods. The results reveal little differentiation across all SSPs. SSP126 and SSP245 yield almost identical predictions for all construction periods, while SSP370 and SSP585 show only marginal differences. For structures constructed in 2000, the carbonation depths under all SSPs follow nearly overlapping trajectories, reaching approximately 12-13 mm by the end of the service life, with inter-scenario differences typically on the order of less than 1 mm. A comparable trend is observed for structures built in 2025, where carbonation depths converge around 13-15 mm, and the maximum deviation between SSP126 and SSP585 remains limited to roughly 1-2 mm. For the 2050 construction case, although scenario separation becomes slightly more apparent after around 2060, the absolute differences remain small, generally not exceeding about 2 mm even at the end of the 50-year period. These results suggest that the TCVN model is relatively insensitive to the range of

climate conditions. Furthermore, the corrosion depth obtained after the simulations showed almost no difference, so the 5%-95% confidence interval is not presented in this graph.

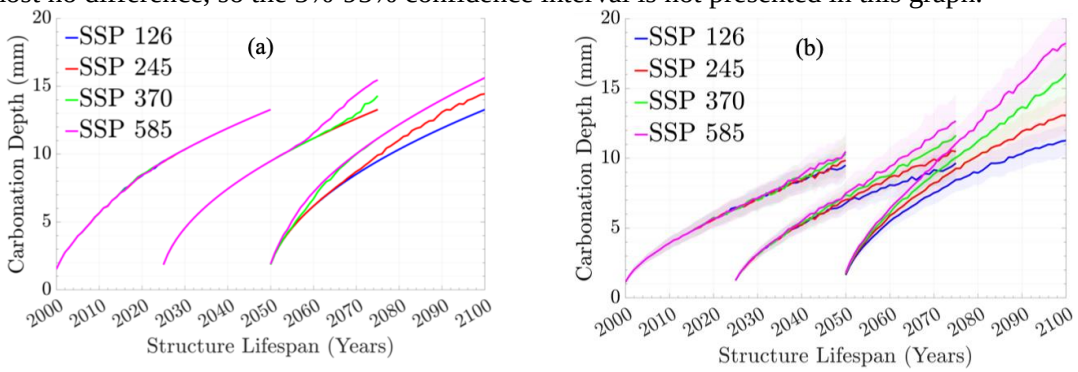

Figure 3. *Carbonation depth evolution for structures built in 2000, 2025, and 2050 using (a) TCVN 12041:2017 models and (b) FIB Bulletin 34*

Figure 3b shows the corresponding results obtained using the FIB Bulletin 34 model. For structures built in 2000, carbonation depths by 2050 range from approximately 8 to 10 mm with all SSP scenarios remaining closely clustered; the differences are typically within about 1 mm, indicating negligible sensitivity to emission pathways during the early exposure period. For structures constructed in 2025 and 2050, carbonation depths become progressively larger and the influence of SSP scenarios becomes more apparent over time. In the 2025 case, carbonation depths at the end of the service life range from about 9 mm under SSP126 to approximately 13-14 mm under SSP585. Similarly, for the 2050 construction case, the predicted depths span from roughly 10 mm to 15 mm across the SSP spectrum. Although this divergence is clearly visible, particularly after around 2060 the absolute differences remain moderate (on the order of 2-4 mm), and the carbonation trends remain broadly similar across scenarios, especially in the first half of the service life where the curves substantially overlap.

The shaded regions represent the 5%-95% confidence intervals, which quantify the dispersion of the predicted carbonation depths due to uncertainties in input parameters such as climate variables and material properties. Specifically, these bands define the range within which 90% of the simulated outcomes fall, bounded by the 5th and 95th percentiles. The widening uncertainty 5%-95% bands indicate that the FIB Bulletin 34 model exhibits a clear scenario-dependent and progressive increase in carbonation depth.

3.2. Comparative Analysis of Model Behavior

The previous section shows that the two models have drastically different sensitivities to environmental parameters. The discrepancy in sensitivity between the two models is analyzed in terms of their treatment of climatic parameters. The FIB model directly incorporates climatic variables, allowing it to capture even minor variations, whereas the TCVN 12041 model introduces these effects through a coefficient α_2. This coefficient exhibits limited responsiveness to changes in climatic parameters and is therefore identified as the primary source of the difference in sensitivity between the two models. Accordingly, the model's sensitivity to climate change can be evaluated by examining how variations in CO_2 and RH influence the assignment of this coefficient. The CO_2 and RH data for different SSPs generated via Monte Carlo simulation (Section 2.4) are utilized such that, for each realization and at each time step, their combined values are mapped onto the classification framework shown in Figure 2a. This mapping categorizes the exposure environment as Normal, Moderate, or Intensive, thereby determining the corresponding discrete value of α_2.

A temporal distribution of the coefficient α_2 in the TCVN model at various SSP conditions is shown in Figure 4. For SSP126 and SSP245, we observe that α_2 stays little more than one exposure class at most throughout the century. As α_2 is the only climate-sensitive parameter and

is able to assume only three discrete values (0.65, 0.85, and 1.00), small variations in CO_2 or RH that exhibit the same severity range are not expected to change the assigned α_2. This discretization of α_2 is therefore a primary reason for the low sensitivity observed in the TCVN model. Even when climate variables evolve continuously across SSP scenarios, their effects are quantized into a limited number of exposure classes, resulting in identical or nearly identical α_2 values over extended periods. Furthermore, climate conditions across SSPs remain close to similar until about 2040, indicating that structures that start service prior to this time have comparable environmental severity whether they follow an emissions pathway or not. Notably, transitions to high α_2 values do not begin even with SSP370 and SSP585 except in the mid-century. As a result, most structures are subjected to the same environmental conditions for much of their service life; hence, carbonation depth differentiation across climate scenarios is weak.

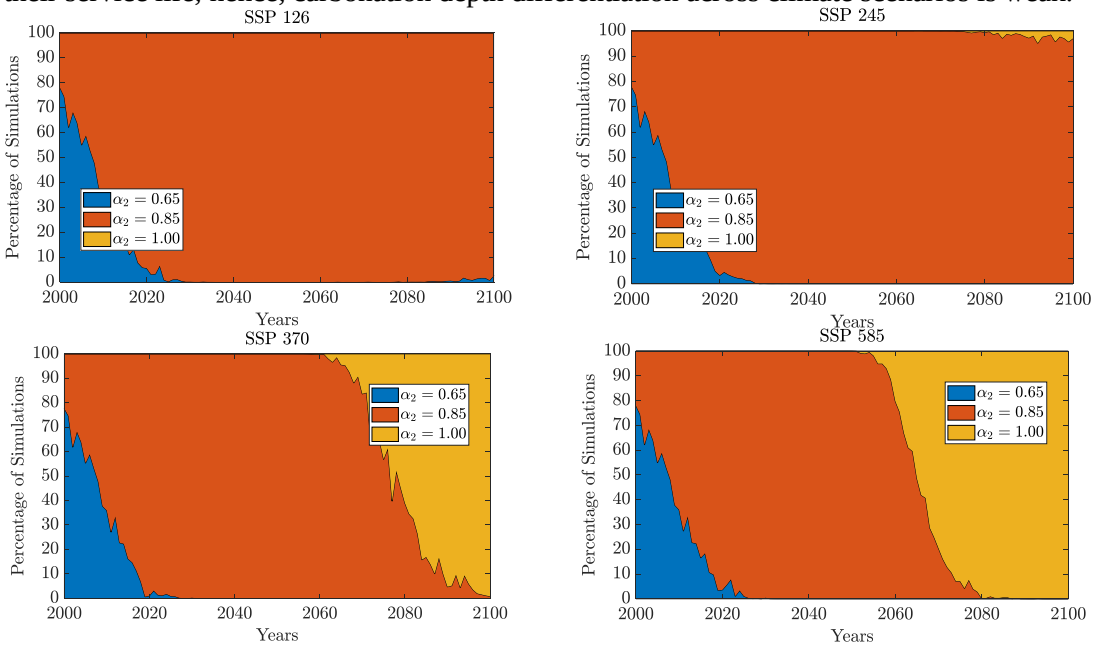

Figure 4. *Temporal evolution of α_2 illustrating the climate sensitivity of the TCVN 12041:2017 model*

In contrast, the FIB Bulletin 34 model incorporates continuous sensitivity to temperature, relative humidity, and CO_2 concentration through modification factors and an Arrhenius-based temperature formulation. This allows progressive climate deterioration to be captured directly, leading to increasing scenario divergence and growing uncertainty in carbonation depth projections.

4. Conclusions

In this study, the climate sensitivity of TCVN 12041:2017 and FIB Bulletin 34 carbonation models under SSP scenarios was studied based on projected CO_2, temperature, and relative humidity data for Hue, Vietnam. The climate sensitivity shows that TCVN 12041:2017 is substantially lower than that of FIB Bulletin 34, which leads to virtually even predictions across scenarios because of its discrete classification system and lack of explicit temperature consideration. The TCVN 12041:2017 model produces nearly invariant carbonation depths across SSP scenarios, with differences typically limited to less than 1–2 mm, even at the end of the service life. In contrast, the FIB Bulletin 34 model yields a systematic spread in predicted carbonation depths, with inter-scenario differences increasing to approximately 2–4 mm or more in later periods, particularly for structures constructed after 2050. Consequently, while TCVN 12041:2017 provides almost uniform predictions across SSP pathways, the FIB Bulletin 34 model captures a progressive divergence driven by evolving climatic conditions. This contrast underscores the importance of continuous environmental parameterization for achieving

reliable climate-adaptive durability assessments. Improving TCVN 12041:2017 by refined α_2 severity classification and explicit incorporation of temperature effects for climate-adaptive durability assessment is recommended.

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