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Experimental investigation on carbonation due to climate change impacts

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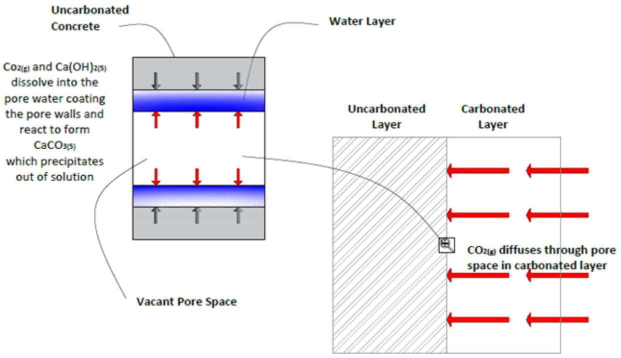
Graphical abstract



Abstract

Various investigations have been carried out to evaluate the infrastructure's increased vulnerability and due to global warming and its effect, carbon dioxide emission level in atmosphere gets increased and this would further increase the probability of carbonation induced corrosion in concrete structures. In this present study, an empirical model is used to identify the diffusion coefficient of carbon dioxide (CO_2) in concrete. Water cement (w/c) ratio of 0.45, 0.5 and 0.55 has been considered with emission scenarios of Representative Concentration Pathway (RCP) 8.5 and 4.5 respectively. The research findings through empirical modeling proved that depth of carbonation has direct relationship with water cement ratio and it is also predicted that by the year 2100, considering 2000 as the base year, the carbonation depth may raise up to 78% for reinforced concrete structures subject to various climatic conditions such as temperature, humidity etc.

Keywords: Climate change, carbonation, representative concentration pathway, anova, diffusivity

1. Introduction

Due to extreme climatic conditions, extreme change has been happening and these conditions not only include temperature but also increase in dry seasons. Building projects without taking into account of environmental change prompts substantial quality disintegration, causing helpless development and thus bringing harm to property (ACI Code, 2019). Extreme environmental change and various ecological conditions happen due to different topography and this change in environment can be classified as related to human factor and normal factor (Saha and Eckelman, 2014). This environmental change has caused an assortment of issues and the most genuine is the expansion in the normal temperature because of a dangerous atmospheric deviation (Kaewunruen *et al.*, 2018; AL-Ameeri *et al.*, 2021a). The environment framework is as of now moving past the examples of regular fluctuation inside which social orders and economies have created and flourished (Talukdar and Banthia 2016; Li *et al.*, 2016).

Although large numbers of financial effects of environment change have been inspected up to this point, one ignored region to be explored is to identify the basic cause and reason for the change in environment (Wang 2019a, 2020) (Cho *et al.*, 2016; Kim *et al.*, 2017). Probabilistic model to evaluate effect of wind hazard for nonstructural parts of building under potential environmental change was developed (Talukdar *et al.* 2014; Peng and Stewart, 2016). The Intergovernmental Board on climate change fourth evaluation report demonstrated a huge expansion in concentration of CO_2 present in air from 285 parts per million (ppm) in 1760 to 390 ppm during 2005. In correlation with preindustrial temperatures, the best assessment of the temperature increment from 1990 brought about expanding climatic factors and carbon dioxide concentrations might go up to 2.2 °C for a CO_2 concentration of 550ppm, 3.1 °C for 700 ppm and 4.5 °C for 1000ppm by the year 2100. There is almost consistent agreement among researchers that increasing ozone harming substance outflows and essentially CO_2 created by human factor are influencing the world's environment. The findings (Stewart *et al.*, 2011; Jiang *et al.*, 2018; Kim and Jung, 2020) tracked down that the ambient concentration of carbon dioxide owing

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to a normal metropolitan climate is 5% to 10% higher than carbon dioxide concentrations existing in rural climatic conditions. Deterioration is viewed as one of the vital factors that could fundamentally change the continuing effects of infrastructure (Kim and Kim 2018; Wang 2019b; Chen *et al.*, 2021).

Climatic change is likely to modify the current environment particularly over prolonged period thus paving way to the enhanced disintegration of structures causing more expensive and problematic fixes in buildings (Castro-Borges and Mendoza-Rangel 2010; Kusin *et al.*, 2020; Tiwari *et al.*, 2020). The effect of change in climate on concrete is ignored in general though the most expected impacts of environmental change on all parts of society are well acknowledged (Hwang *et al.*, 2018). Several elements influence the carbonation process, notably material characteristics, carbonation condition and curing and rate of carbonation is governed by these key factors. As a result, several efforts have been undertaken to comprehend carbon dioxide transit and response processes. Carbonation can diminish the alkalinity of concrete, causing it to lose the steel protection that is precondition for concrete reinforcement corrosion in the ordinary atmospheric environment. Concrete carbonation is a natural phenomenon characterized as the chemical interaction between carbon dioxide, calcium hydroxide and calcium silicate hydrate. Carbonation rates rise for porous, low quality concretes and grouts. Researchers have achieved a rudimentary grasp of the influence of pre cracking on concrete carbonation, and the issue of carbonation under prolonged loads is being researched. Researchers created novel methods for predicting the carbonation coefficient of concrete using several models. Actions in examination of the implementations of environmental change effects help to manage the issues which may arise later on to secure our infrastructure and human settlements. Subsequently based on previous research, these new ecological conditions change the kinematics of carbonation by escalating or decreasing the outcome of harm caused due to corrosion (de Larrard *et al.*, 2014; Behfarnia and Rostami, 2017).

In recent years, many researchers pay attention to explore the impacts of environmental change (Chauhan *et al.*, 2021; Bandh *et al.*, 2021).To characterize the complicated nature of the carbonation coefficient, emerging new modeling approaches are created. Currently, random forest, model tree model, and multi gene genetic programming are being used to perform mix design and concrete strength predictions. This awareness of the relevant parameters provides the researcher with a better grasp of the difficulty of picking the most appropriate variables and, consequently, models. Climate change actually influences the durability properties of concrete structures. The key objective of this research is to predict the depth of carbonation and information from newer climate projections from fifth Intergovernmental board on climate changes evaluation details are utilized to create forecast.

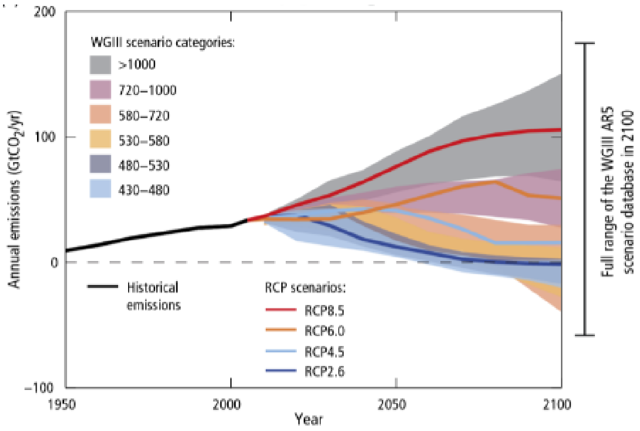


Figure 1. Annual anthropogenic carbon dioxide emission (Source: IPCC, 2013)

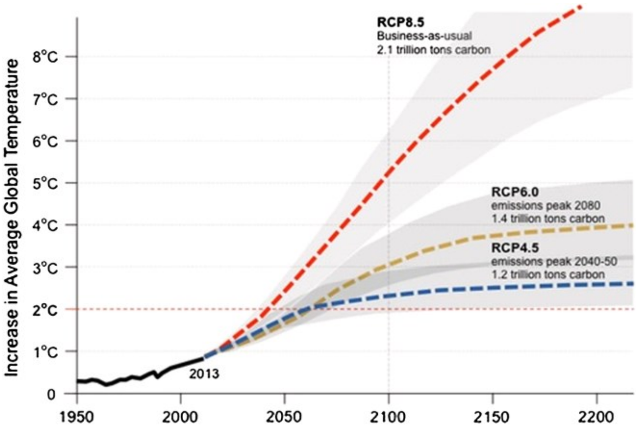


Figure 2. Global temperature projections RCP (Source: IPCC, 2013)

2. Climate change scenario

Most of the evaluations anticipating carbonation depth in concrete have been made depending on carbon dioxide carbonation information given by special report on emission scenarios (SRES IPCC, 2000) (Intergovernmental Panel on Climate Change. Working Group III. 2000). These situations shaped the basics of Intergovernmental Panel on Climate Change (IPCC, 2007) fourth and IPCC (2013) fifth report of evaluation. The upcoming age of environment models at this point don't utilize the SRES scenarios. Another arrangement of RCP is starting to move towards utilization in addition to it has framed the basics of the IPCC (2022) report of sixth assessment (Aldunce, 2022). Outcomes stated by Talukdar depended on environment models for urban areas utilizing the SRES situations namely A1FI, A2, B1 and B2. Mathematical models were produced in order to predict upcoming temperatures and CO_2. It is proved that these informational indexes are currently old and more exact data can be produced utilizing the new RCP information. The four RCP situations depict four potential environment prospects, which are all viewed as conceivable relying upon the greenhouse gases volume to be discharged in the forthcoming years.RCP 2.6, 4.5, 6, and 8.5, are chosen which has a potential scope of radiative constraining qualities that can be observed during 2100 (year) when comparing with pre industrial values (+2.6, +4.5, +6, +8.5) W/m^2.Every RCP situation is related through projections for expansions in temperature and worldwide carbon dioxide concentrations for following hundred years (Figures 1 and 2).

2.1. Concrete carbonation

Carbonation is the chemical reaction between concrete hydration products and environmental CO_2 that leaves the steel rebar helpless against corrosion (Marangu *et al.*, 2019; Tam *et al.*, 2021). A probabilistic investigation (Benítez *et al.*, 2019)showed that irregularity in depth of carbonation is high because of vulnerability and variation of material properties. A simplified deterioration representation was used to evaluate the requirement of increasing concrete cover as a variation amount to reduce the impacts of carbonation (Kusin *et al.*, 2020; Mi *et al.*, 2020). The primary findings tracked down that increasing cover possibly will not be worth, yet outcomes were sensitive to identify the causes of corrosion. Elevated temperature can increase chloride penetration as concrete becomes dry while rate of corrosion also increased simultaneously (Goyal *et al.*, 2018; Jung *et al.*, 2020; Uwanuakwa, 2021). Results from experimentation showed that depths of carbonation were determined for reinforced concrete structures expecting an environmental climatic change expectation of up to 450 ppm, considering the life of building as 100 years. Reports from research (Liu *et al.*, 2020; Huang and Zeng, 2021) assessed the depth of carbonation in concrete because of projected environmental change. An increase in depths varying from 25 to 35 mm was observed because of carbonation alone (Rushendra Revathy *et al.*, 2016; Kim and Kim 2018). Moreover results from research revealed that 5 to 15 percentage rise in likelihood of corrosion initiation is due to environmental change and it has highlighted the vital effect on structural reliability. Carbonation induced corrosion occurs naturally in concrete structures at persistent rate. The carbonation process (Zhang *et al.*, 2020) is presented in subsequent outline.

$$Ca\left(OH\right)_2 \rightarrow Ca^{2+}\left(aq\right) + 2OH^{-}\left(aq\right) \tag{1}$$

$$CSH+CO_2 \rightarrow CaCO_3+SiO_2+H_2O \tag{2}$$

$$3CaO{\cdot}2SiO_2{\cdot}3H_2O+3CO_2 \rightarrow Ca^{2+}\left(aq\right)+2SiO_2{\cdot}3H_2O \tag{3}$$

$$CO_2\left(aq\right)+\left(OH\right)^{-}\left(aq\right)\rightarrow HCO_3^{\ -}\left(aq\right)+H_2O \tag{4}$$

$$HCO_3^{\ -}\left(aq\right)+\left(OH\right)^{-}\left(aq\right)\rightarrow CO_3^{\ 2-}\left(aq\right)+H_2O \tag{5}$$

$$Ca^{2+}\left(aq\right)+CO_3^{\ 2-}\left(aq\right)\rightarrow CaCO_3 \tag{6}$$

Calcium ions are generated as a result of calcium hydroxide and CSH decalcification. CO_2 reacts with CSH and CH simultaneously and that decalcification of CSH occurs before the development of silica gel occurring later in the carbonation process. CH carbonation may be faster at first than CSH gel carbonation, but this quickly reverses due to the formation of a layer of $CaCO_3$ micro crystals on the surface of CH. To maintain equilibrium, the hydrated cement products (i.e., CH and CSH) are decomposed into Ca^{2+} and OH^{-}. The dissolving rate of calcium hydroxide is quicker in the non carbonated region, but it reduces with rising carbonation level due to calcium carbonation precipitation surrounding the calcium hydroxide surfaces. CO_3^{2-} ions are formed as a result of the infiltration and dissolution of carbon dioxide into the alkaline pore solution. The reaction of calcium ions with carbonate ions results in the precipitation of calcium carbonate as shown above (Wang *et al.*, 2021). Carbonation occurs as chemical interaction between CO_2 and calcium hydroxide $Ca\ (OH)_2$ in cement matrix and consequently it results in a small shrinkage under certain humidity condition that creates cracks and thus facilitates the movement of CO_2 and other unsafe agents into the concrete structures that finally leads to corrosion of reinforcement. In addition, corrosion due to carbonation is caused due to decrease in alkalinity of concrete that is caused by drop in value of pH below 9 and in turn, the passivating layer around the reinforcement is broken and it leads to corrosion (Chinchón-Payá *et al.*, 2016). Buildings with higher water cement ratio have higher porosity in microstructure which in turn, affects the depth of carbonation (Sáez del Bosque *et al.*, 2020). Concrete structures in contact among rain can fundamentally influence the increase in carbonation over a long term (Liu *et al.*, 2019). The rate of carbonation relies upon how carbon dioxide can infiltrate and react with hydration process. Concentrations of carbon dioxide, relative humidity and temperature significantly affect the rate of carbonation and maximum value reaches at humidity ranging from fifty to seventy percentage (Elsalamawy *et al.*, 2019). The deterioration caused due to effect of exposure to blend of stress and elevated temperatures harm's a lot more than that subject to a solitary factor and the joined impact of elevated temperature and stress essentially diminishes the carbonation resistant property of concrete. In this research, carbonation progress for an ordinary concrete infrastructure of varying water cement ratios have been used to study the behavior of carbonation progress.

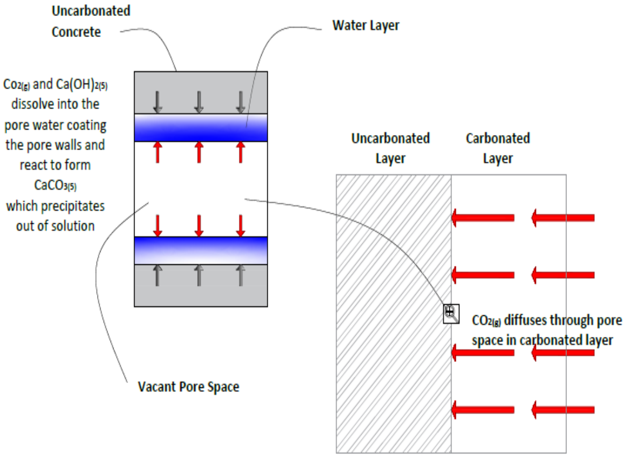


Figure 3. Graphical Representation of Carbonation Process

2.2. Numerical model refinement

The normal carbonation in concrete is a chemical interaction in which natural carbon dioxide in atmosphere interacts with $Ca\ (OH)_2$ to form calcium carbonate

($CaCO_3$). The response primarily used to depict the reaction shown in equation 7.

$$CO_2 + Ca(OH)_2 \xrightarrow{H_2O} CaCO_3 + H_2O \tag{7}$$

With reference to above reaction, carbon dioxide reacts with calcium silicate hydrate (C-S-H) gel to form additional calcium carbonate (von Greve-Dierfeld *et al.*, 2020). As carbonation occurs in concrete, the effect is sufficient enough to scatter two particular layers to form inside concrete. Initial layer is completely carbonated into which CO_2 has infiltrated and responded and second layer is non-carbonated where carbon dioxide is yet to be entered. Carbon dioxide penetrates into non carbonated layer all the way through carbonated layer and the schematic representation is shown in Figure 3.

2.3. Porosity dependence

Rate of diffusion by which molecules are transferred into concrete relies upon size and arrangement of pore structure. When the ratio of water to cement is brought down, the pore framework becomes finer and less associated, prompting lesser transportation rates and a lower diffusivity. The empirical equation (Talukdar *et al.*, 2012) is used to assess the successful diffusivity of carbon dioxide in concrete depending on its porosity.

$$D_{CO_2} = A\left(\frac{V_p}{\frac{C}{pc}+\frac{w}{pw}}\right)^{\alpha} \tag{8}$$

A and ἀ parameters decided tentatively with recommendded standards of A = 1.64 × 10^{-6} m^2 / s and ἀ = 1.7 respectively [24]. Vp = Volume of pores in the cement paste in m^3. c = content of the cement in kg, w = content of water in kg, ρ_c = absolute cement density (3120 kg/m^3), ρ_w = density of water (1000 kg/m^3). Moreover, carbon dioxide interpenetrating through the concrete mix prompts further decrease in porosity because of carbonation. The processes used in simulation are shown in Figure 4.

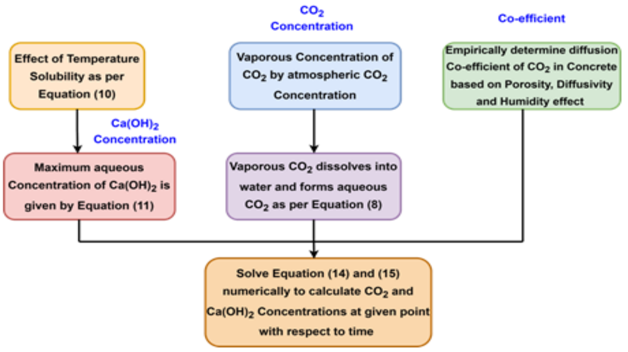


Figure 4. Flowchart for determination of CO2 and Ca (OH)2 concentrations

2.4. Effects of temperature

As the temperature rises, diffusivity of vaporous carbon dioxide rises because of variations in molecular action. Temperature can influence the chemical reaction significantly in range of 20° C to 30°C (Ying Chen *et al.*, 2018). It is moreover necessary to decide the rate of reaction by which carbon dioxide reacts with calcium hydroxide to produce calcium carbonate as it is depending on temperature. An increase in carbonation depth (Talukdar *et al.*, 2012) was found as temperature increases and relationship between them can be described by a linear function and results from research revealed that there was a significant increase in compressive strength of concrete specimens due to carbonation process with products involved in hydration process like CSH etc. In connection with above process, the hydration products steadily decayed and new products without cementitious property were produced.

2.5. Effects of relative humidity

Relative humidity plays a vital role in carbonation resistance where carbonation viably stops when concrete is adequately dry to forestall entrance of carbon dioxide. Past investigations showed that carbonation reaches at the most extreme level of relative humidity in the range of 50 and 70%. In any case, this factor relies upon the moisture level present in the surface of concrete where cyclic moisture conditions could prompt to fluctuations in relative humidity (Lee *et al*., 2020). The dampness content available in concrete is vital. As the carbonation process is controlled by dissemination of carbon dioxide, the rate of reaction drops down steadily when pores present in the concrete are saturated. At this situation, carbon dioxide scarcely reacts with concrete on account of the lower diffusion rate of carbon dioxide in water (Felix *et al.*, 2021). The rate of carbonation likewise eases back if the concrete is excessively dry since, despite the fact that carbon dioxide disperses into the fine pores of the concrete it seldom enters into the slender water layer which causes the fine pores. As the rate of humidity is higher, movement of vaporous carbon dioxide is at slower rate because of water saturation. The ecological situation that influence the moisture substance in concrete firmly influence carbonation rate.

2.6. Framework of carbonation model

Carbon dioxide present at the atmosphere enters into voids present in concrete through air spaces. The pace of dispersion of carbon dioxide through water (Pan *et al.*, 2018; Šomodíková *et al.*, 2020) is a lot more modest in extent and neglect. After arriving at a specified point, vaporous carbon dioxide dissolves in water and above vaporous substance gets converted into aqueous medium at that specified location and concentration as given by Henry's Law.

$$CO_{2(aq)} = HRTCO_{2(g)} \tag{9}$$

H represents Henry's constant (mol/m^3.atm) and R is taken as gas constant (8.2 × 10^{-5} m^3.atm/K mol).Water at the concrete pore in which the CO_2 has dissolved at a particular time responds with dissolved calcium hydroxide at aqueous state to form calcium carbonate and subsequently brings down on the whole concentrations of carbon dioxide at that specified time and location. The rate of reaction (Khunthongkeaw and Tangtermsirikul) is given as

$$r_{CO_2} = K\left(\mathrm{CO}_{2(\mathrm{aq})}\right)\left(\mathrm{Ca(OH)}_{2(\mathrm{aq})}\right) \qquad (10)$$

Where K = reaction rate constant between CO_2 and $Ca(OH)_2$.There is a maximum breaking point to the amount of calcium hydroxide, related to the solvency of calcium hydroxide at which it can break into pore water. But the availability of the concrete pore solvable Ca $(OH)_2$ solvency is very limited. The solitary appropriate condition denoting the dissolvability of calcium hydroxide at a given temperature in concrete mix (Khunthongkeaw and Tangtermsirikul) is given as

$$K_{sp} = \left(0.0125\times10^{9}\right)e^{-0.0197} \qquad (11)$$

where K_{sp} = Ca $(OH)_2$solubility product in mol^3/l^3.

Accepting calcium hydroxide is the dominating element to break in pore water, the extreme aqueous CO_2concentration would then be able to be assessed from an essential equilibrium formula.

$$\mathrm{Ca(OH)}_{2(\mathrm{aq})} = \left[\frac{\mathrm{K_{sp}}}{4}\right]^{1/3} \qquad (12)$$

As a result, CO_2mole balance in pore water ofconcrete at a specific area and time is denoted in terms of vaporous CO_2 diffusion quantity within the concrete mix. It further disintegrates to result in the difference between aqueous $CO_2$and the measure of CO_2 which responds withcalcium hydroxide. Results (Peng and Stewart, 2016) determined the depth of carbonation considering the improved carbon dioxide concentrations by utilizing the average carbon dioxide concentrations with respect to time and it is given in equation (13).

$$x_c(t) = \sqrt{\frac{2f_T(t)D_{\mathrm{CO_2}}(t)k_{site}}{a}\int_{2000}^{t}C_{CO_2}(t)dt \times\left(\frac{1}{t-1999}\right)^{n_m}} \quad t\geq2000 \qquad (13)$$

4

where C_{co2} represents rise in atmospheric concentrations of CO_2 (10^{-3} kg/m^3), x_c (t) = depth of carbonation at a time‘t’, D_{co2} (t) = carbon dioxide diffusion coefficient, D1 = diffusion coefficient of carbon dioxide after one year, n_d = CO_2coefficientage factor, C_e = contentof cement (kg/m^3), a_h = degree of hydration, M_{cao} and $M_{co2}$are molar mass of calcium oxide and carbon dioxide (56 and 44) g/mol respectively. n_m = age factor (0 and 0.12) for sheltered outdoor exposure and unsheltered outdoor exposure respectively. The mean values (Yoon *et al.* 2007) for D1 and n_d are given in Table 1.

Table 1. Mean Values of the Parameter

w/c	D1×10–4cm2s–1	nd
0.45	0.65	0.218
0.5	1.24	0.235
0.55	2.22	0.240

Note: For intermediate values, liner interpolations have to be used.

Rate of diffusion increases at higher temperature prompting to augmented rise in carbonation depths. The consequence of temperature on diffusion coefficient is demonstrated with Arrhenius Law where *T (t)* is taken as 20°C at time ‘t’.

$$\mathrm{f}_T(\mathrm{t}) = \exp\left\{\frac{E}{R}\left[\frac{1}{293.15}-\frac{1}{273.15+T(t)}\right]\right\} \qquad (14)$$

where E = activation energy of the diffusion process (40 kJ/mol),*R*= gas constant (8.314 × 10^{-3} kJ / mol K). Undoubtedly, equation (12) is estimation and there is a requirement for a further developed carbonation model with the aim of considering the time dependent impact of CO_2 concentrations with added parameters like humidity and temperature. Carbonation is generally the most noteworthy for relative humidity ranging 50% to 70%. Reports from research (Russell *et al.* 2001) revealed that carbonation does not occur under overall relative humidity of 30% and results proved that for below 50% humidity, there is a lack of moisture for carbonation reaction. The numerical model created (Nunez and Nehdi, 2021) was a deterministic mathematical dissemination one dimensional model for vaporous state all the way into a permeable substrate dependent on second law of Fick’s diffusion where the equations for CO_2 and $Ca(OH)_2$concentrations inside the substrate [Equations 15 and 16] are solved concurrently and mathematically with respect to humidity, concentrations of carbon dioxide and temperatures.

$$\frac{\partial}{\partial t}\left[CO_{2(aq)}\right] = D\frac{\partial^2}{\partial x^2}\left[CO_{2(g)}\right]HRT - k\left[CO_{2(aq)}\right]\left[Ca(OH)_{2(aq)}\right] \qquad (15)$$

for the domain

$CO_{2(g)}(x,t)\ 0\leq x\leq1$ and $0\leq t\leq\infty$

with boundary conditions

$CO_{2(g)}(x,0)=0$ for $x>0$

$CO_{2(g)}(0,t)=CO_{2(atm)}$ for $t>0$

$\frac{d}{dx}CO_{2(g)}(L,t)=0$ Zero flux boundary

Equation 16 is time dependent boundary condition and on the whole, mole balance for calcium hydroxide is given by

$$\frac{\partial}{\partial t}\left[Ca(OH)_{2(aq)}\right] = D\frac{\partial^2}{\partial x^2}\left[Ca(OH)_{2(aq)}\right] - k\left[CO_{2(aq)}\right]\left[Ca(OH)_{2(aq)}\right] \qquad (16)$$

for the domain

$Ca(OH)_{2(aq)}(x,t) \quad 0\leq x\leq L and 0\leq x\leq\infty$

With initial and final boundary conditions

$Ca(OH)_{2(aq)}(x,t) \quad 0\leq x\leq L and 0\leq x\leq\infty$

$\frac{d}{dx}Ca(OH)_{2(aq)}(L,t)=0$ zero flux boundary

$\frac{d}{dx}Ca(OH)_{2(aq)}(0,t)=0$ zero flux boundary

In concrete, the thermal diffusivity is more prominent than the mass diffusivity. Subsequently, the temperature of the concrete is considered to be consistent whenever there is no compelling reason to tackle the energy equation.

2.7. Experimental program and validation

Tests were performed to accurately measure the carbonation depth of concrete specimens and for validation of carbonation model. Concrete samples of (100×100×100) mm are cast, cured in water bath for twenty eight days. Later the samples were taken from water bath and kept in oven at 60°C for a couple of days before being cooled in room temperature. The above pretreatment could cause the extra moisture to evaporate in concrete specimens and this result in a consistent humidity levels before placed in carbonation chamber. Specimens are placed in carbonation chamber and concentrations of CO_2 was maintained at (1, 1.5 and 2) percentage and temperature, humidity of (27, 29 and 31) °C and 65, 70 and 75 percentage was maintained. Different w/c ratios are used to attain variation in concrete properties. The proportions of mix are mentioned in Table 2. Phenolphthalein solution prepared by dissolving one gram of powder in seventy ml and 30 ml of ethanol and water correspondingly. After exposure, the specimens are taken out from the chamber and phenolphthalein indicator is sprayed over the cut portion of specimen to measure depth of carbonation. The experimental results are based on the shift in color of carbonated concrete with a pH less than 9 as investigated by the phenolphthalein alkalinity indicator (Figures 5–7).

Table 2. Concrete Mix Properties

Mix	Concrete Quantity per unit volume (kg/m3)				
	w/c	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate**
M1	0.45	440	198	755	1042
M2	0.5	396	198	740	1055
M3	0.55	360	198	725	1060

Figure 5. Specimens placed in carbonation chamber

Figure 6. Specimen testing in compression testing machine

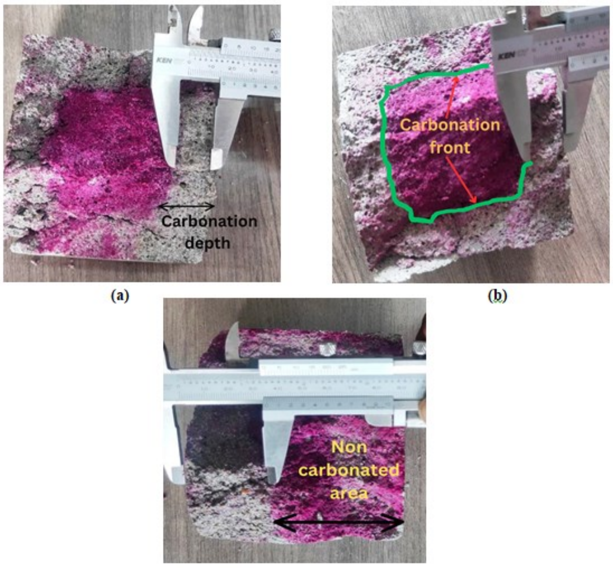


Figure 7. Specimen testing picture for different (w/c): (a) 0.45, (b) 0.5 and (c) 0.55

3. Analysis and discussion

Depth of carbonation was measured using vernier caliper with accuracy of 0.1 mm. If the measuring point contains grit particles, depth is calculated as the average of adjacent measurement points and depth of carbonation is calculated using the formula (17) (Jing-shuang Zhang *et al*. 2020).

$$D_t = \frac{1}{n}\sum_{1}^{n} D_i \qquad (17)$$

D_t = Average depth of carbonation in mm

n = Number of measuring points

D_i = Carbonation depth of measuring points

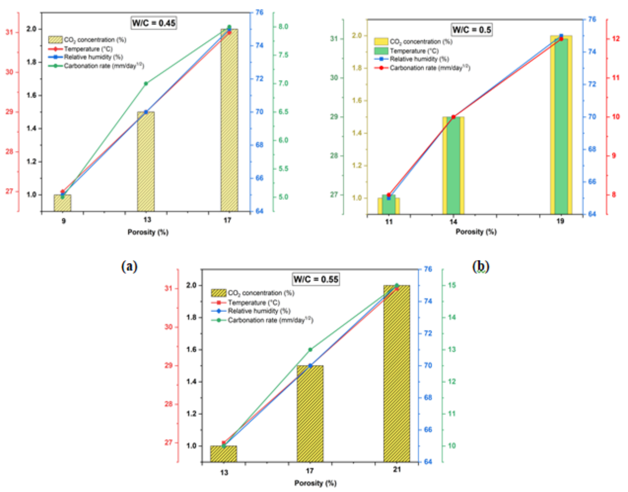


Figure 8. Porosity for various w/c: (a) 0.45, (b) 0.5, (c) 0.55

Carbonation rate increases with increasing porosity, as shown in Figure 8 and test for porosity was conducted as per ASTM C642:2013. The Concentration of CO_2 used during the experiments falls within the range of what causes the similar mineral change in concrete due to carbonation at concentrations in the atmosphere (Abbas *et al*., 2021). From the results shown in Figure 8, it is obvious that rate of carbonation increases with increase in w/c, concentration of CO_2, temperature and relative humidity. The reason for this could be the above environmental factors could quickly accelerate reaction process involved in carbonation making their impacts significant. As shown in Figure 8, when w/c was raised from 0.45 to 0.55, it is observed that porosity and carbonation rate is increased to 21 and 59 percentage correspondingly and micro structures in concrete are fairly spaced (Zhiwu yu *et al*. 2019). In concrete samples, as temperature rises there is a rise in carbonation depth. Concrete carbonation comprises of two components i.e., CO_2 that transmits into concrete and CO_2 that reacts with hydration products to form carbonation reaction. As the temperature increases, there is an increase in transmission and reaction coefficient of CO_2 in concrete and according to Arrhenius equation (Equation 14) resulting in larger CO_2 transmitting into concrete. Due to above reactions carbonation depth in concrete increases as transmitted CO_2 reacts with hydration products. This finding is consistent with the findings of the previously reported study (Ying Chen *et al.,* 2018), (Peng Liuet *et al*., 2020). As a result, much CO_2 can easily enter into the concrete core part, resulting in a greater carbonation depth and be able to conclude that correlation among depth of carbonation and temperature could be described by a linear function. Because of Arrhenius equation (Equation 14), an exponential function can be approximated as a linear function when the temperature variation is very small. The impact of relative humidity on carbonation depth is shown in Figure 8. When the relative humidity varies from sixty to eighty percentages, the carbonation depth varies significantly (Peng Liuet *et al*., 2020). With increasing relative humidity, extra liquid can be coagulated in pores, whereas there is insufficient space for liquid water in pores when relative humidity decreases. The impact of CO_2 concentration on depth of carbonation has been investigated, as depicted in Figure 8. The depth of carbonation increases as CO_2 concentration increases (Zhang K J *et al*. 2018). The above phenomenon is due to higher values of concentration of CO_2, the greater the concentration gradient between the concrete surface and core part of structure which results in larger amount of CO_2 to transmit into concrete and reacts with hydration products. Furthermore, under all conditions, there is a relationship between porosity and carbonation. The rate of carbonation is also affected by the moisture levels in concrete as well as the relative humidity of the surrounding medium. Carbonation depths were significantly influenced by both the amount of compacted pores as well as the relative humidity.

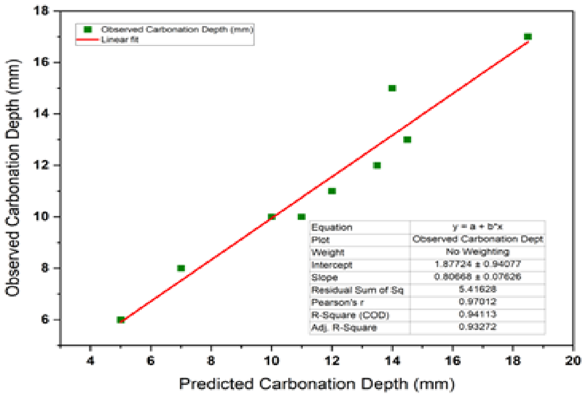


Figure 9. Relationship between predicted and observed carbonation depth

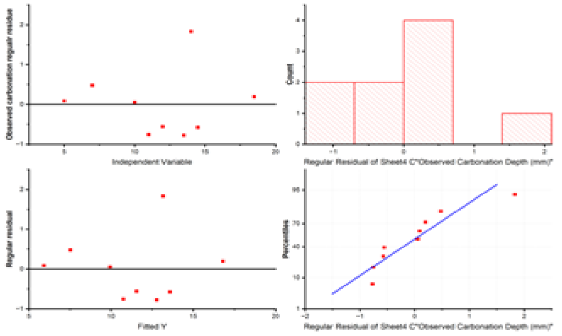
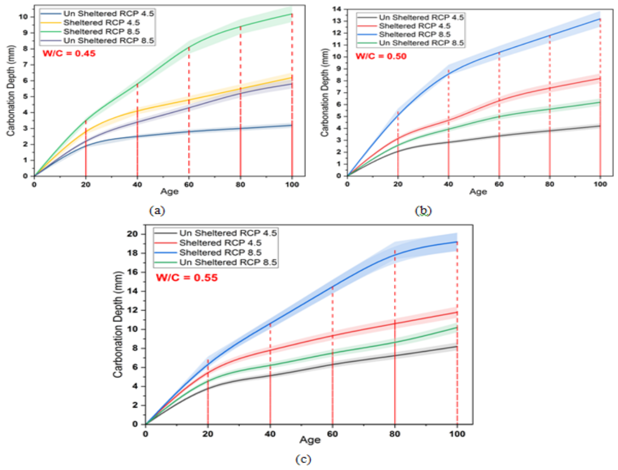


Figure 10. Interaction plot for carbonation depth

The model's results are verified by comparing them to the available experimental findings from this research in addition to other research in the literature. As illustrated in Figures 9 and 10, it is clear that anticipated values agree with experimental findings (the values of R^2 for the majority of these graphs were greater than 0.93) supporting the notion that the carbonation depth can be predicted using the existing model. Since there was less than a 20% difference between the R^2 for every response, it is clear that the models' predictions were accurate. It is clear that all of the residuals from all of the responses are close to the straight line and the difference between model results and the experimental data could be due to the reaction model assumptions for CO_2 and $Ca(OH)_2$ (aq), or other factors that affect the CO_2 coefficient like relative humidity.



(a) (b) (c)

Figure 11. Carbonation depths versus time for different water cement ratios (W/C): (a) 0.45, (b) 0.5and (c) 0.55

Figure 11 demonstrated that Reinforced Concrete Structures (RCC) is exposed to a higher carbonation depth over its life expectancy. This is mainly due to coefficients of diffusion of carbon dioxide and calcium hydroxide and the rate of reaction between the above with aqueous products that increases with the rise in both humidity and temperature values. Both these factors in general guide the diffusion of carbon dioxide into concrete. The experimental verification has been carried out (Talukdar S, *et al*,) for the arrived empirical model to confirm the relevancy of results in line with experimental results. For water to cement ratio of 0.5, considering RCP 8.5 carbonation depth of 3 mm was achieved whereas in experimental verification (Talukdar S, *et al*,) 5 mm was obtained. Similarly corelation has been observed for other scenarios considered. Test results proved that arrived empirical model shows better justification when compared to experimental data that would it can be suitable for most engineering concrete.

Water cement ratios of 0.45. 0.5 and 0.55 and compressive strength of 30 MPa was mathematically demonstrated to calculate the depth of carbonation. It was found that rebar in concrete pretended to have twenty five mm cover which implies that induced corrosion induced due to carbonation starts once the carbonation at front face had advanced twenty mm inwards from the surface. Examination of carbonation depth from Figure 11 shows a significant point that for this given situation. Buildings built in the year 2000 have carbonation up to 8mm in the case of RCP 8.5 sheltered exposure and this can extend up to 20 mm by the year 2100. Similarly an enhancement in extreme carbonation depths for the same scenario between 65 to 70 % by 2040 by the structures for different water cements ratios ranging from 0.45 to 0.55. From the results, it is clearly evident that carbonation is a topographically reliant phenomenon affected by local temperature, humidity, climate scenarios. Increasing the strength of concrete diminishes its porosity, as well as reduces the air content. Lower porosity would probably prompt lower carbon dioxide diffusion rates. The construction procedures are not sufficiently thorough to guarantee conformity of it with design code provisions and quality of cover present in concrete structures may disintegrate on account of assortment of other factors. Model uncertainty is influenced by both internal and external factors. Mix proportions, mix design, and material qualities are internal factors whereas temperature and humidity are external factors.

Table 3. ANOVA table for sheltered RCP 4.5

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	118.239	39.4131	21.51	0.003
W/C	1	0.122	0.1215	0.07	0.807
AGE	1	3.388	3.3876	1.85	0.232
W/C*AGE	1	7.022	7.0225	3.83	0.108
Error	5	9.161	1.8322		
Total	8	127.400			

Table 4. ANOVA table for sheltered RCP 8.5

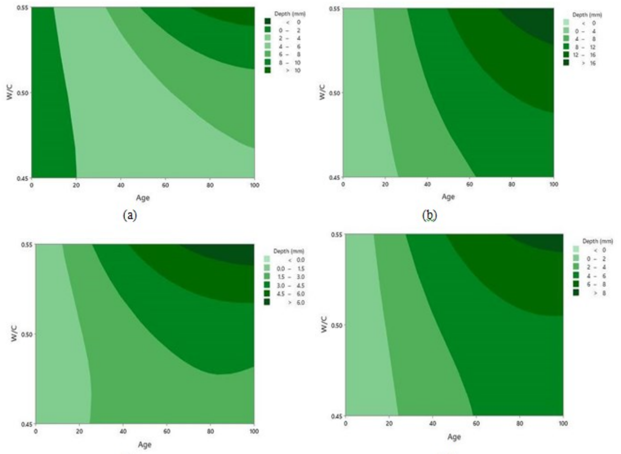
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	351.617	117.206	44.27	0.001
W/C	1	0.054	0.054	0.02	0.892
AGE	1	9.505	9.505	3.59	0.117
W/C*AGE	1	20.250	20.250	7.65	0.040
Error	5	13.239	2.648		
Total	8	364.856			

Table 5. ANOVA table for unsheltered RCP 4.5

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	42.9325	14.3108	14.46	0.007
W/C	1	0.0135	0.0135	0.01	0.912
AGE	1	2.8709	2.8709	2.90	0.149
W/C*AGE	1	4.6225	4.6225	4.67	0.083
Error	5	4.9475	0.9895		
Total	8	47.8800			

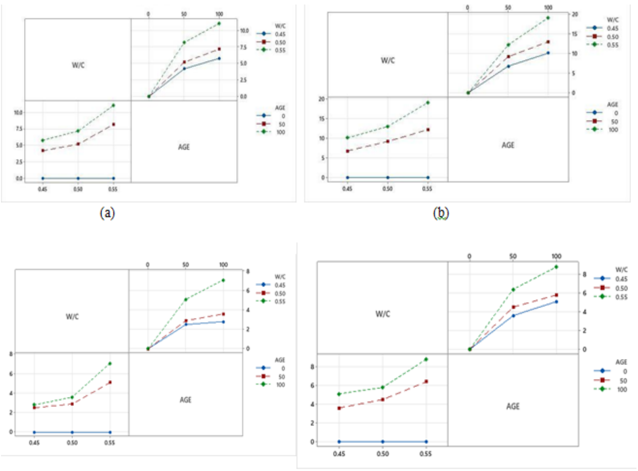
Table 6. ANOVA table for unsheltered RCP 8.5

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	75.1458	25.0486	20.35	0.003
W/C	1	0.0602	0.0602	0.05	0.834
AGE	1	1.4146	1.4146	1.15	0.333
W/C*AGE	1	3.4225	3.4225	2.78	0.156
Error	5	6.1542	1.2308		
Total	8	81.3000			



(a) (b) (c) (d)

Figure 12. Contour plot for carbonation depth versus w/c versus age sheltered RCP 4.5 (a), sheltered RCP 8.5 (b), unsheltered RCP 4.5 (c), un sheltered RCP 4.5 (d)



(a) (b) (c) (d)

Figure 13. Interaction plot for means for sheltered RCP 4.5 (a), sheltered RCP 8.5 (b), unsheltered RCP 4.5 (c), unsheltered RCP 4.5 (d)

Results obtained from analysis of variance (ANOVA) table are shown in Tables 3–6. The model is found to have statistically illustrative capacity. According to the findings of the ANOVA, the current model is more significant than the previous model since the P-value is less than 0.01 on regression. The parameters had a confidence level of 92%, and it was discovered that they were more important. Inferred from the big Fisher F-Test result and the low corresponding probability values (P-values), it was discovered that all of the linear factors, as well as the cross products, had significant impacts on the proportion of w/c age in the population. Furthermore, the lack-of-fit F-value of 0.49 shows that the lack-of-fit is not statistically significant when compared to the overall error. A non-significant lack of fit is considered advantageous in this design. The coefficient of determination, which measures how well the regression model fits the data, provides further evidence of its strong fit (R^2).

As per Taguchi analysis from Minitab software it is then conceivable to characterize equation (17) and decide the depth of carbonation. Considering the humidity of the exposure atmosphere,

$$\text{Carbonation Depth} = -0.7 + 3.0\,w/c - 0.309\,Age + 0.900\,w/c * Age \quad (18)$$

Age = Age in years

w/c = Water cement ratio

Different investigations revealed that the carbonation rate of concrete primarily relies upon the carbon dioxide diffusivity, which consequently relies upon the permeability property of concrete and on its inevitable filling by different substances, especially water. The presence of carbon dioxide in concrete is a vital condition for carbonation yet it is not adequate all alone. However, the relative humidity of the exposure climate plays a key responsibility in the carbonation process. The dissemination of carbon dioxide in a fluid medium is around 10^4 periods slower than in a vaporous medium and subsequently in saturated medium, the entry of carbon dioxide is nil. As a result, the humidity of concrete has adverse impacts on carbonation of concrete. Figure 12 shows the contour plot of carbonation depth with respect to age and water cement ratio and age. Figure 13 presents the maximum carbonation depth obtained for sheltered RCP 8.5 condition with respect to water cement ratio and age. From Taguchi analysis, it is affirmed that depth of carbonation increases as water cement ratio increases and results obtained from ANOVA investigation have shown that water cement ratio and age of the structure have utmost importance on carbonation depth.

4. Conclusions

Based on the results obtained from the carbonation modeling, the following conclusions are drawn.

Global environmental change influences the evolution of higher carbonation depth in concrete. The consequences of the current study affirm the anticipation of higher extreme carbonation depths in the long term which was also reported in previous studies.

In the current study, results were generated with the aid of most recent IPCC RCP information and it clearly demonstrates that nowadays carbonation advances quickly than time period mentioned in previous investigations. Despite the fact that environmental change has maximum impact on concrete durability built today, genuine impacts of environmental transformation can become obvious in the close future. In this way, infrastructures being developed between 2025 to 2030 should start to consider degradation because of environmental change when they are being planned. Problems might be addressed by guaranteeing sufficient concrete cover when required, reduction in permeability of concrete and by providing surface coatings to prevent carbon dioxide ingress.

In regions where carbonation induced corrosion is a worry, for the buildings to be constructed under scenario RCP 8.5 by the year 2040, the life span would decline roughly by 15 to 20 years with indications of evidence in damage whereas in normal scenario, damage might become evident only after 40 to 50 years of construction.

Current codal provisions for mix design of concrete and the cover are adequate enough for the prediction of initiation of corrosion induced by carbonation, but the primary objective is to stick on with the current suggestions. In case, there isn't thorough conformity with codes and if there is a decline in service of the cover provided in concrete due to some other reasons, a premature commencement of corrosion induced due to carbonation can be awaited leading to decrease in the building service life.

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Author's Contributions:

Vivek Deivasigamani: Writing − Original draft, Investigation, Formal analysis. Jayaguru.Chandrasekaran: Supervision, Revision and Editing. Gobi Subburaj Rampradheep & Shankar Subramaniam: Revision, Editing and Validation.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

Ethical approval

All procedures performed were in accordance with the ethical standards of the institutional and national research committee

Consent to participate

All authors were participated in this work

Consent to publish

All authors agree to publish

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