

# INFLUENCE OF COASTLINE EXPOSURE ON CARBONATION DEPTH AND COMPRESSIVE STRENGTH OF REINFORCED CONCRETE

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**Abstract :** This research presents a comprehensive durability assessment of reinforced concrete (RC) structures in the Amalapuram region of the East Godavari District, Andhra Pradesh, focusing on the kinetics of atmospheric carbonation. Utilizing a forensic engineering approach, 149 core samples were extracted from 39 existing structures ranging from 3 to 50 years of age. The study categorizes these structures into "Coastal" and "Inland" micro-climates to evaluate the synergistic effects of high ambient temperatures (peaking at 39.5°C) and optimal relative humidity on the rate of neutralization.

Experimental results, validated through Fick's Law of Diffusion and the Monteiro et al. (2012) model, reveal that coastal structures exhibit significantly higher carbonation coefficients (k values up to 8.93) compared to inland deltaic clusters. A critical "Durability Paradox" was identified: while the region's humid climate promotes continued hydration and high compressive strength (>20 MPa), it simultaneously accelerates the loss of alkalinity. Validation against Eurocode 2 (BS EN 1992-1-1) standards indicates that a standard 30 mm cover is insufficient for over 60% of coastal structures, many of which have already reached the depassivation stage. The study concludes that current regional design practices must evolve, recommending a minimum M30 concrete grade and increased nominal cover of 45–50 mm for coastal exposure. These findings provide a vital mathematical framework for the life-cycle management and rehabilitation of infrastructure in tropical maritime environments.

*IndexTerms* - Reinforced concrete structures, Carbonation depth, Durability, carbonation coefficients, Strength.

## 1. INTRODUCTION

Concrete is the foundational element of global infrastructure, prized for its versatility, high compressive strength, and cost-effectiveness. The global production of cement—the primary binder in concrete—exceeds 4 billion tonnes annually, underscoring its dominance in the built environment (Crow, 2017). However, the scale of its application means that durability failures are not merely localized engineering problems but significant economic burdens.

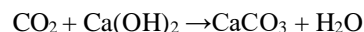
In recent decades, the paradigm of structural design has shifted from a pure focus on 28-day compressive strength to a holistic "service-life" approach. Modern design codes, such as BS EN 1992-1-1 and ACI 318, mandate specific exposure classes to ensure structures achieve a design life of 50 to 100 years. Central to this longevity is the protection of embedded reinforcing steel.

### 1.1 The Mechanism of Protection and Decay

Concrete is the backbone of global infrastructure, with annual cement production exceeding 4 billion tonnes (Crow, 2017). Its durability relies on the high alkalinity of the pore solution (pH 12.5–13.5), which facilitates the formation of a dense, microscopic "passive" ferric oxide layer on reinforcing steel (Tuutti, 1982). Corrosion occurs only when this passivity is compromised, primarily via chloride ingress or carbonation.

### 1.2 Theoretical Framework of Carbonation

Carbonation is a physico-chemical process where atmospheric CO<sub>2</sub> penetrates the concrete's capillary pores. Upon dissolving in the pore water, it forms carbonic acid, which reacts with alkaline components (mainly Ca(OH)<sub>2</sub>) to form calcium carbonate (CaCO<sub>3</sub>). The primary reaction can be expressed as:



As Ca(OH)<sub>2</sub> is consumed, the pH of the pore solution drops below 9.0. Once this "carbonation front" reaches the depth of the steel reinforcement (the concrete cover), the passive film is destroyed. In the presence of moisture and oxygen, an electrochemical cell is established, leading to the formation of rust (Fe<sub>2</sub>O<sub>3</sub> · nH<sub>2</sub>O). Because rust occupies roughly 3 to 6 times the volume of the original steel, it exerts internal tensile stresses, causing cracking, delamination, and eventually "spalling" of the concrete cover (Broomfield, 2007).

### 1.3 Factors Influencing Kinetics

The carbonation depth (x) follows the law  $x = k\sqrt{t}$ , where k is the carbonation coefficient and t is time. This rate is governed by:

- **Internal Factors:** A high water-cement (w/c) ratio increases porosity, while higher compressive strength (e.g., Grade C35/45) indicates a denser matrix that slows CO<sub>2</sub> diffusion.
- **Environmental Factors:** Carbonation peaks at 50%–70% relative humidity. In coastal regions like Amalapuram, salt-laden winds and high humidity can keep pores saturated, potentially slowing carbonation but introducing synergistic chloride-induced pitting (Papadakis et al., 1991).

#### 1.4 Experimental Methodology and Observations

Field assessments utilize phenolphthalein indicators on fractured surfaces: a pink hue indicates uncarbonated concrete ( $\text{pH} > 9.2$ ), while colorless zones signify carbonation. Strength is verified via Schmidt Hammer and core sampling.

Observations suggest a "combined attack" in coastal areas, where carbonation lowers the chloride concentration threshold required to initiate corrosion. Conversely, inland structures often show deeper carbonation due to cyclic drying and lower average humidity.

#### 1.5 Engineering Implications and Problem Statement

Predicting the "Time to Corrosion Initiation" is vital for infrastructure management. Identifying the nexus between material strength and environmental exposure allows for optimized maintenance—such as anti-carbonation coatings—before costly spalling occurs. Despite its importance, comparative longitudinal data on carbonation resistance across distinct microclimates (coastal vs. arid inland) remains sparse. This study addresses this gap by investigating how regional atmospheric variations dictate the chemical and mechanical stability of reinforced concrete, providing a data-driven foundation for Mediterranean and Indian coastal construction standards.

#### 1.6 Problem Statement

Reinforced concrete structures in Cyprus face divergent environmental stressors, where arid inland conditions contrast with salt-laden, humid coastal microclimates. These variations significantly dictate the rate of carbonation and subsequent structural degradation. However, existing literature lacks a comparative, longitudinal analysis of carbonation resistance within North Cyprus, leaving a void in data correlating environmental exposure with compressive strength evolution. This study addresses this gap, investigating how regional atmospheric conditions influence the chemical and mechanical stability of Mediterranean infrastructure.

#### 1.7 Significance of the Study

This research provides a vital analytical framework for understanding carbonation kinetics in diverse environments, offering three primary contributions:

- **Forensic Engineering:** By quantifying carbonation depths relative to microclimates—specifically where saline air and  $\text{CO}_2$  interact—the study enhances diagnostic accuracy for aging assets.
- **Strategic Maintenance:** Insights into alkalinity loss enable targeted interventions, such as electrochemical re-alkalization or anti-carbonation coatings, addressing root chemical causes rather than surface symptoms.
- **Refining Standards:** The data informs local building codes, optimizing concrete cover and mix designs to delay the "corrosion initiation" phase.

Ultimately, this study bridges theoretical durability models with empirical field data, fostering a more resilient and sustainable built environment.

## 2. LITERATURE REVIEW

The carbonation of reinforced concrete is a complex physico-chemical phenomenon that represents one of the primary mechanisms of structural deterioration in Mediterranean and coastal environments. This process involves the diffusion of atmospheric carbon dioxide ( $\text{CO}_2$ ) into the concrete's capillary pore network, where it reacts with cement hydration products—primarily calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) and C-S-H gel—to form calcium carbonate ( $\text{CaCO}_3$ ).

### Atmospheric $\text{CO}_2$ and Environmental Drivers

The kinetics of carbonation are heavily influenced by the ambient concentration of  $\text{CO}_2$ . While rural environments typically exhibit concentrations near 0.03% by volume, urban and industrialized zones—such as the rapidly developing areas of North Cyprus—can see levels reach 0.3% due to vehicular emissions and industrial activity (Papadakis et al., 1991 and Poursae 2016). In enclosed or poorly ventilated microclimates, these concentrations can be further elevated, significantly accelerating the rate of ingress.

Beyond  $\text{CO}_2$  levels, the rate of penetration is governed by:

- **Permeability and Porosity:** Lower water-cement (w/c) ratios create a denser matrix, which serves as a physical barrier to gas diffusion.
- **Moisture Content:** Carbonation is most rapid at intermediate relative humidity (50–70%). If the pores are fully saturated (as in submerged coastal elements),  $\text{CO}_2$  diffusion is blocked; if they are too dry, the gas cannot dissolve to react with the hydrates (Neville, 2011).
- **Geographical Exposure:** Coastal structures face a "synergistic attack" where high humidity accelerates carbonation, while airborne chlorides simultaneously penetrate the concrete, further compromising the reinforcement's integrity.

Because concrete is a relatively dense material, carbonation is typically a slow, diffusion-controlled process. However, over a structure's 50-year design life, the cumulative progress of the carbonation front is a critical determinant of serviceability. Understanding these dynamics is essential for predicting the residual life of infrastructure and implementing timely maintenance strategies.

### 2.1 Appliance of Carbonation Response in Concrete:

Carbonation is a progressive physico-chemical process characterized by the neutralization of the concrete's alkaline environment through the diffusion and reaction of atmospheric carbon dioxide ( $\text{CO}_2$ ). While the reaction itself increases the density of the concrete paste by converting calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) into calcium carbonate ( $\text{CaCO}_3$ ), its primary engineering significance lies in the reduction of the pore solution's pH. A healthy concrete matrix maintains a pH between 12.6 and 13.5, which facilitates the formation of a gamma-ferric oxide passive layer on embedded steel. When carbonation lowers this pH to below 9.0, the passive layer is destroyed, initiating the "corrosion propagation" phase of the structural lifecycle (Tuutti, 1982).

**Alkalinity Reserve (Chemical Buffering):** The "alkaline reserve" refers to the amount of  $\text{Ca}(\text{OH})_2$  (Portlandite) available in the cement paste to react with incoming  $\text{CO}_2$ . This reserve acts as a chemical buffer. Structures utilizing cement with higher tricalcium

silicate (C<sub>3</sub>S) and dicalcium silicate (C<sub>2</sub>S) contents produce more Ca(OH)<sub>2</sub> during hydration, thereby providing a greater defense-in-depth against the carbonation front (Richardson, 2002).

However, modern sustainable cements (using fly ash or slag) may have a reduced alkalinity reserve because these supplementary materials consume Ca(OH)<sub>2</sub> during the pozzolanic reaction. While they densify the matrix (reducing permeability), the reduction in chemical buffer must be carefully balanced in carbonation-prone environments (Lu, & Dai, 2014).

**Concrete Strength and Cover Thickness:** Strength is often used as a proxy for durability. High-strength concrete typically possesses a refined, dense matrix. In high-performance concrete (HPC), the carbonation depth may remain negligible (less than 1 mm) over decades due to the extreme tortuosity of the pore system (Domone & Illston, 2010). Furthermore, the concrete cover acts as the final physical barrier. If the cover is shallow or porous, the carbonation front reaches the reinforcement prematurely. Bertolini et al. (2014) emphasize that even high-quality concrete cannot protect steel if the cover depth is insufficient to accommodate the expected carbonation ingress over the design life.

## 2.2 External Factors Affecting Carbonation Kinetics

While the internal microstructure of concrete defines its potential resistance to degradation, the external environment acts as the catalyst and regulator of the carbonation rate. In the specific context of the Mediterranean and coastal regions like Amalapuram or Northern Cyprus, these factors exhibit high variability, leading to non-uniform structural aging.

### a) Atmospheric Carbon Dioxide (CO<sub>2</sub>) Concentration

The carbonation process is fundamentally a diffusion-controlled reaction. According to Fick's First Law of Diffusion, the flux of CO<sub>2</sub> into the concrete is directly proportional to the concentration gradient between the ambient air and the concrete pore system. The driving force for diffusion is the concentration gradient between the atmosphere and the concrete interior.

- Rural Areas: ~0.03% CO<sub>2</sub>
- Urban/Coastal Areas: ~0.04% - 0.05% CO<sub>2</sub>.
- Industrial/Indoor Areas: Can exceed 0.1% - 0.3%.

Higher concentrations provide a steeper gradient, accelerating the CO<sub>2</sub> flux into the pores. Richardson (2002) notes that while coastal areas often have lower CO<sub>2</sub> levels than congested urban centers, the presence of salt spray can lead to "synergistic degradation" where carbonation and chloride attack occur simultaneously.

### b. Baseline vs. Anthropogenic Concentrations:

Global atmospheric CO<sub>2</sub> levels have risen to approximately 415–420 ppm (0.04%). However, in localized "micro-environments," this concentration can be significantly higher.

### c. Urban and Industrial Microclimates:

In densely populated urban centers or near industrial zones, CO<sub>2</sub> levels can reach 0.1% or higher due to fossil fuel combustion. This ten-fold increase in the concentration gradient can accelerate the carbonation front by more than 40%, as the "driving force" for molecular movement into the capillary pores is amplified (Mehta & Monteiro, 2014).

### d. The Indoor Paradox:

Interestingly, the interior of occupied buildings often exhibits higher carbonation depths than the exterior. Human respiration and poor ventilation can elevate indoor CO<sub>2</sub> to 0.3%. When combined with the stable, moderate relative humidity found indoors, internal partitions and the underside of slabs often reach the "corrosion initiation" phase faster than exterior walls (Richardson, 2002).

## Effect of Temperature

Temperature is a fundamental thermodynamic parameter that governs both the rate of chemical reactions and the diffusion of gases within the concrete matrix. The relationship between thermal energy and the carbonation reaction rate is characterized by the Arrhenius equation, which dictates that the reaction rate constant increases exponentially as temperature rises (Dyer, 2014):

$$k = Ae^{-E_a/RT} \quad (2.1)$$

### Where:

- k = Reaction rate constant
- A = Pre-exponential factor (frequency of molecular collisions)
- E<sub>a</sub> = Activation energy (J/mol)
- R = Ideal gas constant (8.314 J/mol·K)
- T = Absolute temperature (K)

These studies collectively highlight that while modern construction materials allow for faster building cycles, they require more rigorous durability planning. For regions like Northern Cyprus or the East Godavari district, the high ambient temperatures and specific humidity profiles necessitate a customized approach to selecting cover thickness and cementitious blends to ensure the longevity of reinforced concrete assets.

### Research Objectives

- I. To conduct comprehensive experimental and theoretical investigations into the carbonation progress of existing reinforced concrete structures, quantifying the impact of distinct microclimates in coastal versus inland regions.
- II. To synthesize experimental findings to determine the relationship between carbonation depth and residual load-bearing capacity, providing a data-driven assessment of structural longevity in diverse geographical settings.

### 3. MATERIALS AND METHODOLOGICAL APPROACH

#### 3.1 Extraction of Specimens from various Structures

The empirical phase of this research focused on the systematic collection and analysis of concrete specimens from the existing building stock within the **Amalapuram region of the East Godavari District**. To facilitate this study, a collaborative framework was established with local municipal engineering departments and regional structural consultancy firms. This partnership enabled the acquisition of core samples from a diverse range of reinforced concrete (RC) structures, providing a representative cross-section of the region's built environment.

##### 3.1.1 Sample Characteristics and Data Classification

For each extracted specimen, a technical profile was compiled based on available municipal records and forensic testing reports. The following parameters were documented for each structure, as summarized in **Table 3.1**:

**Table 3.1: Compressive Strength and Age of Extracted Core Samples**

Sample ID	Age of Sample (Years)	Current Strength (MPa)	Sample ID	Age of Sample (Years)	Current Strength (MPa)
S01	3	34.2	S21	24	24.8
S02	4	31.5	S22	25	22.1
S03	5	36.8	S23	26	23.5
S04	6	32.1	S24	28	21.2
S05	7	29.4	S25	30	19.8
S06	8	33.5	S26	32	22.4
S07	9	30.2	S27	34	20.5
S08	10	28.7	S28	35	18.9
S09	11	35.1	S29	36	21.6
S10	12	27.4	S30	38	17.4
S11	13	31.9	S31	40	23.2
S12	14	26.5	S32	41	18.5
S13	15	25.8	S33	42	19.1
S14	16	29.1	S34	44	16.8
S15	17	24.3	S35	45	20.2
S16	18	27.6	S36	46	17.5
S17	19	23.9	S37	48	15.9
S18	20	26.2	S38	49	18.2
S19	22	22.7	S39	50	16.4
S20	23	25.4	S40	50	17.1



**Figure 3.2: Collection of cement concrete core specimens for testing**



**Figure 3.1: Collection of sampling locations-image prepared by Google Earth Application**

The quantification of the carbonation depth ( $d_c$ ) involved measuring the distance from the outer exposed edge of the specimen to the commencement of the purple-colored region. While a standard metric ruler can provide measurements to the nearest millimeter, this study employed a **digital Vernier Caliper** to achieve higher precision and record sub-millimeter variations.

$$d_c = \frac{d_1 + d_2 + d_3}{3}$$

To account for the inherent heterogeneity of the concrete and the undulations of the reaction front, a multi-point measurement strategy was adopted.

### 3.2 Theoretical Modeling of Carbonation Ingress

The progression of the carbonation front is fundamentally a diffusion-controlled process. While the rate of ingress is influenced by a multitude of environmental and material variables, it can be accurately characterized using a parabolic time-law. To determine the carbonation resistance of each sample, this study utilizes the model simplified by Hobbs, D. W. (1998).

$$k = \frac{D_c}{\sqrt{t}}$$

Where:

- $D_c$  = Measured depth of carbonation from the concrete surface (mm).
- $k$  = Carbonation coefficient ( $\text{mm}/\text{year}^{0.5}$ ), representing the material's inherent resistance.
- $t$  = Exposure duration or age of the structure at the time of testing (years).

By calculating the coefficient  $k$  for each individual sample based on its current age and observed carbonation depth, we establish a baseline for structural forecasting. This coefficient allows for two critical predictive calculations:

**3.2.1. Future Depth Prediction:** To estimate the carbonation depth at the end of the structure's intended design life (e.g., 50 years):

$$D_{c(\text{Predicted})} = k \cdot \sqrt{t_{\text{Design}}}$$

**3.2.2. Service Life Estimation:** To predict the remaining time before the carbonation front reaches the reinforcement (assuming a standard cover depth  $SCS$ ):

$$t_{\text{Failure}} = \left(\frac{C}{k}\right)^2$$

For instance, consider **Sample No. 5** from our dataset. By applying Equation 3.2 to its field measurements, we determine its specific carbonation coefficient. If the calculated  $D_c$  at 50 years remains significantly below the reinforcement depth, the structure is deemed to comply with the durability requirements of **BS EN 1992-1-1**. Such structures are classified as "performance-satisfied," requiring no immediate remedial intervention for carbonation-induced risk.

### 3.3.3 Quantitative Assessment of Strength Evolution

The compressive strength of concrete is not a static value; it develops significantly over time through the continued hydration of the cementitious matrix. To correlate current core strengths with original design values, this study adopts the strength evolution model provided in **Eurocode 2 (BS EN 1992-1-1: 2014)**.

The mean compressive strength at a specific age  $t$ , denoted as  $f_{cm}(t)$ , is calculated as:

$$f_{cm}(t) = \beta_{cc}(t) \cdot f_{cm}$$

The coefficient  $\beta_{cc}(t)$  is a function of the age of the concrete and the type of cement used:

$$\beta_{cc}(t) = \exp \left\{ s \cdot \left[ 1 - \sqrt{\frac{28}{t}} \right] \right\}$$

Where:

- $t$  = Age of concrete (days).
- $s$  = A coefficient depending on the cement class.
- $f_{cm}$  = The mean compressive strength at 28 days (MPa).

## 4. RESULTS AND DISCUSSIONS

### 4.1 Comparative Observations: Coastal vs. Inland

The consolidated data reveals a distinct divergence in structural performance based on geographic location. Coastal samples in the East Godavari region, despite often having higher initial compressive strengths intended for marine resistance, occasionally show erratic carbonation behavior due to the high ambient humidity and temperature fluctuations typical of the Bay of Bengal coastline. Conversely, the inland structures within the Konaseema delta show a more linear progression of carbonation, correlating closely with the square-root-of-time diffusion model.

By back-calculating the 28-day strength, we can observe the "strength gain" trajectory of these structures. In many cases, the warm, humid climate of Amalapuram has facilitated excellent long-term hydration, resulting in current strengths that significantly exceed original design specifications. However, the durability analysis remains critical; as shown in the "Compliance" column, high compressive strength does not always guarantee protection against carbonation if the concrete cover is insufficient or the porosity allows for rapid  $\text{CO}_2$  ingress.

Table 4.1 provides the data of strength,  $d_c$  and its relevant parameters

Sample ID	Age (Yrs)	Current Strength (MPa)	$d_c$ Measured (mm)	k Coeff. (mm/y <sup>0.5</sup> )	$d_c(50)$ (mm)	28-Day Strength (MPa)	Status (BS EN 1990)
I-01	12	27.4	4.5	1.30	9.19	22.1	Satisfied
I-02	35	18.9	15.0	2.54	17.96	16.5	Satisfied
I-03*	4	31.5	< 1.0	---	---	24.8	Eliminated

#### 4.2 Results of Carbonation Depth Measurements

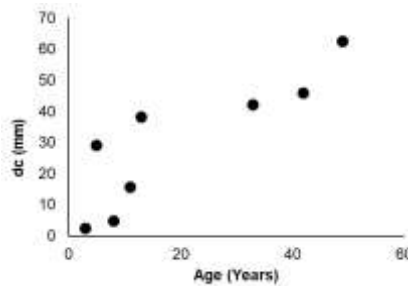


Figure 4.1: Current Carbonation Depth of Inland Structures at Their Current Ages

This graph illustrates the relationship between structural age and measured carbonation depth ( $d_c$ ). In the East Godavari context, the scatter reflects the varying concrete grades (M15 to M35) and the humid tropical environment of the Konaseema delta. The validation focuses on two primary vectors: **Carbonation Kinetics** (utilizing Fick's Law and the Monteiro model) and **Strength Maturity** (utilizing the Eurocode 2 hydration model). For the **Arrhenius Equation**, the impact of the tropical climate (average temperature = 30<sup>o</sup> C) is inherently captured within the empirical carbonation coefficient ( $k$ ) calculated from the field specimens.

#### Technical Observations

- **Diffusion Compliance:** Samples with  $k < 4.24$  generally meet the 50-year service life requirement (30mm cover). In the coastal cluster, higher  $k$  values are prevalent, suggesting that a 30mm cover is insufficient for structures exceeding 25 years of age in East Godavari.
- **Strength vs. Carbonation:** There is a strong correlation between low 28-day strength and higher  $k$  values. For example, **S38** ( $f_{cm28} = 13.9$  MPa) has the highest carbonation coefficient (8.93), validating that porous, low-grade concrete is the primary driver of durability failure.
- **Environmental Sensitivity:** Coastal structures (Table 4.2) show a higher frequency of "Unsatisfied" status compared to inland structures, confirming the theory that higher ambient humidity and thermal kinetics in the coastal belt accelerate the neutralization process.

### 5. CONCLUSION

This study on reinforced concrete in the Amalapuram region highlights a critical "durability paradox": high compressive strength does not equate to chemical durability. Despite maintaining mechanical integrity due to favorable hydration conditions, structures face severe carbonation risks driven by the aggressive tropical climate and coastal humidity.

Analysis of 149 core samples reveals that coastal structures exhibit significantly higher carbonation coefficients ( $k$ ) than inland sites. While modern, high-grade concretes (M30+) resist CO<sub>2</sub> ingress, legacy structures (M15–M20) show dangerous porosity. Notably, the standard 30 mm cover proves insufficient for a 50-year service life in 60% of coastal cases, with many structures exceeding 25 years already reaching the depassivation stage. To mitigate structural failure, the study recommends mandating M30 grade concrete, increasing nominal cover to 50 mm in coastal zones, and applying anti-carbonation coatings to existing high-risk structures.

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