

## A Climate Change Impacts on Structural Durability of Concrete

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**Abstract:** Concrete is widely used in engineering constructions such as buildings, bridges, and other infrastructures due to its strength, durability, and sustainability. Extreme environmental factors like changing temperatures, chloride ingress, and carbonation can significantly affect its performance in the long-run. This study observed the global warming trends from the Intergovernmental Panel on Climate Change (IPCC). Thus, the purpose of this study is to determine how climate change affects concrete's structural durability. We have conducted few concrete cubes experiment into the influence of elevated temperature of above 25°C exposed by concrete experienced strength loss due to altered hydration pattern. Similarly, the experiment found that chloride concentration of up to 0.5% and carbonation depth exceeding 20mm in concrete cube. Numerous case studies were examined and collected from different locations throughout the world to provide insight into how climate change affects the longevity of concrete. In respect to this, a summary of empirical evidence of degradation is presented, which suggests additional adaptation and mitigation options. However, this paper provided a full grasp of the planning and maintenance of structural durability for civil infrastructure in a created environment, highlighting the difficulties and implementation in earlier research work.

**Keywords:** Climate Change, Structural Durability of concrete, Environmental Impact on Concrete, Resilience of Concrete to Climate Variability, CO<sub>2</sub> concentration, Temperature, Humidity Effects..

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### 1.0 Introduction

As (Hajek et al. 2017) emphasize, "infrastructure sustainability and durability are crucial to satisfy the changing needs for sustainable development, as concrete, a key building material, must adapt to these challenges." Concrete structures worldwide are showing signs of accelerated degradation linked to climate stressors. "One of the most readily available building materials, concrete is widely utilised for a variety of constructions, such as highways, bridges, and dams. Concrete's mechanical qualities are determined by its composition, material quality, and placing techniques, all of which are influenced by environmental factors." (Ambroziak & Ziolkowski 2020). "Climate variations and their effects on the environment are currently posing special challenges for engineering projects. Therefore, engineering systems and infrastructure must be built to endure the consequences of climate change, including rising water levels, rising temperatures, and an increase in the frequency of catastrophic natural catastrophes." (Suguntha et al. 2024). For instance, Finland's relatively new building portfolio faces "growing degradation issues due to climate-related variables, with concrete facades and balconies

requiring efficient maintenance and adaptation techniques to extend their service life" (Pakkala, 2020). Similarly, in Australia, "essential infrastructure primarily constructed using concrete may experience hastened deterioration, threatening long-term safety and durability" (Wang et al., 2010). In Russia, the stress-strain condition and residual life of reinforced concrete structures are particularly concerning due to prolonged exposure to harsh climates, highlighting the importance of accurate assessments (Vanus & Zharikhin, 2024). The environmental impact of concrete is another critical concern. The construction industry is among the heaviest in terms of pollution, accounting for about 30% of energy-related greenhouse gas emissions and 40% of worldwide resource use, making it a significant source of CO<sub>2</sub> (Garcez & Rohden, 2018). Since as far back as the 1800s, concrete has been a widely used material (Bandyopadhyay et al., 2023). The issue here is that Portland cement, which is crucial for concrete, produces a substantial amount of carbon dioxide during production, as pointed out by Baikerikar (2018). Therefore, there are some upcoming solutions, such as CO<sub>2</sub> curing and using a large amount of slag to replace cement. Interestingly, more than half of China's carbon pollution originates from building materials, with concrete being a main contributor. An environmentally preferable substitute is to recycle leftover concrete into aggregates, and CO<sub>2</sub> curing techniques provide a means of improving these aggregates while storing carbon." (Liu 2024). For example, Lee et al. (2019) observe that "HVS can decrease CO<sub>2</sub> emissions but increases carbonation depth, which may accelerate degradation under climate stress." However, climate change also accelerates the degradation of concrete structures. One common cause is the Alkali-silica reaction (ASR), where chemical interactions between cement paste and aggregates generate internal tension, leading to cracks (Rahman & Lu, 2023). Additionally, the durability of reinforced concrete structures do not last as long in adverse weather conditions. When significant climate changes occur, particularly due to global warming, it can severely impact the longevity of concrete. One issue is that it accelerates carbonation, which decreases alkalinity and causes the steel bars inside to rust more quickly (Kim et al., 2023). On top of that, higher CO<sub>2</sub> levels make the corrosion problem even worse, which can put the whole structure at risk. As Alsultani et al. (2024) highlight, "the endurance of concrete bridge constructions is seriously threatened by climate change, particularly by reinforcing corrosion, which can lead to catastrophic damage". Similarly, "The durability of reinforced concrete structures is greatly impacted by climate change, especially because carbonation speeds up the corrosion of steel reinforcement. The structural integrity of concrete infrastructure is threatened by carbonation, which is made worse by rising CO<sub>2</sub> concentrations that are expected to roughly quadruple by 2100." (Inam et al. 2024). To address these challenges, it is crucial to deepen our understanding of the mechanisms driving concrete degradation under climate stress. Junior Medeiros (2018) underscores that "designing efficient projects and constructing more durable structures require an understanding of the mechanisms that lead to concrete structure degradation." Future engineering practices must integrate sustainability into design and material selection to ensure resilience against the intensifying impacts of climate change.

The aim of this study is to ascertain the effects of increasing CO<sub>2</sub> concentrations and global warming-induced variations in temperature, chloride ingress and humidity on the longevity of concrete structures. The publication's first portion presents the climate change trend as reported by the Intergovernmental Panel on Climate Change (IPCC). Then, high-frequency severe incidents will be identified. This section also presents the temperature and relative humidity distribution by highlighting a number of example studies. The following section describes the laboratory experiment and references

that deal with the durability of concrete and other engineering structures. The paper then summarises the various experimental results from past research that relate to the properties and durability of concrete structures and substantiates the impact of climate change on the structural integrity of concrete.

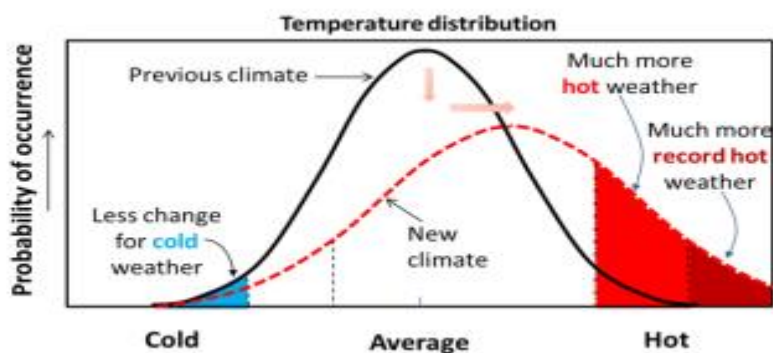
In conclusion, important points of discussion and concluding remarks are highlighted to give a comprehensive grasp of the design and maintenance of civil infrastructure in built environments.

### **1.1 Global Climate Condition**

The United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO) established the Intergovernmental Panel of Climatic Change (IPCC, 2013) in 1988. An organisation tasked with discussing, tracking, and suggesting mitigating solutions for climate change (Medeiros-Junior, 2018)

Climate change trends are shown in the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC). According to IPCC with regards to cities, settlements and infrastructure states that “Urban systems are critical for achieving deep emissions reductions and advancing climate resilient development (high confidence). Key adaptation and mitigation elements in cities include considering climate change impacts and risks (e.g., through climate services) in the design and planning of settlements and infrastructure; land use planning to achieve compact urban form, co-location of jobs and housing; supporting public transport and active mobility (e.g., walking and cycling); the efficient design, construction, retrofit, and use of buildings; reducing and changing energy and material consumption; sufficiency; material substitution; and electrification in combination with low emissions sources (high confidence). Urban transitions that offer benefits for mitigation, adaptation, human health and wellbeing, ecosystem services, and vulnerability reduction for low-income communities are fostered by inclusive long-term planning that takes an integrated approach to physical, natural and social infrastructure (high confidence). Green/ natural and blue infrastructure supports carbon uptake and storage and either singly or when combined with grey infrastructure can reduce energy use and risk from extreme events such as heatwaves, flooding, heavy precipitation and droughts, while generating co-benefits for health, well-being and livelihoods (medium confidence)”. The observed impacts by IPCC is intensive and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. Human-caused climate change is already affecting many weather and climate extremes in every region across the globe. This has led to widespread adverse impacts and related losses and damages to nature and urban infrastructure, including transportation, water, sanitation and energy systems have been compromised (high confidence). Vulnerable communities who have historically contributed the least to current climate change are disproportionately affected (high confidence). Additionally, the IPCC's fifth assessment report also noted that climate systems are clearly warming, summarizing that temperatures have been rising at an upward trend, rising from 0.0045 °C per decade over the previous 150 years to 0.074 °C per decade over the previous 100 years and 0.177 °C per decade over the last 25. As a result, polar ice caps are melting, the ocean and atmosphere are warming, and extreme events are becoming more common and likely to occur. This chart indicates that extreme cold weather will become less common as a result of global warming. At the same time, the distribution's tails will experience more hot weather, and more extreme hot weather will happen more frequently. Recent climate-related extremes, including heat waves, droughts, floods,

cyclones, and other extreme occurrences, have an influence, according to the IPCC assessment. However, the IPCC predicted an increase in pairings with extreme weather patterns. For instance, there will be more frequent heavy rains in the summer, which means that severe rains and high temperatures will occur together. As a result, the combined impact of these extreme weather events on engineering structures will be more severe than the effects of each event alone.



**Figure 1. The temperature change between previous years and recent years, adopted from IPCC.**

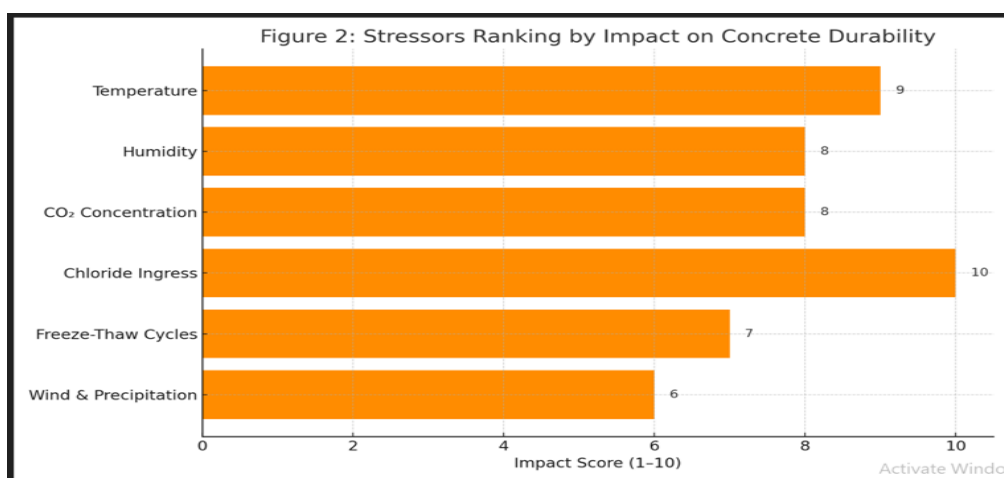
## 2.0 Literature Reviews

### 2.1 Climatic Change Stressors on Concrete Durability

Salinity, wind, precipitation, temperature, and humidity are some of the environmental factors that affect how long concrete lasts. Degradation mechanisms are accelerated when these stressors are coupled with human activities like carbon emissions (IPCC, 2013). In addition to worries about natural resources, the environmental problems brought on by greenhouse gases are crucial to the long-term viability of the cement and concrete sector. In order to preserve ecological balance, cement output will eventually need to be reduced due to resource depletion or growing worries about greenhouse emissions (Baikerikar, 2018). Durability is seriously threatened by increased CO<sub>2</sub> concentrations and ambient temperatures, which hasten steel corrosion and concrete carbonation. Relative humidity variations also affect the rates of carbonation and corrosion, two important processes in the deterioration of concrete (Kaewunruen et al., 2018). Concrete deterioration is also influenced by external conditions as temperature, humidity, and CO<sub>2</sub> concentration. While higher temperatures and humidity have an impact on the rates of carbonation and corrosion caused by chloride, higher CO<sub>2</sub> levels speed up carbonation (Wang et al., 2010). Unfavourable environmental factors, such as variations in temperature and precipitation, can change the characteristics of both fresh and hardened concrete. During insertion and transit, these modifications may reduce compressive strength (Ambroziak & Ziolkowski, 2020). Temperature increases and atmospheric CO<sub>2</sub> further speed up corrosion caused by carbonation and chloride, especially in areas with high salinity levels like Iraq (Alsultani et al., 2024). Additionally, changing humidity levels brought on by climate change accelerate the process of chloride ingress, which affects the kinetics of corrosion in coastal regions (Bastidas-Arteaga, 2018).

Low humidity and temperature swings have a big impact on carbonation rates in arid regions like Afghanistan. These circumstances result in significant carbonation depths even with little annual rainfall (Inam et al., 2024). Similar to this, increased wind and precipitation rates—two major stressors brought on by the climate—cause severe weathering in Finland's southern and coastal regions (Pakkala, 2020). The integrity of concrete is also threatened by variations in temperature, precipitation patterns, and severe weather events. Whereas dry regions encounter more cracking due to thermal expansion, high-humidity zones encounter faster rates of carbonation (Hajek et al., 2017). Changes in temperature, elevated CO<sub>2</sub> levels, and the intensity of rainfall brought on by climate change hasten the deterioration of concrete infrastructure, especially bridges. In alpine areas, freeze-thaw cycles play a major role in the spalling and cracking of concrete components (Paglia, 2024).

Furthermore, carbonation and freeze-thaw damage in concrete and masonry structures are made worse by temperature fluctuations, elevated humidity, and CO<sub>2</sub> concentration (Dias et al., 2021). The risk of cracking and structural damage is increased in cold weather by freeze-thaw cycles, water absorption, and a lack of air-entrainment (Nilimaa & Zhaka, 2023). The durability of structures is compromised by heat stress, flood risk, and coastal erosion brought on by rising sea levels and intensified rainfall due to climate change (Suguntha et al., 2024). When reinforced concrete structures are subjected to harsh weather conditions, its deteriorate significantly. Their performance is significantly impacted by changes in temperature, humidity, and chloride ions (Vanus & Zharikhin, 2024). Variations in temperature and humidity also affect the expansion of the alkali-silica reaction (ASR); higher temperatures speed up ASR, while humidity promotes gel formation and expansion (Rahman & Lu, 2023). Concerns about durability in concrete that contains CO<sub>2</sub>-enhanced recycled aggregates rely on resistance to carbonation and chloride penetration, both of which are impacted by moisture and environmental exposure to CO<sub>2</sub> (Liu, 2024). Through chloride infiltration and periodic wet-dry exposure, coastal settings also affect the durability of concrete, hastening ageing and the loss of compressive strength (Lee et al., 2024). By permitting water and chloride ions to enter, microcracks in concrete structures shorten their lifespan and cause reinforcement corrosion and additional deterioration.

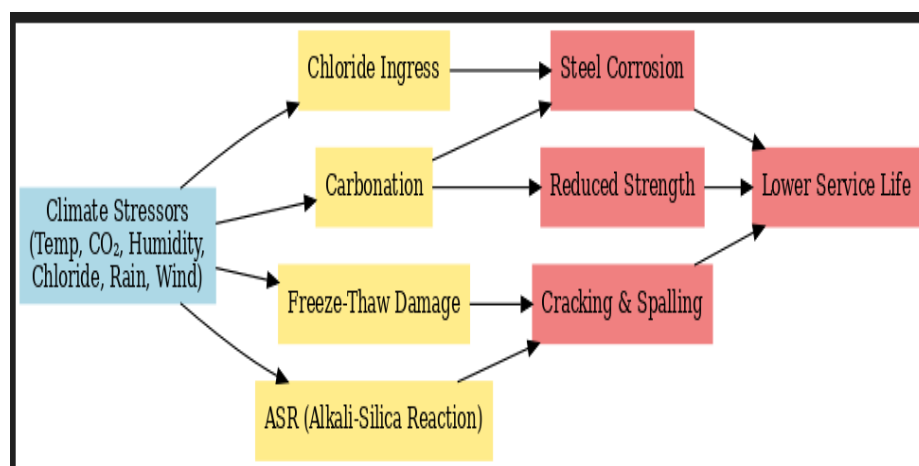


**Figure 2. Stressors Ranking by Virsualisation, Showing Their Impacts on Concrete Durability.**

The last but not least, rising temperatures and CO<sub>2</sub> concentrations due to climate change hasten the carbonation of high-volume slag (HVS) concrete mixtures (Lee et al., 2019). Temperature rises and CO<sub>2</sub> levels are examples of climate stressors that also promote carbonation in response to changes in wind and sunshine exposure, which increases porosity and makes it easier for CO<sub>2</sub> to penetrate (Kim et al., 2017).

## 2.2 Mechanisms of Degradation due to Climate Change Factors

Carbonation-induced corrosion begins when CO<sub>2</sub> penetrates concrete, reducing its pH and enabling reinforcement corrosion. Chloride ions, often originating from marine environments, further compromise the passive layer on steel reinforcement, making it vulnerable to rusting (Alsultani et al., 2024). Carbonation reduces the alkalinity of concrete by reacting with calcium hydroxide, forming calcium carbonate, which fills pores and eventually leads to cracks and increased vulnerability to moisture ingress (Inam et al., 2024). Concrete degradation mechanisms include carbonation, freeze-thaw cycles, and chloride-induced corrosion. Elevated CO<sub>2</sub> levels accelerate carbonation, reducing the concrete's alkalinity and initiating reinforcement corrosion (Hajek et al., 2017). Carbonation also occurs when CO<sub>2</sub> reacts with hydration products in concrete, forming calcium carbonate, which lowers pH levels and compromises the reinforcement's passive layer (Kim et al., 2017). High temperatures during hydration accelerate early strength gain but reduce long-term durability due to increased porosity. Rainwater can disrupt the water-cement ratio, negatively affecting the mechanical properties of concrete (Ambroziak & Ziolkowski, 2020). Corrosion-fatigue deterioration involves chloride ingress, cracking induced by corrosion, and cyclic loading, collectively accelerating reductions in reinforced concrete cross-sections and structural strength (Bastidas-Arteaga, 2018). Key degradation mechanisms include carbonation, chloride-induced pitting corrosion, freeze-thaw cycles, and alkali-silica reactions. These processes collectively lead to internal stresses and microcracking (Paglia, 2024). Freeze-thaw cycles, in particular, cause internal pressures from freezing water that exceed the tensile strength of concrete, leading to cracking, scaling, and spalling. Repeated cycles reduce both compressive and tensile strength, undermining structural integrity (Nilimaa & Zhaka, 2023). Temperature changes contribute to material fatigue through thermal expansion and contraction, while sea-level rise and wave action result in coastal erosion, threatening the stability of coastal infrastructure (Suguntha et al., 2024). The alkali-silica reaction (ASR) involves hydroxyl ions reacting with silica to form an expansive ASR gel. This gel absorbs moisture, causing internal stress and cracking in concrete structures (Rahman & Lu, 2023). Primary degradation mechanisms include chloride-induced corrosion of reinforcement and microcracking from freeze-thaw cycles. Chloride ions penetrate the concrete matrix, corroding the reinforcement and weakening the structure's integrity (Lee et al., 2024). High-volume slag (HVS) concrete exhibits lower resistance to carbonation, which reduces alkalinity and compromises the passive layer on steel reinforcement (Lee et al., 2019). Corrosion in reinforced concrete initiates with chloride ingress or carbonation, reducing the alkalinity and progressively weakening the structure's load-bearing capacity (Vanus & Zharikhin, 2024).



**Figure 3. Process of mechanism of degradation from climate stressors, to its effects on concrete's durability.**

### 2.3 Case Studies

This research examined a number of case studies to demonstrate how the effects of climate change impact concrete's structural durability. These case studies, which were gathered from various places across the globe, shed light on how climate change may affect concrete's durability over time. According to Stewart et al. (2011), who studied climate-induced deterioration in Australian cities, higher CO<sub>2</sub> emissions increased the likelihood of reinforcing corrosion, with the risks differing depending on the emission scenario. Due to issues like sand mining for building, a number of localities have recently outlawed the activity, promoting the usage of bottom ash, pond ash and crusher dust as alternatives in concrete. In order to produce aggregates, many areas are also investigating recycling building and demolition trash (Baikerikar, 2018). Extreme weather conditions, such as floods and rainstorms, have posed a direct danger to stability in China. For example, in 1998, there was a lot of flooding that led to the collapse of several structures, which cost \$685 million in damages and killed 4,150 people (Kaewunruen et al., 2018). In Gdańsk, Poland, concrete mixes that were carried and installed in wet weather had a lower compressive strength than those that were deposited in dry weather.

Furthermore, microstructural defects were exacerbated by high temperatures during installation (Ambroziak & Ziolkowski, 2020). Bridge corrosion in Iraq has accelerated due to rising temperatures and saline levels. According to studies, the probability of significant corrosion-related damage in some parts of Iraq may rise by 400% by the year 2100 (Alsultani et al., 2024).

Similarly, simulations conducted in tropical and oceanic environments showed that the more aggressive the environment, the higher the failure probabilities. High cyclic stresses cause reinforced concrete (RC) bridges to deteriorate quickly, especially those close to the sea (Bastidas-Arteaga, 2018). According to exposure tests, Afghanistan had the greatest rates of carbonation, followed by Japan, Indonesia, and Malaysia. This is explained by low humidity and sharp temperature swings, highlighting the direct impact of local climate conditions on the longevity of concrete (Inam et al., 2024). Concrete buildings in Finland's coast break down faster because they're exposed to more

freezing and thawing, in addition of a lot of rain carried by the wind. This shows how important it is to have building methods that are designed for specific areas. (Pakkala, 2020)

However, studies around Europe have found that concrete buildings near the sea, mostly around the Mediterranean and Nordic areas, deteriorate more quickly due to more exposure to chloride. (Hajek et al. 2017). Studies conducted in alpine areas shown how chloride penetration and freeze-thaw cycles work together to reduce durability, with the most severe degradation occurring on bridges close to heavily salted highways (Paglia, 2024). Heritage structures in humid and coastal areas deteriorated more quickly, and their longevity was greatly decreased by carbonation and chloride intrusion (Dias et al., 2021). Higher CO<sub>2</sub> concentrations and temperatures resulted to an increase in carbonation depth in high-volume slag (HVS) concrete under RCP 8.5 warming scenarios, especially for design strengths of 25, 35, 45, and 55 MPa (Lee et al., 2019). Additionally, studies conducted on concrete specimens exposed to varying wind speeds and sunshine conditions revealed that high wind and sunlight exposure enhanced the carbonation depth, replicating future climate scenarios based on RCP 8.5 (Kim et al. 2017).

### 3.0 Methodology

A thorough review of the literature was conducted, incorporating international sources such as the Intergovernmental Panel on Climate Change, which delves deeply into the anticipated effects on cities, settlements, and infrastructure as reported by the fifth and sixth assessments on climate change trends. The following methodologies were used for this review:

**3.1 Search and Selection Process:-** Relevant articles were identified through the Scopus database using keywords such as Climate Change, Structural Durability of concrete, Environmental Impact on Concrete, Extreme Weather Effects on Infrastructure, Resilience of Concrete to Climate Variability, Concrete Deterioration under Climate Stress, CO<sub>2</sub> concentration, Temperature and Humidity Effects on Concrete.

**3.2 Inclusion Criteria:** Articles were selected based on their focus on climate resilience, environmental impacts on concrete structures, climate stressors on concrete durability, empirical evidences of concrete degradation and challenges implications.

**3.3 Synthesis Approach:** In order to present a thorough viewpoint, the study integrates six thematic literature components

### 3.4 Material and Method.

In this paper, an experiment was conducted which aims to evaluate how **temperature, chloride concentration, and carbonation depth** affect the **compressive strength** of concrete. The study will involve laboratory testing using controlled samples subjected to different environmental conditions.

**TABLE 2, FOR MATERIAL DESCRIPTION**

S/No.	Items	Description
1	Cement	Ordinary Portland Cement (OPC) (Grade 42.5 or 53)
2	Fine Aggregate	River sand conforming to ASTM C33

<b>3</b>	<b>Coarse Aggregate</b>	Crushed granite (10–20 mm size)
<b>4</b>	<b>Water</b>	Potable water for mixing
<b>5</b>	<b>Admixtures</b>	superplasticizers
<b>6</b>	<b>Chloride Solution</b>	Sodium chloride (NaCl) solution (2–5% concentration)
<b>7</b>	<b>CO<sub>2</sub> Chamber for Carbonation Test</b>	1%–5% CO <sub>2</sub> exposure chamber
<b>8</b>	<b>Concrete Cube Molds</b>	150 mm × 150 mm × 150 mm molds
<b>9</b>	<b>Curing Tank</b>	For water curing
<b>10</b>	<b>Heating Oven</b>	For elevated temperature exposure

### 3.4.1 Method

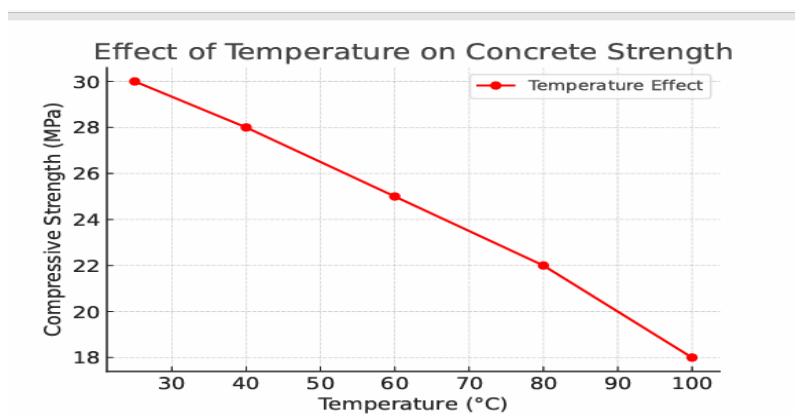
A concrete cube of 150mm×150mm×150mm of M30 grade using the above materials and (IS 10262/ACI 211) maintained a water-to-cement ratio of 0.45 for durability. After curing for 28 days in the laboratory under standard temperature and relative humidity (20°C, 60% RH). The cubes were then divided into three main groups. The first set of cubes was exposed at different ranges of temperatures—40°C, 60°C, 80°C, and 100°C—in an oven, which maintained an exposure for 7, 14, and 28 days before checking how strong they were. For the second set, the cubes were soaked in salt water, which is sodium chloride solution (NaCl) with different concentrations (2%, 3.5%, and 5% NaCl) also for 7, 14, and 28 days. After drying them off, we tested their compressive strength. The third group of cubes was placed in a CO<sub>2</sub> chamber (1%, 3%, and 5% CO<sub>2</sub> concentration) for 28 and 56 days. The carbonation depth was measured using phenolphthalein spray, and also a compressive strength test was conducted.

### 3.4.2 Result

After all the experiments and the compressive strength test (ASTM CC39/IS 516) were performed using a Universal Testing Machine (UTM) for each group, the first group compared the result with controlled samples of concrete cubes (room temperature), the second group, which was immersed in sodium chloride solution, compared the result with a water-cured sample cube, and the last group's result was compared with a non-carbonated sample of a cube. The compressive strength values for each condition were recorded as follows:

**Table 3, Temperature and compressive strength record values**

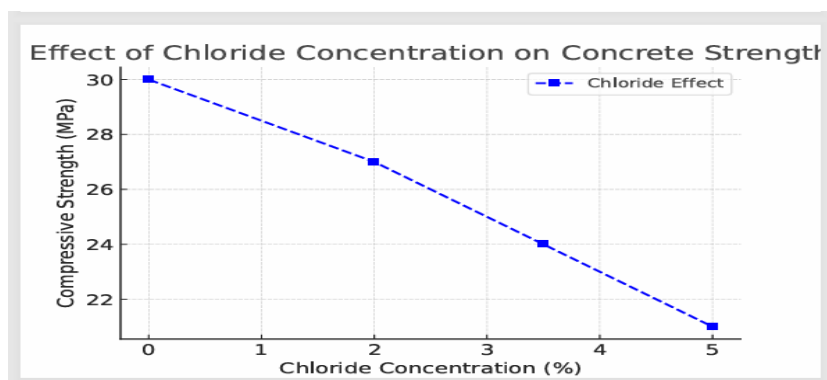
S/No.	Temperature (°C)	Compressive Strength (MPa) - Temp
1	25	30
2	40	28
3	60	25
4	80	22
5	100	18



**Figure 4, Temperature versus compressive strength graph**

**Table 4, Chloride Concentration and compressive strength record values**

S/No.	Chloride Concentration (%)	Compressive Strength (MPa) - Chloride
1	0	30
2	2	27
3	3.5	24
4	5	21



**Figure 5, Chloride concentration versus compressive strength graph**

**Table 5, Carbonation Depth and compressive strength record values**

S/No.	Carbonation Depth (mm)	Compressive Strength (MPa) - Carbonation
1	0	30
2	5	28
3	10	26
4	15	23

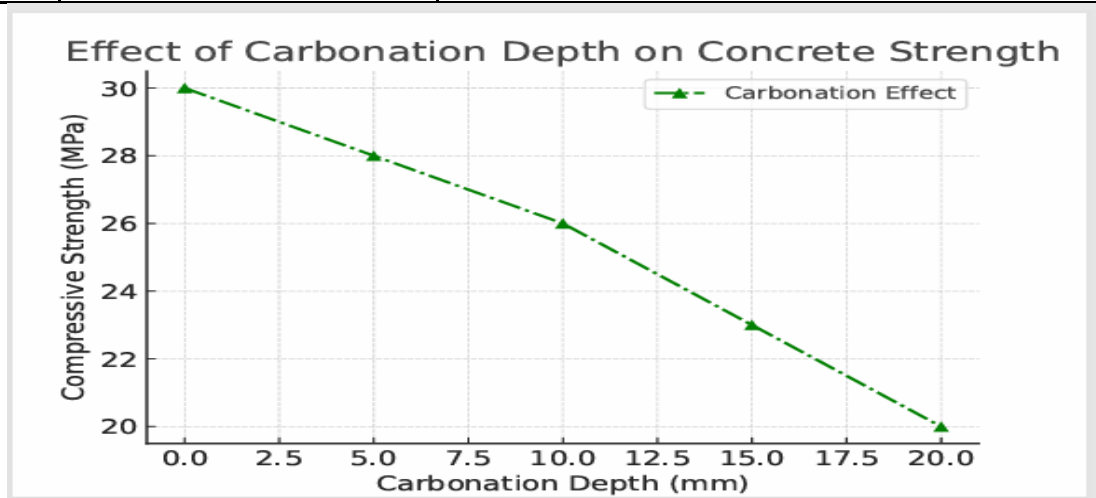


Figure 6, Carbonation depth versus compressive strength graph

### 3.4.3 Discussion

The effect of temperature on concrete strength generally decreases as temperature rises beyond the standard curing conditions. From the given data values, at 25°C the concrete compressive strength is 30 MPa this considered as optimal for normal conditions, as the temperature increases to 40°C and 60°C, the strength drops to 28 MPa and 25 MPa, respectively. This decline is due to the absence of moisture and thermal expansion causing internal microcracks. At intense temperatures of 80°C and 100°C, the strength further reduces to 22 MPa and 18 MPa, respectively, as dehydration of cement paste leads to degradation of the concrete matrix. This shows that prolonged high temperatures exposure negatively impacts durability and reduced the load-bearing capacity of concrete structures. It is important to provide insulation measures or use heat-resistant concrete in high-temperature environments.

However, Chloride penetration in concrete is a critical durability issue, especially in marine and de-icing environments. Without chloride exposure (0% NaCl), concrete retains its full strength (30 MPa). By the time its subjected to 2% NaCl, a slight strength reduction occurs (27 MPa), as chloride ions start disrupting the cement hydration process. At 3.5% and 5% chloride concentration, strength significantly drops to 24 MPa and 21 MPa, respectively. The presence of chlorides accelerates reinforcement corrosion, leading to cracking, spalling, and structural degradation. Therefore, to mitigate this, the use of low-permeability concrete, corrosion inhibitors, and proper concrete cover over reinforcement is recommended.

Similarly, in the context of carbonation which is the reaction between atmospheric CO<sub>2</sub> and calcium hydroxide in concrete, leads to a gradual decrease in alkalinity and increased risk of steel corrosion. At 0 mm carbonation depth, the concrete remains unaffected with a strength of 30 MPa. As carbonation progresses to 5 mm and 10 mm, strength slightly reduces (28 MPa and 26 MPa), and the pH level drops, increasing vulnerability to corrosion. Beyond 15 mm and 20 mm carbonation depth, significant strength loss occurs (23 MPa and 20 MPa), indicating deep penetration of CO<sub>2</sub> and potential corrosion-

induced structural damage. The prevention measures of carbonation effects, are proper curing, surface coatings, low-permeability concrete, and ensuring adequate cover thickness are essential.

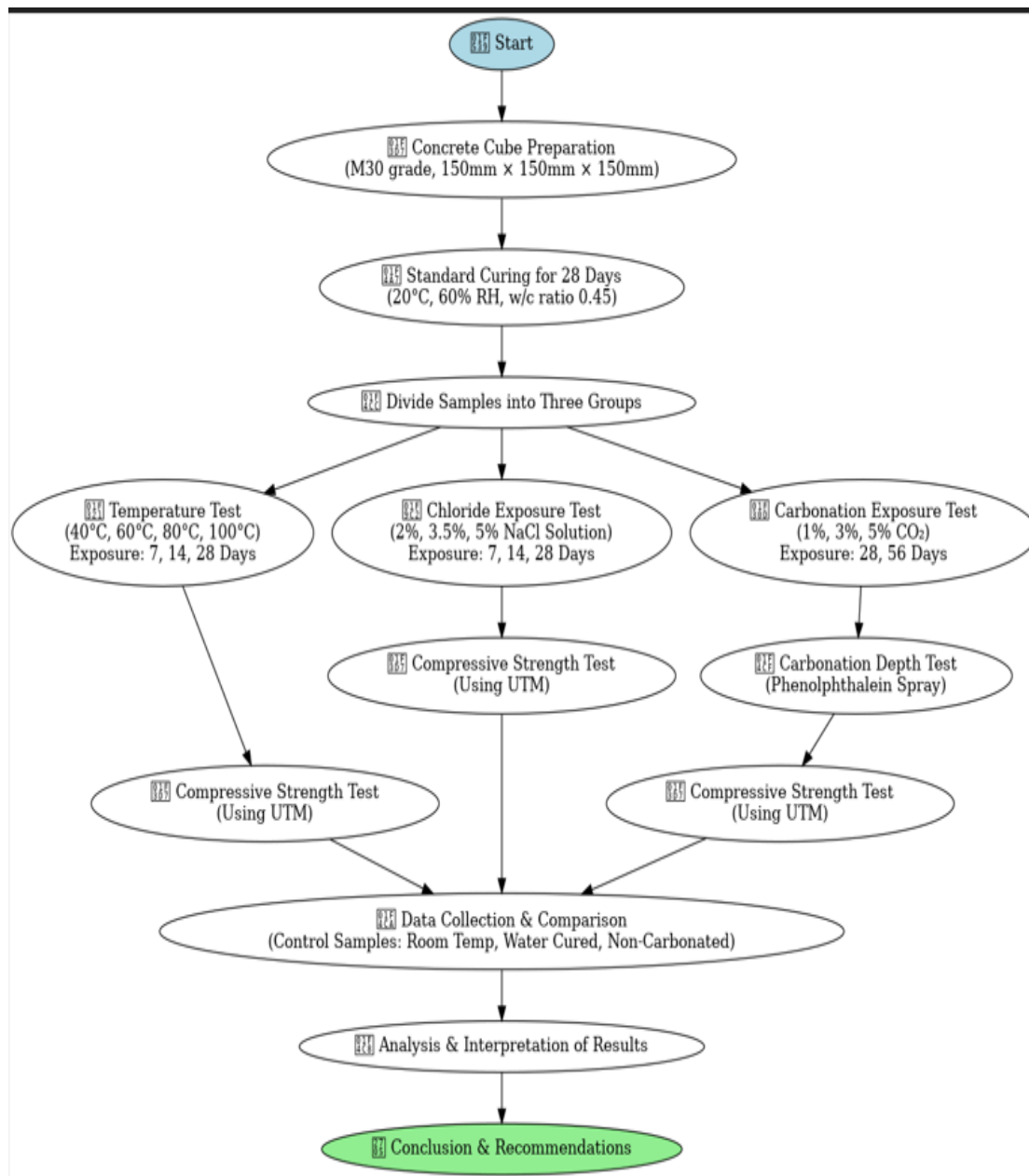
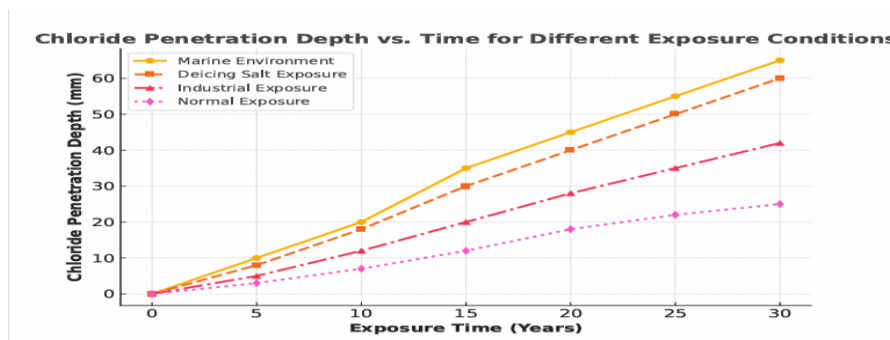
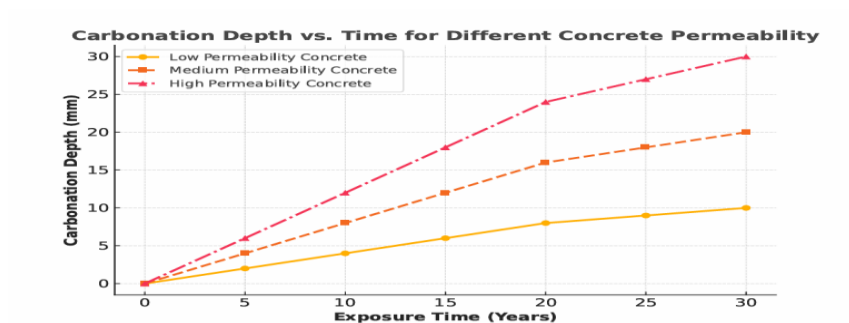


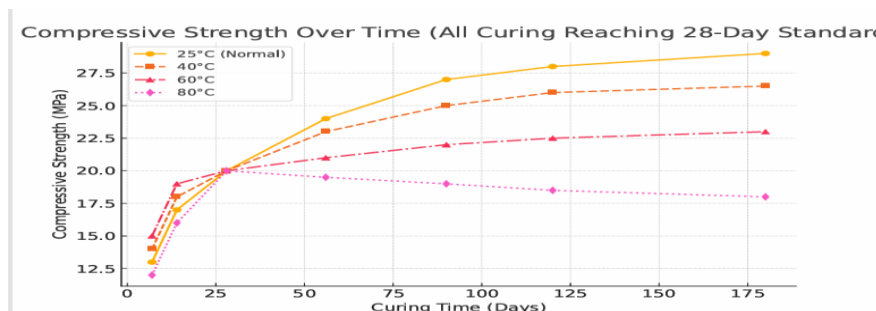
Figure 7, Summary of the Main Steps



**Figure 8 Chloride penetration over time for difference exposure condition**



**Figure 9 Carbonation depth over time for different concrete permeability**



**Figure 10 Compressive strength over time of curing condition**

#### 4.0 Discussion on the Concrete Durability under Climate Change Impacts

##### 4.1 Synthesis of findings

Climate variables are linked to the majority of concrete degradation processes. The Earth's climate is changing, according to data gathered throughout the years. A few examples of climate change phenomena that may affect concrete's durability are global warming and the rise in the mean sea level over time. Studies have already shown how climate change affects the longevity of concrete constructions. Among these measures, this study suggests a stochastic model that takes into consideration how climate change generally affects concrete's structural durability. As a result, the conversation will reflect the combined knowledge gained from studies on the effects of climate change. The compiled study focusses on the interaction of environmental stressors, degradation mechanisms, mitigation tactics, and adaption techniques to highlight climate-induced challenges to concrete durability. Every research highlights the urgent need for material-focused, region-specific solutions. Here is a summary:

#### 4.1.1 Climatic Stressors:

- As temperatures rise, carbonation rates increase, decreasing concrete's alkalinity and exposing steel reinforcements to corrosion. Regions with moderate to high CO<sub>2</sub> emissions scenarios, as RCP 8.5, show this trend (Kim et al., 2017; Nasr et al., 2022).
- One of the main causes of reinforcement corrosion in marine structures, chloride ingress, is made worse by sea level rise in coastal areas (Lee et al., 2019).
- Especially in colder Nordic areas, freeze-thaw cycles cause cracking, spalling, and decreased load-bearing ability (Nilimaa & Zhaka, 2023).

#### 4.1.2 Mechanisms of Degradation:

- As noted in the Nordic and urban areas, temperature and humidity variations accelerate carbonation (Nasr et al., 2022).
- Steel reinforcing in bridge decks and coastal buildings is compromised by chloride infiltration, which is made worse by marine environments and de-icing salts (Wang et al., 2010).
- Concrete structures gradually deteriorate due to micro cracking from alkali-silica reactions (ASR) and freeze-thaw cycles, highlighting the significance of environmental exposure (Rahman & Lu, 2023).

#### 4.1.3 Mitigation and Adaptation Strategies:

- According to Liu (2024) and Knight et al. (2023), adding supplemental cementitious materials (SCMs) including fly ash, slag, and CO<sub>2</sub>-enhanced aggregates increases durability while lowering emissions.
- Real-time structural health monitoring and early degradation detection are made possible by technologies such as digital twins and fiber optic sensors (Qiao et al., 2023).
- Predictive models, like probabilistic analysis for carbonation and chloride diffusion, help with designing infrastructure that can handle climate change (Nasr et al., 2022; Suguntha et al., 2024).

As a result, temperature changes, strong compressive and tensile strength, freeze-thaw cycles, and humidity all contribute to cracking and degradation, mostly in temperate and polar areas. High CO<sub>2</sub> also accelerates carbonation, which drops the alkalinity and corrodes steel reinforcement. Severe weather, like heat waves and heavy rain intensify the degradation processes: drying-wetting cycles increase cracking and porosity, floods followed by heat cause more cracking and structural damage, and saltwater leads to corrosion and weakens concrete – just some problems that coastal structures face. Due to this, standard concrete formulations' materials and designs are not adequately adapted to the climate effects of different regions.

## 4.2 Comparative Analysis

Regional and material performance differences were emphasised. The case studies included examples from all over the world to illustrate the different regional consequences. For example, tropical locations experience high humidity-related chloride intrusion, while desert zones experience thermal cracking as a result of drastic temperature variations. Additionally, sea level rise and salty air have a on coastal communities, while upland places deal with carbonation and freeze-thaw issues. Comparably, traditional concrete is more vulnerable to all types of deterioration, such as carbonation, chloride

ingress, and freeze-thaw cycles, whereas high-performance concrete exhibits decreased tensile strength under extreme temperatures but greater resistance to carbonation and cracking. Concrete durability is impacted by environmental variations, though, as urban areas exhibit faster carbonation due to higher CO<sub>2</sub> concentrations and pollution levels than rural areas, cold climates experience frost heaving and freeze-thaw cycles, and hot climates experience rapid chemical reactions that compromise durability. The following significant distinctions are revealed by looking at regional and material-specific studies:

#### 4.2.1 Regional Variations:

- **Coastal Regions:** Coastal structures face higher degradation risks due to chloride penetration and saltwater exposure. Mitigation strategies in these areas emphasize thicker concrete covers and corrosion inhibitors (Nasr et al., 2022; Lee et al., 2019).
- **Cold Climates:** Freeze-thaw cycles are a dominant stressor in Nordic climates, necessitating air-entrained concrete and protective coatings (Nilimaa & Zhaka, 2023; Wang et al., 2010).
- **Urban Environments:** Urban heat island effects amplify carbonation rates in city structures, necessitating advanced concrete designs and real-time monitoring (Kim et al., 2017; Qiao et al., 2023).

#### 4.2.2 Material Performance:

- **SCMs and CO<sub>2</sub>-enhanced aggregates:** While SCMs reduce emissions and improve resistance to chloride ingress, they can lower carbonation resistance, requiring balanced mix designs (Liu, 2024; Knight et al., 2023).
- **Self-healing Concrete:** Innovations like microbial calcite precipitation (MICP) show promise for reducing microcracking and sequestering CO<sub>2</sub>, though scalability remains a challenge (Liu, 2024; Rahman & Lu, 2023).

#### 4.2.3 Technological Approaches:

- Fiber optic-based monitoring is highly effective but costly, limiting widespread adoption in low-income regions (Qiao et al., 2023).
- Probabilistic models, while comprehensive, face challenges in accounting for simultaneous environmental variables like temperature and humidity changes (Nasr et al., 2022).

### 5.0 Integrated Findings

The synthesis and analysis show that the effects of climate change on the durability of concrete vary greatly depending on the context. Cold climates place a higher priority on freeze-thaw resilience, while coastal constructions require chloride-resistant techniques. Updating predictive models, improving monitoring systems, and implementing SCMs are examples of universal techniques. The study emphasises how crucial it is to use scalable technology and localised solutions to strike a balance between material durability and environmental sustainability. Long-term performance in the face of changing environmental conditions depends on adaptive designs and sophisticated monitoring techniques. The following are the findings of the discussion:

- Rising temperatures hasten carbonation, which lowers pH and jeopardises steel reinforcing, while in colder climates, cracking and spalling are caused by freeze-thaw cycles, which reduce structural integrity.
- In Nordic and coastal regions, studies on high-emissions scenarios (RCP8.5) reveal higher chloride ingress and carbonation depths, which can result in a 30% reduction in service life, and likelihood of corrosion increases when sea level rises because it accelerates chloride penetration.
- Long-term performance in challenging conditions is enhanced by admixture concretes, which lower chloride permeability by 36.4%
- By using SCMs, polymer coatings, and corrosion inhibitors, permeability is decreased and service life is increased.
- Real-time monitoring for predictive maintenance is made possible by technologies such as fibre optic sensors and digital twins.
- Predictive models are made more difficult by environmental factor variability, particularly when it comes to long-term durability under coupled stresses.

## 6.0 Recommendations

These patterns demonstrate fresh methods, developments, and potential avenues for addressing how climate change may affect concrete's structural longevity.

- Carbon-neutral concrete uses additional cementitious materials like fly ash or GGBS to reduce CO<sub>2</sub> emissions during production, fiber-reinforced concrete increases tensile strength and crack resistance under climate-induced stressors, and self-healing concrete uses bacteria or chemical agents that activate to fill cracks when exposed to water.
- The use of IoT sensors for real-time corrosion, humidity, and carbonation rate monitoring in critical infrastructure, as well as AI-based predictive model tools for predicting the long-term effects of climate change on concrete durability, are examples of advanced monitoring techniques.
- Regional concrete mix customisation to address local environmental constraints is one example of sustainable construction methods.
- Sustainable building techniques include adjusting concrete mixes locally to suit local environmental circumstances and prioritising lifespan cost analysis to strike a balance between affordability and resilience.

## 7.0 Future Research

Climate change presents serious problems for concrete structures, such as increased deterioration from carbonation, chloride intrusion, and freeze-thaw cycles. These effects can be lessened by employing sustainable building techniques, such as SCMs and cutting-edge monitoring tools. The significance of proactive adaptation methods that are adapted to local climate conditions and anticipated stresses is supported by empirical research. Predictive modelling, combining material performance with climate change scenarios, and creating resilient infrastructure systems should be the main areas of future research. In a changing climate, putting these techniques into practice is essential to minimising environmental effect and prolonging the service life of concrete structures. Engineers, legislators, and

researchers may improve the sustainability and longevity of concrete infrastructure for future generations by tackling these issues holistically.

## 8.0 Conclusion

Conclusively, this study examines how climate change affects concrete structure durability by addressing stressors such as extreme weather events, rising temperatures, and elevated CO<sub>2</sub> levels.

Elements like freezing and thawing, carbonation, and salt can really deteriorate concrete. These factors make concrete to lose its compressive strength significantly, especially in cities and near the coast where there is a lot of rain, extreme temperature changes, and a lot of salt.

Therefore, one way to make concrete more sustainable is to use materials other than Portland cement. Materials like fly ash, slag, and recycled materials can work. These substances help concrete last longer by reducing the likelihood of water permeation, but they might also decrease its resistance to carbonation.

Cutting-edge methods for identifying and reducing degradation include fibre optic monitoring and microbial-induced calcite precipitation (MICP). Life cycle assessments (LCA) and probabilistic models offer valuable information for modifying infrastructure designs for potential climate change.

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