Journal of Science Engineering Technology and Management Science
Volume 02, Issue 06, June 2025 ISSN: 3049-0952
www.jsetms.com DOI:10.63590/jsetms.2025.v02.i06.pp43-47

Investigation on the Effect of Climate Change on Structural Materials

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To Cite this Article

Nitish Balwada, Deepak Kumar, "Investigation on the Effect of Climate Change on Structural Materials", Journal of Science Engineering Technology and Management Science, Vol. 02, Issue 06, June 2025,pp:43-47, DOI: http://doi.org/10.63590/jsetms.2025.v02.i06.pp43-47

Submitted: 11-04-2025 *Accepted: 20-05-2025* *Published: 28-05-2025*

Abstract

The evolving global climate conditions imposed dangerous challenges on the stability and operational capabilities of construction materials. This research investigates in detail how global temperature increases, precipitation changes, heightened severe weather occurrences and increasing sea levels affect structural materials like concrete, steel and timber. This research demonstrates systematic identification of climate change-induced material deterioration through literary review of previous studies together with performance dataset analysis and case study assessments. This research evaluates modern material solutions which aim to strengthen structural defenses. Construction regulations need adoption to combine advanced materials development for securing future safety and economic stability of infrastructure installations. This research brings civil engineering toward modern climate adaptation.

Key Words: Construction Materials, Material Deterioration, Climate Adaptation, Material development.

1. INTRODUCTION

Human activities are creating escalating threats to the built environment because surface temperatures have increased 1.1°C since industries launched their operations [5]. The observed climate warming started new changes in environmental conditions that include heightened frequency of serious extreme weather events together with modified precipitation pattens and increasing sea level effects [5][11]. The current climate scenarios exceed the design capacity of infrastructure systems built according to historical climate models. The structural engineering field stands before a major challenge because current construction materials together with traditional design approaches likely will not succeed against predicted climate patterns [6]. Concrete steel and wood represent the three primary structural materials throughout the world which demonstrate separate weaknesses during environmental changes. The process of studying material vulnerabilities and developing suitable adaptation methods is essential for protecting infrastructure integrity while ensuring both public security and minimizing lifecycle costs of assets, costs of infrastructure assets [10].

Research Objectives: Systematically investigate the impact that major climate change factors have on the operational performance along with lifespan of primary building materials. Study new material technologies which enhance climate resilience capability.

2. PROBLEM STATEMENT

British infrastructure systems received their primary design basis from 20th century climate observations together with material usage expectations at that time [6]. The present climate models predict major discrepancies when compared to historical norms. Temperature projections indicate an elevation from 1.5 to 4.5 degrees Celsius annually from 2100 through various environmental emission predictions [5]. The patterns of precipitation exhibit reduced predictability because drought conditions intensify while heavy rainfalls grow more frequent. Sealing levels will increase by 0.3 to 1.0 meters before the end of the present century. Scientists project that tropical cyclone frequency will remain steady yet wind force will intensify. The declining temperatures accelerate wear mechanisms while creating additional degradation mechanisms in materials that threaten both operation safety and performance reliability. For example: Concrete material faces increased risk for thermal cracking as well as accelerated carbonation and ice-damage susceptibility [7][8][10]. Steel components located near the coastline will suffer accelerated corrosion at an accelerated rate [2][13]. Wooden buildings undergo increased biological damage when moisture leads to pest activity [3].

3. LITERATURE REVIEW

The Intergovernmental Panel on Climate Change (IPCC) afresh assessments project future climate trends which directly matter to structural engineering field. Temperature Increases: International research confirms that surface temperature levels will remain elevated through the next fifty years. Under SSP2-4.5 medium emission projections scientists predict temperatures will increase from 2.1 to 3.5 degrees Celsius by 2100 [5][11]. The rate of nighttime temperature increase exceeds the rate of daytime temperature increase during daily temperature cycles. Precipitation Changes: The rainfall levels in polar regions together with equatorial areas are predicted to increase. Drought conditions will become more prevalent in subtropical regions [5]. Research shows that across the world heavy rainfall occurrences become more frequent and devastating. Sea Level Rise: From 1901 to 2018 the mean sea level at a worldwide scale rose by 0.20m. The projected increase in global sea levels ranges between 0.28m to 1.01m based on different emission scenario predictions for the year 2100. Regions undergoing land subsidence possibly will suffer a much higher relative sea level rise than areas with no subsidence [5]. Extreme Weather Events: Studies show that the maximum speeds attainable in tropical cyclones continue to increase. Ocean basin areas are experiencing rising significant wave heights. The frequency of joint occurrences (storm surge with added heavy rainfall) has increased [11].

Material-Specific Climate Impacts: Concrete Degradation Mechanisms. The widespread use of concrete as a global building material exposes it to different climate-related problems. Thermal Effects: Concrete materials expand at a rate of 10-14 × 10^{-6} units per degree Celsius in temperature [7]. The stresses reaching over 1 MPa from temperature variations during daily periods can affect restrained elements. Durability suffers from enhancing cracking that also speeds up the natural deterioration mechanisms. Carbonation: Since before the industrial era when atmospheric CO_2 levels were 280 parts per million the world has observed a rise to 420 parts per million. The carbonation depth measurement (x) is determined by $x = k\sqrt{t}$ and k grows with rising CO_2 concentrations. The accelerated carbonation process of modern urban concrete can occur at rates that are 30-50% faster than the natural historical carbonation rate [8]. Freeze-Thaw Damage: More freeze-thaw cycles occur with increased frequency throughout temperature regions. Concrete shows signs of damage when the water content inside its porous structure exceeds 90% saturation. Concrete becomes less effective against scaling damages when the number of freeze-thaw events increases [10]. Chloride Ingress: The rising sea levels together with storm surges result in higher levels of chloride substance exposure. The temperature affects chloride diffusion coefficients through the equation $D = D_0 \exp(-E/RT)$. Ten degrees Celsius increment in temperature leads to possible doubling of chloride penetration rates [8][12]. Steel Corrosion Processes: The degradation of structural steel elements happens swiftly during their operational period. Atmospheric Corrosion: The corrosion rate (r) follows this specific relation: $r = A \cdot \exp(B \cdot RH) \cdot [SO_2]^\alpha \cdot [Cl^-]^\beta$. Thresholds for relative humidity (RH): Below 60%: Minimal corrosion, 60-80%: Moderate corrosion, Above 80%: Severe corrosion. The electrochemical reaction rates increase exponentially with elevated temperature when measured by $Q_{10} \approx 2$ [13]. Marine Environments: The amount of salt accumulation becomes greater when moving towards coastal regions. Common corrosion rates: Atmospheric zone: 50-200 μm/year, Splash zone: 200-500 μm/year, Submerged zone: 100-300 μm/year [2]. High-Temperature Effects: The yield strength decreases when operation temperatures rise. 10% reduction at 200°C, 30% reduction at 400°C, 50% reduction at 600°C [9].

Timber Deterioration Factors: Rainforests face deterioration risks from biological and physical hazards that affect their wooden structures. Moisture Content Effects: The fiber saturation point exists between 25-30% moisture content. Decay fungi need wood which contains more than 20% moisture content. The equilibrium moisture content of wood materials depends on the relative humidity through the relationship $EMC \approx 0.25H - 0.021H^2 + 0.14H^3$ ($H = RH/100$). $EMC \approx 0.25H - 0.021H^2 + 0.14H^3$ ($H = RH/100$) [3]. Insect Damage: The activity levels of termites increase as temperatures rise. Each decade subterranean termites move their range approximately 50 kilometers toward the north. Wood-boring beetles flourish in warmer conditions [3]. Mechanical Property Changes: A 1% boost in wood moisture leads to a 2% reduction in elasticity value. Strength characteristics show identical dependency on the moisture content in wood materials [3]. Current Adaptation Strategies in Practice-Material Innovations: Ultra -high performance concrete (UHPC) offering greater durability By implementing stainless steel and weathering steel rebar and corrosion-resistant building materials construction methods achieve operational advantages. Engineered wood solutions have been developed to keep moisture from damaging these products [4][9]. Monitoring and Maintenance: The infrastructure has built-in sensors for uninterrupted status evaluation. Algorithms for predictive maintenance, Robotic systems for inspection purposes [12].

4. METHODOLOGY

Research Framework: The research employs a multi-method strategy by combining two approaches which involve:

- Systematic Literature Review -An extensive evaluation of peer-reviewed journal articles, Analysis of technical documents from authoritative organizations (e.g., IPCC, ASCE). The evaluation investigated relevant building codes and standards for evaluation purposes.
- Case Study Analysis: Identification of representative cases of infrastructure failures, Comprehensive assessment of climate-related damage mechanisms. The team extracted vital information about lessons and advanced methods from research data.
- Comparative Material Performance Assessment: A synthesis combines laboratory-derived data obtained through aging experiments with artificial speedup. Analysis of field performance data from long-term monitoring sites, A computational approach helps to analyze degradation processes.
- Literature Review Protocol: Database sources: Web of Science, Scopus, Engineering Village, Search terms: ("climate change" AND ("concrete" OR "steel" OR "timber") AND ("durability" OR "degradation")), Inclusion criteria: Peer-reviewed articles, English language, publications post-2010.
- Case Study Selection: Geographic variability (tropical, temperate, arid regions), The study includes buildings as well as bridges and coastal structures among its structure types. Documented instances of climate-related damage.
- Material Data Analysis: The research obtained available datasets which specified material properties. Normalization of testing conditions for inter-study comparability, Statistical examination of degradation rates. Climate Data Processing: Local adaptation of global climate models, Design loads get determined using extreme value analysis methods, Time-series analysis of environmental variables.
- Material Degradation Modeling: Fickian diffusion serves as the primary model to predict chloride penetration into the concrete. The testing implements temperature acceleration factors based on Arrhenius principles. The prediction of service life depends on probabilistic analysis-based methods. Structural Performance Assessment: The research team executes Finite element modeling of components which undergo climate-related stresses. Reliability assessments under varying environmental loads, Lifecycle cost evaluations of adaptation strategies.

5. RESULTS AND DISCUSSION

Material Degradation Findings:

Concrete Performance: Whenever CO_2 concentration rises by 100 ppm the concrete carbonation grows between 0.1 to 0.3 millimeters per square root of yearly duration. Temperature-sensitive chloride diffusion coefficients contain energy requirements between 0.025 eV and 0.035 eV. Expected temperature elevations increase the likelihood of thermal cracking between 15 and 25 percent [12].

Steel Corrosion Data: Rates of atmospheric corrosion increase by 30-50% in high-humidity conditions. Marine corrosion accelerates non-linearly during intensified sea level height increases. Temperature-related effects follow Arrhenius behavior patterns and generate Q_{10} rate constants between 1.8-2.2 [2][13].

Timber Durability: The decay rates experience a doubling effect whenever the temperature rises by 5 degree Celsius within the preferred moisture conditions. Researchers found that timber insect damage locations advance at a rate between 4-6 kilometers per year toward the north. The mechanical strength of materials decreases by more than 20% when operating in conditions of high humidity [3].

Parameter	Concrete	Steel	Timber
CO_2 rise by 100 ppm	+0.1–0.3 mm/year carbonation depth	N/A	N/A
Temp increase by 10°C	~2x chloride ingress rate	~2x corrosion rate ($Q_{10} \approx 2$)	~20% loss in strength at high humidity
Temp increase by 5°C	N/A	N/A	Doubles decay rate (if high moisture present)
RH above 80%	Slight scaling damage risk	Severe corrosion (>80% RH threshold)	Moisture content increases beyond FSP
Mechanical property loss per 1% moisture	Minimal	N/A	~2% reduction in elasticity

Structural-Level Adaptations: Thermal Management: The integration of phase change materials allows buildings to reduce their thermal load capacity by 30% percent. Absorbing reflective coatings on building surfaces decrease temperatures on external surfaces by five to ten degrees Celsius [9]. Moisture Control: Implementation of capillary break systems, Development of advanced drainage solutions, Utilization of hydrophobic surface treatments [10]. Load Adaptation: Adjusted live load factors for extreme weather events, Incorporation of adaptive structural systems, Adoption of fail-safe design principles [6].
Implementation Challenges: Technical Barriers: Absence of long-term performance data for novel materials. The multiple effects between different degradation mechanisms remain complex for researchers to study. Challenges in scaling laboratory-developed solutions [9]. Economic Considerations: The adoption of advanced materials requires organisations to allocate additional resources through higher initial expenditures ranging from ten to thirty percent. Necessity for lifecycle cost-benefit analyses. Insurance sector along with finance system need to adapt to new models [12]. Regulatory Hurdles: Slow updating of codes (with revision periods of 5-10 years), Inconsistencies between jurisdictions. The development of performance-based standards remains essential because of existing requirements [6].

6. CONCLUSION AND RECOMMENDATIONS

This research paper determines climate change affects structural materials through these three main effects: Complex interactions between temperature and moisture exposure and chemical substance effects make up the nature of these effects, Each material requires unique solutions because its effects are specific to itself between concrete and steel and timber products, The need exists for location-specific adaptation strategies because the effects vary region to region. Time presents two demands: first, assessment of dynamic variations in addition to second, observation of severe climate events.
Recommendations for Practical Application: For Selecting Materials: Projects in demanding climates should use concrete mixes which have reduced permeability rates. The selection of corrosion-resistant alloys should be made for all critical structural components that require these properties. Proper treatment methods should be used to prepare timber products which will be utilized in environments with high humidity conditions [4][9]. For Developing Policy: The process of building code updates should occur rapidly to match real-world climatic conditions. The production of databases containing material performance results from various climate zones should become a priority. Standards of design layout for climate adaptation need to be created through comprehensive guidelines [6]. Directions for Future Research: Long-term field testing of advanced materials should be performed, Develop frameworks for multi-hazard resilience, Development of digital twin systems needs investigation for climate adaptation solutions [12]. The study should explore how the circular economy could be used to maximize material efficiency.

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