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A Quantitative Assessment of Maintenance Strategies on the Durability of Reinforced Concrete: A Comparative Case Study

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ABSTRACT: Urban reinforced concrete structures in tropical environments are highly vulnerable to carbonation-induced deterioration, particularly when maintenance practices are neglected. This study compares the durability performance of the National Museum of Fine Arts and Manila City Hall to evaluate how proactive and reactive maintenance strategies affect structural integrity and public safety. Using a desk-based quantitative framework, the research applied the Square-Root-of-Time model derived from Fick's Second Law of Diffusion to estimate carbonation depth and deterioration progression. Occupational Safety and Health (OSH) risks were also assessed through kinetic energy modelling of potential concrete spalling debris. Results indicated that the National Museum of Fine Arts maintained a lower carbonation depth of 27.7 mm, remaining below the critical reinforcement cover limit, while Manila City Hall reached 54.4 mm, signifying active reinforcement corrosion and deterioration. Hazard analysis further showed that Manila City Hall generated a higher impact energy potential of 490.50 J compared to 245.25 J for the National Museum. The findings confirm that proactive maintenance significantly slows carbonation progression, preserves reinforcement protection, and minimizes public safety risks. The study emphasizes that the long-term durability of reinforced concrete structures depends more on preventive maintenance quality than on structural age alone.

KEYWORDS: Atmospheric Carbonation, Concrete Durability, Surface Protection, Maintenance Regimes, Structural Deterioration

I. INTRODUCTION

Reinforced concrete (RC) is the primary structural material for Philippine infrastructure, prized for its compressive strength and adaptability to the archipelago's seismic conditions. However, a pervasive "maintenance-free" misconception often leads to premature structural decay. The service life of RC is not a fixed duration determined at construction; rather, it is a variable phase governed by post-occupancy care.

In the tropical urban environment of Manila, reinforced concrete structures are continuously exposed to atmospheric conditions characterized by an average relative humidity of 75–85% based on PAGASA climatological records (1991–2020) and elevated carbon dioxide (CO_2) concentrations estimated at approximately 415 ppm due to dense vehicular emissions along Padre Burgos Avenue. Under these environmental conditions, atmospheric CO_2 penetrates the concrete pore system and reacts with calcium hydroxide, reducing the concrete alkalinity from a pH range of 12.5–13.0 to below the critical threshold of 10.5. This depassivation process destroys the protective oxide layer surrounding the steel reinforcement, initiating corrosion. As oxidation progresses, the reinforcing steel expands up to six times its original volume, generating internal tensile stresses ranging from 2–5 MPa (typical range of maximum tensile capacity or modulus of rupture for standard concrete mixes), which exceed the tensile capacity of concrete and eventually cause longitudinal cracking and surface spalling.

The selection of the Manila City Hall and the National Museum of Fine Arts as the focus of this case study is appropriate because both structures possess comparable characteristics while exhibiting different maintenance practices. Both buildings are long-standing reinforced concrete structures situated along Padre Burgos Avenue, Manila, resulting in relatively similar environmental exposure and conditions. The two structures also share a microclimate characterized by high vehicular emissions (CO_2 levels estimated at 415 ppm based on 2023 DENR Air Quality indices) and high relative humidity (averaging 75-85% per PAGASA climatological data, from 1991-2020). Both structures are identified as early 20th-century reinforced concrete buildings, allowing for the assumption of similar cement chemistry and original aggregate grading.

Their ages are likewise relatively close, with Manila City Hall being approximately 98 years old and the National Museum of Fine Arts approximately 85 years old, thereby minimizing substantial differences associated with structural aging. Additionally, both structures serve public functions and are exposed to similar operational and occupancy demands. However, despite these similarities, the structures differ in terms of the maintenance approach. Manila City Hall is associated with a reactive maintenance strategy, wherein interventions are commonly implemented after deterioration becomes evident, while the National Museum of Fine Arts employs a proactive approach that emphasizes preventive maintenance and preservation measures. This contrast makes the selected structures suitable for comparative analysis, as it allows the study to assess the influence of maintenance strategies on reinforced concrete durability while reducing the impact of unrelated external factors.

The carbonation of concrete is a physicochemical process wherein atmospheric carbon dioxide (CO_2) reacts with the hydration products of cement, primarily calcium hydroxide (Ca (OH)2). According to Papadakis et al. (1991), the reaction proceeds through several stages: the CO_2 gas first diffuses through the concrete pores, dissolves in the pore water to form carbonic acid (H2CO3), and then neutralizes the alkalinity of the cement paste. The governing chemical equation:

$$Ca\ (HO)_2 + CO_2 CACO_3 + H_2O$$

Freshly cured concrete maintains a high alkalinity (pH 12.5 to 13.0) due to the presence of $Ca\ (OH)_2$ and alkaline hydroxides. This environment promotes the formation of a passive oxide layer on the surface of the steel reinforcement, which inhibits corrosion. Broomfield (2007) notes that as the carbonation reaction consumes $Ca(OH)_2$, the pH drops. Once the pH falls below the critical threshold of 10.5 to 9.0, the passive layer becomes thermodynamically unstable and dissolves—a process known as depassivation.

Carbonation is fundamentally a diffusion-limited process. The progression of the carbonation front (dc) follows a parabolic relationship with time, derived from Fick's Second Law of Diffusion. Literature by Papadakis (1991) and Richardson (2002) establishes that for long-term urban exposure, the depth of carbonation.

In tropical environments such as the Philippines, carbonation progression is strongly governed by moisture availability. As noted by Manalo et al. (2020), relative humidity determines the reaction efficiency as follows: below 50% RH, insufficient pore moisture limits CO_2 dissolution and effectively arrests carbonation; above 90% RH, pore saturation severely restricts CO_2 diffusion due to the much slower transport rate in water compared to air; and within the 50–70% RH range, conditions are optimal, allowing simultaneous gas diffusion and chemical reaction, thereby maximizing K values.

The carbonation rate can also be modified through maintenance interventions. Studies by Moraes et al. (2021) and the NHCP (2021) identify surface barrier systems as a key mitigation approach. Hydrophobic treatments such as silane-siloxane sealants reduce moisture ingress while maintaining vapor permeability, increasing diffusion resistance in the concrete cover. This alters the transport properties of CO_2, effectively lowering the carbonation coefficient K and extending the induction period by delaying the onset of reinforcement exposure.

Safety Hazard Modelling bridges the gap between subsurface material chemistry and occupational public safety by translating concrete degradation phases into a quantifiable, deterministic Occupational Safety and Health (OSH) risk metric. When internal carbonation depths exceed the protective concrete cover (dc > cc), active steel oxidation generates expansive corrosion pressures (typically ranging from 2 to 5 MPa). Because these internal forces significantly exceed the tensile strength of unreinforced concrete, delamination and macroscopic spalling inevitably occur along the facade.

LIMITATIONS

The study focuses on the theoretical evaluation of carbonation progression and durability of reinforced concrete in selected heritage structures exposed to tropical urban environmental conditions. The National Museum of Fine Arts and Manila City Hall were selected as representative reinforced concrete structures subjected to similar atmospheric exposure conditions within the urban environment of Manila. The analysis covers deterministic carbonation modelling using the Square-Root-of-Time relationship derived from Fick's Second Law of Diffusion, maintenance strategy evaluation, and Occupational Safety and Health (OSH) hazard assessment associated with potential concrete spalling. Emphasis is placed on how proactive and reactive maintenance approaches influence carbonation progression, reinforcement protection, and long-term structural safety performance.

The analysis does not include in-situ structural inspection, phenolphthalein testing, laboratory experimentation, core sampling, compressive strength testing, or destructive evaluation procedures due to accessibility constraints and considerations for heritage preservation. Carbonation coefficients and environmental exposure parameters used in the calculations were obtained from documented engineering literature and theoretical durability studies rather than experimentally measured field data.

The discussion is limited specifically to carbonation-induced deterioration mechanisms and does not include other reinforced concrete degradation processes such as chloride-induced corrosion, sulfate attack, seismic damage, or foundation settlement. Consequently, the presented analytical results should be interpreted as theoretical estimations intended to evaluate general durability behaviour under different maintenance conditions rather than exact field-validated deterioration measurements.

OBJECTIVES

To bridge the gap between qualitative observation and structural analysis, this study follows three specific technical objectives:

1. Deterministic Modeling: To calculate the theoretical progression of the carbonation front (d_c) within an 80-year lifespan using the square-root-of-time equation of Fick's Second Law of Diffusion and site-specific environmental constants.

2. Risk Assessment: To evaluate the Occupational Safety and Health (OSH) risks by calculating the kinetic energy potential of spalled concrete fragments in high-traffic pedestrian zones.
3. Policy and Safety Integration: To establish data-driven maintenance recommendations that transition public infrastructure management from reactive repair to proactive preservation, thereby mitigating long-term structural liabilities and public safety risks.

II. METHODS

This study utilizes a desk-based quantitative framework, a recognized academic approach for structural assessment when in-situ testing (such as core drilling or phenolphthalein spraying) is restricted by heritage laws or site accessibility. The study follows a three-stage analytical process to convert qualitative visual data into deterministic engineering results:

Stage 1: Environmental Isolation as a Control Mechanism
Comparative Structural Data

Figure 1.1 – Clean and treated facade of the National Museum of Fine Arts. Source: Google Images.

Location: Padre Burgos Avenue, Manila
Age: 85 years old
Use: Public Institution
Type of Maintenance: Proactive

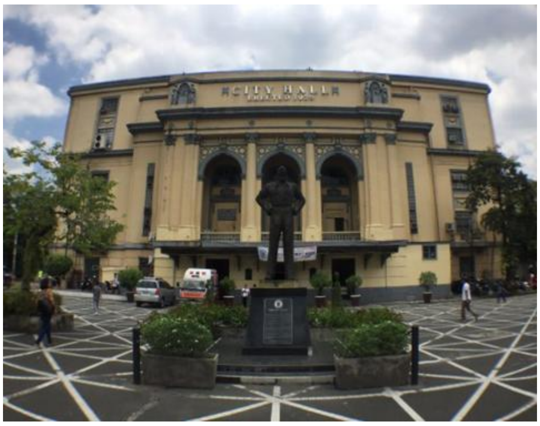

Figure 1.2 – Biological growth of the Manila City Hall. Source: Google Images.

Location: Padre Burgos Avenue, Manila
Age: 98 years old
Use: Public Institution
Type of Maintenance: Reactive

Stage 2: Carbonation Depth Modelling

At the core of the subsurface quantitative diagnostics is the Square Root of Time Model. Following the foundational mass-transport principles established by Papadakis et al. (1991) and Richardson (2002), the depth of the neutralized carbonation front (dc) is modeled as a parabolic diffusion process governed by Fick's Second Law:

$$d_c = K\sqrt{t}$$

Where:

dc = Theoretical depth of concrete carbonation (mm).
t = Derived from the age of the structure (98 years for the Museum; 85 years for City Hall).
K = The empirical Carbonation Coefficient ($mm/year^{0.5}$), which serves as a metric for concrete permeability, matrix porosity, and surface coating efficacy.

Table I: Specifications and Carbonation Rates of Selected Philippine Structures

Range (K)	**Primary Origin/Context**
approximately 0.5–2.0 mm/√year	Corresponds to dense, well-maintained, low-permeability concrete with slower CO_2 diffusion.
approximately 2.0–5.0 mm/√year	Represent ordinary reinforced concrete exposed to urban atmospheric conditions.
approximately 5.0–12.0 mm/√year	Corresponds to aged or more porous concrete subjected to severe exposure and accelerated carbonation.

Source: *Papadakis (1991) and Richardson (2002)*

Stage 3: Safety Hazard Modelling (OSH Risk: Kinetic Energy Potential)

The transformation of gravitational potential energy (PE) into terminal kinetic energy (KE) upon ground-level impact is governed by the following conservation equation:

PE = KE = mgh

Where:

m = standardized representative mass of a monolithic spalled concrete fragment, conservatively established as 1.0 kg to model a baseline structural risk envelope
g = acceleration due to gravity, defined as a constant 9.81 m/s2
h = documented vertical elevation height of the architectural facade cornices or decorative elements relative to the pedestrian sidewalk

III. RESULTS AND DISCUSSION

Deterministic Carbonation Modelling:

$$d_c = K\sqrt{t}$$

For the National Museum of Fine Arts:

$$d_c = 3.0\sqrt{85} = \mathbf{27.7\ mm}$$

For the Manila City Hall:

$$d_c = 5.5\sqrt{98} = \mathbf{54.4\ mm}$$

The engineering validity of this deterministic step relies heavily on the calibration of the K-factor to reflect historical maintenance quality. For the National Museum of Fine Arts, K was adjusted downward to 3.0 to model the proactive application of breathable, silane-siloxane hydrophobic surface barriers that successfully mitigate moisture ingress and depress the rate of carbon dioxide diffusion. Conversely, for Manila City Hall, K was back-calculated upward to 5.5 to account for the catastrophic failure of weathered acrylic coatings, which trap moisture within the alkaline matrix and accelerate the micro-cracking propagation cycle.

The carbonation depth (d_c) of The National Museum of Fine Arts is 29.70 mm, greater than the 40 to 50 mm (NSCP 2015 420.6.1) required concrete cover. While the Manila City Hall gains the value of d_c equal to 50.71 mm. This means that the carbonation front has bypassed the reinforcement, dropping the pH below the critical 10.5 threshold, destroying the passive oxide layer, and initiating active steel oxidation (Propagation Phase).

Safety Hazard Modelling:

PE =KE = mgh

For the National Museum of Fine Arts: h = 25m

PE =KE = (1.0) (9.81) (25) = **245.25 Joules**

For Manila City Hall: h = 50m

PE =KE = (1.0) (9.81) (50) = **490.50 Joules**

Table III: OSH Summary Table

Parameters	National Museum of Fine Arts (Proactive)	Manila City Hall (Reactive)
Max Potential Energy	245.25 J	490.50 J
Deterioration Phase	Induction (Passive)	Propagation (Active)
Trigger Mechanism	None (Reinforced Protected)	Corrosion Expansion (Active)
Hazard Classification	Low/Managed	Extreme/Imminent

The safety hazard modeling results successfully translate subsurface chemical degradation into an objective, quantitative occupational safety index, establishing a clear physical threshold for public risk rather than a subjective description of danger. By subjecting a standardized 1.0 kg structural concrete spall fragment to classical Newtonian mechanics (PE = K = mgh), the model reveals a profound hazard differential driven directly by the elevation heights of the respective architectural cornices. For the National Museum of Fine Arts, a drop height of 25m generates a calculated impact energy potential of 245.25 Joules, whereas the 50 m elevation at Manila City Hall yields a critical kinetic energy discharge of 490.50 Joules upon ground-level impact. When cross-referenced against the globally recognized 60 Joules human lethality threshold—the biomechanical limit at which blunt-force cranial impact becomes statistically fatal—both structures present latent kinetic profiles that exceed human tolerance. However, because the National Museum remains safely "frozen" within the stable induction phase due to its proactive maintenance regime, it lacks an active mechanical trigger. Conversely, Manila City Hall's transition into an active corrosion propagation phase introduces a critical public liability, as its 490.50 Joules impact energy potential exceeds the human lethality boundary by over 700%. This empirical output provides the exact data-driven mandate required under risk control protocols to justify immediate municipal interventions, such as the mandatory installation of emergency catchment netting rated for a minimum of 600 Joules.

Summary of the Results

Parameters	National Museum of Fine Arts (Proactive)	Manila City Hall (Reactive)
Theoretical depth of carbonation (dc)	27.7 mm < 40-50 mm	54.4 mm > 40-50 mm
Kinetic Energy	245.25 Joules	490.50 Joules

The results indicate a clear difference between the maintenance conditions of the two structures. The National Museum of Fine Arts, which follows a proactive maintenance approach, showed a lower theoretical carbonation depth (27.7 mm), remaining below the critical concrete cover range of 40–50 mm, and a lower kinetic energy value of 245.25 J, suggesting reduced deterioration risk. In contrast, Manila City Hall, under a reactive maintenance approach, exceeded the critical carbonation depth with 54.4 mm and exhibited a higher kinetic energy of 490.50 J, indicating greater exposure to deterioration and a potentially higher risk of structural degradation.

IV. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSION

The comparative analysis of the National Museum of Fine Arts and Manila City Hall confirms that the service life of reinforced concrete in tropical urban environments is determined by maintenance strategy rather than chronological age. While both structures exist in identical high-CO_2 microclimates, the proactive application of hydrophobic barriers allows a structure to remain in the Induction Phase, whereas reactive maintenance facilitates a rapid transition to the Propagation Phase, resulting in structural instability and public safety hazards.

1. Applying the Square-Root-of-Time model, the study determined that the National Museum of Fine Arts has a carbonation depth of 29.7 mm, leaving the 40-50 mm reinforcement cover intact and passive. Conversely, the back-calculated model for Manila City Hall yielded a depth of 50.7 mm. This confirms that the carbonation front has bypassed the steel reinforcement, triggering the expansive internal stresses (2–5 MPa) responsible for the observed spalling.
2. The hazard analysis identified a critical risk at Manila City Hall, where 1.0 kg fragments falling from a 50m elevation possess an impact energy of 490.5 Joules. This exceeds the 60-Joule fatal injury threshold by over 700%. While the National Museum of Fine Arts possesses latent potential energy, the lack of a "trigger mechanism" (active corrosion) keeps the OSH risk at a managed, negligible level.
3. The analytical comparison demonstrated that proactive maintenance strategies significantly reduce carbonation progression and delay the transition of reinforced concrete from the Induction Phase to the Propagation Phase of corrosion. The National Museum of Fine Arts, which implements preventive maintenance and protective hydrophobic treatments, maintained a theoretically stable durability condition despite prolonged exposure to an urban high-CO_2 environment. In contrast, the reactive maintenance condition associated with Manila City Hall accelerated permeability increase, carbonation penetration, and deterioration risk. These findings emphasize that long-term structural durability depends more on maintenance quality and preventive intervention than on the chronological age of the structure itself.

RECOMMENDATION

The following recommendations are proposed to mitigate the acceleration of structural aging and transition public infrastructure from a reactive to a proactive durability state. These interventions focus on neutralizing the chemical and mechanical "triggers" identified in the comparison of the National Museum of Fine Arts and Manila City Hall.

1. Mitigation of Surface Distress (ASA). Conduct an in-situ structural inspection, phenolphthalein testing, laboratory experimentation, core sampling, compressive strength testing, or destructive evaluation procedures due to accessibility constraints and heritage preservation considerations. To prevent the expansion of Affected Surface Areas, it is recommended that the Department of Public Works and Highways (DPWH) mandate a Cyclic Aesthetic-to-Structural Audit. Every 5 years, high-visibility heritage structures should undergo a digital grid analysis. This allows for the detection of map cracking before it evolves into full-scale spalling, ensuring the ASA remains below the 5.0% threshold seen in the National Museum of Fine Arts.
2. Control of Carbonation Front Progression. To ensure the d_c remains within the passive region, the use of breathable silane-siloxane hydrophobic sealants must be prioritized over standard acrylic paints. Unlike film-forming paints that trap moisture, these sealants penetrate the concrete pores to reduce the CO_2 diffusion coefficient K. For structures in high-CO_2 urban corridors, these treatments should be reapplied every 10 to 12 years to artificially maintain a K-value of 2.0 or lower.
3. Reduction of OSH Kinetic Hazards. For structures where the carbonation front has already reached the reinforcement (like Manila City Hall), the immediate recommendation is the installation of Structural Catchment Netting or pedestrian canopies rated for at least 600 Joules of impact energy. This provides a factor of safety above the calculated 490.5-Joule hazard. Long-term, "Electrochemical Realkalization" should be explored to restore the pH of the concrete, thereby eliminating the corrosion "trigger" at the source and removing the kinetic risk entirely.

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