ASSESSMENT OF REINFORCED CONCRETE DURABILITY IN WATER TREATMENT FACILITIES

Rupali Dehariya[1], Dr. Jyoti Yadav[2], Vivek Shukla[3]

Research Scholar, Department of Civil Engineering, SRK University, Bhopal[1]

Professor, Department of Civil Engineering, SRK University, Bhopal[3]

Assistant Professor, Department of Civil Engineering, SRK University, Bhopal[2]

ABSTRACT

Reinforced concrete (RC) structures remain critical infrastructure in water treatment systems globally, yet their long-term durability performance under aggressive chemical environments continues to present significant engineering challenges. This empirical study presents a comprehensive assessment of 47 water treatment facilities across diverse climatic and operational conditions, evaluating structural integrity, material degradation mechanisms, and design performance. Through systematic field investigations, laboratory analysis, and quantitative data assessment, this research identifies critical durability indicators and performance metrics associated with corrosion, alkali-aggregate reactions, and microcracking phenomena. Our findings reveal that 62% of facilities aged 20-30 years exhibited moderate to severe durability concerns, with carbonation depth and rebar corrosion constituting the primary degradation mechanisms. Advanced statistical analysis correlates design parameters, material composition, and environmental factors with observed damage patterns. The research implements optimization strategies utilizing supplementary cementitious materials, enhanced surface treatments, and innovative protective coatings that demonstrated 35-45% improvement in durability indicators. Additionally, this study proposes predictive models for service life estimation incorporating climate data, loading patterns, and maintenance regimes. The integrated methodology provides practical frameworks for design optimization and rehabilitation strategies applicable to existing and future water treatment infrastructure. Recommendations emphasize preventive maintenance protocols, material innovation, and performance-based design approaches to extend facility lifespan by 15-20 years. These findings contribute significantly to sustainable infrastructure development and resource optimization in water management sectors.

Keywords: *Reinforced concrete durability[1], Water treatment facilities[2], Carbonation[3], Rebar corrosion[4], Service life prediction[5], Design optimization[6], Performance assessment[7], Concrete degradation[8].*

1. INTRODUCTION

Water treatment facilities represent essential infrastructure for providing safe, potable water to populations worldwide. These facilities face continuous exposure to aggressive chemical environments, including sulfates, chlorides, and organic compounds present in raw water sources and treatment processes. Reinforced concrete serves as the primary structural material in most water treatment plants globally, chosen for its inherent chemical resistance, availability, and cost-effectiveness. However, despite these advantages, RC structures in water treatment environments experience accelerated deterioration compared to structures in conventional environments. The durability performance of RC water treatment facilities significantly impacts public health, economic sustainability, and environmental protection. Prolonged facility downtime due to structural failures or maintenance demands disrupts water supply chains and increases operational costs substantially. Understanding the long-term performance characteristics of existing infrastructure and optimizing design strategies for future facilities remains a critical research priority for civil engineering practitioners and water utility managers.

1.1 DURABILITY CHALLENGES IN RC WATER TREATMENT SYSTEMS

The primary durability challenges affecting reinforced concrete water treatment facilities stem from multifaceted material-environment interactions. Carbonation phenomena, wherein atmospheric carbon dioxide penetrates the concrete matrix and reduces alkalinity, represents the foremost mechanism initiating corrosion of embedded reinforcement steel. This carbonation process advances at rates dependent upon concrete permeability, relative humidity, and environmental CO_2 concentrations. Field investigations across 47 facilities revealed average carbonation rates ranging from 2.3 to 8.7 mm per decade, with considerable variation based on exposure classification and concrete quality. Chloride ingress presents another critical degradation pathway, particularly in coastal and de-icing salt environments. Chloride ions penetrate concrete pores through diffusion and capillary transport mechanisms, eventually reaching critical threshold concentrations that initiate localized corrosion of reinforcing steel. The corrosion process generates expansive rust products, inducing internal stresses that culminate in concrete cracking, spalling, and structural capacity reduction. Additionally, alkali-aggregate reactions (AAR), involving deleterious reactions between Portland cement alkalinity and certain aggregates, generate expansive gel products causing systematic deterioration. Microcracking patterns observed through scanning electron microscopy revealed AAR gel formation in 34% of sampled facilities constructed with reactive aggregates prior to aggregate screening implementation. These degradation mechanisms frequently operate synergistically, accelerating material deterioration substantially beyond rates predicted by single-mechanism models.

1.2 DESIGN AND MATERIAL INNOVATION APPROACHES

Contemporary design philosophies increasingly incorporate performance-based approaches prioritizing durability characteristics alongside conventional structural capacity considerations. Supplementary cementitious materials (SCMs) including fly ash, silica fume, and ground granulated blast furnace slag (GGBFS) have demonstrated significant efficacy in enhancing concrete durability through mechanisms including refined pore structure, reduced permeability, and diminished alkaline conditions. Research specimens incorporating 20-30% silica fume replacement exhibited carbonation depths approximately 40% lower than control specimens containing conventional Portland cement exclusively. Similar enhancements were observed with fly ash incorporation, though optimal percentages varied depending upon concrete strength requirements and environmental exposure classification. Advanced protective surface treatments, including hydrophobic coatings, silane-based impregnants, and permeable membranes, provided variable performance depending upon application methodology and coating selection. Electrochemical protection systems, comprising impressed current cathodic protection and sacrificial anode arrangements, offer established methodologies for rehabilitating actively corroding steel reinforcement, though initial capital costs remain substantial. Innovative design optimization strategies incorporating numerical modeling, artificial intelligence algorithms, and sensor integration enable real-time performance monitoring and predictive maintenance scheduling. These multifaceted innovation approaches collectively facilitate extended service life predictions and improved sustainability metrics for water treatment infrastructure.

1.3 RESEARCH OBJECTIVES AND SCOPE

This empirical research investigation addresses critical knowledge gaps regarding long-term performance characteristics of reinforced concrete treatment facilities across diverse environmental, design, and operational contexts. The primary research objectives encompass: (1) systematic quantitative assessment of durability performance indicators across existing water treatment infrastructure, including carbonation depth, rebar corrosion extent, crack formation, and structural integrity; (2) identification and statistical analysis of environmental, design, and material factors influencing observed degradation patterns; (3) evaluation of advanced material compositions and protective technologies demonstrating enhanced durability performance; (4) development of predictive service life models incorporating climate data, environmental classification, and maintenance regimes; and (5) formulation of design optimization and rehabilitation strategies applicable to both existing and future water treatment facility development. The investigation encompasses 47 water treatment facilities located across distinct climatic zones, ranging from humid tropical environments to arid desert conditions, ensuring geographically diverse representation. Facilities spanning construction periods from 1965 to 2015 provide temporal variation enabling assessment of evolving design standards, material technologies, and construction methodologies. The multidisciplinary research approach integrates field investigation protocols, laboratory experimentation, statistical analysis, and predictive modeling methodologies to provide comprehensive understanding of RC durability performance in water treatment applications.

2. SURVEY OF EXISTING LITERATURE

Extensive research literature addressing concrete durability has accumulated over several decades, providing foundational understanding of degradation mechanisms and mitigation strategies. Early investigations by Tuutti (1982) established fundamental carbonation rate models incorporating diffusion principles and environmental parameters, providing theoretical frameworks subsequently validated through field observations. Contemporary research by Mindess et al. (2003) comprehensively reviewed concrete durability phenomena, including detailed analysis of carbonation kinetics, chloride transport mechanisms, and preventive design approaches. Relevant studies by Montemor et al. (2010) specifically addressed concrete durability in aqueous environments, identifying specialized challenges in water-exposed infrastructure distinct from conventional building applications. Research investigating supplementary cementitious materials by Ismail et al. (2009) demonstrated quantifiable improvements in carbonation resistance and chloride transport reduction, with optimal dosage recommendations varying based on SCM type and cement chemistry. Electrochemical protection methodologies received comprehensive assessment through investigations by Pedeferri (1996), establishing theoretical principles underlying impressed current cathodic protection systems and presenting field performance data spanning 20+ year monitoring periods. Advanced durability assessment methodologies utilizing non destructive techniques were developed and validated through research by Basheer et al. (2006), enabling comprehensive structural evaluation without intrusive sampling requirements. Predictive modeling research by Mindess and Young (1981) established fundamental frameworks for service life estimation, subsequently refined through accelerated testing protocols and field validation studies. Research specifically addressing water treatment facility challenges received limited attention historically, with most durability literature emphasizing building structures and civil infrastructure such as bridges and parking structures. This research gap necessitates dedicated investigation of water treatment facility-specific challenges, including prolonged immersion conditions, chemical-laden environments, and operational loading patterns distinct from conventional structural applications. Recent investigations by Stanish et al. (2005) addressed accelerated testing methodologies applicable to water-exposed concrete, providing laboratory protocols replicable across research institutions. Contemporary research trends increasingly emphasize sustainability metrics, life-cycle assessment approaches, and circular economy principles in concrete design and maintenance optimization strategies. Integration of sensor technologies and structural health monitoring systems represents emerging research domain facilitating real-time performance assessment and predictive maintenance implementation.

3. METHODOLOGY

This empirical investigation implemented comprehensive mixed-methods research design integrating quantitative field measurements, laboratory testing protocols, statistical analysis, and predictive modeling methodologies. The investigation encompassed 47 water treatment facilities selected through stratified random sampling ensuring representation across geographic regions, facility age categories, design standards, and operational characteristics. Selection criteria prioritized facilities with construction documentation availability, accessibility for non-destructive testing, and operational history spanning minimum 15-year periods enabling meaningful durability assessment. Initial Phase I involved systematic documentation of facility design specifications, material specifications, construction methodologies, maintenance history, and operational parameters through comprehensive literature review of technical documentation and facility management records. This documentation phase enabled establishment of design baseline characteristics and identification of temporal variations in design standards and material requirements across different construction periods. Field investigation protocols in Phase II encompassed non-destructive testing utilizing established methodologies including half-cell potential measurements for corrosion assessment, ultrasonic pulse velocity for concrete homogeneity evaluation, carbonation depth determination through phenolphthalein indicator application, chloride profiling through grinding and chemical analysis, and visual crack documentation through standardized photographic protocols. Measurements occurred at systematically distributed locations across representative structural elements including beams, columns, and wall sections, with sampling density determined through preliminary statistical power analysis to ensure adequate representation for meaningful statistical inference. Quantitative measurements were conducted by trained technicians following established standards including ASTM C876 for half-cell potential measurement and ASTM C1585 for rapid chloride penetration testing (RCPT), ensuring methodological consistency across facilities.

Phase III laboratory analysis encompassed comprehensive characterization of concrete samples extracted through strategic coring at locations exhibiting suspected degradation. Concrete compressive strength was determined through testing of cylindrical specimens extracted from cores, evaluated at standard 28-day equivalent strength determination. Petrographic examination utilizing optical and scanning electron microscopy (SEM) provided detailed microstructural characterization including evaluation of cement hydration extent, aggregate composition, porosity distribution, and evidence of deleterious reactions including alkali-aggregate reactions and sulfate attack. Mercury intrusion porosimetry (MIP) enabled quantitative porosity assessment and pore size distribution determination, providing relationships between porosity characteristics and transport properties. Rapid chloride penetration testing (RCPT) following ASTM C1202 procedures quantified chloride transport resistance through measurement of coulombs passed under applied electrical potential. Accelerated carbonation testing followed ASTM G85 procedures, exposing concrete samples to elevated CO_2 concentrations (5% CO_2, 50% relative humidity) for standardized 28-day periods with subsequent carbonation depth determination through phenolphthalein indicator application. Chemical analysis of pore fluid extraction determined pH, alkalinity, and ion concentrations through titration and inductively coupled plasma (ICP) spectrometry, enabling assessment of concrete alkalinity preservation critical for steel protection. Rebar corrosion assessment incorporated weight loss determination through steel coupon analysis and electrochemical impedance spectroscopy (EIS) providing non-destructive corrosion rate estimation.

Phase IV statistical analysis and predictive modeling incorporated multivariate regression analysis establishing quantitative relationships between environmental variables (temperature, humidity, chloride deposition), design factors (concrete cover, water-cement ratio, binder composition), and observed performance indicators (carbonation depth, corrosion rate, crack extent). Correlation matrices and principal component analysis identified dominant factors influencing durability performance. Regression models were developed using ordinary least squares (OLS) and robust regression methodologies to account for outlier observations and heteroscedasticity potentially present in field measurement datasets. Model validation employed cross-validation techniques and independent dataset testing using approximately 30% of collected data reserved for validation purposes. Service life prediction models were formulated utilizing Fick's second law governing diffusion processes combined with empirical field observations, incorporating probabilistic approaches accounting for uncertainty in material properties and environmental parameters. Monte Carlo simulation techniques enabled probabilistic service life estimation with confidence interval determination. Regression discontinuity design analytical frameworks facilitated investigation of threshold effects in degradation phenomena. Geographic information systems (GIS) mapping enabled spatial analysis of durability performance variation across facilities and identification of regional patterns correlates with climatic and environmental characteristics.

4. DATA COLLECTION AND ANALYSIS

Comprehensive data collection across 47 water treatment facilities yielded quantitative performance measurements, qualitative degradation assessments, and facility-specific characteristics enabling multifaceted analysis of durability performance. Table 1 presents summary statistics of environmental and design parameters characterizing the facilities investigated. Environmental classification data reveals considerable geographic diversity with climatic conditions ranging from desert arid environments (mean annual rainfall <200 mm, relative humidity 25-35%) to humid tropical regions (annual rainfall >2000 mm, relative humidity 75-90%). Facility age distribution spans 50-year range (constructed 1965-2015), with mean facility age of 28.4 years and standard deviation of 12.3 years enabling investigation of age-related degradation progression. Concrete cover specifications evolved temporally, with older facilities (pre-1985) averaging 45 mm cover and modern facilities (post-2005) incorporating 50-65 mm cover reflecting increased emphasis on durability-driven design. Water-cement ratios reflected varying design standards, ranging from 0.65 in older facilities to 0.45 in contemporary designs incorporating advanced concrete technology. Supplementary cementitious material incorporation remained limited in historical facilities, with 79% containing pure Portland cement, whereas modern facilities incorporated SCM in 68% of cases, primarily fly ash (38% of facilities) and GGBFS (22% of facilities).

Table 1: Environmental and Design Characteristics of Investigated Water Treatment Facilities

Parameter	Mean	Std Dev	Min	Max	Unit
Facility Age	28.4	12.3	5	50	Years
Carbonation Depth	32.7	18.5	8	78	mm
Half-Cell Potential	-285	145	-650	-50	mV
Concrete Cover	52.3	9.8	35	75	mm
Water-Cement Ratio	0.55	0.09	0.42	0.72	Ratio

Table 1: Summary statistics of environmental and design parameters characterizing 47 investigated water treatment facilities. Carbonation depth measurements represent maximum penetration documented at sample locations; half-cell potential values indicate electrochemical corrosion probability with values more negative than -350 mV indicating high corrosion probability. Water-cement ratio includes equivalent water content adjustments for admixtures utilized in contemporary designs. Detailed durability performance measurements presented in Table 2 demonstrate quantitative variation in degradation indicators across the investigated facilities. Compressive strength measurements revealed mean value of 38.2 MPa with substantial variation

(range 18-62 MPa) reflecting age related strength gains, hydration completeness variations, and material composition differences. Chloride penetration depth determination through grinding and titration analysis documented considerable variation from minimal penetration (8 mm) to severe penetration (245 mm), with mean value of 67.4 mm. Rapid chloride penetration testing coulomb values ranged from 1,847 to 8,634 coulombs, indicating highly variable transport characteristics dependent upon concrete quality and exposure duration. Corrosion extent quantification through gravimetric mass loss analysis of recovered reinforcement steel documented mean corrosion extent of 3.8% with substantial variation (0.2-18.5%), indicating variable degradation progression rates. Alkali-aggregate reaction evidence through petrographic analysis revealed gel formation in 16 of 47 facilities (34%), with gel distribution ranging from minor (<1% area fraction) to extensive (>15% area fraction) involvement, indicating significant AAR presence in subsets of older facilities.

Table 2: Durability Performance Indicators of Reinforced Concrete Water Treatment Facilities

Durability Indicator	Mean	Std Dev	Min	Max	Count
Compressive Strength (MPa)	38.2	11.4	18	62	47
Chloride Penetration Depth (mm)	67.4	48.2	8	245	47
RCPT (Coulombs)	4,856	1,923	1,847	8,634	42
Steel Mass Loss (%)	3.8	4.2	0.2	18.5	35
AAR Gel Coverage (%)	4.2	6.8	0	24.3	16

Table 2: Durability performance measurements across water treatment facilities investigated. RCPT: Rapid Chloride Penetration Testing; AAR: Alkali-Aggregate Reaction. Count column indicates number of facilities evaluated for each indicator, with variation in count reflecting testing availability and sample quality considerations. Steel mass loss determined through weight-loss analysis on recovered reinforcement samples. Table 3 presents degradation severity classification results across the facility sample. Facilities were classified into five severity categories (minimal, mild, moderate, severe, critical) based upon integrated assessment of carbonation depth, corrosion indicators, and structural integrity observations. Approximately 21% of facilities (10 of 47) exhibited minimal degradation concerns with carbonation depth <15 mm and corrosion probability <10%, representing well-maintained newer structures or facilities with exceptional design durability characteristics. Mild degradation classification encompassed 19% of facilities (9 of 47) with carbonation depths 15-30 mm and corrosion probability 10-25%, generally reflecting facilities aged 15-25 years with adequate but not exceptional durability design. Moderate degradation characterized 26% of facilities (12 of 47) with carbonation depths 30-50 mm and corrosion probability 25-50%, representing facilities aged 25-35 years with emerging durability concerns warranting monitoring. Severe degradation classification included 21% of facilities (10 of 47) with carbonation depths 50-75 mm and corrosion probability exceeding 50%, indicating

active corrosion progression and structural capacity reduction requiring intervention planning. Critical degradation classification encompassed 13% of facilities (6 of 47) with carbonation depths exceeding 75 mm, active reinforcement corrosion with mass loss exceeding 10%, and visible structural damage including spalling and cracking patterns, necessitating urgent remediation implementation.

Table 3: Classification of Degradation Severity in Water Treatment Facilities

Severity Class	Count	Percentage (%)	Carbonation (mm)	Corrosion Prob. (%)	Action
Minimal	10	21	<15	<10	Monitor
Mild	9	19	15-30	10-25	Inspect
Moderate	12	26	30-50	25-50	Plan
Severe	10	21	50-75	50-75	Repair
Critical	6	13	>75	>75	Urgent

Table 3: Degradation severity classification distribution across 47 water treatment facilities. Classification based upon integrated assessment incorporating carbonation depth, corrosion probability (estimated through half-cell potential and RCPT), and structural integrity observations. Action column indicates recommended intervention level ranging from routine monitoring to emergency remediation requirements. Performance comparison between facilities incorporating supplementary cementitious materials versus those constructed with conventional Portland cement exclusively is presented in Table 4. Statistical analysis revealed statistically significant differences across multiple durability indicators.

Carbonation depth in facilities incorporating fly ash (mean 22.4 mm) or GGBFS (mean 19.8 mm) was substantially lower than pure Portland cement facilities (mean 44.2 mm) despite no significant age differences ($p<0.001$, t-test). RCPT coulomb values demonstrated similar trends, with SCM-inclusive concretes yielding mean coulombs of 2,847 (fly ash) and 2,156 (GGBFS) compared to 6,234 coulombs for conventional concrete ($p<0.001$). Corrosion probability assessment through half-cell potential measurement revealed mean values of -258 mV for fly ash concrete and -224 mV for GGBFS concrete versus -342 mV for conventional concrete, indicating superior corrosion resistance in SCM-modified systems. Steel mass loss measurements showed mean loss of 1.2% for fly ash concrete and 0.9% for GGBFS concrete versus 5.8% for conventional concrete ($p<0.001$). These quantitative findings provide compelling evidence that supplementary cementitious material incorporation provides substantial durability enhancement even when specimens attained similar ages, suggesting improved material formulation efficacy relative to conventional cement chemistry.

Table 4: Comparative Durability Performance of Concrete with Supplementary Cementitious Materials

Performance Indicator	Pure OPC (n=10)	Fly Ash 20% (n=18)	GGBFS 25% (n=10)	Silica Fume 7% (n=9)	P-value

Carbonation Depth (mm)	44.2±8.3	22.4±6.1	19.8±5.4	16.2±4.8	<0.001
RCPT (Coulombs)	6,234±1,234	2,847±892	2,156±764	1,483±512	<0.001
Half-Cell Potential (mV)	-342±98	-258±76	-224±68	-186±52	<0.001
Steel Mass Loss (%)	5.8±2.3	1.2±0.8	0.9±0.6	0.4±0.3	<0.001

Table 4: Comparative durability performance analysis for facilities incorporating supplementary cementitious materials versus conventional Portland cement (OPC) systems. Values presented as mean±standard deviation. Sample sizes (n) indicate number of facilities within each category. P-values derived from one-way ANOVA analysis with post-hoc Tukey comparison. Statistical significance indicated at $p<0.05$ level. Temporal degradation progression analysis presented in Table 5 establishes quantitative relationships between facility age and observed durability performance metrics. Facilities were stratified into four age cohorts (<10 years, 10-20 years, 20-30 years, >30 years) enabling assessment of aging-related degradation patterns. Carbonation depth demonstrated clear age-dependent progression, with mean values increasing from 10.2 mm in newer facilities (<10 years) to 62.4 mm in oldest facilities (>30 years), revealing approximately 6.1 mm per decade average carbonation rate consistent with literature values. RCPT coulomb values similarly increased with age, ranging from 2,134 coulombs in young facilities to 7,523 coulombs in older installations ($p<0.001$). Corrosion probability assessment through half-cell potential showed negative trend toward more active corrosion with age, with mean values shifting from -156 mV (young facilities, low corrosion probability) to -438 mV (old facilities, high corrosion probability). Notably, facilities in the 20–30-year age range exhibited rapid degradation acceleration, with carbonation depth increasing approximately 35-40 mm over approximately 10-year period, suggesting critical threshold attainment in corrosion initiation kinetics. This temporal analysis reinforces necessity of preventive maintenance intervention in the 15–20-year age window to mitigate subsequent accelerated degradation progression characteristic of older installations.

Table 5: Age-Based Degradation Progression of Reinforced Concrete Water Treatment Facilities

Age Cohort (Years)	Count (n)	Carbonation (mm)	RCPT (C)	HCP (mV)	Severity
<10	8	10.2±4.3	2,134±567	-156±45	Minimal
10-20	12	21.6±7.8	3,456±934	-256±67	Mild
20-30	16	38.4±12.2	5,234±1,456	-334±89	Moderate
>30	11	62.4±16.8	7,523±2,234	-438±124	Severe-Critical

Table 5: Temporal degradation progression analysis stratified by facility age cohorts. Data demonstrates age-dependent carbonation progression averaging approximately 6.1 mm per decade. Rapid acceleration observed in 20-30 year age range suggests critical degradation threshold attainment. HCP: Half-Cell Potential; RCPT: Rapid Chloride Penetration Testing.

5. DISCUSSION

Critical analysis of empirical findings reveals complex relationships between environmental factors, design parameters, material composition, and observed durability performance in reinforced concrete water treatment facilities. The investigation demonstrates that carbonation phenomenon represents the dominant degradation mechanism initiating reinforcement corrosion across the studied facility population, with mean carbonation depth of 32.7 mm and maximum observed penetration exceeding 78 mm. These findings correlate closely with carbonation depth observations reported by Papadakis et al. (1989) in environmental assessment studies, though observed rates in water treatment environments exceed typical building structures by approximately 1.5-2.0 times, attributable to prolonged moisture exposure and elevated relative humidity conditions characteristic of water facility environments. The mean carbonation rate of approximately 6.1 mm per decade documented in this investigation aligns with predictions from Tuutti's model adjusted for water facility environmental parameters, validating theoretical frameworks for accelerated degradation in aqueous environments. Statistical analysis revealed that concrete cover thickness significantly influences carbonation progression, with Pearson correlation coefficient $r=0.72$ ($p<0.001$) between cover depth and carbonation resistance, suggesting that each additional 10 mm cover increase corresponds to approximately 8-9 year extension of initiation period before corrosion onset. This relationship underscores importance of rigorous quality control during construction to ensure designed cover depths are achieved, as cover variations observed in field measurements (±15 mm from design specifications) create substantial uncertainty in service life predictions.

Chloride ingress analysis means penetration depth of 67.4 mm with substantial spatial variation reflecting heterogeneous concrete quality and exposure history. RCPT coulomb values averaging 4,856 coulombs indicate moderate-to-high chloride transport in majority of investigated facilities, substantially higher than typical chloride-resistant concrete specifications (ASTM C1202 high resistance <2,000 coulombs). This elevated chloride transport capacity directly correlates with age-related degradation, microcracking formation, and reduced concrete alkalinity, creating synergistic mechanisms accelerating corrosion initiation. Interestingly, chloride penetration depth demonstrated weaker correlation with carbonation depth ($r=0.34$, $p>0.05$), suggesting independent degradation pathways potentially operative simultaneously without direct interaction between mechanisms. This observation differs from conventional assumptions that carbonation necessarily precedes chloride-induced corrosion, possibly reflecting the extraordinary chloride exposure present in water treatment environments where chloride concentrations may substantially exceed those in maritime/de-icing salt environments. Analysis of half-cell potential measurements revealed that approximately 62% of facilities exhibited half-cell potential values more negative than -350 mV, indicating high corrosion probability according to ASTM C876 criteria. This high incidence of probable corrosion correlates with observed mass loss measurements (mean 3.8%) and visible structural damage documentation in severe and critical degradation classifications, validating electrochemical assessment methodologies for practical durability evaluation. Material composition analysis reveals compelling evidence that supplementary cementitious material incorporation provides substantial durability enhancement quantifiable across multiple degradation mechanisms. Facilities incorporating fly ash demonstrated approximately 49% reduction in carbonation depth compared to conventional Portland cement systems, with mean values of 22.4 mm versus 44.2 mm despite comparable facility ages. Similarly, GGBFS incorporation yielded 55% carbonation reduction (19.8 mm), exceeding fly ash performance at equivalent replacement levels. These quantitative improvements substantially exceed predictions from simplified linear models, suggesting that SCM materials operate through multiple mechanisms including refined pore structure modification, reduced permeability, and altered pore solution chemistry preserving higher alkalinity. The superior performance of GGBFS over fly ash aligns with findings by Ismail et al. (2009) in accelerated testing programs, though field validation across extended time periods and diverse climatic conditions provides practical confirmation of theoretical predictions. Notably, silica fume incorporation (7% replacement) demonstrated even superior performance with mean carbonation depth of 16.2 mm, representing 63% reduction relative to conventional concrete. However, silica fume utilization remained limited to only 9 facilities in the study sample, likely reflecting cost constraints limiting widespread adoption in water treatment facility construction despite superior durability characteristics. The cost-benefit analysis remains essential consideration for facility operators, as initial material cost premiums for SCM incorporation must be balanced against extended service life and reduced maintenance expenses over facility lifetime.

Temporal degradation analysis reveals age-dependent deterioration patterns with distinct acceleration phases. Facilities younger than 10 years demonstrated minimal degradation with mean carbonation depth of 10.2 mm and half-cell potential values indicating low corrosion probability (<10% facilities). This initial phase generally reflects adequate alkalinity preservation and protective concrete cover efficacy. However, facilities in the 20-30 year age range exhibited dramatic degradation acceleration, with carbonation depth increasing approximately 17 mm over the subsequent 10-year period (versus approximately 11 mm increase in 10-20 year cohort), suggesting attainment of critical degradation threshold. This acceleration may reflect combined effects of progressive carbonation front advancement, microcrack formation reducing concrete integrity, and reduced surface concrete quality from weathering exposure. Importantly, this 20-30 year timeframe aligns with typical design service life assumptions in earlier design standards (1960s-1980s construction period), suggesting these older facilities may now exceed intended design service periods. Facilities exceeding 30 years demonstrated severe degradation with mean carbonation depth of 62.4 mm, corrosion probability exceeding 75% in majority cases, and visible damage documentation in numerous structural elements. This age-dependent pattern suggests optimal intervention timing in the 15-20 year facility age window, during which preventive maintenance or protective system implementation could mitigate subsequent accelerated degradation. Current industry practice emphasizing periodic inspection protocols beginning at approximately 10-year facility age appears scientifically justified based upon observed degradation kinetics.

5.1 COMPARATIVE ANALYSIS WITH HISTORICAL PERFORMANCE DATA

Comprehensive comparison of empirical findings with historical durability research literature reveals general alignment with theoretical predictions combined with critical deviations attributable to water treatment facility-specific environmental characteristics. Tuutti's fundamental carbonation model (1982) established theoretical framework predicting carbonation depth proportional to √time relationship, with rate constant dependent upon concrete properties and environmental CO_2 concentration. Comparison of observed carbonation progression against Tuutti model predictions using field-measured environmental parameters (ambient CO_2 concentration, relative humidity, temperature) reveals that observed field progression rates approximately 1.5-2.0 times exceed model predictions, likely reflecting prolonged moisture exposure (90-100% relative humidity) and enhanced water film presence on concrete surfaces characteristic of aqueous environments. This systematic overestimation by Tuutti model suggests necessity for environment-specific model refinement incorporating aqueous exposure effects not adequately captured by conventional atmospheric exposure assumptions. Contemporary research by Stanish et al. (2005) addressing accelerated carbonation testing methodologies demonstrated applicability of laboratory test protocols (5% CO_2, 50% RH) to field progression prediction with appropriate rate constant adjustments, yielding closer agreement between predicted and observed field values. The present investigation's empirical carbonation rates average approximately 6.1 mm per decade, substantially higher than typical building structure rates (2-4 mm per decade documented for conventional construction) but consistent with earlier predictions by Montemor et al. (2010) specifically addressing water facility environments. This consistency across independent investigations provides confidence in rate estimates applicable for service life prediction modeling.

Chloride transport characterization in the present investigation provides data substantially complementary to extensive research by Basheer et al. (2006) on chloride penetration in marine structures, though important distinctions emerge reflecting water treatment environment specificity. RCPT coulomb values obtained in this study (mean 4,856 coulombs) substantially exceed typical specifications for high chloride resistance (<2,000 coulombs) and approach values documented by Basheer et al. (6,000-8,000 coulombs) for aging marine structures, despite comparable or potentially lower environmental chloride exposure than coastal marine environments. This observation suggests that water treatment facility chemical composition may include chloride or other ionic species enhancing transport rates beyond what would be expected from chloride exposure alone. Alternatively, elevated coulomb values may reflect microcracking progression and degradation-induced porosity changes reducing transport resistance. The weak correlation between carbonation depth and chloride penetration depth (r=0.34) observed in this investigation contrasts with stronger interdependencies documented in marine structure research (r=0.65-0.75), suggesting that degradation mechanisms operate more independently in water treatment environments than in conventional marine exposure conditions. This distinction has important implications for durability modeling, as simplified approaches assuming coupled degradation mechanisms may inadequately predict actual progression rates. Investigation of chloride threshold for corrosion initiation (critical chloride concentration) through pore solution analysis revealed mean values of approximately 0.82% by weight of cement, somewhat lower than typical threshold values (1.0-1.5%) documented in laboratory studies, possibly reflecting reduced pH in aged concrete specimens diminishing chloride threshold due to alkalinity depletion.

Electrochemical assessment through half-cell potential measurements provides rapid, non-destructive evaluation of corrosion probability, with extensive validation literature supporting interpretation criteria. The present investigation's findings showing 62% of facilities with half-cell potential more negative than -350 mV indicate high corrosion probability align with field observations of active corrosion evidenced through visual inspection and mass loss measurements. Comparison with research by Pedeferri (1996) on impressed current cathodic protection systems confirms that facilities exhibiting half-cell potentials <-350 mV respond favorably to electrochemical protection implementation, validating practical utility of half-cell measurements for rehabilitation planning. Notably, relationship between half-cell potential and actual mass loss measurements demonstrated moderate correlation ($r=0.58$, $p<0.01$), suggesting that while potential provides probabilistic corrosion indicator, actual corrosion rate varies substantially based upon concrete resistivity and moisture availability, underscoring necessity for multiparameter assessment rather than reliance upon single electrochemical indicator. Advanced EIS (Electrochemical Impedance Spectroscopy) testing conducted on subset of 12 facilities provided superior sensitivity to corrosion rate estimation compared to half-cell potential alone, with EIS-derived corrosion rates showing stronger correlation ($r=0.78$) with gravimetric mass loss measurements. However, EIS methodology requires more sophisticated instrumentation and technical expertise than half-cell measurement, limiting widespread adoption despite superior information content. These findings suggest that optimal assessment protocols should incorporate half-cell measurements for rapid facility screening combined with EIS analysis at locations exhibiting ambiguous or elevated corrosion probability indicators.

Alkali-aggregate reaction findings documented in 34% of investigated facilities (16 of 47) indicate substantial prevalence exceeding typical incidence rates (15-20%) reported in building structure research literature. This elevated incidence likely reflects two contributing factors: (1) historical construction practices predating comprehensive aggregate screening protocols for reactive silica phases, and (2) prolonged moisture exposure in water treatment environments accelerating AAR kinetics substantially beyond reaction rates in conventional dry environments. Early AAR detection through petrographic examination and gel quantification enabled assessment of progression severity in affected specimens. Facilities exhibiting AAR gel coverage exceeding 10% area fraction demonstrated enhanced cracking patterns and reduced compressive strength compared to AAR-free specimens, with mean strength reduction of approximately 12% attributable to gel expansion and microcracking. Comparison with AAR research by Mindess et al. (2003) reveals that observed gel distributions align with expected patterns for long-term field exposure, with greatest gel formation occurring at external surfaces and reducing with concrete depth, reflecting moisture gradient effects on reaction progression. The

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severity classification scheme developed in this investigation appropriately identified AAR-affected facilities as candidates for enhanced monitoring and potential mitigation measures, recognizing that while AAR-related degradation typically progresses slowly, cumulative effects over 50+ year facility lifetimes can produce substantial structural impact. Importantly, facilities constructed subsequent to 1985 (post-aggregate reactivity screening implementation) showed negligible AAR incidence (none of 11 facilities <20 years age exhibited significant gel formation), providing confirmation that aggregate quality assurance programs have effectively mitigated this historical durability concern.

Supplementary cementitious material benefits observed in this investigation provide quantitative field validation of extensive laboratory research establishing SCM durability improvements. The 49% carbonation reduction with fly ash incorporation (22.4 mm versus 44.2 mm) closely aligns with predictions from Ismail et al. (2009) accelerated testing program showing similar magnitude reduction in accelerated test specimens. However, field performance demonstrates sustained benefits through 20–30-year monitoring periods, confirming that early-age performance improvements persist through extended facility lifetimes. GGBFS performance surpassing fly ash (55% carbonation reduction) reflects superior pozzolanic reactivity and more refined pore structure generation, consistent with research by Neville (2003) on GGBFS cementitious efficiency. The present investigation contributes important evidence to ongoing debate within materials science community regarding optimal SCM selection criteria and replacement percentage optimization for durability applications. Previous research emphasized late-age strength development favoring higher GGBFS replacement percentages, whereas early-age chloride resistance favors lower replacement levels. Field observations spanning 20-30 years enable assessment of long-term balance between early-age performance and extended durability, revealing that 20-25% GGBFS replacement represents approximate optimal balance minimizing both early-age chloride transport and carbonation progression through full facility design life. However, substantial cost-benefit analysis must accompany any specific recommendation, as SCM material expenses and potential construction scheduling implications require economic evaluation against service life extension benefits. The 15-20 year extension in initiation period preceding corrosion onset estimated for facilities with 20% SCM replacement likely justifies material cost premiums of 15-20%, representing favorable economic return through extended maintenance-free service periods.

Integration of empirical findings with existing literature base reveals that water treatment facility durability challenges exceed conventional structural durability concerns quantitatively, necessitating specialized design approaches and enhanced maintenance protocols. The systematic degradation acceleration observed in 20–30-year age range across multiple independent indicators (carbonation progression, corrosion probability elevation, chloride penetration depth) suggests that this timeframe represents critical intervention window for optimal service life extension through preventive measures. Contemporary design standards increasingly recognize this temporal characteristic, with prescriptive durability requirements adjusted upward for water facility applications relative to general building structures. The present investigation's field data provides compelling empirical foundation supporting these enhanced requirements, demonstrating that conventional design assumptions derived from building structure experience systematically underestimate degradation rates in water treatment environments. Future research addressing climate change effects on durability performance remains essential, as projected increases in ambient temperature and humidity extremes suggest potential acceleration of carbonation and chloride ingress beyond historical precedent, requiring model refinement incorporating evolving environmental conditions.

6. CONCLUSION

This comprehensive empirical investigation of 47 water treatment facilities across geographically diverse locations and construction periods (1965-2015) establishes quantitative performance baselines for reinforced concrete durability in aqueous environments. Systematic field investigations, laboratory analysis, and statistical assessment reveal carbonation depth and chloride ingress as primary degradation mechanisms, with mean carbonation penetration of 32.7 mm and average chloride penetration depth of 67.4 mm across facility population. Degradation severity classification demonstrates that 62% of facilities aged 20-30 years exhibit moderate to severe durability concerns, with carbonation advancing at mean rate of approximately 6.1 mm per decade, substantially exceeding progression rates in conventional building structures. Electrochemical assessment through half-cell potential measurements indicates corrosion probability exceeding 50% in 62% of investigated facilities, correlating with observed reinforcement steel mass loss measurements and visible structural damage. Temporal analysis reveals distinct degradation acceleration phase in 20-30 year age range, suggesting optimal timing for preventive intervention implementation to mitigate subsequent accelerated deterioration characteristic of aging infrastructure. Material composition analysis provides compelling evidence that supplementary cementitious material incorporation, particularly ground granulated blast furnace slag (25% replacement) and fly ash (20% replacement), yields substantial durability enhancement quantifiable as 49-55% reduction in carbonation depth relative to conventional Portland cement systems. These SCM-incorporating facilities demonstrated mean corrosion probability substantially reduced (half-cell potential -224 to -258 mV versus -342 mV for conventional concrete) and steel mass loss minimized (0.9-1.2% versus 5.8%) despite comparable aging exposure. Predictive service life modeling informed by empirical field data suggests that SCM incorporation can extend corrosion-free service periods by 15-20 years, potentially justifying material cost premiums through extended maintenance-free facility operation. Critical analysis comparing field findings with historical research literature confirms general alignment with theoretical degradation prediction frameworks while identifying water treatment environment-specific mechanisms requiring enhanced modeling consideration. Recommendations emerging from this investigation emphasize: (1) adoption of enhanced concrete durability specifications for new water treatment facility construction incorporating SCM materials and increased concrete cover; (2) establishment of preventive maintenance protocols initiating systematic inspection and potential protective measure implementation beginning at facility age 15-20 years; (3) implementation of structural health monitoring systems enabling real-time performance assessment and predictive maintenance scheduling; and (4) continued research addressing climate change effects and emerging protective technologies ensuring ongoing optimization of water infrastructure sustainability. Integration of performance-based design approaches with condition-based maintenance strategies offers optimal pathway toward extended service life and improved resource utilization in critical water treatment infrastructure.

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