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STEEL REINFORCING BAR UNDER MULTI-DEGRADATION MECHANISMS: CURRENT FINDINGS, NEEDS, AND PROPOSED INNOVATIVE METHODOLOGIES

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ABSTRACT

This review investigates the effects of combined degradation mechanisms (CDMs)—including chloride ingress, carbonation, freeze-thaw cycles (FTC), alkali-silica reaction (ASR), and sulfate attack (SA)—on rebar corrosion in reinforced concrete (RC). While chloride and carbonation are well-known corrosion initiators, their interaction with other mechanisms such as FTC, ASR, and SA can significantly accelerate deterioration by increasing permeability and promoting deeper ingress of aggressive ions. Although CDMs are expected to intensify damage compared to single degradation mechanisms (SDMs), some early studies on plain concrete have reported mixed results, underscoring the need to focus on CDM impacts specific to rebar corrosion. This review emphasizes the importance of generating corrosion parameters—such as time to initiation and propagation—to improve service life modeling. However, testing remains a major challenge due to the absence of standardized CDM protocols. To address this, the study proposes innovative, multi-agent methodologies that simulate real-world exposure conditions. These frameworks aim to enhance the durability assessment of RC structures, especially in harsh environments and critical infrastructure like nuclear power plants and marine facilities.

Keywords: rebar corrosion, chloride attack, carbonation, freeze-thaw cycles, alkali-silica reaction, sulfate attack, combined degradation mechanisms

INTRODUCTION

This review examines the influence of combined degradation mechanisms (CDMs) on reinforced concrete (RC), focusing on how chloride ingress, carbonation, freeze-thaw cycles (FTC), alkali-silica reaction (ASR), and sulfate attack (SA) interact to accelerate rebar corrosion. While the individual effects of chloride and carbonation are well established, their interaction—along with FTC, ASR, and SA—can produce synergistic, sequential, or antagonistic effects on corrosion progression (Kashani et al., 2013). Chloride depassivates rebar above a critical threshold (C_crit), while carbonation lowers pH, weakening passive films . However, limited research exists on critical carbonation thresholds (CCT) and corrosion initiation times (t_i), especially under CDMs where pH, permeability, and film stability fluctuate significantly (Castorena, 2008). Mechanisms like FTC and ASR amplify deterioration through cracking and increased permeability (Esposito & Hendriks, 2019), and SA can further destabilize passive films (Babu & Kondraivendhan, 2020). These mechanisms may act concurrently or sequentially, with environmental factors—such as splash or tidal zones—modulating their severity (Morozov et al., 2022). Despite widespread use of SDM-based durability standards (e.g., CSA A23.1-14), CDM studies remain inconsistent in exposure design and often rely on artificial cracking, limiting real-world applicability (Y. Wang et al., 2018). This review underscores the need for standardized CDM protocols and proposes region-specific methodologies to generate realistic corrosion data, advancing the durability design of RC infrastructure (Huang et al., 2024).

Table1. Summary of single degradation mechanisms and their effects on reinforced concrete

Mechanism	Primary Effect	Impact on RC
Chloride Attack	Depassivates steel once chloride threshold (C_crit) is exceeded	Accelerated rebar corrosion, cracking, reduced service life
Carbonation	Lowers pH, destabilizes passive film on steel	Gradual corrosion initiation, reduced alkalinity, shrinkage cracks
Sulfate Attack (SA)	Forms expansive ettringite and gypsum, cracking concrete	Increased permeability, ITZ degradation, potential passive film disruption
Freeze-Thaw Cycles (FTC)	Induces internal cracking due to ice expansion	Microcracks that facilitate ingress of Cl^- and CO_2, structural weakening
Alkali-Silica Reaction (ASR)	Forms expansive gels from reactive silica and alkalis	Microcracking, increased permeability, calcium depletion, risk of corrosion

REGIONAL DURABILITY CHALLENGES

Regional climate significantly influences the degradation of reinforced concrete (RC) through mechanisms like chloride ingress, carbonation, sulfate attack (SA), freeze-thaw cycles (FTC), and alkali-silica reaction (ASR) (Cho, 2007). In cold regions, FTC and chloride-based de-icers (15–21% Cl^-) cause cracking and accelerate corrosion, with snowmelt further increasing chloride diffusion (Peng et al., 2023; R. Wang et al., 2022). Coastal and tropical zones face high humidity and CO_2, promoting both chloride ingress and carbonation-induced corrosion, even when chloride transport slows above 80% RH (Angst et al., 2009; Ekolu, 2016). Hot deserts experience accelerated SA, DEF, and ASR due to high temperatures and seasonal humidity (Mazarei et al., 2017). Temperate climates alternate between chloride-driven winter corrosion and summer carbonation, complicating long-term durability predictions (Lv & Li, 2022). High-altitude areas suffer from intense FTC and snowmelt-driven chloride ingress (Xu et al., 2022), while polar regions primarily face FTC-induced microcracking and increased carbonation risk (Xu et al., 2022). Additional environmental stressors acid rain, solar radiation, and windborne salts—amplify deterioration, especially in urban and coastal environments (Elmoaty, 2018). These climate-specific degradation profiles underscore the need for regionally adapted durability models, as illustrated in Figure 1. For example, cold climates are dominated by chloride damage, deserts by sulphate and ASR, and mixed zones by year-round CDMs. This is particularly critical for nuclear power plants and other critical infrastructure, where concrete deterioration under harsh regional exposure could compromise structural integrity and safety margins over long service lives. Therefore, understanding the interaction between environmental conditions and CDMs is essential for ensuring durability in safety-critical applications.

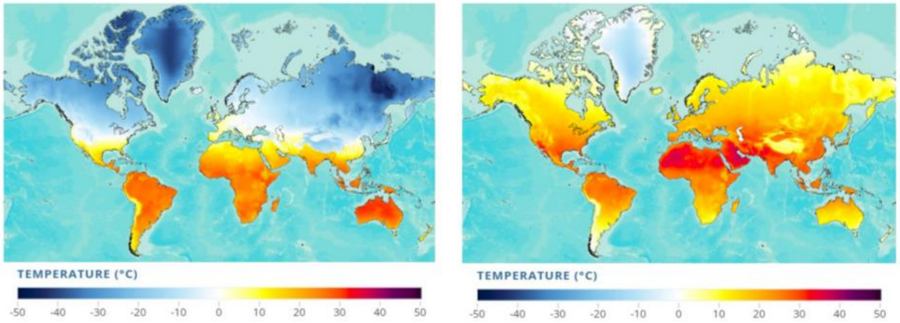


Figure 1. Observed climatology of average mean surface air temperature during 1991-2020: a) Winter months; December, January, and February and b) Summer months; June, July, and August (*Climatic Research Unit - Groups and Centres*).

METHODOLOGY

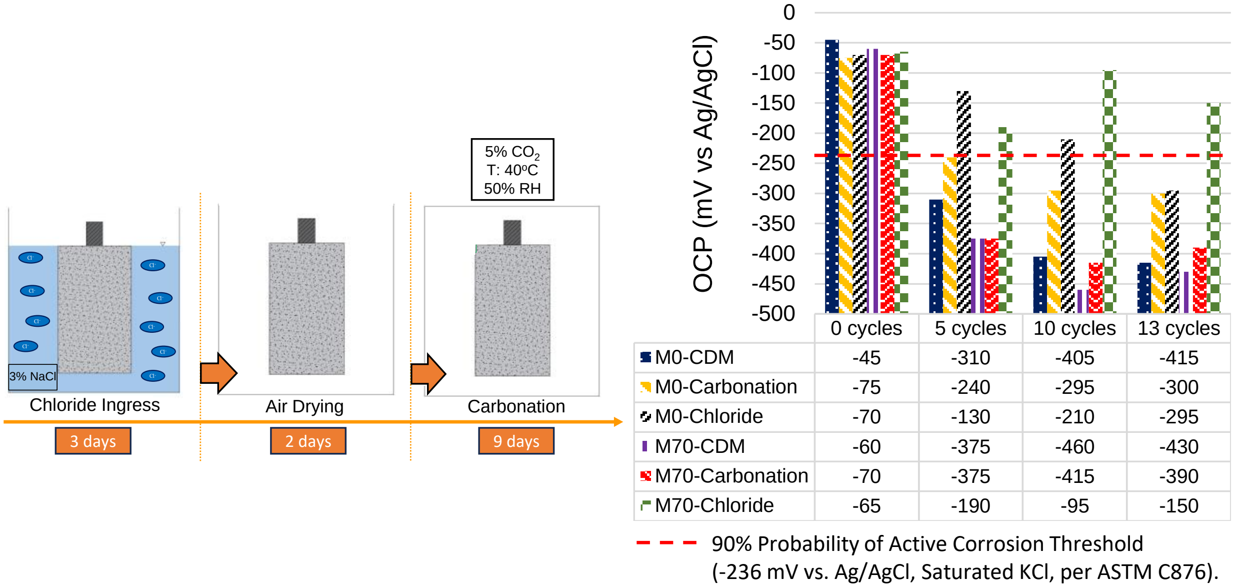
This review adopted a structured approach to assess how combined degradation mechanisms (CDMs) affect rebar corrosion in cement-based systems, focusing on five primary processes: chloride attack, carbonation, sulfate attack (SA), alkali-silica reaction (ASR), and freeze-thaw cycles (FTC). A systematic search of major academic databases yielded a broad range of studies, from which a refined selection of high-quality research was chosen based on relevance and methodological rigor. These studies were categorized into seven CDM themes: chloride + carbonation, chloride + ASR, chloride + SA, chloride + FTC, carbonation + ASR, carbonation + FTC, and carbonation + SA. The final dataset spanned peer-reviewed journals, conference proceedings, book chapters, and theses. Trends in publication show a growing interest in CDM research in recent years, with leading contributions from *Construction and Building Materials*, *Journal of Building Engineering*, and *Corrosion Science*. This thematic classification enabled targeted synthesis of findings and helped identify significant research gaps in durability assessments involving combined degradation mechanisms.

COMBINED EFFECT OF CHLORIDE AND CARBONATION ON REBAR CORROSION

Reinforced concrete (RC) structures are highly vulnerable when exposed to both chloride ingress and carbonation, especially under sequential or simultaneous conditions. The sequence of exposure significantly influences corrosion severity: chloride-first ($Cl^- \rightarrow CO_2$) releases bound chlorides during subsequent carbonation, lowering pH and accelerating corrosion before the critical chloride threshold (C_crit) is reached (Castellote et al., 2009). Conversely, carbonation-first ($CO_2 \rightarrow Cl^-$) can reduce chloride ingress by refining pores, but this effect is temporary due to pH decline and passive film destabilization (Cui et al., 2017).

Simultaneous exposure intensifies damage through debonding and interfacial cracking (Castellote et al., 2004). In synthetic pore solutions (SPS), Martin and Bastidas (Martin & Bastidas, 2023) observed that combined exposure (pH 9.1, 4 wt% Cl^-) caused a 22% drop in OCP, 90% drop in Rp, and a 132% increase in crack growth. Sequential cycling further worsens corrosion, as shown by Pakawat and Uomoto (P. 'Sancharoen, 2005) and Tiwari et al. (Tiwari et al., 2023), where repeated chloride–carbonation exposures increased i_corr in both OPC and PPC concretes. Zivica (Živica, 2003)found that initial chloride exposure (e.g., $MgCl_2$) lowered OCP, while subsequent carbonation slightly reversed corrosion—most effectively in Mg-rich systems (Zhang et al., 2020).

Roventi et al. (Roventi et al., 2014) reported that carbonation initially reduced i_corr (290 → 1.9 µm/year) in galvanized steel, but chloride exposure under wet-dry cycles reactivated corrosion (up to 36 µm/year). In LC3 concretes, Wang et al. (Y. Wang et al., 2023) observed that carbonation released bound chlorides, raising i_corr to 18 $\mu A/cm^2$ in 14 days. Similarly, Yeih et al. (W.C. Yeih et al., 2016) found that combined exposure in OPC and Type II cement dropped OCP below −400 mVSCE, confirming severe corrosion risk. These findings confirm the synergistic deterioration caused by chloride–carbonation interactions and highlight the need for integrated models and testing strategies.



	0 cycles	5 cycles	10 cycles	13 cycles
M0-CDM	-45	-310	-405	-415
M0-Carbonation	-75	-240	-295	-300
M0-Chloride	-70	-130	-210	-295
M70-CDM	-60	-375	-460	-430
M70-Carbonation	-70	-375	-415	-390
M70-Chloride	-65	-190	-95	-150

Figure 3. Exposure setup (left) and OCP values for OPC + 0%/70% GGBFS concrete under cyclic-sequential CDM exposure using SDM as control (right) from Pakawat and Uomoto (P. 'Sancharoen, 2005).

Table2. Key studies on the combined effect of chloride and carbonation on rebar corrosion

Author	**Research Focus**
Martin and Bastidas (Martin & Bastidas, 2023)	Investigated the simultaneous effect of carbonation and chloride on AISI 1018 steel in simulated pore solution (SPS). Found 22% OCP drop, 90% Rp drop, and 132% increase in crack propagation, highlighting severe synergistic corrosion.
Pakawat and Uomoto (P. 'Sancharoen, 2005)	Studied sequential cyclic exposure of carbonation and chloride on slag-blended cement. Found that repeated cycling sharply reduced corrosion resistance.
Tiwari et al. (Tiwari et al., 2023)	Reported that under 50 cycles of chloride–carbonation exposure, corrosion current (i_corr) increased significantly for both OPC and PPC concrete—even with inhibitors.
Zivica (Živica, 2003)	Showed that initial chloride exposure (NaCl, $CaCl_2$, $MgCl_2$) decreased OCP significantly (−524 to −458 mV), and subsequent carbonation partially reversed corrosion, particularly in $MgCl_2$.
Roventi et al. (Roventi et al., 2014)	Investigated galvanized steel. Found that carbonation initially lowered i_corr (from 290 to 1.9 µm/year), but wet-dry chloride cycling reactivated corrosion (i_corr up to 36 µm/year).
Wang et al. (Y. Wang et al., 2023)	In LC3 concrete, carbonation broke down chloride-binding phases, releasing chlorides and raising i_corr from 0 to 18 µA/cm^2 in 14 days.
Yeih et al. (W.C. Yeih et al., 2016)	Studied OPC and Type II cement with admixed chlorides. Found combined chloride–carbonation exposure dropped OCP below −400 mVSCE, indicating severe corrosion risk.

COMBINED EFFECT OF CHLORIDE AND SULFATE ON REBAR CORROSION

Sulfate attack (SA) is a major durability concern for reinforced concrete (RC), as SO_4^{2-} ions react with cement hydrates to form expansive ettringite and gypsum, inducing microcracks and weakening the interfacial transition zone (ITZ) (Sathe et al., 2022). In cold, wet conditions, Thaumasite Sulfate Attack (TSA) may develop, forming a soft, non-cohesive mass that severely disrupts the concrete matrix (J. Wang et al., 2018). Standard test methods (e.g., ASTM C1012, C452) lack consistency in mix design and exposure parameters, complicating comparisons across studies (Piasta, 2017).

When combined with chloride ingress, sulfate-induced damage becomes significantly more severe. Chloride-first exposure accelerates depassivation, followed by sulfate-induced cracking (Metalssi et al., 2023); the reverse sequence increases porosity, enhancing Cl^- ingress and corrosion (Song, Y. et al., 2025). Metakaolin (MK) enhances resistance in OPC–MK mixes under $MgCl_2$ + $MgSO_4$ exposure, reducing icorr and delaying corrosion compared to plain OPC (Babu & Kondraivendhan, 2020). Zuquan et al. (Zuquan et al., 2015)observed chloride-driven macrocracks, with sulfate increasing internal micro-defects even when surface damage was limited. Under electric fields, X. Yu et al. (Yu et al., 2023) found that sulfate initially delayed but later worsened corrosion through enhanced crack growth.

Long-term studies confirm these synergistic effects. A.A. Jee et al. (Jee & Pradhan, 2022) found that $MgSO_4$ mitigated corrosion more effectively than Na_2SO_4 in 5% NaCl environments over 27 months. Dehwah et al. (Dehwah et al., 2002) and Abubakar et al. (Abubakar et al., 2020) reported icorr exceeding 4 µA/cm² under 10% sulfate and 15% chloride conditions. Liu et al. (G. Liu et al., 2016) showed that sulfate initiated corrosion at lower concentrations than chloride in simulated pore solutions (SPS), with combined exposure decreasing Rct by ~70×. Contrarily, Ogunsanya et al. (Ogunsanya, I. G. & Hansson, C. M., 2019) noted that sulfate slightly delayed corrosion in stainless steel, likely by reinforcing the passive film—indicating material-specific responses under CDMs.

Overall, sulfate–chloride interactions significantly amplify deterioration, underscoring the need to assess CDMs within corrosion frameworks rather than in isolation.

Table 3. Key studies on the combined effect of sulfate and chloride on rebar corrosion

Author	Focus of Study
Liu et al. (G. Liu et al., 2016)	Assessed corrosion initiation in simulated pore solution with sulfate and chloride. Found that sulfate initiates corrosion at lower concentrations than chloride (0.02–0.03 mol/L vs. 0.05–0.06 mol/L), and that combined exposure dramatically reduces corrosion resistance (Rct dropped ~70×).
Zuquan et al. (Zuquan et al., 2015)	Used X-CT and potentiostatic testing to study NaCl + Na_2SO_4 exposure. Found chloride drives macrocracking, while sulfate increases internal micro-defects.
Babu et al. (Babu & Kondraivendhan, 2020)	Studied $MgCl_2$ + $MgSO_4$ exposure in OPC–MK concrete. Metakaolin delayed corrosion initiation and reduced i_corr compared to OPC.
A.A. Jee et al. (Jee & Pradhan, 2022)	Conducted long-term (27 months) study under realistic wet-dry cycles with NaCl + Na_2SO_4 and $MgSO_4$. Found Mg^{2+} improved corrosion resistance, Na^+ worsened it.
Dehwah et al. (Dehwah et al., 2002)	Studied 5% NaCl + varying sulfate concentrations. Noted increased i_corr (>4 µA/cm²), showing sulfate amplifies chloride-induced corrosion.
Abubakar et al. (Abubakar et al., 2020)	Observed high chloride (15%) + 5% Na_2SO_4 caused elevated corrosion rates, confirming strong CDM effects.
Ogunsanya et al. (Ogunsanya, I. G. & Hansson, C. M., 2019)	Found that sulfate in chloride-rich environments delayed corrosion in stainless steel by stabilizing passive films, indicating material dependency.

COMBINED EFFECT OF SULFATE AND CARBONATION ON REBAR CORROSION

The combination of sulfate attack and carbonation forms a critical degradation mechanism that significantly accelerates corrosion in reinforced concrete. When sulfate-induced cracking occurs first, it increases concrete permeability, allowing deeper CO_2 ingress and leading to passive film breakdown at the steel interface. Conversely, carbonation lowers pore solution alkalinity, which intensifies sulfate-induced expansion and internal damage.

In industrial conditions, Huang et al. (Huang et al., 2024) exposed RC specimens to alternating SO_2 and CO_2, observing a sharp drop in OCP (−200 to −450 mV in 70 days) and a steep decline in Rct (1460 to 9 $k\Omega \cdot cm^2$), confirming severe corrosion beyond individual exposure effects. These results underscore the synergistic deterioration potential of this CDM.

Although chloride–sulfate remains the most aggressive CDM—especially under cyclic wet-dry conditions—sulfate–carbonation also presents a serious threat. While supplementary cementitious materials (SCMs) like metakaolin (MK) and fly ash (FA) improve resistance by refining pore structure, they are not sufficient to fully mitigate multi-ion interactions. These findings highlight the urgent need for testing methods and material solutions that reflect real-world exposure to multiple degradation agents in marine, industrial, and urban environments.

COMBINED EFFECT OF ASR AND CHLORIDE ON REBAR CORROSION

Alkali-silica reaction (ASR) occurs when alkalis from cement react with reactive silica in aggregates, forming expansive gels that extract calcium from C-S-H and create microcracks in concrete (Stanton, 1942). These cracks increase permeability, enabling deeper penetration of chloride (Cl^-) and carbon dioxide (CO_2), while calcium loss destabilizes passive films on steel, raising corrosion risk (Lindgård et al., 2011).
ASR–chloride interaction is particularly severe, with chloride salts like NaCl and $CaCl_2$ both promoting corrosion and intensifying ASR expansion—from 0.36% to 0.61% with NaCl exposure (Heisig et al., 2016). ASR-induced cracking facilitates chloride transport, accelerating rebar corrosion. Barragán-Ramos et al. (Barragán-Ramos et al., 2022) showed faster corrosion and reduced polarization resistance (Rp) under combined ASR–chloride exposure compared to single mechanisms.

Fly ash (FA) at 20% replacement reduced chloride diffusivity and delayed corrosion, though higher FA levels were less effective (Mazarei et al., 2017). Lithium-based treatments were also beneficial under elevated temperatures, improving Rp and OCP stability under ASR–chloride conditions (Ueda et al., 2014). Interestingly, ASR gels may partially block chloride ingress by filling microcracks, though this effect remains inconsistent across studies and requires standardized testing to confirm (Rangaraju et al., 1979).
Overall, the synergy between ASR and chloride attack significantly amplifies deterioration, underscoring the need for integrated mitigation approaches and a deeper understanding of their coupled effects on RC durability.

COMBINED EFFECT OF ASR AND CARBONATION ON REBAR CORROSION

The interaction between alkali-silica reaction (ASR) and carbonation presents a dual role—either mitigating or intensifying degradation depending on exposure conditions. When applied during early curing, carbonation can suppress ASR expansion by up to 98%, forming $CaCO_3$ that refines pores and improves strength (Z. Liu et al., 2022). In contrast, when carbonation occurs as a deterioration process, it lowers pore solution pH, destabilizes passive films, and alters ASR gel chemistry.
Under cyclic ASR–carbonation exposure, studies report increased cracking and expansion due to reduced alkalinity and unstable gel formation (Thomas et al., 2019). ASR-induced microcracks allow deeper CO_2 ingress, accelerating corrosion risk. Simultaneously, carbonation reduces calcium availability, weakening ASR gel structure and potentially reducing expansion, but compromising matrix integrity (Chen et al., 2004).

These complex interactions highlight the importance of assessing ASR and carbonation together, particularly in environments with both CO_2 and alkali presence, to ensure accurate durability predictions for reinforced concrete structures.

RECOMMENDATIONS FOR FUTURE RESEARCH

While standardized tests exist for evaluating individual degradation mechanisms—such as ASTM C1260 and C1293 for ASR—there remains a critical need for research focused on the combined impact of multiple degradation processes on rebar corrosion. Most existing studies emphasize physical expansion or chemical reactivity, often neglecting electrochemical responses under realistic field conditions.

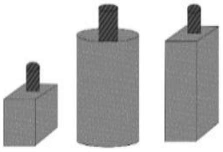
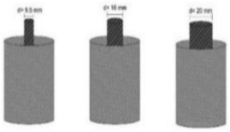
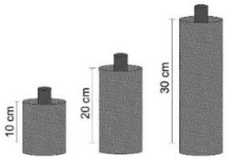
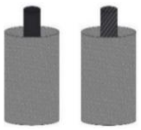
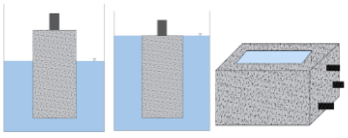
Future research should focus on developing comprehensive experimental frameworks that simulate combined degradation mechanisms CDMs, including chloride ingress, carbonation, sulfate attack, alkali-silica reaction (ASR), and freeze-thaw cycles FTC. These frameworks should reflect practical exposure conditions and account for the complex interactions that occur in real-world structures.

A promising approach is to categorize future experiments into the following areas:

- **a.** ***Carbonation-based CDMs:*** Studies should examine how carbonation interacts with chloride, sulfate, ASR, and FTC across various sequences (pre-, co-, and post-exposure). Recommended parameters include CO_2 concentrations of 0.03–3%, chloride levels of 3–15%, and tracking of carbonation depth, ASR expansion, sulfate reaction kinetics, and corrosion indicators.
- **b.** ***Chloride-based CDMs:*** Investigations should address how chloride accelerates degradation when combined with sulfate, ASR, or FTC. Chloride may be applied via ponding, fogging, or spraying. Simulated FTC cycles (e.g., −5°C to 23°C) should be included to mimic environmental cracking, with long-term electrochemical monitoring.
- **c.** ***Multi-factorial CDMs:*** Advanced scenarios—such as ASR + Cl^- + FTC or SO_4^{2-} + CO_2 + FTC—should be employed to replicate aggressive marine or urban exposures. Suggested performance indicators include crack development, ionic transport, and corrosion kinetics (e.g., i_corr, Rct).

These future methodologies should be rooted in the setup parameters documented in earlier experimental studies (as outlined in Table 4), ensuring consistency and relevance. Developing such protocols will enable more accurate durability modeling, material performance evaluation, and ultimately, the design of RC structures capable of withstanding the synergistic effects of multiple degradation mechanisms.

Table 4. Variabilities in the corrosion test setup considering physical properties and exposure conditions

Varied set-up parameters and scenarios encountered in literature (bottom row)				
1. Specimen shape (cube, cylinder, prism)	2. Rebar diameter	3. Rebar length	4. Rebar surface (ribbed, unribbed)	5. Exposure condition (partially or fully immersed, and ponding well)
				

CONCLUSION

This review underscores the need to transition from single degradation mechanism (SDM) assessments to combined degradation mechanism (CDM) frameworks, as CDMs cause substantially greater damage. Corrosion current density (i_corr) increases by 1.5–3× under CDMs, and up to 15× in chloride–sulfate cases. Charge transfer resistance (Rct) may drop by 10×, signaling rapid passive film breakdown.

Sequential effects, like carbonation before chloride exposure, can lower pH and raise corrosion rates by ~70%. Freeze-thaw cycles also intensify sulfate-driven damage by 2–3×. Existing test protocols often overlook these interactions, underestimating real-world deterioration.

To address this, region-specific, multi-agent testing strategies must be developed. Durability models should reflect actual exposure sequences, especially for critical infrastructure in marine, nuclear, and industrial settings. Enhanced materials—such as high-performance concrete, nano-coatings, and corrosion inhibitors—must be explored to mitigate CDM effects. This work supports the development of standardized, CDM-focused methods for more accurate durability prediction and resilient concrete design.

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