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The Use of Urea as a Corrosion Inhibitor in Concrete: A Review

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Abstract

Corrosion of reinforcing steel in concrete structures remains a significant challenge, leading to premature deterioration and high repair costs. This review examines the application of urea as a potential corrosion inhibitor in reinforced concrete, drawing from experimental studies on simulated concrete pore solutions and actual concrete mixes. Urea, an organic compound commonly used as a fertilizer, has shown promise in mitigating chloride-induced corrosion through the formation of protective films on steel surfaces. Key findings indicate inhibition efficiencies up to 86% in simulated environments, though results in real concrete are mixed, with some studies reporting reduced penetrability but limited corrosion protection and potential adverse effects on concrete durability, such as decalcification and strength reduction. Mechanisms, effectiveness, limitations, and influences on concrete properties are discussed, highlighting the need for optimized concentrations and further long-term studies.

Keywords: corrosion, concrete, inhibitor

Introduction

Corrosion of reinforcing steel is widely recognized as the primary cause of premature deterioration in reinforced concrete structures, leading to enormous economic losses, safety risks, and environmental impacts worldwide. In chloride-contaminated environments (e.g., marine structures, de-icing salt exposure, or contaminated aggregates), the breakdown of the passive oxide layer on embedded steel triggers active corrosion, resulting in expansive rust products that induce cracking, spalling, and loss of structural integrity. The global cost of corrosion in civil infrastructure is estimated to exceed hundreds of billions of dollars annually, with a significant portion attributable to reinforced concrete degradation.

Traditional approaches to mitigate rebar corrosion include the use of high-quality concrete, increased cover thickness, epoxy-coated or galvanized reinforcement, cathodic protection, and the addition of conventional corrosion-inhibiting admixtures such as calcium nitrite, sodium mono fluoro phosphate, or amine-based organic inhibitors. Although effective in many cases, these solutions often suffer from drawbacks: high cost, potential toxicity and environmental concerns (especially nitrite-based inhibitors), leaching over time, or limited long-term performance in severe exposure conditions.

In this context, urea ($CO(NH_2)_2$), a low-cost, non-toxic, and readily available organic compound traditionally used as a nitrogen fertilizer and in the chemical industry, has emerged as a promising alternative corrosion inhibitor for steel in concrete. Early studies dating back to the 1990s and 2000s initially explored urea for its ability to reduce chloride-induced corrosion through mechanisms such as chloride binding, pH buffering, formation of protective films, or competitive adsorption on the steel surface. More recent research (2015–2025) has revisited and expanded these findings using advanced electrochemical techniques, surface analytics (XPS, FTIR, SEM-EDS), and long-term exposure tests, demonstrating that urea can achieve inhibition efficiencies comparable to or, in some cases, superior to commercial inhibitors, particularly when used at optimum dosages of 1–4 % by weight of cement.

Despite these encouraging results, the exact inhibition mechanisms of urea remain a subject of debate, with proposed pathways including urea hydrolysis to form ammonium and carbonate ions, direct adsorption via carbonyl and amine groups, and the promotion of stable iron–urea complexes or calcium carbonate precipitation in the pore solution. Moreover, questions persist regarding dosage optimization, potential side effects on cement hydration and mechanical properties, long-term durability, and performance in different concrete mixtures and exposure conditions.

This review paper critically examines the state-of-the-art research on the application of urea as a corrosion inhibitor in reinforced concrete. It consolidates findings on inhibition efficiency and mechanisms, evaluates effects on fresh and hardened concrete properties, compares performance against established inhibitors, identifies knowledge gaps, and discusses practical feasibility and future research directions. By providing a comprehensive assessment, this work aims to clarify whether urea can transition from a promising laboratory candidate to a viable, sustainable, and cost-effective solution for extending the service life of reinforced concrete infrastructure in aggressive environments.

Literature Review

Early studies focused on urea's performance in SCP solutions mimicking the alkaline, chloride-contaminated environment within concrete pores (pH ~13.5). In one investigation, urea at concentrations of 0.2%, 0.5%, and 1% was added to a SCP solution (2% KOH + 3% NaCl). Open circuit potential (OCP) measurements over 28 days showed a shift toward more positive values, indicating passivation, while potentiodynamic polarization revealed reduced corrosion current densities and rates. Similar results were reported in other works, confirming urea's ability to inhibit corrosion in saline media.

Transitioning to actual concrete, experiments on M20-grade normal weight concrete admixed with urea at 3%, 5%, and 7% by cement weight demonstrated varied outcomes. Compressive strength tests at 7, 28, and 91 days showed initial reductions (up to 27.8% at 28 days for 5% urea), though design strengths were achieved long-term. Sorption tests indicated decreased water absorption and sorptivity, suggesting reduced penetrability due to urea crystallization in pores. However, half-cell potential measurements on steel-embedded specimens cured in sodium chloride solution revealed severe to high corrosion risk, implying limited inhibitory effectiveness in real-world chloride exposure.

Broader studies on corrosion inhibitors have included urea among options like zinc oxide and sodium nitrate, but specific data on urea was limited or absent in some reviews. Recent syntheses of urea-based oligomeric inhibitors (e.g., polymethylene bis-urea and bis-thiourea) optimized conditions for enhanced inhibition, though not directly applied to concrete. In durability assessments, urea did not induce steel corrosion or concrete damage in non-chloride-exposed structures, but offered no mitigation in pre-exposed ones.

Mechanisms of Action

Urea functions as a mixed-type inhibitor, predominantly anodic, by adsorbing onto steel surfaces and forming a protective Fe^{2+}–urea complex that reinforces the natural passive layer (γ-Fe_3O_4) in alkaline environments. The nitrogen and oxygen atoms facilitate electron transfer, creating a barrier against chloride ions and oxygen. In SCP solutions, this leads to positive shifts in corrosion potential and reduced Tafel slopes, indicating control over both anodic dissolution and cathodic hydrogen evolution. However, excess urea may dissolve the film, reducing efficiency at higher concentrations. In concrete, urea's crystallization may block pores, indirectly aiding inhibition by limiting ingress of corrosive agents, though this does not fully prevent corrosion in aggressive environments.

Effectiveness and Limitations

Urea's inhibition efficiency peaks at around 0.5% in SCP solutions, achieving up to 86.15% after 7 days immersion, with corrosion rates dropping to 0.0324 mmpy. Efficiencies range from 63.8% to 86.15% across concentrations, outperforming controls in simulated settings. In concrete, however, effectiveness is inconsistent; while it reduces sorptivity by up to 100% at higher doses, corrosion risks remain high in chloride-cured specimens. Limitations include concentration dependency—efficiencies drop at 1% (72.6%)—and potential inefficacy in pre-chlorinated concrete. Environmental factors like pH and chloride levels influence performance, and long-term data is sparse.

Influence on Concrete Properties

Effects on Fresh Concrete Properties

The incorporation of urea as a corrosion inhibitor in concrete mixtures has been observed to influence several key properties of fresh concrete, primarily enhancing its handling and placement characteristics while also providing benefits in challenging environmental conditions.

Workability is notably improved with the addition of urea. Studies have shown that urea acts as a plasticizer, increasing the slump values and flowability of concrete mixes. For instance, slump measurements rise progressively with increasing urea concentrations, from approximately 80 mm in plain concrete to 110 mm at 10% urea by weight of cement. This enhancement is attributed to urea's ability to reduce inter-particle friction and improve dispersion of cement particles, making the mix more fluid without necessitating additional water.

Setting time is another property affected by urea, typically resulting in prolongation. Initial and final setting times can extend significantly; for example, at 30 kg/m³ urea dosage, initial setting time increases to 155 minutes and final to 185 minutes compared to control mixes, while higher dosages (60 kg/m³) can delay initial setting to nearly 9 hours. This retardation is linked to urea's inhibitory effect on early cement hydration, which slows the formation of hydration products like calcium silicate hydrate (C-S-H).

Urea also reduces the heat of hydration and lowers the temperature of concrete during the casting stage and throughout the hydration process, which can be advantageous in mass concrete pours to mitigate thermal cracking. In cold weather conditions, urea serves as an effective antifreeze admixture, depressing the freezing point of mixing water and protecting fresh concrete from freezing damage up to -10°C without requiring additional insulation measures. This property is particularly beneficial for winter concreting, allowing placement and initial curing in sub-zero temperatures.

Overall, these effects on fresh concrete suggest that urea can improve constructability, especially in adverse weather, though careful dosage control is essential to avoid excessive delays in setting that could impact construction schedules.

Effects on Hardened Concrete Properties

In the hardened state, urea as a corrosion inhibitor generally contributes positively to the mechanical and durability performance of concrete, with some variations depending on dosage, environmental conditions, and combination with other admixtures.

Compressive strength is often enhanced by urea addition. Research indicates increases of up to 16% at 28 days for dosages around 7% by weight of cement, with strength values peaking at approximately 57.8 MPa compared to 49.76 MPa in plain concrete. This improvement is attributed to urea's role in accelerating later-stage hydration by increasing the solubility of tricalcium silicate (C_3S) and dicalcium silicate (C_2S), leading to a denser microstructure without introducing reactive ions that might disrupt cement phases. However, in extreme cold conditions (e.g., -15°C to -20°C), early-age strength may be lower initially, though long-term strength (up to 365 days) can recover and even exceed controls, particularly when urea is combined with accelerators like calcium nitrate, yielding up to 82% higher strength. Some studies report minimal impact on overall compressive strength, suggesting that the inhibitory effect on early hydration does not significantly compromise long-term mechanical properties.

Durability aspects are favorably influenced by urea. It does not adversely affect the long-term integrity of reinforced concrete, with no evidence of deleterious effects on reinforcing steel or concrete matrix under standard conditions. Urea enhances resistance to carbonation by elevating the pH of the concrete pore solution (e.g., from 10.625 in plain concrete to 10.90 at 7% urea), maintaining levels above the threshold for passivation of steel and reducing carbonation depth. Additionally, it reduces void volume, limiting the ingress of aggressive agents like chlorides, which supports its role as a corrosion inhibitor. In terms of shrinkage and ultrasonic pulse velocity (UPV), urea influences these properties positively over extended curing periods, contributing to improved structural performance in exterior winter exposures.

It is worth noting that while urea immersion on hardened concrete can lead to decalcification and reduced surface strength due to hydrolysis reactions, this scenario differs from its use as an admixture and is more relevant to external exposure risks rather than internal incorporation. As a corrosion inhibitor, urea's overall impact on hardened properties underscores its potential for enhancing concrete longevity in corrosive environments, though optimal dosages (typically 3-10% by cement weight) should be determined based on specific project requirements to balance benefits with any potential early-age drawbacks.

Beyond inhibition, urea impacts concrete durability. In hydrated cement pastes exposed to 20% urea solutions, it causes decalcification, reducing pH in outer layers (to ~11.97) and forming secondary calcite, leading to a weakened, porous surface layer up to 20 mm thick. This results in microcracks and altered microstructures, with increased leachable calcium and conductivity changes indicating dissolution. Compressive strength initially declines (up to 27.8%), though recovers over time. Urea does not inherently damage air-entrained concrete but may cause scaling if crystallized on surfaces. Overall, while it may enhance impermeability, risks of decalcification and strength loss warrant caution.

Comparison of Urea's Performance as a Corrosion Inhibitor in Concrete against Established Inhibitors

Corrosion inhibitors are widely employed in reinforced concrete to mitigate chloride-induced degradation of steel reinforcement, thereby extending structure lifespan. Established inhibitors, such as calcium nitrite and sodium nitrite, function primarily as anodic inhibitors by promoting the formation of stable passive oxide films on steel surfaces, effectively increasing the chloride threshold level and reducing corrosion rates. For instance, calcium nitrite, a benchmark inhibitor, has been shown to stabilize the passive layer by competing with chloride ions, leading to inhibition efficiencies often exceeding 90% in chloride-contaminated environments, while also acting as a set accelerator without significantly compromising concrete's mechanical properties. Sodium nitrite operates similarly, oxidizing Fe^{2+} to Fe^{3+} to form protective γ-Fe_2O_3 films, with reported efficiencies up to 92% in simulated concrete pore solutions, though its use is increasingly restricted due to toxicity concerns. Amine-based inhibitors, including monoethanolamine (MEA), diethanolamine (DEA), and triethanolamine (TEA), act as mixed-type inhibitors through adsorption, forming hydrophobic films that repel aggressive ions; they exhibit inhibition efficiencies of 70-96% and are effective as migrating inhibitors in existing structures, but may increase porosity at higher dosages. Phosphates and other inorganics, like sodium monofluorophosphate, precipitate protective layers in the presence of oxygen, achieving comparable efficiencies but with potential environmental drawbacks.

In contrast, urea, an amide-based organic compound, has been explored as a potential green or synthetic inhibitor, particularly for its low cost, availability, and non-toxicity. Its mechanism involves adsorption onto the steel surface via polar groups, potentially reacting with calcium hydroxide in the concrete matrix to form calcium carbonate, which refines pore structure and reduces permeability to corrosive agents. While urea is more commonly studied for mild steel in acidic media, where it demonstrates moderate inhibition (improved by substitution with sulfur to form thiourea, yielding higher efficiencies due to enhanced polarizability), its application in alkaline concrete environments is emerging. Recent studies indicate urea can enhance hydration products like ettringite and calcium silicate hydrate (CSH) gel, leading to denser microstructures and antifreeze properties that mitigate freeze-thaw damage.

Direct comparisons of urea with established inhibitors are limited, but a key experimental investigation in M20-grade concrete (with inhibitors at 2% by cement weight) under normal, freeze-thaw, and deicing salt exposures provides valuable insights. Urea outperformed several alternatives in durability under adverse conditions, exhibiting lower chloride permeability and corrosion probabilities. However, it generally shows intermediate performance relative to top nitrites in terms of corrosion inhibition efficiency, with potential trade-offs in long-term stability compared to amines. The table below summarizes key performance metrics from this study, including comparisons with sodium nitrate (a nitrate-based inhibitor akin to nitrites in mechanism) and other tested compounds like zinc oxide and magnesium oxide, which serve as proxies for inorganic alternatives.

Inhibitor	**Compressive Strength Increase (%)**	**Ultrasonic Pulse Velocity (km/s)**	**RCPT (Coulombs, Normal Conditions)**	**Half-Cell Potential (V vs. CSE)**	**Inhibition Efficiency Notes**
Control (No Inhibitor)	0	3.85	4314 (High)	-0.43 (High Corrosion)	Baseline
Urea	48	4.91 (Excellent)	1820 (Low)	-0.30 (Intermediate)	Strong in freeze-thaw; reduces porosity via $CaCO_3$ formation
Sodium Nitrate	~20 (Moderate)	4.52 (Good)	3541 (Moderate)	-0.36 (High)	Lower durability under stress than urea

Calcium Nitrite*	0-10 (Minimal impact)	Not tested	Low (Typically <2000)	Low corrosion risk	Benchmark; higher Cl threshold than urea in literature
Amines (e.g., TEA)*	Variable (0-20)	Good	Moderate to Low	-0.20 to -0.35	Migrating; better long-term migration than urea
Zinc Oxide	Lower than urea	4.12 (Medium)	3908 (Moderate)	-0.37 (High)	Delays hydration; poorer under stress
Magnesium Oxide	55	4.75 (Excellent)	Moderate	-0.32 (Intermediate)	Highest strength but higher permeability under freeze-thaw
Sodium Molybdate	High	4.82 (Excellent)	1722 (Low)	-0.34 (Intermediate)	Excellent normal conditions but degrades under stress

*Data for calcium nitrite and amines derived from literature reviews for contextual comparison; not directly from the same study.

Overall, urea demonstrates promising mechanical enhancements (e.g., 48% strength increase) and durability benefits, particularly in coastal or cold climates, rivaling or surpassing sodium nitrate and oxides in adverse exposures. However, its inhibition efficiency (inferred from potential and permeability reductions) may not consistently match that of calcium nitrite (up to 95% IE) or optimized amines (70-96% IE), which offer superior long-term protection in high-chloride scenarios due to stronger film stability and migration capabilities. Further research is needed to evaluate urea's long-term field performance and synergies with established inhibitors, positioning it as a cost-effective, eco-friendly adjunct in concrete formulations.

Conclusions

Urea shows potential as a cost-effective, eco-friendly corrosion inhibitor in reinforced concrete, particularly in simulated chloride environments where it achieves high efficiencies via protective film formation. However, its performance in actual concrete is less robust, with benefits in reducing penetrability offset by persistent corrosion risks and adverse effects on durability, such as decalcification and initial strength reductions. Optimal concentrations (around 0.5%) are critical, and urea may be more suitable as an admixture in non-aggressive settings or in combination with other inhibitors. Future research should focus on long-term field trials, synergistic formulations, and green derivatives to enhance viability.

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