https://doi.org/10.1051/matecconf/202540914003

Experimental investigation of seashell concrete with anti-corrosion agent enhancement

Ali Abbas [1*], *Khalid* Abdalla[1*], *Gopika Saji*[1]

[1]School of Architecture, Computing and Engineering, University of East London, 4-6 University Way, London E16 2RD, United Kingdom

Abstract. This research investigates the performance of seashell concrete enhanced with anti-corrosion agents, focusing on sustainability and durability. The study evaluates workability, density, compressive strength, modulus of elasticity, and corrosion resistance. Results show that seashell powder improves workability and density but requires adjustments due to higher water absorption and lower specific gravity. The control mix (30% seashell powder) achieved 42 MPa compressive strength and 35 GPa modulus of elasticity. Adding 4% NitCal reduced these values to 38 MPa and 28 GPa, while 8% NitCal further decreased them to 30 MPa and 28 GPa. However, 8% NitCal significantly enhanced corrosion resistance, delaying crack formation from 72 hours to 220 hours and reducing corrosion current. Although anti-corrosion agents slightly increased the carbon footprint, seashell powder improved sustainability by reducing cement dependency. The findings highlight the potential of seashell concrete with anti-corrosion additives for durable, eco-friendly construction. Future research should optimize formulations and assess long-term performance to maximize benefits.

Keywords: Corrosion; Seashell; material properties; carbon negative

1 Introduction

1.1 Overview

In today's construction industry, concrete is a vital material prized for its strength, durability, and versatility. However, the environmental impact of concrete production, particularly the carbon emissions from cement manufacturing, has driven the search for more sustainable alternatives. One emerging approach involves substituting a portion of conventional cement with eco-friendly materials. Seashell as shown in Figure 1, derived from marine waste, offers a promising solution. Its incorporation into concrete not only helps address waste management challenges but may also enhance the material's performance, particularly in improving corrosion resistance, a critical factor in many reinforced construction projects.

Fig. 1. Seashell

Corrosion of reinforced concrete is a significant issue, especially in environments exposed to chloride rich conditions, such as coastal areas. Chloride ions can penetrate the concrete and reach the steel reinforcement, initiating a corrosion process that compromises the structural integrity and shortens the lifespan of the concrete. The use of anti-corrosion agents has been a common strategy to address this problem. These agents work by either forming a protective layer on the steel or modifying the chemical environment within the concrete to reduce the likelihood of corrosion.

Incorporating seashell powder as a partial replacement for cement in concrete presents a dual benefit. Firstly, seashell powder can contribute to sustainability by reducing the amount of traditional cement required, thus lowering the overall carbon footprint of concrete production. Secondly, seashell powder, due to its chemical composition and fine particle size, may enhance the concrete's resistance to corrosion. The calcium carbonate in seashells can help maintain a more alkaline environment within the concrete, which is conducive to protecting the steel reinforcement from corrosion. Additionally, the improved microstructural properties of seashell concrete may further reduce the permeability to corrosive agents.

Incorporating anti-corrosion agents into seashell concrete is significant because they can enhance the natural advantages of seashell powder. While seashell powder alone may improve corrosion resistance by refining the concrete's microstructure and chemical composition, combining it with conventional anti-corrosion agents could amplify these benefits [1]. This

*Corresponding author: K.abdalla@uel.ac.uk

study explores how the synergy between seashell powder and anti-corrosion agents can boost concrete durability.

Examining this interaction is key to designing a concrete mix that not only repurposes waste material but also excels in corrosive conditions. The findings could pave the way for a more sustainable and high-performance concrete solution one that minimizes reliance on excessive anti-corrosion additives while delivering strong protection against degradation.

This paper focuses on examining various properties of concrete mixed with seashell powder. It includes assessing physical attributes such as workability, setting time, and bulk density, as well as chemical properties will be analysed through microstructural studies using techniques like Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD). Mechanical characteristics, including compressive strength, elasticity, and shrinkage, will be tested on hardened concrete samples. These evaluations aim to provide a detailed understanding of how seashell powder affects the performance and quality of the concrete.

1.2 Environmental impact of cement production

Cement manufacturing represents one of the most environmentally damaging industrial processes, primarily because of its massive CO_2 emissions. Accounting for about 4.5% of global CO_2 output, the cement industry's climate impact is substantial. The 377 million metric tons of CO_2 released in 2007 (NRMCA, 2008) [36] comes principally from two sources: the calcination process (50% of emissions) and fossil fuel combustion in kilns (40%) [2]. With each ton of cement generating nearly 900 kg of CO_2 [27], the sector's contribution to climate change and ozone depletion has become untenable. This environmental crisis has accelerated research into sustainable alternatives, driving innovation in low-carbon cement substitutes and energy-efficient production techniques [3]. The construction industry now faces urgent pressure to adopt these greener solutions and fundamentally transform one of its most polluting processes.

In response to the significant environmental impact of traditional Portland cement production, particularly its contribution to global CO_2 emissions, researchers and industry stakeholders are increasingly exploring alternative cementitious materials. These alternatives are designed to either partially or fully replace conventional cement, aiming to reduce carbon footprints while maintaining or enhancing the mechanical and durability performance of concrete [4].

Such sustainable substitutes, often derived from industrial by-products or natural pozzolans, enable the construction sector to adopt low-carbon solutions, supporting efforts to decarbonize infrastructure development [5]. This shift not only addresses environmental concerns but also aligns with global goals for sustainable construction and climate resilience.

1.3 Seashell Waste as a Sustainable Additive for Eco-Friendly Concrete

Seashells, especially those from marine bivalves like flat scallops (family Pectinidae), are primarily composed of calcium carbonate, making up about 95% of their weight. The remaining 5% consists of organic materials and trace minerals that help maintain the shell's structural integrity [6,31]. These seashells are commonly recognized for their distinctive, flat, and fan-shaped appearance. Their high calcium carbonate content is particularly advantageous for concrete production, as calcium carbonate can engage in the pozzolanic reaction, which may improve the mechanical properties of the concrete [7].

Annually, the seafood industry generates approximately 45,000 tons of seashell waste, with a high concentration in coastal regions where seafood processing facilities are predominantly located [8]. This substantial volume of waste presents significant disposal challenges and environmental concerns, emphasizing the need for effective management and potential recycling solutions. Improper disposal of these shells can cause environmental issues, including soil contamination and visual pollution. Traditional disposal methods like landfilling are not sustainable, highlighting the need for innovative solutions to manage this waste [28,29]

Incorporating seashell waste into concrete provides a valuable dual benefit: it helps manage excess seashells and reduces the environmental impact of cement production. By using seashells as a substitute for conventional aggregates or as a supplementary material in concrete, it is possible to lessen the reliance on natural resources and cut down on CO_2 emissions from cement production [30].

Incorporating seashells into concrete mixtures represents an innovative method to improve the material's durability and resistance to corrosion, especially in marine environments. This portion examines the recent research papers to elucidate the effects of seashells on concrete properties, with a focus on their impact on corrosion resistance and overall structural performance.

While seashells ground into fine powder have potential as a supplementary cementitious material (SCM), their use in concrete is currently limited due to the absence of established regulatory standards. Research indicates that seashell powder can enhance the microstructure of concrete, leading to improved durability and resistance to chloride penetration [25].

[21] Investigated the incorporation of seashell powder into polymer composites, highlighting its improved moisture resistance attributed to its natural adaptation to marine environments. This inherent moisture resistance results in improved wear and corrosion performance of the composites. Their research highlights that seashell powder, known for its durability and seawater resistance, contributes to a more robust and defect-free composite. The enhanced properties are attributed to the seashells' ability to reinforce both the physical and mechanical attributes of the composite material.

Similarly, [8] investigated the effects of substituting cement with seashells on the durability and mechanical properties of concrete. Their study reveals that seashell powder chemically interacts with the concrete mix to produce calcite ($CaCO_3$) and increase the levels of portlandite (CH). This chemical reaction enhances the concrete's alkalinity, which in turn helps to preserve the protective oxide layer on steel reinforcement, thereby improving its resistance to corrosion. The increased alkalinity counteracts acidic conditions that could otherwise undermine the reinforcement's protective layer.

[12] provided a comprehensive review of the mechanical and durability characteristics of concrete incorporating seashells, with a particular focus on carbonation depth and environmental stresses. Their review found that the carbonation depth in seashell-containing concrete is not significantly affected by the ratio of seashell aggregate used; however, carbonation depth tends to increase with exposure time. They also noted the need for further research to assess the effects of seawater and fire on concrete containing seashells, as these factors could accelerate degradation processes such as alkali-aggregate reactions and corrosion.

In a focused study, [20] examined the corrosion performance of steel rebar in cement blended with snail shell ash (SSA). Their findings indicated that SSA, when used as a partial replacement for cement, markedly improves corrosion resistance. Specifically, corrosion rates were reduced by up to 1.408 times at a 20% replacement level compared to control samples. The study also found that replacement levels of 20% to 30% SSA enhance both the strength and durability of concrete. However, at higher replacement levels, the effectiveness of SSA decreases as chloride ions penetrate and diffuse through the iron hydroxide layer on the steel, leading to increased corrosion rates.

1.4 Corrosion in Reinforced Concrete

Steel reinforcement corrosion is a major factor contributing to the deterioration of reinforced concrete (RC) structures, compromising their structural integrity and longevity. Understanding corrosion mechanisms and applying effective monitoring techniques is essential to enhance the durability of RC structures. This review summarizes the main causes of corrosion in reinforced concrete and discusses the electrochemical methods used to monitor and assess corrosion rates.

The corrosion of steel reinforcement within concrete structures is a major concern, impacting their durability and lifespan. Despite significant research advancements, corrosion remains a persistent issue, often leading to severe structural deterioration. This review critically explores the primary mechanisms driving corrosion in reinforced concrete, with a focus on carbonation, chloride ion infiltration, and the impact of cracking in the concrete. The interactions among these factors highlight the complex nature of corrosion and emphasize the challenges in effectively mitigating its effects.

Concrete's alkaline environment, typically characterized by a pH greater than 12.6, is crucial for protecting steel reinforcement against corrosion. This high pH environment promotes the formation of a passive oxide layer on the steel surface, which serves as a barrier against corrosive elements. However, this protective mechanism is not foolproof. Assuming that the alkaline environment will indefinitely preserve the passive layer overlooks the dynamic interactions between the concrete, environmental factors, and the steel reinforcement. While the passive layer is widely acknowledged as a key protective feature, its effectiveness can be compromised by several factors, raising concerns about the long-term reliability of relying solely on the concrete's alkalinity for corrosion protection.

One of the most significant threats to the passive layer's integrity is carbonation. Carbonation occurs when carbon dioxide (CO_2) from the atmosphere penetrates the concrete and reacts with calcium hydroxide to form calcium carbonate, leading to a reduction in the concrete's pH [21]. This pH reduction can break down the passive layer, exposing the steel to corrosion. Although carbonation is a natural process that occurs over time, its impact on reinforced concrete structures is far from benign. The variability in carbonation rates, which are influenced by factors such as concrete porosity, permeability, and environmental conditions, complicates the prediction of corrosion onset, making maintenance and repair efforts more challenging. Moreover, while carbonation is often highlighted as a primary corrosion mechanism, there is a need for a more comprehensive understanding of how it interacts with other degradation processes in various environmental contexts.

Chloride ions pose another significant risk to steel reinforcement in concrete, particularly in structures exposed to marine environments or de-icing salts. Chloride-induced corrosion is particularly concerning because it can occur even in environments where the pH remains high, thereby bypassing the protective effect of the concrete's alkalinity. The traditional view that chloride ions disrupt the passive layer, leading to localized pitting corrosion, is supported by substantial evidence [9]. However, this perspective may oversimplify the complex electrochemical processes involved in chloride-induced corrosion. For example, the interaction between chloride ions and other aggressive agents, such as sulphates or nitrates, can exacerbate the corrosion process, yet these interactions are often underexplored in standard corrosion models. Furthermore, current standards for acceptable chloride levels in concrete may need re-evaluation, as new research suggests that even low concentrations of chlorides can initiate corrosion under certain conditions [13].

Cracking in concrete is another critical factor that significantly influences corrosion. Cracks can develop due to various reasons, including mechanical loading, thermal stress, shrinkage, and poor construction practices. These cracks provide direct pathways for the ingress of moisture, oxygen, CO_2, and chloride ions, thereby accelerating the corrosion process. The role of cracking in corrosion is well-established, yet it is often treated as a secondary concern in corrosion studies [21].

This oversight is problematic because the severity of corrosion is closely linked to the presence and extent of cracking. The traditional approach of viewing cracks merely as a physical defect that requires repair fails to acknowledge the proactive role that crack prevention and management could play in mitigating corrosion. Additionally, there is growing evidence that micro-cracks, which may not be visible to the naked eye, can also contribute significantly to corrosion [21]. This raises important questions about the adequacy of current inspection and monitoring practices, which often focus only on visible cracks.

In conclusion, the mechanisms of corrosion in reinforced concrete are complex and interrelated, making it a challenging phenomenon to predict and control. The reliance on the alkaline environment of concrete for corrosion protection, while effective to some extent, is undermined by factors such as carbonation, chloride ingress, and cracking. Each of these factors presents unique challenges that must be addressed through a combination of improved materials, better design practices, and more rigorous maintenance regimes. While the existing literature provides a solid foundation for understanding these mechanisms, there is a clear need for more integrated approaches that consider the interactions between different corrosion processes. As new materials and construction techniques are developed, it is crucial to revisit and potentially revise existing standards and guidelines to reflect the complexities of corrosion in modern reinforced concrete structures.

Electrochemical methods are vital for evaluating corrosion in RC structures. The half-cell potential technique is widely used to measure the potential difference between steel reinforcement and a reference electrode, identifying areas at high corrosion risk. This method is non-destructive and reliable, making it a key tool in routine inspections [21]. Other techniques like linear polarization resistance (LPR) and electrochemical impedance spectroscopy (EIS) provide detailed insights into corrosion rates by analyzing the current response to an applied potential. These methods are crucial for assessing the effectiveness of corrosion prevention measures and estimating the remaining service life of RC structures [9]. Standard tests like ASTM B117 [37] are commonly used to evaluate the corrosion resistance of materials in a saline environment, offering a controlled and standardized approach. Though primarily used for metals, it can be adapted for assessing protective coatings and inhibitors in RC structures. Additionally, continuous development in monitoring techniques is essential for improving the accuracy and reliability of corrosion assessments [24]. The Impressed Voltage Test is a widely used laboratory method for accelerating corrosion in steel reinforcement. By applying a constant voltage to steel bars in a concrete specimen immersed in saline solution, researchers can simulate corrosion and evaluate material performance under controlled conditions. [33] demonstrated that this method effectively measures corrosion rates, providing valuable data for research and material testing.

The impressed voltage technique is a widely used method for accelerating corrosion in reinforced concrete, offering notable advantages such as time efficiency and cost-effectiveness [16]. This technique applies a constant voltage to steel bars embedded in concrete, simulating corrosion conditions that typically occur over extended periods. [9,10] have highlighted that while this method accelerates corrosion processes, it also imposes an artificial polarization on the steel, which may not accurately reflect natural corrosion behaviour.

[11] further observed discrepancies between corrosion patterns induced by impressed voltage and those seen in naturally corroded bars, suggesting that the impressed current technique might not fully replicate real-world conditions. Despite these limitations, the impressed voltage technique remains a valuable tool due to its speed in generating corrosion data.

Recent studies have examined the efficiency of this method compared to slower techniques, such as macro-cell corrosion and exposure tests. The impressed voltage technique has been shown to provide corrosion results comparable to those obtained from longer, more complex methods [25]. This advantage is attributed to the straightforward setup and the ability to rapidly initiate corrosion, making it a practical choice for assessing the effectiveness of corrosion protection measures, particularly in evaluating different blended cements.

A regression power equation proposed in recent research aims to predict changes in chloride-induced corrosion protection based on concrete's durability characteristics, such as chloride ion penetrability and water permeability. This empirical approach facilitates the evaluation of how different cements affect corrosion resistance [25]. However, further validation is necessary to confirm the repeatability and reliability of these findings across various cement blends and environmental conditions.

Accurate post-test procedures are essential for assessing the corrosion of steel reinforcement embedded in concrete. [9] highlights the importance of carefully removing the steel reinforcement from the concrete once testing is complete. This step must be conducted with precision to avoid damaging the steel, which is crucial for ensuring the accuracy of the subsequent measurements. After removal, the steel needs to be thoroughly cleaned to eliminate any corrosion byproducts, scale, or other residues that might have formed during the test. Depending on the degree of corrosion, this can be achieved using abrasive brushing or chemical cleaning methods [9]. Proper cleaning is vital for obtaining an accurate weight loss measurement, which is critical for determining the corrosion rate. Once the cleaning is finished, the steel reinforcement is re-weighed to obtain the final weight. The corrosion rate is calculated by subtracting this final weight from the initial weight to determine the weight loss. This weight loss is then used to calculate the corrosion rate according to Faraday's law of electrolysis. Faraday's law provides a standardized approach for converting weight loss into a corrosion rate, reflecting the degree of corrosion over time [9]. These post-test procedures are integral to obtaining reliable data on corrosion, allowing for an effective evaluation of corrosion mitigation measures.

Implementing these methods ensures that the corrosion assessments are accurate and reflective of actual conditions affecting reinforced concrete structures.

Research has demonstrated that calcium nitrate improves both the mechanical and durability properties of concrete. Specifically, [19] observed enhanced compressive and bond strength, reduced water absorption, and increased pH levels, which collectively help mitigate reinforcement corrosion, although optimal dosages were not defined.

[21] quantified this effect, reporting that a 4% dosage (by cement weight) of calcium nitrate reduced carbonation penetration by approximately 30%. However, its efficacy declines once corrosion initiates, suggesting limitations in long-term corrosion control.

[12] found that calcium nitrate does not compromise compressive strength, yet it is less effective than calcium nitrite in delaying corrosion, aligning with [13], who showed that increasing calcium nitrite dosage significantly reduced corrosion rates in chloride-rich environments.

NitCal International's NitCal, a commercial calcium nitrate product, has been used since the 1990s and functions as both a setting accelerator and corrosion inhibitor. It is praised for environmental safety, cost-effectiveness, and ease of use (Concrete Corrosion Inhibitor, 2022).

The effective dosage range for corrosion inhibition generally lies between 3–5%, balancing corrosion protection and mechanical performance [9]. While higher dosages (5–10%) further improve resistance, they may negatively influence workability and other physical characteristics of concrete.

For practical applications, evaluating both 4% and 8% dosages allows engineers to optimize performance and cost, with 4% offering a cost-effective balance and 8% providing enhanced durability under more aggressive environmental conditions.

In summary, while the impressed voltage technique presents clear benefits in terms of speed and cost, its artificial nature and potential discrepancies with natural corrosion highlight the need for continued refinement and validation to ensure accurate assessment of corrosion protection in concrete.

2 Experimental study

An extensive programme of testing is currently underway to evaluate the effect of using seashell powder as a partial replacement for cement on carbon emissions and the performance of corrosion inhibitors in concrete samples subjected to accelerated corrosion conditions .

2.1 Materials used

The cement selected for the project is Hanson Portland Cement CEM I 52.5N. Seashells were collected from a seafood industry and provided by the University of East London. The shells varied in size from 15 mm to 60 mm.. It was selected as a replacement material for 30% of the cement content in the concrete mix. The preparation of seashell ash powder involved several meticulous steps to ensure its suitability for concrete production.

The seashells were thoroughly washed and soaked in water to remove any attached sand, debris, and residues. This cleaning process was crucial for eliminating contaminants and ensuring the purity of the seashells. The cleaned seashells were then dried in an oven at 100 degrees Celsius for 24 hours. This drying process made the shells more brittle, facilitating easier crushing. Following drying, the seashells were subjected to crushing in an Los Angeles Abrasion testing machine for approximately 5 hours at a speed of 45 rpm. This process transformed the shells into a fine powder. The resultant powder was then sieved through a 63-micron sieve to achieve the desired particle size. This step was essential to match the particle size of the seashell powder with that of standard cement which ensuring its effective integration into the concrete mix. Travis Perkins sharp sand was used as the fine aggregate. This type of sand, also known as coarse or gritty sand, has a particle size ranging from 0 to 4 millimetres. For the coarse aggregate, 10-20mm uncrushed natural gravel was selected.

2.2 Anti-corrosion inhibitor

In the mid-1990s, NitCal introduced NitCal, a refined specialty nitrate formulated as a concrete setting accelerator with the added benefit of mitigating reinforcement corrosion (Yara, 2023). By reducing the rate of steel corrosion within concrete, NitCal contributes to enhanced structural strength, thereby promoting long-term durability of buildings, infrastructure, and civil engineering works. This improvement in durability translates to lower life-cycle costs by minimizing the need for repairs and reconstruction. Functioning as a concrete corrosion inhibitor, NitCal is specifically engineered to prevent or slow down the onset of corrosion in steel-reinforced concrete. It is available in both granular and liquid formulations, and can be introduced into the concrete mix either before or during mixing, depending on the desired modifications to the material's performance.

The anti-corrosion inhibitor used in this research is NitCal, a widely recognized form of calcium nitrate commonly used in concrete to prevent corrosion by sealing reinforcing steel bars against corrosion. By increasing the concrete's alkalinity (Calcium nitrate promotes early hydration, which generates more portlandite ($Ca(OH)_2$) and thus raises pH locally), NitCal promotes the formation of a protective passivation layer around steel reinforcement, effectively preventing corrosion. The advantages of calcium nitrate are well-documented, with studies showing that it significantly reduces corrosion rates, thereby extending the lifespan of concrete structures [12]. In this study, NitCal will be tested at two concentrations (4% and 8%) to assess its effectiveness in mitigating corrosion while maintaining the mechanical integrity of the concrete. These concentrations are based on empirical research and theoretical principles, ensuring an optimal balance between efficiency and feasibility. This investigation aims to evaluate the influence of NitCal concentrations on concrete's corrosion resistance, helping to determine the most effective dosage for enhancing structural durability.

2.3 Testing Programme

In this study, the mix design was formulated using the Building Research Establishment (BRE) method. The BRE 1992 method provides a detailed framework for determining the ideal proportions of each ingredient in the concrete mix. By utilizing these guidelines, the study aims to produce a concrete mix that meets specific performance standards, ensuring that the resulting product is both effective and durable for its intended purpose.

The mix constituents for this research are shown in Table 1.

Table 1. Mix design

Sample		**M40 Mix Design**	**Con-trol mix 30 % Seashell**	**Con-trol +B**	**C + 4% Y**	**C + 8% Y**	**C +B + 4% Y**	**C +B + 8% Y**
Cement, Kg/m^3		350	245	245	245	245	245	245
Fine Aggregate Kg/m^3		510	510	510	510	510	510	510
Coarse Aggregate, kg/m^3	10mm	465	465	465	465	465	465	465
	20mm	925	925	925	925	925	925	925
Water ,kg/m^3		160	160	160	160	160	160	160
Seashell, Kg/m^3		0	105	105	105	105	105	105
NitCal (Yara), kg/m^3		0	0	0	9.80	19.60	9.80	19.60
Self-healing agent,Kg (Basilisk)/m^3		0	0	7.35	0	0	7.35	7.35

3 Results and discussion

This study presents a comprehensive analysis of the strength characteristics of the tested materials, focusing on compressive strength and corrosion resistance. The results of the experimental investigations are systematically examined and discussed to evaluate their implications for material performance and durability. The findings contribute to a better understanding of the structural integrity and long-term behaviour of the materials under varying environmental conditions.

3.1 Compressive strength test

The compressive strength tests were carried out to evaluate the structural strength of concrete mixtures including a 30% seashell cement replacement, with and without Self-healing agent and various proportions of NitCal.

Many samples were prepared, with several specimens for each variation and the average value was then considered. The compressive strength test was carried out according to (BS EN 12390-3:2019+A1:2022) [27] for both cylindrical and cube samples (200mm × 100 mm and 100 mm × 100 mm × 100 mm respectively). The strength of samples was measured at 28 days. The results showed compressive strength outcomes for the concrete mixes highlight the impact of incorporating Self-healing agent and varying levels of NitCal on the structural integrity of the concrete, as compared to the control mix. The control mix, which includes a 30% replacement of cement with seashells, achieved a compressive strength of 42 MPa, establishing a reference point for comparison. When Self-healing agent was added alone, the compressive strength dropped to 39 MPa, reflecting a 8 % reduction from the control mix. This decrease suggests that while Self-healing agent may improve properties such as durability or self-healing, it slightly diminishes the concrete's compressive strength.

In the mix with Self-healing agent and 4% NitCal, the compressive strength further declined to 38 MPa, marking a 11% reduction from the control. This outcome indicates that although NitCal as a plasticizer enhances workability, its combination with Self-healing agent does not improve compressive strength and may even contribute to a slight additional decrease.

The mix with Self-healing agent and 8% NitCal exhibited a more substantial reduction in compressive strength, falling to 30 MPa, a 29% decrease from the control mix. This significant drop suggests that higher NitCal concentrations, when combined with Self-healing agent, may considerably weaken the compressive strength, potentially due to over-plasticization or reduced cohesion in the mix.

In summary, the compressive strength results reveal that while Self-healing agent and NitCal additives influence workability and other properties, they generally reduce the compressive strength of the concrete, with higher NitCal percentages leading to more significant reductions.

3.2 Modulus of Elasticity

The modulus of elasticity, representing the maximum stress concrete can withstand, offers key insights into its stiffness and structural integrity, which are critical for assessing its behaviour under load. The data reveal how the inclusion of Self-healing agent and varying proportions of NitCal influence this property. A control mix, where 30% of cement is replaced with seashells, serves as the benchmark, exhibiting a maximum stress of 35 MPa. The mix containing only Self-healing agent records a reduced maximum stress of 32 MPa, marking an 8% decline compared to the control. This suggests that Self-healing agent alone diminishes the concrete's stiffness and load-bearing capability. Introducing 4% NitCal alongside Self-healing agent leads to a further drop in maximum stress to 28 MPa, equating to a 21% reduction from the control. Although NitCal may improve workability, its interaction with Self-healing agentSelf-healing agent appears to compromise the concrete's stiffness and resistance to stress.

In the mixture with Self-healing agent and 8% NitCal, the maximum stress declines to 28 MPa, reflecting a 19% decrease from the control (Figure 2). This notable reduction indicates a considerable loss in stiffness, likely caused by excessive plasticization and weakened cohesion resulting from the higher NitCal content.

Overall, the results demonstrate that while the combination of Self-healing agent and NitCal enhances workability, it concurrently leads to a reduction in the modulus of elasticity, with more significant reductions observed at higher NitCal concentrations.

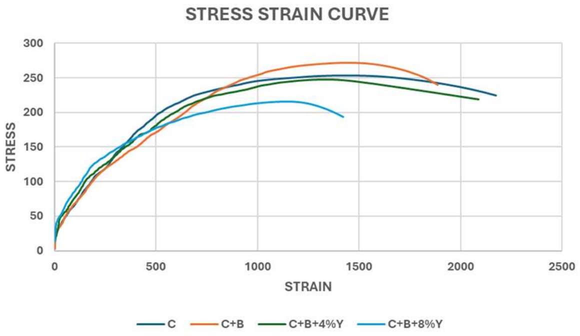


Fig. 2. Stress-Strain curves.

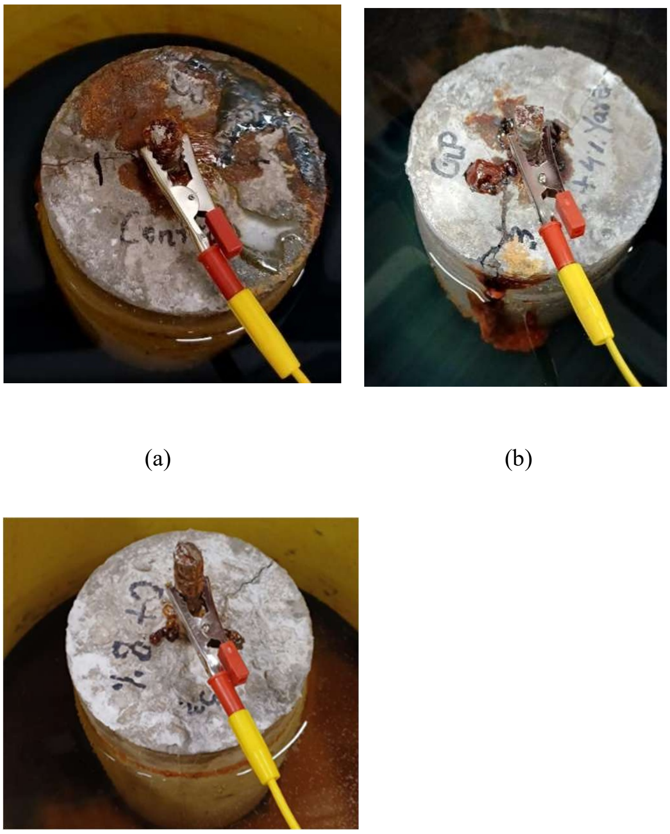
3.3 Corrosion Tests

In this paper, the impressed voltage technique test was used to investigate corrosion resistance of concrete. The test was carried out to initiate quick corrosion on steel bars embedded in concrete cylindrical samples. A 6 Volt DC power supply was connected to steel bars as an anode and the negative terminal was connected to the steel plate electrode as a cathode.

The current readings for all test conditions Control, Control+4% NitCal, and Control+8% NitCal demonstrate a general increase as time progresses. This trend indicates that the system becomes more conductive or that the electrochemical processes become more active over time, likely due to ongoing corrosion or other chemical reactions. Specifically, the Control sample exhibits a significant increase in current, rising from 36.8 mA at 0 hours to 86.2 mA at 366.75 hours. This suggests that the Control sample experiences higher corrosion rates or lower resistance compared to the treated samples as shown in Figure 3. In contrast, the current values for Control+4% NitCal and Control+8% NitCal are lower over the same period. The 4% NitCal treatment reduces the current moderately, indicating some effectiveness in reducing corrosion or enhancing resistance. The 8% NitCal treatment shows the lowest current values, suggesting it is the most effective at mitigating corrosion and increasing resistance among the conditions tested.

Crack formation times provide additional insights into the durability of the materials. Cracking occurs earliest in the Control mix at 72.25 hours, which indicates a lower resistance to cracking and possibly greater susceptibility to degradation. For the Control+4% NitCal treatment, cracks appear at 213.6 hours, reflecting an improved resistance to cracking. The Control+8% NitCal treatment shows the latest crack formation at 220 hours, suggesting superior durability compared to both the Control mix and the 4% NitCal treatment. These observations indicate that increasing the concentration of NitCal enhances material performance by delaying both the increase in current and the onset of cracking.

The test results reveal that the control mix shows the highest increase in current and the earliest crack formation, indicating lower resistance to corrosion and cracking. In comparison, the 4% NitCal treatment offers moderate improvements in both aspects, while the 8% NitCal treatment provides the best performance, demonstrating the highest resistance to corrosion and cracking. For applications where enhanced durability and resistance to cracking are essential, higher concentrations of NitCal, particularly 8%, are recommended. This treatment significantly improves material longevity and reliability compared to the untreated Control mix.



(a) (b)

(c)

Fig. 3. (a) Crack on Control mix (b) Crack on Control+ 4% NitCal sample (c) Crack on Control+ 8% NitCal sample.

4 Conclusion

The experimental research investigations described in the present article were aimed at examining the performance of the seashell concrete mixed with various anti-corrosion agents. The behaviour was investigated by performing compressive strength, modulus of elasticity and corrosion resistance.

This study demonstrates a clear trade-off between mechanical strength and durability enhancements when incorporating Self-healing agent and NitCal additives into concrete with 30% seashell powder replacement. While the control mix exhibited the highest compressive strength (42 MPa) and modulus of elasticity (35 GPa), the inclusion of Self-healing agent and increasing concentrations of NitCal led to marked reductions in both parameters—up to 29% in strength and 21% in stiffness. These decreases are likely due to matrix modifications and interactions between the additives that impair load transfer and bond integrity within the concrete.

Conversely, corrosion resistance and crack propagation performance significantly improved with NitCal inclusion. The control mix showed early crack initiation (72.25 hours) and high corrosion activity (86.2 A at 366.75 hours). However, mixes containing 4% and 8% NitCal delayed crack formation to over 213 hours and reduced corrosion current, indicating enhanced resistance to electrochemical degradation. Notably, the 8% NitCal dosage provided the most substantial protection, suggesting its potential for applications where durability under aggressive environments is paramount.

Overall, the findings indicate that while Self-healing agent and NitCal additives may compromise mechanical performance, particularly at higher dosages, they offer considerable improvements in corrosion resistance and crack durability. This suggests their suitability in environments where long-term durability and resistance to degradation are prioritized over compressive strength, reinforcing the need for application-specific optimization of concrete formulations.

Journal Articles

1. Söylev, T.A., & Richardson, M.G. (2008). Corrosion inhibitors for steel in concrete: State-of-the-art report. *Construction and Building Materials, 22*(4), 609–622. https://doi.org/10.1016/j.conbuildmat.2006.10.013
2. Van Oss, H.G., & Padovani, A.C. (2002). Cement manufacture and the environment: part I: chemistry and technology. *Journal of Industrial Ecology, 6*(1), 89–105.
3. Gartner, E. (2004). Industrially interesting approaches to “low-CO₂” cements. *Cement and Concrete Research, 34*, 1489–1498. https://doi.org/10.1016/j.cemconres.2004.01.021
4. Ashraf, W. (2016). Carbonation of cement-based materials: Challenges and opportunities. *Construction and Building Materials, 120*, 558–570.
5. Imbabi, M.S., Carrigan, C., & McKenna, S. (2012). Trends and developments in green cement and concrete technology. *International Journal of Sustainable Built Environment, 1*, 194–216. https://doi.org/10.1016/j.ijsbe.2013.05.001
6. Dutton, J., Smith, S., & Kelly, R. (2019). Calcium carbonate and its applications in construction materials. *Journal of Sustainable Building Materials, 11*, 87–102.
7. Shi, J., et al. (2020). Evolution of mechanical properties and permeability of concrete during steam curing process. *Journal of Building Engineering, 32*, 101796.
8. Tayeh, B.A., et al. (2020). Durability and mechanical properties of seashell partially-replaced cement. *Journal of Building Engineering, 31*, 101328. https://doi.org/10.1016/j.jobe.2020.101328
9. Ahmad, S. (2003). Reinforcement corrosion in concrete structures, its monitoring and service life prediction – a review. *Cement and Concrete Composites, 25*, 459–471. https://doi.org/10.1016/s0958-9465(02)00086-0
10. Austin, Simon A., Richard Lyons, and M. J. Ing. "Electrochemical behavior of steel-reinforced concrete during accelerated corrosion testing." Corrosion 60.2 (2004): 203-212.
11. Yuan, S. J., and S. O. Pehkonen. "Surface characterization and corrosion behavior of 70/30 Cu–Ni alloy in pristine and sulfide-containing simulated seawater." Corrosion Science 49.3 (2007): 1276-1304.
12. Al-Amoudi, O.S., et al. (2003). Effectiveness of corrosion inhibitors in contaminated concrete. *Cement and Concrete Composites, 25*, 439–449. https://doi.org/10.1016/s0958-9465(02)00084-7
13. Ann, K., et al. (2006). Effect of calcium nitrite-based corrosion inhibitor in preventing corrosion of embedded steel in concrete. *Cement and Concrete Research, 36*, 530–535. https://doi.org/10.1016/j.cemconres.2005.09.003
14. Bamigboye, G., et al. (2021). Mechanical and durability assessment of concrete containing seashells: A review. *Cogent Engineering, 8*, 1883830. https://doi.org/10.1080/23311916.2021.1883830
15. Bolzoni, F., Brenna, A., & Ormellese, M. (2022). Recent advances in the use of inhibitors to prevent chloride-induced corrosion in reinforced concrete. *Cement and Concrete Research, 154*, 106719. https://doi.org/10.1016/j.cemconres.2022.106719
16. Guendouz, M., et al. (2023). Valorization of coffee waste as bio-aggregates in crushed sand concrete production. *Environmental Engineering and Management Journal, 22*,

147–156. https://doi.org/10.30638/eemj.2023.013

17. Guendouz, L., et al. (2023). Use of seashell waste in construction: A review. *Journal of Environmental Management, 333*, 116553. https://doi.org/10.1016/j.jenvman.2023.116553
18. Güneyisi, E., Özturan, T., & Gesoğlu, M.A. (2005). Study on reinforcement corrosion and related properties of plain and blended cement concretes under different curing conditions. *Cement and Concrete Composites, 27*, 449–461.
19. Kumar, M.P., Mini, K., & Rangarajan, M. (2018). Ultrafine GGBS and calcium nitrate as concrete admixtures for improved mechanical properties and corrosion resistance. *Construction and Building Materials, 182*, 249–257. https://doi.org/10.1016/j.conbuildmat.2018.06.096
20. Mian, M.A., Zhang, J., & Dong, Z. (2013). CO_2 emission reduction in the cement industry: A review of techniques and strategies. *Journal of Cleaner Production, 51*, 126–134. https://doi.org/10.1016/j.jclepro.2012.10.023
21. Ormellese, M., Bolzoni, F., & Brenna, A. (2022). Effect of a nitrate-based corrosion inhibitor on carbonation-induced corrosion. *Corrosion*, Article 4160. https://doi.org/10.5006/4160
22. Raghav, M., et al. (2021). Assessment of corrosion performance of steel rebar in snail shell ash blended cements under marine environments. *Materials, 14*, 7286. https://doi.org/10.3390/ma14237286
23. Rodrigues, Alisson Mendes, et al. "Development of eco-friendly mortars produced with kaolin processing waste: durability behavior viewpoint." Sustainability 13.20 (2021): 11395.
24. Sakthi Balan, G., et al. (2020). Investigation on water absorption and wear characteristics of waste plastics and seashell powder reinforced polymer composite. *Journal of Tribology*, –, 57–70.
25. Sharkawi, A.M., & Seyam, A.M. (2019). Efficiency of accelerated techniques for assessing corrosion protection of blended cements. *Magazine of Concrete Research, 71*, 637–646. https://doi.org/10.1680/jmacr.17.00269
26. Song, H.W., & Saraswathy, V. (2007). Corrosion Monitoring of Reinforced Concrete Structures – A Review. *International Journal of Electrochemical Science, 2*, 1–28. https://doi.org/10.1016/s1452-3981(23)17049-0
27. Etuk, B.R., Etuk, I.F., & Asuquo, L.O. (2012). Feasibility of using sea shells ash as admixtures for concrete. *Journal of Environmental Science and Engineering, A1*, 121–127.
28. Lertwattanaruk, P., Makul, N., & Siripattarapravat, C. (2012). Utilization of ground seashells in cement mortars for masonry and plastering. *Cement and Concrete Composites, 34*, 893–903.
29. Abinaya, S., & Venkatesh, S.P. (2016). An effect on oyster shell powder's mechanical properties in self-compacting concrete. *International Journal of Innovative Research in Science, Engineering and Technology, 5*, Article 0506296. https://doi.org/10.15680/IJIRSET.2016.0506296

Books / Book Chapters

27. Mahasenan, N., Smith, S., & Humphreys, K. (2003). The cement industry and global climate change: Current and potential future cement industry CO_2 emissions. In: *Greenhouse Gas Control Technologies* (pp. 995–1000). Elsevier. https://doi.org/10.1016/B978-008044276-1/50157-4
28. JeyaSundar, P.G.S.A., et al. (2020). Waste treatment approaches for environmental sustainability. In: *Elsevier eBooks* (pp. 119–135). https://doi.org/10.1016/b978-0-12-819001-2.00006-1

Conference Proceedings

29. JeyaSundar, D., Sundaravadivelu, R., & Ramachandran, K. (2020). Exploring seashell waste for sustainable construction. *Materials Today: Proceedings, 27*, 1234–1241. https://doi.org/10.1016/j.matpr.2020.02.564
30. Olivia, M., & Oktaviani, R. (2017). Properties of concrete containing ground waste cockle and clam seashells. *Procedia Engineering, 171*, 658–663.
31. Dutton, A., Webster, J.M., & Zwartz, D. (2019). The impact of sea-level rise on coral reefs: A global synthesis. *Geological Society, London, Special Publications, 498*, 205–234.
32. Mohammad, W.A.S.B.W., et al. (2017). A review on seashells ash as partial cement replacement. *IOP Conference Series: Materials Science and Engineering, 271*, 012059. https://doi.org/10.1088/1757-899X/271/1/012059
33. Satish, V.L., & Ravindra, V. (2021). Evaluation of corrosion resistance of corrosion inhibitors in concrete structures by Impressed voltage test. *IOP Conference*

Series: Materials Science and Engineering, 1025, 012002. https://doi.org/10.1088/1757-899X/1025/1/012002

Web Resources

34. Circular Ecology. (n.d.). *Embodied carbon footprint database.* https://www.circularecology.com/embodied-carbon-footprint-database.html
35. Yara International. (2022). *Concrete Corrosion Inhibitor.* https://www.yara.com/industrial-nitrogen/concrete-additives/concrete-corrosion-inhibitor/.
36. NRMCA, Concrete CO_2 Fact Sheet, National Ready Mixed Concrete Association, Silver Spring, MD, 2008. [Online]. Available: https://www.nrmca.org/wp-content/uploads/2020/10/ConcreteCO2FactSheet07.pdf.

Standards

37. ASTM B 117-03, "Standard Practice for Operating Salt Spray (Fog) Apparatus" (West Conshohocken, PA: ASTM).