MICROBIAL AND CO_2-REACTIVE CEMENT CHEMISTRY SYNERGY FOR AUTONOMOUS CRACK HEALING AND CARBON SEQUESTRATION IN SUBSURFACE WELLS

Tashdeed Rifa Raisa*[1], Nowrin Afrin[2] and Afsana Khanom Monika[3]

[1] *Student,* Military Institute of Science and Technology,Dhaka, Bangladesh*, e-mail:* tashdeedrifaraisa@gmail.com
[2] *Student,* Military Institute of Science and Technology,Dhaka, Bangladesh*, e-mail:* nowrinafrin29@gmail.com
[3] *Student,* Military Institute of Science and Technology,Dhaka, Bangladesh*, e-mail:*afsanakhanommonika13@gmail.com

*** Corresponding Author**

ABSTRACT

The preservation of long-term well integrity remains a critical challenge in petroleum production and CO_2 storage operations, particularly where cement is exposed to corrosive CO_2 environments and mechanical stress. Conventional oilwell cement lacks self-healing capability and is prone to chemical degradation, reducing its effectiveness in maintaining zonal isolation and increasing the risk of gas migration or leakage. Studies have shown that up to 30% of well failures can be attributed to cement sheath deterioration under such conditions. This study presents a dual-healing cement system engineered to address both mechanical crack formation and chemical CO_2 attack through an integrated material design. The system combines microbially induced calcium carbonate precipitation (MICP) using dormant bacterial spores activated upon water ingress with CO_2-reactive cement chemistry, enabling autonomous crack sealing and simultaneous mineralization of intruding CO_2. By combining biological self-healing mechanisms with CO_2-reactive cement chemistry, this dual-healing system represents a transformative advancement toward sustainable well integrity management in harsh CO_2-rich environments. The proposed formulation also incorporates supplementary cementitious materials such as fly ash to enhance durability and reduce the carbon footprint of cement production. The concept is evaluated for its applicability in CO_2-prone gas fields and injection wells, with a focus on field conditions. The dual-healing approach aims to extend the service life of cement sheaths by at least 50%, reduce intervention frequency, and support the transition toward CO_2-resilient, sustainable well construction materials.

Keywords: *Self-healing cement, CO_2 mineralization, MICP, well integrity, CO_2-prone reservoirs*

1. INTRODUCTION

The integrity of wellbores represents a cornerstone in the safe, efficient, and long-term operation of both hydrocarbon production and geological carbon dioxide (CO_2) storage initiatives. The cement sheath responsible for zonal isolation, structural support, and sealing between formations and the casing is exposed to a complex interplay of mechanical loading, thermal cycling, and aggressive chemical environments in CO_2-rich subsurface settings. Quantifying the scale of cement-related well-integrity failures under CO_2 operations is challenging due to heterogeneous reporting, but several surveys indicate this is a non-negligible contributor to sustained casing pressure (SCP) and leakage pathways. One review reported that more than 50 % of wells older than 15 years exhibited at least one casing string with SCP, and in a Gulf of Mexico survey, roughly one-third of SCP cases were attributed to a cement sheath issue (Yousuf et al., 2021).

Studies emphasised that degradation of the cement sheath is among the principal leak-tightness concerns in geological CO_2 storage. When CO_2 dissolves in formation water, it forms carbonic acid, which can lower pH, attack calcium-silicate-hydrate (C-S-H) phases, and cause portlandite ($Ca(OH)_2$) to dissolve. This weakens the cement matrix and increases porosity (Eissa et al., 2025). Studies have demonstrated that under conditions typical of CO_2 storage (elevated pressure, temperature, and brine salinity), the outer layers of class H cement can suffer significant deterioration through such mechanisms (Eissa et al., 2025).Mechanical stresses such as cyclic loading from injection/production operations and thermal or pressure changes compound this chemical degradation by promoting micro-crack formation and debonding at the casing–cement or cement–formation interfaces(Ibukun et al., 2024)

This work presents a dual-healing cement system for autonomous crack repair and carbon sequestration in subsurface wells that combines CO_2-reactive cement chemistry with microbially induced calcium carbonate precipitation (MICP) in a unique way. This design allows for the simultaneous sealing of biological cracks and the mineralization of CO_2, in contrast to earlier methods that deal with mechanical or chemical degradation independently. The system is designed for well environments with high temperatures and CO_2 concentrations, where traditional cements are unable to self-heal. The formulation reduces maintenance interventions, turns CO_2 from a corrosive agent into a stabilizing mineral phase, and improves long-term well integrity by combining dormant bacterial spores with CO_2-reactive additives like fly ash and MgO.

2. LITERATURE REVIEW

Conventional oil-well cements (Class G, Class H, Portland cement) are widely used for well-bore sealing and casing support. However, when exposed to CO_2-rich environments (such as injection wells or CO_2-storage wells), they are subject to chemical and mechanical degradation. For example, exposure to supercritical CO_2 or CO_2-saturated brine at elevated temperature/pressure leads to carbonation, matrix alteration, and permeability increase. (Kutchko et al., 2007). A review specifically on well cement degradation under CO_2 storage conditions emphasises that downhole conditions (temperature, pressure, fluid chemistry) significantly influence failure mechanisms (Mammadov et al., 2025).

Therefore, self-healing, sustainable cementitious systems that can repair integrity in situ, seal cracks and defects on their own, and assist in achieving carbon-sequestration or carbon-reduction goals are desperately needed. Carbonation, in which CO_2 (or CO_2-saturated water) diffuses into cement pore structure and reacts with portlandite ($Ca(OH)_2$) and C-S-H phases to form $CaCO_3$, $Ca(HCO_3)_2$, etc., is one of the main chemical degradation mechanisms. Although the matrix may initially become denser, this eventually causes alkalinity to leach, microcracking, and strength loss. (Mammadov et al., 2025). (b) Leaching: Acidic or carbonated brines may leach calcium, destabilise hydration products, and increase porosity/permeability (Yousuf et al., 2021). (c) Corrosive attack: In wells containing CO_2, H_2S, brines, or acids, the cement sheath may suffer chemical attack (corrosion) of its matrix or the cement-casing/formation interface (Gu et al., 2020).

These mechanisms often act synergistically. For example, mechanical loading or micro-cracking can accelerate CO_2 ingress and thus chemical attack. To extend service life and reduce intervention needs, self-healing cementitious systems have been developed. These include Autogenous healing (limited crack widths, inherent in cement hydration), Engineered chemical healing, where added admixtures (e.g., crystalline admixtures, sodium silicate, calcium nitrate, expansive phases) react when water or

crack ingress occurs (Osibodu et al., 2025) and Biological self-healing, which is the incorporation of microbial spores or bacteria that precipitate calcium carbonate upon activation.

In cementitious materials, MICP has shown promise as an autonomous crack sealing technique. When water intrusion occurs, dormant bacterial spores (like Bacillus species) or other microorganisms embedded in the cement matrix come alive and precipitate calcium carbonate ($CaCO_3$) to fill voids and cracks (Osibodu et al., 2025)Crack closure rates of up to ~97% for cracks smaller than 100 μm were reported with MICP treatment in a recent study using low-clinker LC3 cement (Wei et al., 2024). Despite the concept's potential, there are still issues with nutrient and microbial viability, encapsulation techniques, long-term durability, and scaling up to harsh subsurface conditions (high temperature, pressure, and CO_2 presence) (Yip et al., 2022).

Beyond self-healing, there is growing interest in cementitious systems that actively react with CO_2 (or other reactive species) to mineralise it and/or improve durability. Accelerated carbonation techniques, for instance, allow CO_2 to mineralize into $CaCO_3$ and $MgCO_3$ in cement-based materials, lowering net carbon emissions and possibly improving material qualities (FERNANDEZBERTOS et al., 2004). The CO_2 mineralization route is also being explored for well cements: e.g., pozzolan-amended Class H cement exposed to CO_2-saturated brine displayed significant carbonation penetration but remained low in permeability (Kutchko et al., 2009). However, such approaches are still emergent in downhole well environments, and field validation is limited.

Prior studies have attempted combinations of these technologies (e.g., self-healing + supplementary cementitious materials, or CO_2-resistant cements). A study on fly-ash/blended cement with pozzolan in CO_2-saturated brine showed that although carbonation penetrated 170–180 mm after 30 years equivalent exposure, permeability remained low, and the system performed reasonably (Kutchko et al., 2009). Reviews on cement degradation emphasise that while modifications (e.g., polymer-modified cements, additives) can reduce the rate of degradation, full autogenous healing or CO_2-mineralisation functionalities are rarely achieved (Mammadov et al., 2025). Self-healing concrete research (mostly in the infrastructure context) has provided crack-closing results but has not yet translated to the downhole high-pressure/high-temperature/CO_2-rich environment typical of wells (Osibodu et al., 2025). Therefore, while individual components (self-healing, CO_2-reactive chemistry, SCMs) have been explored, their integration into a single cement system specifically engineered for subsurface CO_2-rich well environments remains a significant research gap.

3. CONCEPTUAL FRAMEWORK OF DUAL-HEALING CEMENT

3.1 Design Philosophy

The proposed dual-healing cement system is founded on the principle of autonomous, internal repair and CO_2-sequestration within a downhole cement sheath exposed to a CO_2-rich environment. In essence, the material is engineered to respond to two distinct triggers: ingress of water or formation fluid, which activates a microbial self-healing process, and ingress or diffusion of CO_2, which initiates a chemical mineralisation response as demonstrated in Figure 1. By combining these two healing pathways, the system aims to seal cracks, restore mechanical integrity, and consume/immobilise CO_2 intruding into the cement sheath zone.

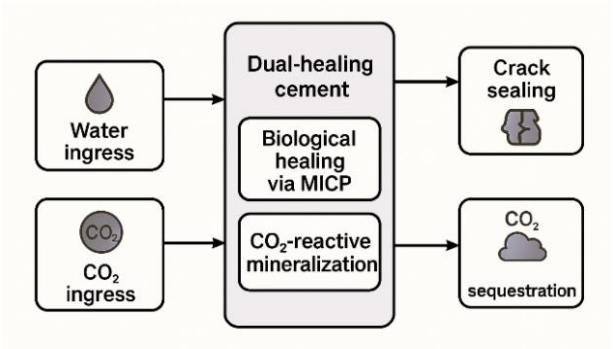

Figure 1: Conceptual framework of the proposed dual-healing cement system

3.2 Dual Mechanisms

(a) Biological healing via MICP (Microbially Induced Calcium Carbonate Precipitation): Dormant bacterial spores (from Sporosarcina pasteurii or Bacillus pseudofirmus) are embedded in the cement matrix in encapsulated form, as demonstrated in Figure 2. On crack or micro-void formation and subsequent water ingress, the spores germinate, metabolise supplied nutrients (e.g., urea) and produce urease, driving precipitation of calcium carbonate ($CaCO_3$) that occludes the defect. Studies show improved crack-sealing and strength recovery in concrete systems using MICP.

$$CO(NH_2)_2+3H_2O \rightarrow^{(urease)} 2NH_4^+ + HCO_3^- + OH^- \quad (1)$$

$$Ca_2^+ + HCO_3^- + OH^- \rightarrow CaCO_3(s) + H_2O \quad (2)$$

This sequence of reactions ultimately precipitates $CaCO_3$ in voids or cracks, increasing sealing and reducing permeability (De Muynck et al., 2010).

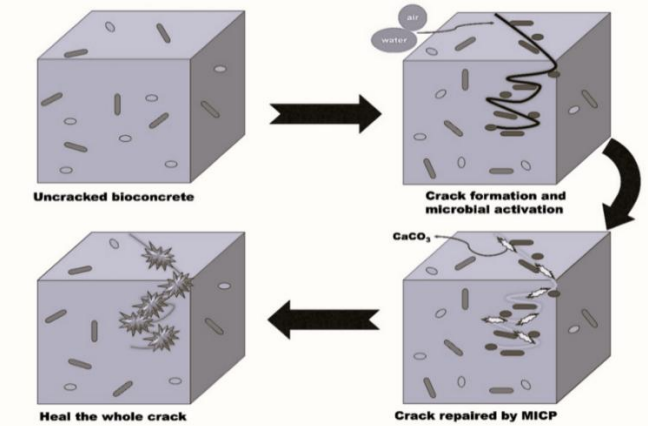

Figure 2: Schematic diagram of crack healing by MICP(Ojha et al., 2025)

(b) Chemical self-mineralisation of CO_2 via reactive cement chemistry: Parallel to the microbial route, the cement formulation incorporates reactive mineral phases (e.g., MgO, wollastonite, silica fume, fly ash) and designs the matrix so that CO_2 ingress (as supercritical, gaseous or dissolved CO_2) reacts with $Ca(OH)_2$ and silicate phases to form stable carbonate or calcium–silicate–carbonate phases.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (3)$$

In this reaction, CO_2 is chemically fixed as solid calcium carbonate ($CaCO_3$) within the cement matrix. Through the reduction of pore connectivity, the sealing of microcracks, and the permanent capture and storage of CO_2 in a mineral form, this process enhances the mechanical integrity and durability of the cement sheath.

$$2CaO \cdot SiO_2 + CO_2 + H_2O \rightarrow CaCO_3 + SiO_2 \cdot H_2O \ (C–S–H, carbonate\text{-}silicate\ phase) \quad (4)$$

Calcium silicate phases (e.g., C_2S) react with CO_2 and water, producing $CaCO_3$ and hydrated silica that densify the matrix.

$$MgO + CO_2 \rightarrow MgCO_3 \quad (5)$$

Reactive MgO additives capture CO_2 to form magnesite, enhancing chemical stability and long-term sealing. These reactions collectively describe how CO_2 intrusion triggers self-mineralization, resulting in the formation of $CaCO_3$ and $MgCO_3$ crystals that heal cracks and reduce permeability within the cement sheath.

4. MATERIALS AND FORMULATION DESIGN

The study adopts a conceptual and literature-based methodology to propose and theoritically assess a dual-healing cement system for C02-rich subsurface wells. No laboratory experiments, numerical simulations, or field validation were performed. Instead, the formulation design, healing mechanisms, and expected performance are derived from established chemical reactions, microbial self-healing theory, and correlations reported in prior experimental studies on MICP, CO_2–cement interactions, and well integrity degradation under downhole conditions (De Muynck et al., 2010; Kutchko et al., 2007; Yousuf et al., 2021)

Table 1: Proposed materials and composition ranges

Component	Typical % mass	Role in dual-healing system	Remarks
API Class G cement clinker	60–70 %	Primary binding phase	Standard well-cement base
Fly ash (Class F)	20–30 %	SCM for durability + lower CO_2 footprint	Bangladesh's local sourcing potential
Silica fume	5–10 %	Pozzolanic, refine pore structure	Enhances matrix tightness
MgO / Wollastonite	5–10 %	CO_2-reactive mineralization	Adjust based on availability
Encapsulated bacterial spores + nutrients	0.5–2 %	Enable MICP crack healing	Includes carrier and nutrient pouch

The proposed composition ranges are designed to remain compatible with standard API well cementing practices and can be adjusted based on downhole temperature, pressure, and CO_2 concentration.

4.1 Base Cement Composition

Group G API Portland cement is recommended as the base material for the dual-healing system because it is the industry standard for oilwell applications due to its high compressive strength, temperature-pressure stability, and compatibility with any downhole additives. Group G Portland cement contains the phases of tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF) that provide the hydration reactions leading to both early strength gain and long-term structural stability of class G cement (Erik B. Nelson & Dominique Guillot, 2006).

This form of cement is preferred because it can tolerate high temperatures and pressures, up to 150 °C and 20–30 MPa, which is generally typical for subsurface wells. Once again, it provides sufficient amounts of $Ca(OH)_2$ and C–S–H phases after hydration, serving as reactive sites for CO_2 mineralization and microbial $CaCO_3$ precipitation in the proposed dual-healing framework (Carey et al., 2007). It also offers broad compatibility with supplementary cementitious materials (SCMs) such as fly ash, silica fume, or magnesium oxide to enhance durability and reduce carbon footprint, which will be used in future formulations. The hydrated matrix of Class G cement provides mechanical integrity while allowing the controlled pore structure needed for healing reactions — making it an ideal platform for later microbial and CO_2-reactive modifications.

4.2 Bacterial Spore Selection

Selection of a robust, spore-forming ureolytic bacterium is critical to the microbial self-healing mechanism within the cement matrix. The organism must exhibit high urease activity with a short lag phase to promote rapid $CaCO_3$ precipitation, survive the highly alkaline and low-moisture conditions of hydrated cement, remain dormant as spores until fluid ingress, and tolerate downhole temperature and salinity extremes. Among candidate microorganisms, Sporosarcina pasteurii demonstrates exceptionally high urease activity and biocalcification potential, with urease comprising approximately 1% of its cell dry weight, enabling efficient $CaCO_3$ precipitation, as illustrated in Figure 3.(Wu et al.,

2021). A second candidate, Bacillus pseudofirmus (an alkaliphilic spore-forming Bacillus species), has been demonstrated to survive in highly alkaline environments, produce spores effectively, and exhibit crack-filling via biomineralisation in engineering contexts (Sharma et al., 2017).

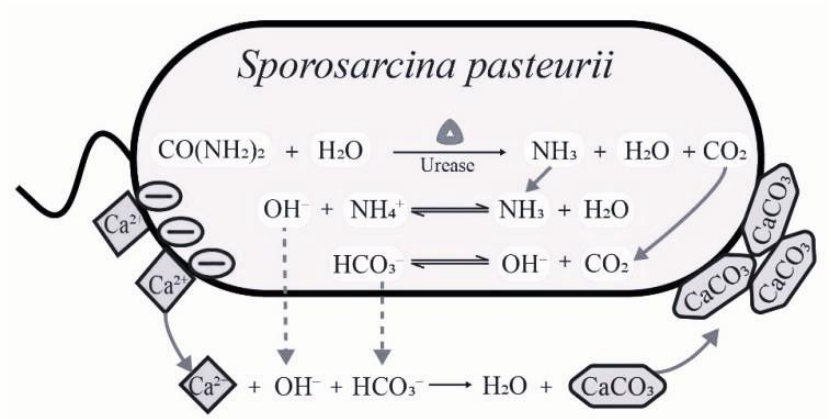

Figure 3: Mechanism of microbially induced calcium carbonate precipitation (MICP) facilitated by *Sporosarcina pasteurii* bacteria.(Wu et al., 2021)

Encapsulation strategies are recommended to protect spores during the cement hydration process and control their activation upon water ingress. Typical carriers include silica-gel microcapsules, expanded perlite, or other inert porous microspheres, which can isolate the spores and nutrient pack until triggered by moisture. A co-embedded nutrient assembly (e.g., urea and a calcium source) supports germination and urease production when the crack allows fluid ingress.

4.3 CO_2-Reactive Additives

To enhance the CO_2 capture and mineralisation capacity of the cement formulation, CO_2-reactive mineral phases are incorporated. Reactive MgO (magnesia) reacts with CO_2 to form stable magnesium carbonates ($MgCO_3$ or hydromagnesite), enabling long-term carbon sequestration while improving strength through pore structure refinement. Wollastonite ($CaSiO_3$) supplies Ca^{2+} and silicate ions that carbonate to form $CaCO_3$ and amorphous silica gel, promoting crack sealing and matrix densification. Additionally, silica fume and Class F fly ash function as supplementary cementitious materials (SCMs) that refine pore structure, reduce permeability, enhance long-term pozzolanic reactivity, and support secondary carbonation. The synergistic interaction of SCMs and CO_2-reactive minerals improves mechanical durability and chemical resistance while enabling the cement to act as an active carbon-mineralising material, supporting both well integrity and subsurface carbon sequestration objectives.

4.4 Encapsulation & Activation Strategy

The standard surface mixing method of producing oilfield primary cementing can be accomplished by combining mud-encapsulated microbial carriers with CO_2 reactive additives through the conventional method of dry-blending with the Class G type of cement in advance of slurry forming. For encapsulation, there are several material choices, such as silica gel and lightweight porous microspheres, which can withstand shear conditions during transit to the surface during pumping and also prevent microbial activation before hydration. The dosages of additives used for blending of cement fall within the same range as those used for the modified and lightweight well cements, allowing for compatibility with conventional placement methods. It is essential to delay activation until a microcrack forms, allowing the entry of oilfield formation water or brine, which enables a controlled release of nutrients and facilitates microbial germination, ultimately leading to the MICP process. In addition, CO_2 diffusing into the reactive mineral phases at that time will allow for the simultaneous mineralisation of reactive minerals.

5. MECHANISMS OF HEALING

5.1 Microbial Healing Cycle

The microbial self-healing process operates through a closed recursive cycle that is activated whenever any cracking takes place in the cement sheath. The complete microbial healing cycle, including crack formation, activation, mineral precipitation, and return to dormancy, is summarized in Figure 4. The cycle begins with crack formation, which is caused by mechanical loading, shrinkage, or thermal stress. Once a crack forms, water or brine enters and dissolves the encapsulated nutrient carriers within the cement matrix. The combination of moisture creates a favorable microenvironment that allows spores from bacteria encapsulated in the cement matrix to begin germination, including the liquorophilic spore/stress-forming bacterium Sporosarcina pasteurii, which has a very high urease activity (1% of cell dry weight) in addition to the spore-forming bacterium, Bacillus pseudofirmus, which grows and thrives in high-pH cement conditions.

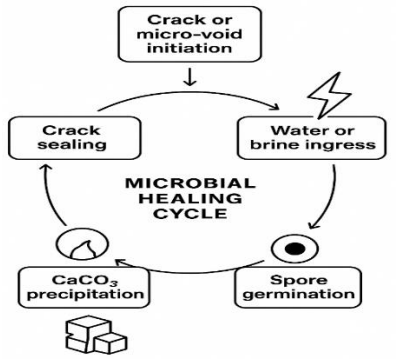

Figure 4: Microbial healing cycle

Following activation, the bacteria enter the metabolic phase, during which urease catalyzes the hydrolysis of urea into ammonium (NH_4^+), bicarbonate (HCO_3^-), and hydroxide (OH^-) ions. The produced bicarbonate reacts with calcium ions (Ca^{2+}) available from cement hydration products or additives to induce calcium carbonate ($CaCO_3$) precipitation. The biomineralisation phase will lead to gradual deposition of calcite in the crack network, bonding the crack faces together and restoring continuity in the matrix. Over time, during the sealing cracks process, permeability decreases, fluid movement is curbed, and conditions in the microenvironment become increasingly stable, allowing the system to restore itself to a state of dormancy until the next crack forms and the cycle continues. This sustained cycle of self-activation and healing through the continuous microbial activity contributes to the long-term durability and functionality of the cement sheath under subsurface conditions.

5.2 CO_2-Reactive Mineralisation Cycle

The CO_2-reactive mineralisation process operates through a cyclic sequence of physicochemical reactions initiated when gaseous or dissolved CO_2 penetrates the cement sheath via microcracks and capillary pores. Upon entering the cement matrix, CO_2 dissolves into pore water to form carbonic acid (H_2CO_3), a weak acid that partially dissociates to produce bicarbonate (HCO_3^-) and hydrogen (H^+) ions. The bicarbonate ions and hydrogen ions are reactive and will interact with the calcium-bearing phases, such as portlandite [$Ca(OH)_2$] and calcium silicate hydrates (C–S–H), to produce calcium carbonate ($CaCO_3$) and a secondary silica gel ($SiO_2 \cdot H_2O$). The precipitation of calcium carbonate ($CaCO_3$) fills in microcracks and voids, progressively reducing porosity and increasing matrix densification, which inhibits further CO_2 diffusion and creates a self-limiting carbonation front. This cycle continues whenever new pathways are available for CO_2 ingress, creating a dynamic mechanism for sealing and densifying the cementitious matrix.

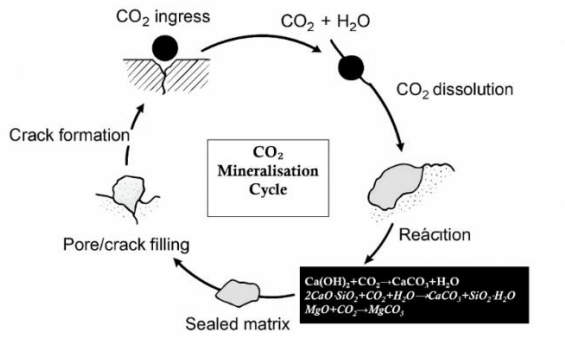

Figure 5: CO_2-Reactive Mineralisation Cycle

In order to foster this natural mineralization process, additions of reactive minerals into the cement mix design can be used. Reactive magnesium oxide (MgO), for example, acts as a CO2-binding phase that reacts with CO2 in aqueous solution to form stable magnesium carbonates (e.g., magnesite (MgCO3) and hydromagnesite [Mg5(CO3)4(OH)2·4H2O]), contributing to long-term carbon sequestration and microstructural refinement. Consequently, wollastonite (CaSiO3) delivers a further source of Ca2+ and silicate ions, which react with CO2 to yield CaCO3 and amorphous silica gel to further help seal cracks and retain strength. In addition, supplementary cementitious materials (SCMs) like silica fume and Class F fly ash also supplement the above reactions, facilitating pore-structure refinement and sustaining secondary pozzolanic and carbonation reactions. The combined synergy of these reactive minerals and SCMs transforms the cement into an active carbon-mineralising matrix that not only self-seals through repeated carbonation cycles but also contributes to permanent CO_2 immobilisation within the wellbore environment.

6. RESULT AND DISCUSSION

6.1 Synergy Between Both Processes

The results discussed in this section are based on conceptual modeling, mechanistic reasoning, and correlations reported in the literature rather than new experimental measurements. The dual-healing cement system discussed combines biological self-healing with a chemically reactive CO_2 mineralization process in a single autonomous process (Figure 6). In the bio-mechanism, the microbial composition (e.g., Sporosarcina pasteurii) is activated as water enters the microcracks, then promotes hydrolysis of the urea and localized precipitation of $CaCO_3$ (calcite) to seal cracks and reduce permeability. In addition to promoting a return to physical integrity, this first mechanism reduces the potential for further gas ingress of CO_2 through the seal. In a second step, the CO_2 mineralization mechanism is established where diffused CO_2 reacts with the cement hydration products ($Ca(OH)_2$ and C–S–H) and any other in-service reactive minerals (e.g., MgO and fly ash), resulting in stable carbonate minerals (e.g., $CaCO_3$ and $MgCO_3$) formation that makes the microstructure more stable and further traps the CO_2.

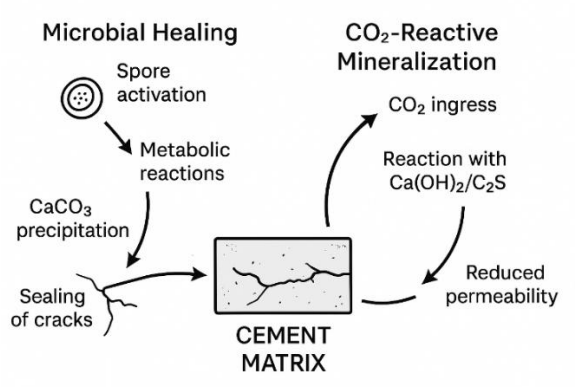

Figure 6: Conceptual illustration of the synergistic interaction between microbial healing and CO_2-reactive mineralisation

The synergy created by the two mechanisms establishes a self-triggered dual-healing cycle where biological sealing and chemical mineralization occur in series and are complementary. The result is longer-term durability while diminishing microchannel formation, while sustaining the integrity of the wells under cycling thermal and pressure stresses associated with the CO_2 gas system

6.2 Permeability Reduction and Crack Closure Correlation

In the absence of new laboratory or simulation data, the expected healing performance of the proposed dual-healing cement system is estimated through established correlation models and first-order mechanistic reasoning. The permeability response of the cement matrix after healing can be approximated using a power-law correlation between the effective permeability (k), the baseline unhealed permeability (k_0), and the crack closure fraction (χ)(Rahal & Sellier, 2019)

$$k=k_0(1-\chi)^n \quad (6)$$

where n is a microstructural sensitivity factor, typically ranging from 2 to 3 for cementitious materials. For a representative unhealed permeability of 10^{-15} m² and an average healing fraction of $\chi = 0.9$ (i.e., 90 % crack closure), the healed permeability is calculated as $k_{healed} \approx 10^{-15} \times (1 - 0.9)^3 = 10^{-18}$ m². This result indicates a reduction of nearly two orders of magnitude compared with conventional cement, demonstrating the significant sealing potential of the dual-healing system. To further validate this trend, a Kozeny–Carman-type relationship was considered to assess the influence of porosity reduction due to microbial $CaCO_3$ deposition (Costa, 2006)

$$k \propto \frac{\phi^3 r^2}{(1-\phi)^2} \quad (7)$$

where ϕ is porosity and r is the effective pore radius, assumed to scale geometrically as $r \propto \phi^{1/3}$. For a conservative porosity reduction from 0.15 (unhealed) to 0.10 (healed), the predicted permeability ratio k_1/k_0 is approximately 0.2, representing a five-fold reduction. Although this matrix densification alone cannot explain the two-order magnitude improvement, the result reinforces that fracture and crack sealing, not merely pore refinement, is the dominant mechanism in permeability reduction.

6.3 CO_2-Reactive Mineralisation and Long-Term Resistance

Chemical mineralisation complements the microbial process by reacting intruding CO_2 with residual $Ca(OH)_2$, MgO, and C_2S phases to form stable carbonates ($CaCO_3$, $MgCO_3$, and C–S–H-derived carbonates). Studies have shown that such carbonation reactions can immobilize approximately 5–10 % of intruding CO_2 and simultaneously enhance compressive strength by 10–20 % (Ashraf, 2016). This process further reduces diffusion and stabilizes the healed zone against re-opening, thus promoting long-term durability of the system to CO_2-rich environments.

Beyond the healing of structural defects, the system enables permanent CO_2 sequestration by converting intruding CO_2 into stable carbonates, which are locked within the cement matrix. Mineral trapping is a long-term, non-reversible form of carbon storage that allows a cement sheath to act as an active CO_2 sink instead of simply a barrier. As a result, the dual-healing cement not only improves well integrity but also supports net-carbon-reducing well construction over the life of the asset.

6.4 Comparison with conventional cement

Table 2: Comparison with Conventional Class G Cement

Property	Conventional Class G	Dual-Healing Cement System	Improvement Rationale
Self-healing ability	None	Autonomous microbial + CO_2-driven healing	Respond to new cracks without intervention
CO_2 resistance	Moderate → deteriorates over time	Enhanced due to carbonate mineral formation	Stabilizes the matrix against acid attack
Permeability over service life	Often increases due to microcracking	Decreases due to progressive mineral infilling	Maintains zonal isolation long-term
Expected lifespan	Baseline	+≥50% projected extension	Reduced failure and repair frequency

The comparison presented in Table 2 emphasizes that the advantage of the dual-healing cement is not only in crack repair, but in its ability to interrupt the well-failure pathway. In conventional Class G systems, microcracks may remain dormant initially, but gradually evolve into connected leak pathways under pressure/temperature cycling, especially in CO_2-bearing environments. Once connectivity forms, interventions are costly and sometimes technically impractical in deep wells. The proposed dual-healing system changes this failure progression by enabling in-situ, passive intervention, where microbial precipitation restores sealing before leakage becomes continuous, and CO_2-reactive mineralisation stabilizes the repaired region into a chemically resistant carbonate matrix. Rather than simply improving initial material properties, this system alters the time-evolution behavior of well integrity, shifting the cement sheath from a degrading barrier to a self-maintaining barrier. This is especially significant in fields with long storage or production horizons where frequency of intervention, probability of leakage, and cost of intervention become important lifecycle metrics.

7. ENVIRONMENTAL AND SUSTAINABILITY ASSESSMENT

The dual-healing cement system outperforms conventional cement by lasting longer and requiring less repair, producing significant benefits over the cement's life cycle. It further promotes the capture, utilization, and storage of CO_2 (CCUS) by embedding CO_2 within the matrix while providing a green and resilient approach to construction. Compared to traditional cement, the dual-healing cement system lasts longer with less required repair, providing considerable benefits throughout the cement life cycle. This also supports the capture, utilization, and storage of CO_2 through the incorporation of CO_2 into the matrix, while offering a green and resilient construction approach.

The System will be associated with marginally higher up-front material costs from a microbiological encapsulation and reactive additive perspective; however, the economic impact over the full well life is expected to be positive due to reduced remediation cementing operations, reduced risk of sustained casing pressure, and an extended service life of cement. The cement formulation was specifically designed to work with existing oilwell cementing infrastructure and will require neither specialized placement equipment nor significant procedural changes. Deployment challenges include maintaining long-term microbial viability under high-temperature conditions and optimizing additive dosages for varying well environments, both of which will be addressed through laboratory qualification testing before field deployment.

8. CHALLENGES AND FUTURE ASPECTS

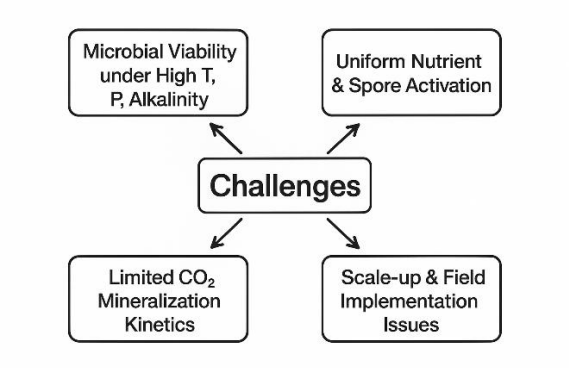

Figure 7: Challenges of Dual-healing Cement system

Figure 7 summarizes the key technical, operational, and deployment challenges associated with implementing the proposed dual-healing cement system. Although this study demonstrates the dual-healing cement system's conceptual viability and synergistic potential, experimental validation is still a crucial next step. Future studies should use laboratory-scale testing under simulated downhole temperature, pressure, cyclic loading, and CO2 exposure to assess crack-healing efficacy, permeability reduction, and mechanical property recovery. Numerical simulations at the microstructural scale can further elucidate coupled transport–reaction and healing kinetics, but pilot-scale field trials in CO2-prone wells are necessary to evaluate long-term durability, microbial viability, encapsulation performance, and operational reliability. To move the suggested system toward field-ready deployment, developments in microbial encapsulation, extremophile bioengineering, optimized nutrient delivery, nanostructured SCMs, and real-time cement health monitoring will be crucial.

9. CONCLUSION

This study describes a dual-phase cement system that combines microbial self-healing with CO_2-responsive minerals to enhance long-term well integrity in a CO_2-rich environment. This system contains dormant ureolytic bacterial spores and CO_2-reactive amendments (MgO, wollastonite, SCMs) that allow for self-sealing of microcracks, densification of the cement matrix, and irreversible stabilization of CO_2 into solid carbonate minerals. Mechanistic evaluation indicates that the dual-healing system can reduce permeability by several orders of magnitude while improving long-term durability, projecting at least 50% more service life compared to existing Class G cements. Finally, the dual-healing system not only improves performance but also provides a sustainable well construction design through less frequent interventions, lower embodied CO_2, and active carbon sequestration. Although several challenges remain related to microbial viability, reaction kinetics, and field application of this cementing scheme, dual-healing systems represent a method that transforms the development of CO_2-resilient and sustainable infrastructure for subsurface operations and offers an attractive way to incorporate carbon management with oilfield and CO_2-storage activities.

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