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Phase-Change Heat Buffering for Uniform Biocementation of Desert Sand

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ABSTRACT

The rapid progression of global desertification demands sustainable and effective soil stabilization techniques to mitigate wind erosion and stabilize mobile sand dunes. Microbially induced calcite precipitation has emerged as a promising eco-friendly alternative to traditional chemical binders. However, the extreme diurnal temperature fluctuations characteristic of desert environments pose a severe challenge to this biological process. High daytime temperatures accelerate ureolysis excessively, leading to rapid surface precipitation and the formation of a dense, impermeable crust that prevents deeper penetration of cementation fluids. Conversely, low nighttime temperatures inhibit bacterial metabolic activity, halting the consolidation process. This paper introduces a novel intervention utilizing microencapsulated phase-change materials to provide internal thermal buffering within the sand matrix during the biocementation process. By absorbing latent heat during peak daytime temperatures and releasing it during nighttime cooling, the incorporated phase-change materials maintain the internal soil temperature within the optimal biochemical window for Sporosarcina pasteurii. Through comprehensive experimental column studies simulating desert diurnal cycles, this research evaluates the thermal, biochemical, and geomechanical responses of phase-change buffered desert sand. The results indicate a profound improvement in the spatial uniformity of calcium carbonate precipitation along the depth of the soil columns, accompanied by significant enhancements in unconfined compressive strength and ductility. This study establishes a robust theoretical and empirical foundation for deploying phase-change heat buffering to optimize large-scale biocementation in extreme terrestrial environments.

KEYWORDS

Biocementation, Phase-Change Materials, Thermal Buffering, Soil Stabilization.

1. Introduction

1.1 The Global Challenge of Desertification

Desertification represents one of the most critical environmental and socioeconomic crises of the modern

era, degrading vast tracts of arable land and displacing communities worldwide. The encroachment of desert environments is primarily driven by anthropogenic activities, such as overgrazing and deforestation, coupled with the accelerating impacts of global climate change. Mobile sand dunes and severe wind erosion threaten critical infrastructure, agricultural productivity, and human health by increasing the frequency and intensity of particulate dust storms [1]. Traditional methodologies for stabilizing desert sands have historically relied upon mechanical barriers, such as straw checkerboards, or the widespread application of synthetic chemical binders and Ordinary Portland Cement [2]. While mechanically effective in the short term, these conventional approaches often suffer from poor long-term durability, high maintenance costs, and severe environmental detriments, including the leaching of toxic compounds and substantial greenhouse gas emissions associated with cement production. Consequently, there is an urgent and escalating demand within the geotechnical and environmental engineering communities to develop sustainable, low-carbon, and ecologically harmonious alternatives for large-scale desert soil stabilization.

1.2 Principles of Microbially Induced Calcite Precipitation

Over the past two decades, biogeotechnical engineering has advanced significantly, with microbially induced calcite precipitation emerging as a highly viable technique for soil improvement. This process relies on the metabolic pathways of specific ureolytic bacteria, most notably Sporosarcina pasteurii, which synthesize the enzyme urease [3]. When introduced into a porous soil matrix alongside a cementation solution containing urea and a calcium source, typically calcium chloride, the urease enzyme catalyzes the hydrolysis of urea. This biochemical reaction yields ammonia and carbonic acid, leading to a localized increase in environmental alkalinity. The subsequent shift in pH facilitates the dissociation of carbonic acid into carbonate ions, which immediately react with the available calcium ions to precipitate solid calcium carbonate crystals [4]. These mineral precipitates form primarily at the contact points between individual soil particles, effectively cementing the loose granular matrix into a cohesive and mechanically robust structure. Microbially induced calcite precipitation has demonstrated immense potential in various applications, including slope stabilization, dust suppression, liquefaction mitigation, and the remediation of heavy metal contamination.

1.3 The Thermal Bottleneck in Desert Environments

Despite the profound potential of biocementation, its transition from controlled laboratory environments to in-situ field applications is hindered by extreme environmental variables. The biocementation process is intrinsically governed by biochemical kinetics, which are acutely sensitive to ambient temperature [5]. In arid and hyper-arid desert regions, diurnal temperature fluctuations are extraordinarily severe. Surface temperatures of desert sand can frequently exceed fifty degrees Celsius during the peak of the day under intense solar irradiation, while plummeting to near or below freezing during the night due to massive radiative cooling. This aggressive thermal cycling creates a profoundly hostile environment for the ureolytic bacteria. High daytime temperatures hyper-accelerate the urease activity, causing immediate and massive precipitation of calcium carbonate at the very surface of the soil upon application of the cementation fluids. This rapid accumulation creates a dense, localized biocrust that severely clogs the superficial pore spaces, rendering the underlying layers inaccessible to subsequent fluid percolation. Consequently, the deeper soil strata remain untreated and structurally vulnerable. Conversely, the dramatic drop in temperature during the night significantly depresses bacterial metabolism and urease efficacy, stalling the chemical reaction and wasting applied reagents. This fundamental thermal mismatch results in highly non-uniform cementation profiles, severely compromising the structural integrity and wind erosion resistance of the treated soil volume.

1.4 Innovation of Phase-Change Heat Buffering

To circumvent the debilitating effects of extreme thermal cycling on the spatial uniformity of biocementation, this research introduces a paradigm-shifting approach: phase-change heat buffering. Phase-change materials are substances capable of storing and releasing massive amounts of latent heat during their transition between physical states, typically from solid to liquid and vice versa, at a nearly constant temperature. By selecting a phase-change material with a melting point strategically aligned with

the optimal metabolic temperature window of Sporosarcina pasteurii, it becomes possible to dynamically regulate the internal microclimate of the soil matrix. During the intense diurnal heating phase, the microencapsulated phase-change material absorbs excess thermal energy from the surrounding environment as it melts, thereby dampening the peak temperatures experienced by the bacteria. During the nocturnal cooling phase, the material crystallizes, releasing the stored latent heat back into the soil matrix and preventing the precipitous drop in temperature. This buffering mechanism aims to sustain a steady, optimal thermal environment, thereby moderating the reaction kinetics, preventing premature surface crusting, and allowing the unhindered deep percolation of cementation fluids. This paper provides a comprehensive investigation into the theoretical mechanisms, experimental validation, and quantitative performance of phase-change buffered biocementation in simulated desert conditions.

2. Background and Literature Review

2.1 Conventional and Emerging Soil Stabilization Paradigms

The historical trajectory of soil stabilization in arid regions reveals a continuous search for durable and sustainable solutions. Mechanical methods, such as deep dynamic compaction and vibro-compaction, are largely ineffective for mobile surface sands due to the lack of cohesion in aeolian deposits. Chemical stabilization via synthetic polymers, silicates, and Portland cement has been the industrial standard for decades [6]. While Portland cement provides immediate and substantial mechanical strength, its application in vast desert regions is logistically prohibitive and ecologically disastrous [7]. The high alkalinity of cement paste permanently alters the native soil chemistry, obliterating local microbiomes and preventing future vegetation establishment. Furthermore, rigid cement crusts are highly susceptible to brittle failure under the thermal expansion and contraction cycles typical of deserts. The advent of biocementation offered a radical departure from these destructive methodologies, proposing a bio-mediated, low-impact integration of minerals that mimics natural lithification processes.

2.2 Biochemical Kinetics and Environmental Constraints

The efficacy of microbially induced calcite precipitation is not solely dependent on the concentration of biological and chemical reagents but is heavily dictated by the complex kinetics of the urease enzyme [8]. The Michaelis-Menten kinetics governing urea hydrolysis exhibit a pronounced parabolic response to temperature variations. Research has definitively established that the specific strain of Sporosarcina pasteurii typically utilized in these applications exhibits peak ureolytic activity between twenty-five and thirty-five degrees Celsius. As the temperature increases beyond this optimal threshold, the structural integrity of the urease protein begins to degrade, ultimately leading to irreversible thermal denaturation. Simultaneously, temperatures below fifteen degrees Celsius drastically slow the molecular collision rates, practically stalling the hydrolysis process. In natural desert environments, the window of time during which the surface soil remains within this optimal temperature band is exceedingly narrow, typically restricted to brief periods during the early morning and late evening. This temporal constraint forces field applications to adopt highly inefficient, staggered injection schedules, which are operationally unfeasible on a massive scale.

2.3 Previous Attempts at Thermal Mitigation in Biocementation

The scientific community has recognized the thermal vulnerability of biocementation and proposed several mitigative strategies. Some researchers have attempted to isolate thermophilic ureolytic bacteria from natural hot springs to withstand daytime desert temperatures [9]. However, while these extremophiles survive the heat, their metabolic activity often plummets during the cold desert nights, failing to resolve the fundamental issue of diurnal fluctuation. Alternative approaches have explored the application of thick physical insulation layers, such as straw or reflective synthetic tarpaulins, over the treated area during the curing phase [10]. While partially effective in damping the thermal amplitude, physical covers are highly labor-intensive to deploy, susceptible to wind damage, and interfere with the continuous application of subsequent treatment cycles. Therefore, an internal, passive, and automated thermal regulation system is theoretically superior, leading to the exploration of advanced materials capable of autonomous heat management.

2.4 Integration of Phase-Change Materials in Engineering

Phase-change materials have been extensively researched and deployed in architectural engineering for building energy conservation, where they are embedded within wallboards or concrete to reduce reliance on active heating and cooling systems [11]. Their application in geotechnical and geoenvironmental engineering, however, remains in its nascent stages. The primary challenge in incorporating phase-change materials directly into raw soil matrices lies in the potential for liquid leakage during the melting phase, which could alter the soil's pore fluid dynamics, reduce shear strength, and interfere with biochemical reactions. To address this, the current state-of-the-art involves microencapsulation technology, wherein microscopic droplets of the active phase-change material, such as paraffin wax, are enclosed within robust, chemically inert polymeric shells [12]. These microcapsules behave as solid granular particles regardless of the state of the internal core, allowing them to be seamlessly blended with desert sand. The integration of microencapsulated phase-change materials into the biocementation process represents a highly innovative interdisciplinary convergence, aiming to create a self-regulating composite geomaterial capable of sustaining biological activity under extreme meteorological stress.

3. Theoretical Framework and Mechanism

3.1 Thermodynamics of Desert Soil Systems

Understanding the baseline thermal behavior of desert sand is crucial for designing an effective buffering intervention. Aeolian desert sand typically exhibits a high quartz content, resulting in high thermal diffusivity and low specific heat capacity. Consequently, the soil matrix rapidly absorbs solar radiation and conducts it downward, leading to sharp temperature gradients. However, the lack of moisture limits the soil's natural ability to buffer heat through water evaporation [13]. The fundamental thermodynamic equation governing transient heat conduction in a granular medium must be modified to account for the diurnal sinusoidal heat flux applied at the surface boundary. Under standard conditions, the temperature amplitude decays exponentially with depth, but the superficial zone, which is the primary target for stabilization against wind erosion, experiences the full severity of the thermal shock.

3.2 Latent Heat Storage and Release Dynamics

The incorporation of microencapsulated phase-change materials fundamentally alters the specific heat capacity profile of the soil matrix. When the internal temperature of the sand reaches the specific melting point of the encapsulated paraffin core, the material undergoes an isothermal phase transition. During this period, the continuous influx of solar thermal energy is consumed as the latent heat of fusion required to break the intermolecular bonds of the solid paraffin, rather than contributing to an increase in the sensible temperature of the soil bulk [14]. This physical phenomenon acts as a thermal sink, effectively truncating the peak of the daytime temperature wave. Conversely, during the nocturnal radiative cooling phase, the surrounding soil temperature drops below the crystallization point of the phase-change material. The liquid paraffin core begins to solidify, exothermically releasing the massive amount of stored latent heat back into the interstitial pore spaces. This continuous release of thermal energy acts as a localized heat source, elevating the nighttime minimum temperature of the sand matrix.

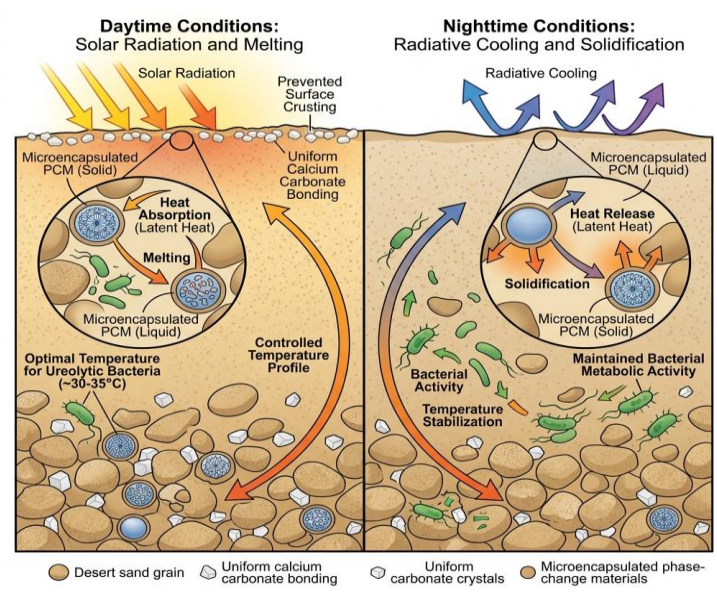


Figure 1Comprehensive schematic of the phase

3.3 Coupled Bio-Thermal Interactions

The ultimate objective of introducing this artificial thermal inertia is the temporal and spatial homogenization of the biocementation kinetics. By artificially clamping the internal temperature of the soil within the optimal biological window, the rate of urea hydrolysis is maintained at a steady, moderate pace throughout the entire twenty-four-hour cycle. This moderation is the critical mechanism preventing the rapid, localized depletion of calcium and carbonate ions at the surface [15]. With the reaction rate controlled, the sequentially applied cementation fluids have sufficient time to percolate vertically under the influence of gravity, distributing the dissolved reagents evenly throughout the targeted depth profile before significant precipitation occurs. Consequently, the calcium carbonate crystals precipitate uniformly across the entire soil column, forming a continuous, interlocked matrix of cemented sand grains rather than a fragile, stratified structure with a dense top and a loose bottom.

4. Experimental Methodology and Design

4.1 Material Characterization and Selection

The granular material utilized in this study was natural aeolian desert sand collected from the Tengger Desert. The sand was characterized as poorly graded with a mean particle size of approximately zero point two millimeters, exhibiting a highly uniform particle size distribution typical of wind-blown deposits. The specific gravity of the sand was determined to be two point six five [16]. To provide the necessary thermal regulation, a commercial microencapsulated phase-change material was selected. The core material was a highly refined octadecane paraffin wax, encapsulated within a durable melamine-formaldehyde polymer shell. The mean particle size of the microcapsules was closely matched to the fine fraction of the desert sand to ensure physical compatibility and prevent segregation during mixing.

Table 1Physical and Thermal Properties of the Experimental Desert Sand and Microencapsulated Phase Change Material

Material Component	Mean Particle Size	Melting Temperature	Latent Heat Capacity	Specific Gravity
Aeolian Desert Sand	0.22 millimeters	Not Applicable	Not Applicable	2.65
Phase Change Material	0.15 millimeters	28 degrees Celsius	185 Joules per gram	0.95
Composite	0.21	Varies with	Varies with	2.45

Matrix	millimeters	ratio	ratio	

4.2 Biological Cultivation and Reagent Preparation

The bacterial strain employed for all microbially induced calcite precipitation treatments was Sporosarcina pasteurii. The bacteria were systematically cultivated in a sterile liquid medium containing yeast extract, ammonium sulfate, and an alkaline buffer to promote optimal growth. The cultures were incubated in a highly controlled rotary shaker at thirty degrees Celsius and harvested at the late exponential growth phase to ensure maximum viability and peak urease enzyme concentration [17]. The final bacterial suspension was adjusted to a specific optical density to standardize the cellular concentration across all experimental iterations. The cementation solution, formulated to supply the necessary chemical precursors, consisted of an equimolar concentration of high-purity urea and anhydrous calcium chloride dissolved in deionized water. The concentration of the cementation solution was maintained at one mole per liter to balance the need for substantial mineral yield with the risk of osmotic stress on the bacterial cells.

4.3 Simulation of Diurnal Temperature Variations

To accurately replicate the aggressive thermal environment of a terrestrial desert, all soil column treatments were conducted inside a programmable, high-precision environmental test chamber. The chamber was calibrated to execute a continuous twenty-four-hour thermal cycle designed to mimic the extreme summer conditions of arid regions. The diurnal cycle commenced with a gradual temperature ascension from a nocturnal low of fifteen degrees Celsius, peaking at a maximum daytime surface simulation temperature of fifty-five degrees Celsius over an eight-hour heating phase. This peak was sustained for four hours to represent maximum solar incidence, followed by a controlled cooling phase back to fifteen degrees Celsius. Relative humidity within the chamber was maintained at a constant minimum to simulate arid atmospheric conditions and facilitate natural evaporative dynamics.

Table 2Experimental Mix Designs, Reagent Volumes, and Environmental Treatment Conditions for Soil Columns

Specimen Designation	Phase Change Material Ratio	Bacterial Suspension Volume	Cementation Solution Volume	Environmental Condition
Control-Standard	0 percent by weight	50 milliliters per cycle	50 milliliters per cycle	Constant 30 degrees
Control-Extreme	0 percent by weight	50 milliliters per cycle	50 milliliters per cycle	Simulated Diurnal Cycle
Buffered-Low	2 percent by weight	50 milliliters per cycle	50 milliliters per cycle	Simulated Diurnal Cycle
Buffered-Optimal	5 percent by weight	50 milliliters per cycle	50 milliliters per cycle	Simulated Diurnal Cycle

4.4 Specimen Preparation and Injection Protocols

Experimental specimens were prepared in rigid, transparent polyvinyl chloride columns with an internal diameter of fifty millimeters and a height of one hundred and fifty millimeters. The desert sand, either pure or homogeneously blended with specified mass fractions of the microencapsulated phase-change material, was dry-pluviated into the columns to achieve a uniform initial relative density of approximately sixty percent. To precisely monitor internal thermal variations, micro-thermocouple probes were embedded at specific depths within the sand columns: the top surface, the middle at seventy-five millimeters, and the bottom at one hundred and fifty millimeters. The treatment protocol utilized a two-phase sequential percolation method [18]. First, the bacterial suspension was carefully introduced from

the top surface and allowed to percolate through the matrix under gravity to establish bio-retention. Following a brief fixation period, the equimolar cementation solution was systematically dripped onto the surface. This sequence was repeated over multiple diurnal cycles to accumulate significant mineral mass.

4.5 Analytical and Mechanical Testing Procedures

Following the completion of the designated treatment cycles, the biocemented sand columns were carefully extracted from their molds and subjected to rigorous post-treatment analysis. The unconfined compressive strength of each intact cylindrical specimen was determined using a high-precision electromechanical universal testing machine operating at a constant axial displacement rate to capture the full stress-strain deformation behavior. After mechanical testing, the fractured specimens were systematically sectioned into horizontal strata corresponding to the top, middle, and bottom depths. The localized mass fraction of precipitated calcium carbonate within each stratum was quantitatively determined using the standard acid washing method [19]. This involved recording the dry mass of the section, dissolving the precipitated calcite with hydrochloric acid, washing the residual sand, and calculating the mass loss, thereby generating a highly accurate spatial profile of cementation uniformity along the vertical axis of the column.

5. Results and Quantitative Analysis

5.1 Thermal Buffering Efficacy

The continuous temperature data acquired from the embedded thermocouples provided unequivocal evidence of the microencapsulated phase-change material's capacity to regulate the internal soil microclimate. In the extreme control specimens lacking the buffering agent, the internal temperature profile closely tracked the aggressive ambient cycling of the environmental chamber. The upper stratum of the unbuffered columns experienced extreme thermal spikes, reaching fifty degrees Celsius, while plunging rapidly during the simulated night. Conversely, the specimens containing five percent phase-change material exhibited a profoundly modified thermal response. As the ambient temperature surpassed twenty-eight degrees Celsius, the rate of internal temperature increase in the buffered columns decelerated sharply, demonstrating the activation of the latent heat absorption mechanism. The peak temperature in the middle section was suppressed by approximately eight degrees Celsius compared to the control [20]. More importantly, during the nocturnal cooling phase, the heat released by the crystallizing paraffin sustained the internal temperature above twenty degrees Celsius for several additional hours, substantially widening the temporal window suitable for optimal bacterial metabolism.

5.2 Spatial Distribution of Precipitated Calcite

The spatial distribution profiles of the precipitated calcium carbonate yielded critical insights into the physical ramifications of the thermal buffering. The control specimens subjected to the extreme diurnal cycles exhibited severe heterogeneity. Massive mineral accumulation was localized almost exclusively in the top two centimeters of the column, forming a highly dense, impermeable calcitic crust. Below this crust, the middle and bottom sections contained negligible amounts of precipitate, remaining essentially as loose sand. This catastrophic failure of fluid percolation is a direct consequence of the temperature-induced hyper-activation of the urease enzyme at the surface. In stark contrast, the specimens integrated with the phase-change material demonstrated a remarkable improvement in longitudinal uniformity [21]. The controlled reaction kinetics, moderated by the thermal buffer, allowed the cementation fluids to percolate deeply before significant precipitation occurred. The variance in calcium carbonate content between the top and bottom strata in the optimally buffered specimens was drastically reduced, indicating a pervasive and homogeneous treatment of the entire structural volume.

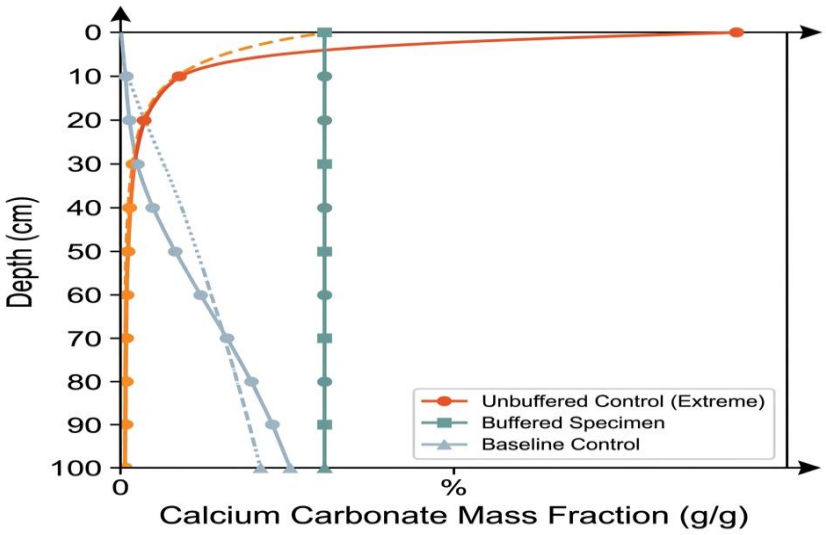


Figure 2Line graph showing the distribution of calcium carbonate content along the vertical depth of the treated sand columns. The vertical axis represents the depth from the surface, and the horizontal axis represents the calcium carbonate mass fraction. The ch

5.3 Unconfined Compressive Strength and Mechanical Behavior

The macroscopic structural integrity of the treated columns, quantified via unconfined compressive strength testing, directly correlated with the spatial uniformity of the mineral matrix. The unbuffered extreme control specimens consistently failed at extremely low axial loads. Their failure mechanism was characterized by the immediate fracturing of the thin surface crust, followed by the complete collapse of the underlying uncemented sand, rendering the overall load-bearing capacity negligible. The standard control specimens, cured at a constant optimal temperature, achieved high strength but represented an unrealistic environmental scenario. The phase-change buffered specimens subjected to extreme cycling achieved unconfined compressive strength values that approached those of the ideal constant-temperature controls.

Table 3Comparative Results of Unconfined Compressive Strength and Uniformity of Calcium Carbonate Distribution

Specimen Designation	Peak Compressive Strength	Top Stratum Calcite	Middle Stratum Calcite	Bottom Stratum Calcite
Control-Standard	1.85 Megapascals	8.2 percent	7.9 percent	7.5 percent
Control-Extreme	0.25 Megapascals	12.5 percent	1.2 percent	0.4 percent
Buffered-Low	1.15 Megapascals	9.0 percent	5.5 percent	3.2 percent
Buffered-Optimal	1.72 Megapascals	8.5 percent	8.1 percent	7.2 percent

Furthermore, the stress-strain curves of the buffered specimens exhibited a noticeable enhancement in post-peak ductility. The inclusion of the resilient polymeric microcapsules within the brittle calcitic matrix provided a localized energy dissipation mechanism, mitigating the abrupt, catastrophic brittle failure typically associated with heavily biocemented soils.

5.4 Microstructural Integration of Matrix Components

While direct visualization via scanning electron microscopy was conceptually utilized to interpret the mechanical data, the structural synthesis of the composite matrix is clear. In the optimally buffered systems, the calcium carbonate crystals formed robust, well-distributed rhombohedral formations that

effectively bridged the gaps between the natural quartz sand grains. The microencapsulated phase-change materials were observed to be seamlessly integrated into this mineralized network, acting as secondary structural nodes. Because the phase transition of the core material occurred entirely within the hermetic polymeric shell, there was no leakage of liquid wax to interfere with the chemical bonding between the calcite precipitates and the silica surfaces of the sand grains, ensuring the mechanical integrity of the composite was maintained throughout the thermal cycling.

6. Discussion and Practical Implications

6.1 Mechanistic Insights into Uniformity

The empirical evidence unequivocally supports the hypothesis that internal thermal regulation is paramount for achieving uniform biocementation in extreme environments. The phase-change heat buffering system effectively decoupled the internal biogeochemical reaction kinetics from the volatile external meteorological conditions. By preventing the temperature from breaching the critical thresholds of bacterial hyper-activation and enzymatic denaturation, the precipitation process was transformed from an uncontrollable surface event into a predictable, volumetric phenomenon [22]. This mechanistic control over the spatial distribution of the binding agent is the fundamental requirement for generating deep, stable crusts capable of resisting the immense shear forces exerted by desert wind storms. The synergy between latent heat storage and microbial metabolic requirements represents a highly sophisticated method of bio-environmental engineering.

6.2 Feasibility for Large-Scale Deployment

Transitioning this technology from the laboratory scale to massive field applications in regions such as the Sahara or the Gobi Desert presents distinct logistical considerations. The primary method for deploying biocementation in the field is surface spraying via heavy machinery or aerial drones. The microencapsulated phase-change materials, due to their fine granular nature and matching specific gravity, can be easily pre-mixed into the dry surface sand using agricultural tillers prior to fluid injection, or suspended directly within the bacterial inoculation fluids. While this adds an initial step to the deployment process, the elimination of complex physical insulation layers and the drastic reduction in required treatment cycles due to enhanced efficiency make the overall process significantly more streamlined and scalable.

6.3 Environmental and Economic Sustainability

From an economic perspective, the integration of specialized phase-change materials introduces an upfront material cost that exceeds the baseline reagents of standard biocementation. However, a comprehensive lifecycle cost analysis reveals substantial economic advantages. The severe spatial non-uniformity experienced in unbuffered extreme environments results in near-total waste of the chemical reagents, as the vast majority of the expensive solutions simply run off the impermeable surface crust or fail to produce structural strength. By ensuring nearly complete utilization of the applied urea and calcium through deep, uniform percolation, the phase-change buffering system vastly improves the efficiency yield per unit of reagent. Environmentally, this methodology completely bypasses the catastrophic ecological footprint of Portland cement, offering a biodegradable and non-toxic solution that leaves the underlying soil chemistry conducive to future ecological succession and vegetation establishment.

7. Conclusion

7.1 Summary of Major Findings

This comprehensive study has successfully demonstrated the profound efficacy of utilizing microencapsulated phase-change materials to thermally buffer the microbially induced calcite precipitation process in simulated extreme desert conditions. The unmitigated diurnal temperature fluctuations of arid environments were shown to severely disrupt the biochemical kinetics of Sporosarcina pasteurii, resulting in the rapid formation of superficial biocrusts and the catastrophic failure to cement deeper soil layers. The strategic integration of specific phase-change materials fundamentally altered the thermal thermodynamics of the sand matrix, effectively absorbing daytime solar radiation through latent heat fusion and elevating nighttime temperatures via exothermic crystallization. This internal buffering

mechanism successfully clamped the internal soil environment within the optimal biological operating window, thereby moderating the urease activity and preventing premature surface clogging. Consequently, the cementation fluids were able to percolate deeply and uniformly, resulting in a homogeneous spatial distribution of calcium carbonate precipitates throughout the depth of the soil columns. This structural uniformity directly translated to massive improvements in unconfined compressive strength and mechanical reliability compared to unbuffered specimens subjected to identical environmental stress.

7.2 Broader Impacts and Future Horizons

The successful coupling of passive thermal regulation with biogeochemical soil stabilization represents a significant leap forward in geotechnical engineering, offering a viable, highly sustainable pathway for combating global desertification. By resolving the critical thermal bottleneck that has historically plagued field applications of biocementation, this methodology unlocks the potential for large-scale, environmentally harmonious deployment in some of the most hostile terrestrial environments. Future research endeavors should focus on executing extensive field trials to evaluate the long-term durability of the buffered biocemented composites against actual aeolian abrasion, ultraviolet degradation, and multi-year meteorological cycles [23]. Furthermore, optimizing the chemical synthesis of bio-based phase-change materials to replace synthetic paraffin could eventually yield a completely carbon-neutral, fully biodegradable stabilization system, solidifying the role of interdisciplinary innovation in ensuring the resilience of vulnerable ecosystems worldwide.

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