EXPLORING THE FEASIBILITY OF BIOCEMENTATION FOR ISRU CONSTRUCTION ON MARS.

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Introduction: Sustainable human presence on Mars will require safe, cost-effective construction methods that minimize reliance on Earth-supplied materials [1]. Extreme environmental conditions combined with launch mass constraints make *in situ* resource utilization (ISRU) essential for long-term exploration. Planetary, and specifically Martian regolith represents a promising construction feedstock for infrastructure such as landing pads, habitats, and roadways [1,2]. Biomineralization, a microbially mediated process that forms minerals under ambient conditions with low energy input, offers a potentially sustainable alternative to conventional cement-based construction by leveraging natural regolith chemistry [3,4]. This work evaluates the feasibility of applying biomineralization for Martian construction by analyzing regolith composition, identifying viable mineralization pathways compatible with Martian substrates, and assessing environmental constraints, automation potential, and key research gaps for robotic implementation.

Martian Regolith as a Substrate for Biocementation: Martian regolith is compositionally rich in silica (SiO_2 ~42–47%), alumina (Al_2O_3 ~7–10%), iron oxides (FeO and Fe_2O_3), and magnesium oxide (MgO), with more limited calcium oxide (CaO ~6%) [5,6,7,8] relative to terrestrial Portland cement systems. Although this chemistry precludes straightforward *in situ* production of a true Portland cement analog, it provides multiple pathways for biologically mediated mineralization aligned with ISRU strategies [9]. SiO_2, while chemically stable and not directly metabolized by microbes, can participate in secondary cementitious reactions when combined with Ca^{2+}, Al^{3+}, Fe^{3+}, or Mg^{2+} under alkaline conditions, enabling formation of calcium silicate hydrates or geopolymer-like binders [10]. Microbial weathering processes may mobilize Al for aluminosilicate formation [11], iron reduction pathways could generate dense Fe-bearing minerals [12] potentially useful for radiation shielding applications, and Mg-bearing phases may support Mg-carbonate precipitation under biologically induced alkalinity [12]. Among candidate pathways, calcium carbonate precipitation via Microbially Induced Calcium Carbonate Precipitation (MICP) remains the most promising strategy for generating a binding phase capable of stabilizing regolith aggregates [9].

However, Mars' extreme environmental conditions including low atmospheric pressure, high UV radiation flux, perchlorate-rich regolith, reduced gravity, limited liquid water stability, and large diurnal temperature fluctuations [13] impose significant constraints on microbial viability, enzymatic activity, and precipitation kinetics. Risk mitigation strategies are therefore essential. In accordance with current Moon-to-Mars autonomous construction priorities, robotic systems would excavate and sieve regolith to achieve particle size distributions optimized for biocementation, with additive manufacturing or *in situ* injection techniques enabling scalable fabrication of landing pads, berms, and habitat components prior to crew arrival. Early construction phases may be conducted within pressurized, foldable, UV-shielded geodesic enclosures to stabilize temperature, retain water, protect microbial cultures, and enhance process repeatability while minimizing the need for extensive genetic modification [9]. Seasonal scheduling (particularly during southern hemisphere summer near pre-aphelion) could further improve metabolic performance by leveraging longer intervals of relatively warm daytime temperatures. Together, regolith chemistry, robotic preparation, environmental shielding, and operational timing define an integrated framework in which biocementation becomes a plausible Martian construction strategy.

Integration with Martian ISRU: Biocementation offers strong potential for integration with ISRU by coupling construction with resource extraction, waste recycling, and life-support systems. Ca that is required for carbonate precipitation may be derived from basaltic regolith during metal or oxygen extraction processes, while urea for ureolytic pathways can be sourced from crew waste streams (or transported for robotic missions), enabling partial nutrient recycling in early settlement phases. Photosynthetic pathways utilize Martian atmospheric CO_2 and incident light, potentially co-producing oxygen as a valuable byproduct for habitat support. Water (likely obtained from subsurface ice or hydrated minerals) remains the critical limiting resource and may require purification due to perchlorate and other contamination risks. In this way, biocementation becomes not only a construction strategy but also a key part of a broader closed-loop resource architecture linking regolith processing, life support, agriculture, and structural fabrication. As settlement capacity grows, these coupled systems could transition from partially Earth-supplied inputs to increasingly autonomous resource loops, progressively

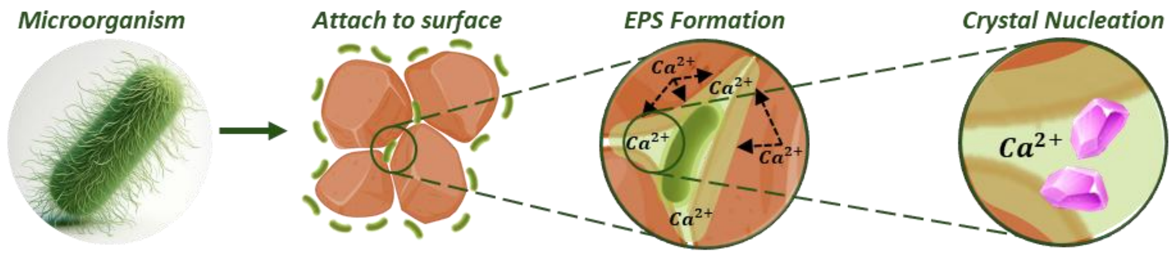

Figure 1. Schematic representation of the biocementation process.

reducing logistical dependence on terrestrial resupply.

From an energy perspective, biocementation operates at low temperatures and pressures relative to thermal or microwave sintering, suggesting substantial energy savings under power-constrained Martian conditions [9]. Reduced peak energy demand may also simplify reactor design, decrease thermal management requirements, and improve compatibility with intermittent solar power systems. Its compatibility with additive manufacturing further supports scalable, robotic construction using local regolith feedstocks. Microbial slurries can be extruded or injected into prepared regolith beds, with automated control of moisture, pH, and ion delivery enabling adaptive material tuning for specific structural or shielding requirements. When integrated with robotic systems and predictive modeling tools, biocementation-based ISRU could support modular infrastructure growth, structural repair, and autonomous construction while minimizing imported mass (Table 1), reducing mission risk, and enabling phased expansion of Martian surface operations.

Table 1. Comparison of components and masses required for conventional cement and biocementation to make 1 m^3 assuming identical construction methods (e.g., additive manufacturing).

System	Component	Weight (kg)
Portland Cement	Cement	350
	Water	175
Biocementation	Calcium Source	107.6
	Water	96.8
	Urea	161.3
	Sporosarcina pasteurii	4
	Growth nutrient	30

Discussion and Conclusion: Biocementation for Martian construction remains at an early, largely conceptual stage [9]. The approach is inherently multidisciplinary, requiring coordinated advances in microbiology, geochemistry, materials science, robotics, and construction engineering, yet current efforts remain disparate and lack standardization. Critical unknown factors include microbial survival, gene expression, and metabolic performance under combined Martian stressors such as low pressure, radiation, perchlorates, and reduced gravity. Long-duration experiments under high-fidelity environmental simulations and compositionally accurate regolith simulants are essential.

Maturing biocementation concepts to deployable infrastructure technologies introduces challenges such as reactor lifetimes, water management, gas exchange, clogging prevention, regolith feedstock handling, and payload mass/volume limitations. Scalable implementation will require automation and closed-loop integration with life support and ISRU systems. Yet, biocementation presents a compelling low-energy alternative to high-temperature regolith processing methods and offers the possibility of coupling construction with waste recycling and oxygen generation. With systematic cross-disciplinary research, high-fidelity environmental testing, and incremental robotic demonstrations, biomineralization could evolve from a speculative concept into a viable strategy for sustainable Martian infrastructure development.

Acknowledgements: This work was directly supported by the NASA Solar System Exploration Research Virtual Institute (SSERVI) Cooperative Agreement Numbers #80NSSC23M0161 (LunaSCOPE) and #80NSSSC19M0124 (CLASS).

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