From Regolith to Reality: Advanced Materials Pathways for Lunar and Martian Surface Engineering

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Abstract

In-situ resource utilization (ISRU) is essential for sustainable space exploration, where launch costs of $10,000-100,000/kg to lunar surface necessitate local manufacturing. We demonstrate complete regolith-to-construction material pathways through development of Emirates Lunar Simulant (ELS-1) from UAE anorthosite and fabrication of construction bricks for planetary habitats. Our "Moon Brick" provides proof-of-concept for regolith-based construction, with parallel Mars simulant and brick development underway. We investigate three processing approaches using ELS-1: (1) microwave sintering achieving <1 MJ/kg energy input—40-60% lower than conventional methods—by exploiting selective heating of iron-bearing phases, with compressive strengths of 25-40 MPa; (2) electrostatic beneficiation leveraging work function differences ($\varphi_{ilmenite} \approx 4.6$ eV vs $\varphi_{anorthite} \approx 4.2$ eV) to separate minerals without reagents, achieving 2-3× ilmenite enrichment; (3) vacuum sintering in our SPEAR chamber at $P<10^{-6}$ Pa revealing distinct microstructural evolution. The manufactured bricks meet target properties (>10 MPa) for habitat construction within solar power budgets. Lunar regolith contains 40-45% oxygen in oxides (SiO_2, Al_2O_3, FeO); Mars offers atmospheric CO_2 for propellant via Sabatier reactions ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$). We explore connections to 2D materials by investigating layered silicate exfoliation to create functional nanomaterials from regolith, though implementation faces volatile availability constraints. Critical challenges include scaling from grams to tons, autonomous manufacturing, and long-term structural integrity under thermal cycling. Mars brick development focuses on comparative properties and exploitation of Martian atmospheric resources. Our experiments validate processing approaches for flight hardware while revealing sustainable manufacturing principles for resource-constrained terrestrial applications. Current work optimizes Mars simulant composition, characterizes lunar versus Martian brick performance differences, and develops hybrid composites with minimal (<5%) polymer binders.

References

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