

Lunar-Regolith Photocurable Composites: Simulant Identity, Binder Demand, Vacuum, Radiation and Structural Qualification

Qualification of regolith-rich photocurable feedstocks from simulant selection to lunar-environment service

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Abstract

Lunar-regolith photocurable composites combine a particulate mineral phase with a light-reactive binder to enable shaped green bodies and, in some routes, subsequent binder removal and sintering. Their qualification cannot be reduced to regolith loading or terrestrial printability. Simulant mineralogy and particle-size distribution, optical attenuation, binder demand, debinding route, residual porosity and environmental exposure all affect the interpretation of structural performance. This review defines a qualification framework for lunar-regolith photocurable composites, separates polymer-retaining composites from ceramic-conversion routes, and identifies the evidence needed before terrestrial demonstrations can support lunar-use claims.

Keywords: lunar regolith; vat photopolymerisation; simulant; binder demand; debinding; sintering; vacuum; thermal cycling; qualification

1. Significance and scope

Regolith-based photopolymer processing is attractive because the liquid binder can temporarily provide flow, shape retention and optical cure while a high mineral fraction supplies most of the eventual solid. Vat-photopolymerisation studies with lunar-regolith simulants demonstrate that the route is technically feasible, but the studies also show strong sensitivity to particle state and downstream heat treatment [1-3].

This review owns the qualification of photocurable lunar-regolith composites. ER-448 owns the broader ISRU feedstock and logistics problem; this review starts once a regolith-derived particulate feedstock has been selected for a photocurable route.

2. Simulant identity is a controlled input

A lunar simulant is not simply “regolith”. Its mineralogy, glass fraction, particle morphology, size distribution and milling history determine optical scattering, sedimentation tendency, packing and sintering response. Low-titanium and other compositionally distinct simulants can therefore produce different slurry and fired-part behaviour even when nominal solids loading is similar [1,3].

Qualification records should identify the simulant by source and batch, report particle-size distribution and any grinding, sieving or drying, and preserve a retained sample. A formulation result should not be transferred to a different simulant solely because both are labelled lunar regolith.

Water or other process aids may lower apparent viscosity or improve paste retention, but they also change evaporation, pore formation and debinding behaviour. Any volatile added to improve recoating becomes part of the environmental and post-processing problem [2].

3. Binder demand couples rheology and cure

Higher mineral content can reduce terrestrial-binder demand per unit of final ceramic, but it raises viscosity, scattering and recoating resistance. The useful variable is therefore not maximum solids fraction in isolation; it is the feasible window linking flow, suspension stability, cure depth and defect-free layer formation.

Optical qualification should report wavelength, irradiance or dose basis, working curve or equivalent cure metric, layer thickness and the optical state of the slurry. Regolith composition and particle size alter both absorption and scattering, so exposure settings cannot be treated as transferable machine constants.

4. Green-body success is not final structural qualification

Printed geometry at the green-body stage demonstrates shaping, not structural qualification. Regolith VPP studies commonly require binder removal and sintering before high mechanical performance is obtained [1]. The green body and the final fired body are therefore different material states and require separate identifiers.

Debinding rate, atmosphere and sintering schedule control gas evolution, shrinkage, porosity and cracking. Wang and co-workers showed that heat-treatment strategy and particle-size state materially affect the final outcome, so post-processing must be reported as part of the manufacturing route rather than as an afterthought [3].

If the polymer binder is retained, radiation, vacuum, outgassing and thermal cycling act on an organic-inorganic composite, so ceramic-conversion data cannot establish its durability.

Vacuum can alter resin volatility and bubble behaviour before cure, while thermal cycling and radiation age retained polymer after cure; room-condition printing does not close either problem.

5. Lunar environment and device-level verification

Thermal-weathering studies show that processing and repeated cycling can change porosity, stiffness and chemical state, so qualification needs a defined thermal history and post-exposure properties.

Radiation evidence should state radiation type, spectrum or energy where known, absorbed-dose basis, temperature and retained function.

Device-level verification should separate dimensional fidelity, load-bearing capability and environmental retention; representative joints and wall sections are needed before habitat or tooling claims.

Axis	Measurement	Failure mode
Regolith state	simulant, PSD, mineralogical basis	transfer between non-equivalent simulants
Slurry/cure	solids fraction, rheology, cure metric	maximum loading treated as printability
Material state	green, fired or polymer-retaining	properties assigned to wrong state
Post-processing	debinding, atmosphere, sintering, shrinkage	heat treatment omitted from route
Environment	vacuum, thermal cycle, radiation	room-condition coupon treated as lunar qualified

Table 1. Domain-specific qualification matrix for lunar-regolith photocurable composites.

6. Transfer limits and minimum reporting dataset

Qualification should also track lot-to-lot regolith variability. A process window that depends on a narrow optical or rheological state should include incoming-feedstock acceptance limits rather than relying on a single research batch.

Report simulant identity, particle state, solids fraction, binder/initiator system, rheology, cure conditions, green density, final material state, shrinkage, porosity and test geometry.

For lunar-use claims, add vacuum, thermal-cycle and radiation histories and identify whether the object is green, fired or polymer-retaining.

7. Minimum qualification framework

A minimum programme should separate feedstock, green-body process and final-state qualification, with acceptance variables that distinguish simulant, cure, post-processing and environmental failures.

Transfer limits should be explicit: changes in simulant, particle state, binder lot, exposure, debinding atmosphere or service environment require proportionate requalification.

8. Engineering conclusions

Lunar-regolith photocurable manufacturing is credible only when the chain from identified simulant to final service state remains traceable; printability cannot substitute for controlled post-processing and lunar-environment retention testing.

References

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Competing interest

Juan Seguro is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L., which develops and commercialises photopolymer materials and related additive-manufacturing technologies. This review is an engineering analysis and does not constitute a product-performance claim or a device qualification.