Mineralogical Characterization of Cast Lunar Regolith Simulants. K. Edison[1] and, K. M. Cannon[1,2]. [1]Colorado School of Mines Space Resources Program, Golden CO, 80401. kedison@mines.edu. [2]Colorado School of Mines Department of Geology and Geological Engineering, Golden CO, 80401.

Introduction: The casting of regolith simulants provides insights into manufacturing feasibility for lunar applications. In this study, tiles were produced using regolith simulants then casting into molds made of either sand or ceramic, followed by controlled annealing. The objective was to investigate the effects of different annealing schedules on phase development, crystallization behavior, glass formation, and porosity. While multiple annealing profiles are planned, two schedules have been tested so far. Post-casting mineralogical analysis was conducted to assess phase evolution and material properties. These findings contribute to a deeper understanding of thermal treatment effects on cast regolith-based materials.

Methodology: Using a natural gas furnace, mare and mixed mare/anorthosite regolith simulants were melted and cast into tiles and a cylindrical sample. To examine the impact of cooling strategies on phase development, the cast samples were subjected to different annealing conditions. Some tiles remained in sand molds covered with Kaowool for gradual air cooling, while others underwent controlled annealing in a kiln. During casting, a significant foam layer formed on the melt surface, which was poured off before casting to reduce porosity.

Two annealing schedules were tested:

1. *Stepped Annealing Schedule:* Adapted from a patent [4], this process involved preheating the kiln to 900°C, transferring cast samples inside, and holding at 900°C for 2–3 hours. The temperature was reduced to 750°C and held for 2 hours before being reheated to 900°C. The kiln was then shut off and cooled naturally.
2. *Slow Cooling Schedule:* Based on Edison et. al., (2023), the kiln was preheated to 900°C, and samples were placed inside. The kiln was then cooled at 25°C per hour until reaching the target temperature before shutting off and cooling naturally.

After casting, tile samples were cut and processed into thin sections for petrographic analysis. Additionally, thin section analysis was performed on the Greenspar anorthosite used in the production of CSM-LHT-1 simulant to establish its mineralogical composition and identify possible phase transformations during casting and annealing.

Results: *Hand Sample Observations*

Flash-Cooled Samples: Cast samples left in sand molds and exposed to open air exhibited significant vitrification, severe heat tearing, and in some cases, complete shattering. These materials flash-cooled and appeared black in color.

Annealed Samples: Samples subjected to the stepped annealing schedule (900°C → 750°C → 900°C → shutdown) displayed devitrification, reduced heat tearing, and brown/gold coloration. Annealing prevented flash vitrification. Figure 1 shows A) a cast and devitrified basalt cylinder featuring large pores and B) a basalt-anorthosite cast tile cross section featuring silica blebs.

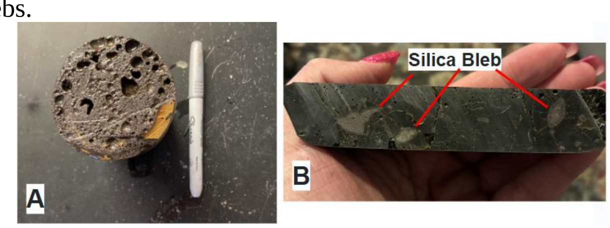

Figure 1 shows A) a cast basalt cylinder with significant porosity and B) a cross section of a cast basalt-anorthosite tile showing large silica blebs.

Foaming Reduction: The initial basalt melts exhibited significant surface foaming. These first pours had significant porosity before the foam layer was identified. Once identified the foam layer was removed before casting, porosity significantly decreased. In the basalt-anorthosite mix, the melt was first poured into an ingot mold to separate the foam layer before final casting, resulting in lower porosity and a dark grey, partially glassy texture. Figure 2 shows micrographs of (A) a basalt cast tile and (B) a basalt–anorthosite cast tile. Porosity is significantly higher in (A), while (B) features silica blebs embedded in a glassy matrix.

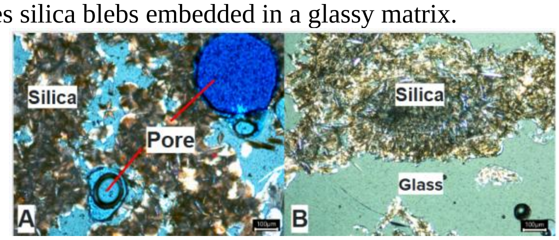

Figure 2 Micrographs of A) a cast basalt tile and B)Basalt-anorthosite cast tile.

Slow Cooling Limitations: The alternative 900°C slow cooling schedule (25°C/hr.) produced similar results to stepped annealing but was abandoned due to impracticality, taking over two days to complete.

Thin Section Analysis

Greenspar Anorthosite: The Greenspar anorthosite exhibited anhedral texture and was composed primarily of plagioclase (>90%) ($(Ca,Na)(Al,Si)_4O_8$) with polysynthetic twinning characteristic of albite ($NaAlSi_3O_8$). The remaining ~10% consisted of clinopyroxene ($Ca(Mg,Fe)Si_2O_6$), orthopyroxene ($(Mg,Fe)SiO_3$), biotite ($K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$), and minor clinozoisite ($Ca_2Al_3(Si_3O_{12})(OH)$), The presence of biotite and clinozoisite suggest a small but significant portion of bound water content [2]. Figure 3 shows Greenspar thin sections: (A) displaying plagioclase with twinning, and (B) showing evidence of clinozoisite.

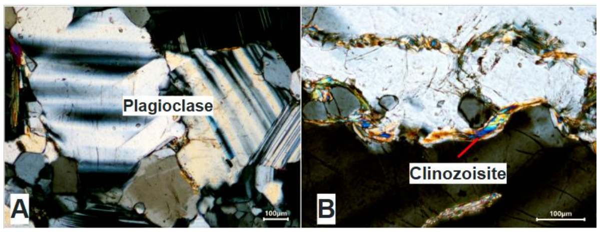

Figure 3 Micrograph of Greenspar thin sections A) Plagioclase and twinning, and B) Evidence of Clinozoisite.

Cast Basalt and Basalt-Anorthosite Samples: Thin section analysis revealed differences in crystallization, porosity, and phase development influenced by composition, annealing schedule, and mold type.

Silica & Green Sand Molds: Produced dark brown devitrified glass matrices with bladed, star-like crystals indicative of silica-rich melt. These exhibited undulose extinction, suggesting strain-induced deformation [3].

Accessory Clinopyroxene: Present in all samples, likely from secondary crystallization or incomplete melting of precursors.

Basalt-Anorthosite Samples: Displayed a vitrified glass rind surrounding silica-rich inclusions with radial acicular growth, likely strained tridymite. Vein-like tridymite networks and interlocking blades suggest high-temperature crystallization and subsequent polymorphic transformation [3].

Porosity: Ranged from 5–30%, varying with composition, cooling rate, and degassing behavior.

Annealing had a significant impact on material evolution. Stepped schedules promoted devitrification with minimal tearing, while flash-cooled samples showed more vitrification and fracturing. Thin sections of samples cooled at 25 °C/hr. to 900 °C are in preparation; analysis is pending.

Discussion: *Mineralogy of Cast Materials*

Thin section analysis showed silica polymorphs such as tridymite and cristobalite consistently formed in all melts regardless of if it was a basalt melt or basalt-anorthosite mix. Suggesting rapid heating and cooling in a silica rich melt. In mixed melts the plagioclase within the anorthosite transitioned to crystallization of strained tridymite or cristobalite. Possible minor mullite formation was also observed.

Differences Between Lunar Regolith & Simulant

Hydrous minerals (biotite, clinozoisite), in Greenspar anorthosite do not exist in lunar regolith and are likely releasing water vapor upon melting, potentially contributing to porosity. Other key differences include:

Plagioclase Composition: Lunar anorthosites are nearly pure anorthite (90–100% $CaAl_2Si_2O_8$), ~1,553°C melting point [2], while Greenspar contains Na-bearing plagioclase, lowering the melting point to ~1,450°C [5].

Nanophase Iron Grains: Lunar regolith contains Fe^0 grains in silica-rich glass rims due to solar wind reduction of FeO, absent in terrestrial regolith simulants [1].

Conclusion: These findings highlight the influence of composition, cooling rate, and annealing conditions on the crystallization and porosity of cast regolith-based materials. The presence of hydrous minerals and volatile sodium species may contribute to the observed foaming behavior. Future studies will focus on XRD confirmation of mineral phases, refining casting techniques to minimize porosity, and optimizing annealing schedules to enhance material properties. Mechanical testing of the cast samples is currently being conducted.

References:

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