**CASTING AND ANNEALING EXPERIMENTS OF LUNAR MARE AND ANORTHOSITE REGOLITH SIMULANTS.** K. Edison1 and, K. M. Cannon1,2. 1Colorado School of Mines Space Resources Program, Golden CO, 80401. kedison@mines.edu. 2Colorado School of Mines Department of Geology and Geological Engineering, Golden CO, 80401.

**Introduction:** Terrestrial basalt casting has been a practice for over a hundred years [1,2], however, adapting this technology to the Moon has not been as widely researched. Several casting experiments have been conducted at the Colorado School of Mines Foundry to conduct a proof of concept study on casting molten lunar regolith. These experiments aim to test molding materials, optimal melting and pouring temperatures and determine an annealing schedule to produce well-formed and durable materials.

Our overall series of casting experiments include 1) casting molten basalt and anorthosite regolith, then mixtures thereof; 2) casting molten regolith into various types of ceramic/refractory molds 3) casting molten aluminum (available as surplus from spacecraft) into a mold with silicate grains, the aluminum acts as a binding agent. So far, experiments have been conducted for basalt, basalt/anorthosite mix, and aluminum over silicate grains. Due to the anorthosite's high melting point of ~1,550–1,600 °C, pure highlands compositions have not been done; we are currently preparing a furnace that can reach these temperatures. Only the basalt and basalt/anorthosite mixture melts will be discussed here, but we anticipate presenting results for the full set of experiments.

**Basalt Casting**: A typical pour includes 2-3 kg of coarse grain (.5 – 1 cm) basalt in a 5 kg silicon carbide (SiC) crucible and fired in a natural gas furnace. So far there have been 7 basalt pours, at various temperatures. Several molds have been tested including an open-faced green sand mold, a closed green sand mold, and a ceramic shell. Several molds are made for each pour, usually providing 3-4 materials. Fig. 1 shows CSM students pouring molten basalt regolith simulant into an open-faced green sand mold.

*Fig. 1 Basalt pouring into an open-faced green sand mold.*

**Basalt/Anorthosite Mix Casting:** Highland-type regolith is made up of 90–100% Ca-plagioclase feldspar (anorthite), and ~10% of mafic minerals such as pyroxene, ilmenite, and olivine [3]. Although anorthosite melting hasn't been attempted yet for this research, an anorthosite/basalt mixture has been. For these experiments, 3 kg of basalt and 2 kg of anorthosite were put into the crucible and melted.

**Results:** Results of the experiments are displayed in Table 1. Thus far there have been 7 pours. Each pour is characterized based on composition, temperature, mold type, and whether the material was annealed or not.

*Table 1. Results of each pour and their characteristics based on temperature, composition, mold type, and whether the materials were annealed or not.*

| Basalt (B) / mixed (B/A) | Temp. °C | Mold | Annealed (?) | Material Characteristics |
|---|---|---|---|---|
| B | N/A | Open-faced green sand | N | Vitrified and shattered |
| B | N/A | Closed-faced green sand | N | Vitrified and shattered |
| B | N/A | Ceramic Silica Shell | Y | Non-vitrified and intact |
| B | N/A | Open-faced green sand | Y | Slightly vitrified, unshapely, and intact |
| B | 1,330 | Open-faced green sand | Y | Non-vitrified, better shape, intact |
| B | 1,330 | Open-faced green sand | Y | Non-vitrified and intact |
| B | 1,330 | Open-faced green sand | Y | Non-vitrified, well shaped, and intact |
| B/A | 1,350 | Open-faced green sand | Y | Vitrified and shattered |
| B/A | 1,360 | Open-faced green sand | Y | Non-vitrified, well shaped, and intact |

**Discussion:** The results of the first experiments produced completely vitrified materials that would heat tear or shatter completely upon cooling. This indicated that the material was too hot and needed to cool slowly. To facilitate this slow cooling process the basalt was poured and then taken to a kiln for annealing. Annealing has shown to significantly reduce the amount of vitrification and the number of noticeable defects in the cast materials. There are several pours that do not include data for temperature due to a lack of equipment. The temperature was gauged by sight, time in the furnace, and testing the viscosity with a steel rod. Later the temperature was taken using a stainless steel type-K thermocouple. Fig. 2 shows molten basalt in an open-faced sand mold before it was taken to annealing and Fig. 3 shows the final result of that material after annealing.


*Fig. 2 & 3: (2) Molten regolith poured into a green sand mold and (3) the result of that pour after annealing.*

The ceramic mold was easier to pour into and place into the kiln. This mold was not reusable; however, it did seem to yield the best results in terms of shape, and intactness, but when it was cut into, it proved to be very porous. Fig. 4 shows a basalt cylinder broken out of its ceramic shelling after annealing.

After several pouring attempts the materials became well-shaped and less vitrified, however, it was noted that for every pour the first material made was always highly defective containing a porous surface and some cracking. It was determined that the top layer of the melt was mostly gas and creates a sort of foam surface. To mitigate this issue the foamy layer is poured off into an ingot before being poured into a mold. Fig. 5 displays a cast basalt CSM "M" after trying to remove the foamy layer of the melt before pouring.


*Fig. 4 & 5: (4) Basalt cylinder poured and annealed in a silica-based ceramic mold. (5) Basalt "M" poured into an open-faced green sand mold and annealed.*

The first attempt at the basalt/anorthosite melt showed that adding anorthosite to the mix raised the melting temperature to ~ 1,350 °C, while still taking ~1 hr. to melt. The second attempt took over 2 hours to melt and reached 1,360 °C. There are a few reasons why melting took much longer than previously 1) possible shortage of available natural gas in the foundry, 2) large previously melted basalt samples were mixed in along with the anorthosite, which did not mix as well in the crucible possibly not melting as uniformly as the basalt grains. The materials that came from this melt were mostly well-shaped except for some warping from removing the materials from the mold to the kiln. The mixing of the basalt and the anorthosite yielded slightly vitrified materials, darker than those made from just basalt, and in some cases better formed than the previous materials. Fig. 6 shows 2 CSM "M's" and 2 tiles. Tile 3 shows a clear warping defect on its left side, caused by removing the material from the mold while it was still too hot.


*Fig. 6 Basalt/anorthosite mix pour into a green sand mold and annealed. Slight warping from removing the molten material from the mold and placed into the kiln.*

**Discussion**: More testing will be needed for both basalt and basalt/anorthosite mix pouring such as molding materials, annealing schedules, temperature, and accuracy of pouring into the molds. Thin sections will be cut to compare the mineral structures of unmelted basalt/anorthosite compared to melted. Other plans include Scanning Electron Microscope (SEM) testing and eventual strength testing.

**References:** [1] Kopecký, L., & Voldan, J. (1965). The cast basalt industry. *Annals of the New York Academy of Sciences*, *123*(2), 1086-1105. [2] Isnugroho, K., Hendronursito, Y., & Birawidha, D. C. (2018). Characterization and utilization potential of basalt rock from East-Lampung district. In IOP Conference Series: Materials Science and Engineering (Vol. 285, No. 1, p. 012014). IOP Publishing. [3] Xu, X., Hui, H., Chen, W., Huang, S., Neal, C. R., & Xu, X. (2020). Formation of lunar highlands anorthosites. Earth and Planetary Science Letters, 536, 116138.