THERMAL AND RHEOLOGICAL PROPERTIES OF LUNAR SIMULANTS FROM AMBIENT TO MOLTEN TO GLASS. Alan. G. Whittington[1], Aaron A. Morrison[1], Anis Parspapoor[1], and Austin Patridge[1], [1]HAMsTER lab, Department of Earth and Planetary Sciences, University of Texas at San Antonio, alan.whittington@utsa.edu.

Introduction: In-situ resource utilization (ISRU) of lunar regolith, to make bricks for construction, glass for various applications, etc., is studied on Earth using a range of simulants that vary in their chemical and mineralogical properties [1,2]. The lunar regolith also varies in composition, most notably between basaltic mare and anorthositic highlands terranes [3], but with additional complexities due to regional-scale internal chemical anomalies (e.g. the Th-rich Procellarum-KREEP terrane) and lateral mixing via impacts, which also produce impact glass and agglutinates. We previously studied the melting behavior of mixtures of JSC-1A basalt and Stillwater anorthosite [4], and found that bulk chemical composition and glass content are both important in determining the energy required to achieve sintering and melting.

Here we characterize the thermal and rheological properties of several mare (JSC-1A, JSC-2A, OPRL2NT, LMS-1, LMT-1, LCATS-1) and highland (CSM-LHT-1, LHS-1, NU-LHT-2M, NU-LHT-5M, Stillwater norite, Stillwater anorthosite, Shawmere anorthosite and agglutinate-LHT) simulants, to assess their variability as a function of chemical and mineralogical composition over a much wider range. These experimental data also serve to test the predictions of models that are typically calibrated on terrestrial materials [5].

Methods: Simulant powders were characterized using X-Ray Diffraction (XRD) for mineralogy, X-ray Fluorescence (XRF) for chemical composition, helium pycnometry for density, and Differential Scanning Calorimetry (DSC) for heat capacity and enthalpy of fusion. The viscosity of some molten samples was determined using concentric cylinder viscometry with a rotating spindle (RSV), and thermal diffusivity of quenched glasses was determined using light flash analysis (LFA).

Results: Most simulants contain a combination of plagioclase, olivine, and pyroxene, the most abundant minerals on the Moon, and some fraction of basaltic glass. The anorthosites are dominated by plagioclase feldspar, and contain no glass. Highlands simulants are generally a mixture of basaltic and anorthositic material.

Heat capacity. When heated at 30˚C/minute, most mare simulants show a small glass transition bump at ~700˚C, a small release of latent heat of crystallization around 800-900˚C, and melting between ~1100 and 1300˚C with the peak around 1150-1200˚C (Fig. 1). LMS-1 peaks at about 1300˚C and requires a higher temperature than other simulants to achieve complete melting, and apparently contains little glass.

When heated at 30˚C/minute, most highland simulants show a barely detectable glass transition around 750˚C, a barely detectable crystallization trough above that, and undergo melting between ~1200 and 1400˚C with a peak around 1300˚C (Fig. 2). The agglutinate-LHT is very glassy, shows a strong glass transition feature around 750˚C, followed by crystallization at ~1000˚C, and remelting between 1150-1450˚C, peaking around 1250˚C. The crystalline Stillwater and Shawmere anorthosite samples only start melting at about 1400˚C, and melt completely at ~1500˚C.

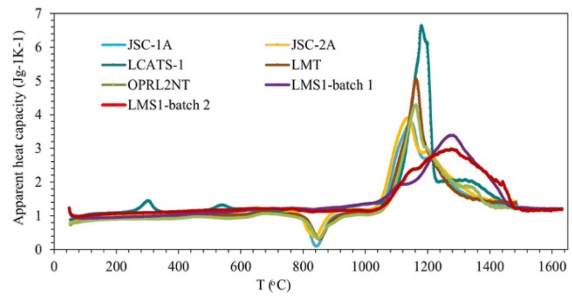

Figure 1. Apparent heat capacity data for mare simulants

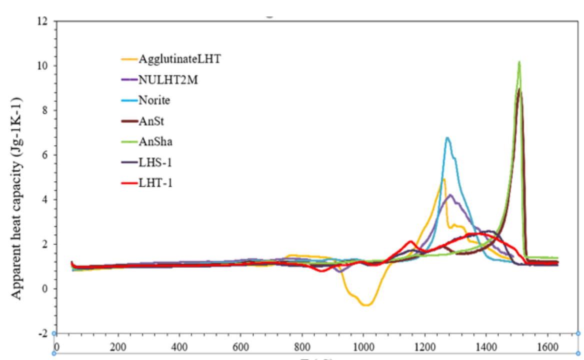

Figure 2. Apparent heat capacity data for highland simulants

Viscosity. Highland simulants are more viscous than mare simulants at a given temperature, although the range in mare simulants is quite large, with LMT-1 being most viscous and the melilite olivine nephelinite LCATS-1 being the least viscous (Fig. 3). The Ti-rich

OPRL2NT is only slightly less viscous than LMS-1. Above the liquidus, most melt viscosities are between 1 and 30 Pa s.

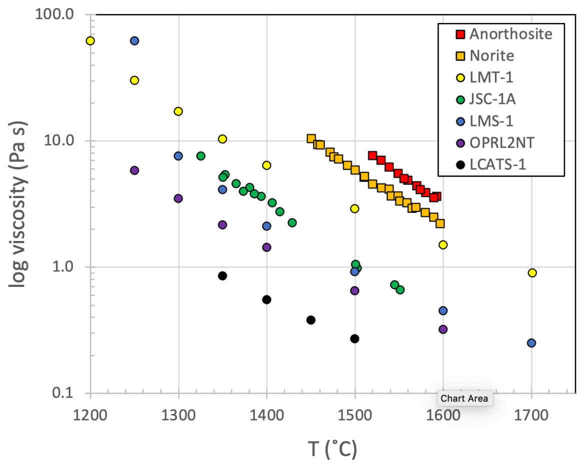

Figure 3. Viscosity data for highland simulants (anorthosite, norite from Stillwater [6]) and mare simulants (JSC-1A data from [6])

Differences between simulants and terrestrial rocks: We found the properties of simulants could be reasonably well predicted using models for heat capacity [7,8] and viscosity [9,10] that are calibrated on igneous compositions.

Bulk composition. Mare simulants are not too different from terrestrial basalts, which often form some (or all) of their constituents. Highlands simulants can have high liquidus temperatures approaching 1500˚C due to the high anorthite content, which takes them outside the realm of traditional igneous compositions. Impacts can produce melts of anorthosite composition on the Moon so data on the properties of these melts is pertinent for both scientific and engineering applications.

Agglutinates. Plutonic igneous rocks on Earth are typically holocrystalline, while many volcanic samples are partially glassy. Agglutinate particles make up ~30-50% of regolith samples [3] and these will allow sintering and crystallization to occur at ~800-1000˚C. Terrestrial basalt materials may provide reasonable chemical analogs of the agglutinates for mare, but probably do not work so well for the highlands, which should contain feldspathic agglutinates.

Discussion: Thermal properties of simulants vary considerably as a function of composition and glass content. Variability within each group (compare JSC-2A or LMT-1 vs. LMS-1 for mare; and NU-LHT-2M vs anorthosite for highlands) is as great as differences between these groups. Differences between fully crystalline and substantially glassy starting materials also affect melting behavior very strongly (compare NU-LHT-2M vs agglutinate-LHT for highlands).

Once fully molten, viscosities may vary by an order of magnitude between mare and highlands, similar to the effect of varying temperature by ~200˚C. If viscosity needs to be tuned for a particular application, modest temperature variations can compensate for variability in melt composition.

Conclusions: Designs for ISRU processes that can work with raw materials encompassing the range of glassy basalt to crystalline anorthosite should accommodate most lunar regolith, although some aspects of lunar chemistry (e.g. very low K contents) cannot be replicated with terrestrial rocks.

Acknowledgments: This work was supported by NASA STTR 21-1-T7.04-1428 KSC and a subcontract from Physical Sciences, Inc, via from Astroport Space Technologies.

References: [1] Lunar Simulant Database, https://simulantdb.com/. [2] Blewett D. et al. (2021) *2021 Lunar Simulant Assessment,* 43 pp., JHU APL. [3] McKay D.S. et al. (1991) in *Lunar Sourcebook: A User's Guide to the Moon*, 475–594. [4] Whittington A. G. and Parsapoor A. (2022) *New Space, 10*, 193-204. [5] Schreiner S. S. et al. (2016) *Adv Space Res, 59,* 1209-1222. [6] Morrison A. A. et al. (2019) *Icarus, 317,* 307-323. [7] Richet P. (1987) *Chem. Geol*., *62*, 111-124. [8] Stebbins J. F. et al. (1984) *Contribs. Mineral. Petrol*., *86,* 131-148. [9] Giordano D. et al. (2008) *Earth Planet. Sci. Lett., 271,* 123–134. [10] Sehlke A. and Whittington A. G. (2016) *GCA*, *191*, 277-299.