FROM REGOLITH TO LIVING OFF THE LAND: FORMULATING A DATA MODEL TO CATALOG LUNAR CONSTRUCTION MATERIALS.

R. D. Lomboy[1] and S. J. Seitz[1], [1]NASA Ames Research Center, Moffett Field, CA 94035, sarah.j.seitz@nasa.gov

Introduction: Artemis Program objectives for sustainable, long-term presence on the Moon [1] and more distant planetary surfaces will require learning to "Live off the Land", relying on in-situ resource utilization to produce infrastructure and building materials from lunar regolith, icy subsurface deposits, and residual waste materials [2]. Meeting demand for consumables while scaling development with resources found within the landing zone will require detailed data on the geology and environment of the lunar surface. Lunar infrastructure development will generate vast amounts of new engineering data regarding availability of processed feedstocks and their performance in building materials. Lunar engineering data accessible to program partners, research institutions and industry may help situate processes and specifications within the in-situ GIS context. Lunar missions to date have generated geological [3] and ice favorability maps [4] of the lunar surface, and recent technology studies have tested automated construction systems [5, 6] and novel material formulations using regolith simulants and binders [6, 7, 8, 9]. Current discussions focus on identifying key feedstocks, quantities required for nominal mission scenarios and infrastructure plans, and mapping the value chain from regolith to feedstock to consumables and construction materials [10].

This study has reviewed features of select databases and repositories currently in use for mapping planetary exploration sites and cataloging performance of materials. Guiding questions have included:

1. How does technical knowledge get captured as builders iterate and evolve ideas?
2. How might we generalize the approach from designing for Earth or the Moon to designing with unknown materials in new planetary environments?
3. What are the best data model examples we can draw on for thinking about lunar materials, and what are their useful features?
4. What kinds of data models will be needed to support a transition from mapping and sampling surface regolith to manufacturing and building in-situ?

Databases and Tools Surveyed: The following categories of databases were explored as models for desirable features and capabilities:

1. Lunar and terrestrial surface geology and mineralogy
2. Planetary simulant materials and analog site studies
3. Engineering and testing values for construction materials
4. User-generated recipe databases documenting experimentation with ceramic materials

Key content and capabilities of each database are summarized in **Figure 1**.

Ceramics Databases. Glazy and DigitalFire are ceramics databases that allow users to input material information and recipe formulations [11, 12, 13]. Both offer users control over custom material and recipe creation, providing interfaces to select materials and adjust proportions. Users can also compare materials to similar compounds if an ingredient substitution is needed. Recipe fields in Glazy include recipe name, material name and proportion, glaze description, type and subtype, transparency, firing temperature, firing atmosphere, specific gravity, location of tests, and revision of prior recipes. Data inputs in DigitalFire include recipe name, material name and proportion, chemical composition, variation on prior recipes, physical test data, usage notes, and pictures.

USGS Geospatial Databases. The Mineral Resources Data System (MRDS) displays records of raw mineral resources indicating location, type, and production information [14]. The Terrestrial Analogs Data Portal (TADP) contains descriptions, datasets, and resources for terrestrial analog studies [15, 16].

Simulants Databases. The Planetary Simulants Database (PSD) contains records of past and present regolith simulants, including their mineralogy, bulk chemistry, and physical properties, as well as details of where and by whom they are manufactured [7].

Materials Engineering Databases. For materials in its database, TotalMateria displays specifications and manufacturer information, with suggestion of suitable substitutions if necessary. It provides mechanical performance data for multiple test and specimen types with stress diagrams, fatigue and fracture test data that support engineering calculations [17]. Likewise, studies of the geopolymers catalogued in the UC Irvine Concrete Machine Learning Dataset using neural networks offer performance data based on adjustment of experimental variables [18].

Capabilities and Criteria: Data entry fields for user-sourced in-situ resource materials database might include serialized batches, specimens or instances, geolocated records, indication of test standard or equipment. These data may be input via guided data entry forms, linked via API to other data interfaces, or exported to standard file formats and engineering software. For calculation of engineering values, it will need to identify the types of tests performed and the conditions under which the tests were performed. It will be helpful to be able to distinguish between tests performed using simulants or analog site environments, and between tests conducted in terrestrial ambient conditions, cryochambers, thermal vacuum chambers, or in low- or zero gravity. **Figure 2** provides a matrix indicating which of the databases reviewed provide the features desirable in a lunar value chain database.

In the lunar context, this database would need to consist of: raw material data for in-situ, excavated regolith and processed feedstocks; formulations for other building materials to be manufactured on the lunar surface; data on processes and equipment for lunar building material manufacturing; details of materials preparation, test sites and test dates for each formulation and specimen. Industry engagement could be encouraged by providing user accounts featuring test history, preferred recipes, and compatibility with autonomous hardware, as well as mapping of feedstocks upstream and nominal demand downstream.

Recommendations & Next Steps: This study has formulated a preliminary framework for capturing and linking datasets to track lunar materials from exploration and extraction through their lifecycle in lunar infrastructure. Additional surveys of geopolymer databases, particularly those in use by the construction 3D printing industry, would be helpful, alongside surveys of supply chain planning and monitoring tools.

Further planning of surface infrastructure development, construction operations and optimization of resource use will require a means to: 1) map and model the materials supply chain and availability of individual feedstocks, 2) model performance of materials with minor variations in composition, preparation, and manufacturing, 3) catalog the characteristics and performance data that define these raw feedstocks and manufactured material formulations in orderly fashion, indicating possible trades and substitutions within the infrastructure system at any given stage of development, and 4) optimize utilization of materials, energy, and hardware resources throughout the scaling of lunar infrastructure development. It is hoped that thoughtful design of interfaces to engage stakeholder users and log experimentation with novel lunar materials will serve to validate designs adapted to in-situ conditions, capture new knowledge to apply toward further exploration, and contribute to generation of a digital twin for the lunar materials value chain.

Acknowledgements: This work has been supported by NASA's AAFTER ISFM and the MUREP program through NASA's Office of STEM Engagement.

References: [1] NASA (2020). *Artemis III SDT Report*. NASA/SP20205009602. [2] NASA (2023). *M2M Strategy & Objectives*. AS-3, LI-7, LI-8, OP-3. [3] Moriarty & Petro (2023). LSSW Artemis III. 2023. [4] Cannon & Britt (2020). Icarus 347. [5] Yashar et al. (2022). ASCE E&S. [6] Clinton et al. (2022). *MMPACT*. IAC2022. [7] Planetary Simulants Database (2022) simulantdb.com [8] Seitz et al. (2022). ASCE E&S. [9] Dhakal et al. (2021). ASCE E&S. [10] LSIC (2023). ISRU Focus Group. [11] Moradi et al. (2022) Glaze Epochs. 10.1145/3490149.3501310 [12] Au, Derek. (2015) *Glazy*. glazy.org [13] Hansen, Tony. (2012) *DigitalFire*. digitalfire.com [14] USGS. (2022) *Mineral Resources Data*. mrdata.usgs.gov [15] USGS. (2022) *TADP*. tadp.astrogeology.usgs.gov [16] Baker et al. (2021). 5PDW. 7046. [17] TotalMateria (2023) totalmateria.com [18] Yeh, I. (2006) ASCE-JMCE. 10.1061/(ASCE)0899-1561(2006)18:4(597)

Database or Tool Name:	Material Types	Material Formulations	Mineralogy	Geochemistry	Chemistry	Material Mining & Mfg Data	Engineering Values	Procurement Info	Individual Instances
Glazy	Ceramics - Clays & Glazes	x		x	x	x			x
DigitalFire	Ceramics - Clays & Glazes	x		x	x				x
Planetary Simulants Database	Regolith Simulants		x	x	x	x		x	x
USGS Mining Data	Raw Mineral Resources		x	x	x	x		x	
USGS Terrestrial Analogs Data Portal	Field Science Data & Descriptions		x	x		x		x	
TotalMateria	Metal Alloys, Plastics, Composites			x	x		x	x	x
UC Irvine Concrete ML	Concrete & Geopolymers	x		x			x		x

Figure 1 *– Content of Materials Databases.*

Database or Tool Name:	User Accounts	Serialized Batch IDs	Geolocated Records	Multiple Test Types	Multiple Specimen Types	Data Entry via Form	Data Entry via Upload	Data Synth via API	Data Export
Glazy	x	x				x	x		x
DigitalFire	x	x		x	x	x	x		x
Planetary Simulants		x			x				
USGS Mining Data		x	x					x	x
USGS Terrestrial Analogs			x						x
TotalMateria	x	x		x	x				x
UC Irvine Concrete ML					x				x

Figure 2 *– Database Functionality Criteria Comparison.*