Acta Astronautica 131 (2017) 45–49

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

Development of a Martian regolith simulant for in-situ resource utilization testing

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ARTICLE INFO

Keywords:
Mars
Regolith
Simulant
Basalt

ABSTRACT

Long-term human habitation of Mars will require in situ resources for construction and infrastructure development. In order to determine how to utilize in situ resources, such as Martian regolith, these materials need to be synthesized on Earth for testing and development. Here we address the process of synthesizing a targeted Martian simulant (i.e., Gusev Crater regolith near the Columbia Hills region on Mars) in sufficient quantities required for infrastructure development studies using volcanic material obtained from Banks Peninsula, New Zealand. Martian simulant produced via crushing, sieving, washing and blending of basalts and volcanic glass resulted in accurately reproducing material similar in particle size, chemistry and mineralogy to Gusev Crater regolith. Overall, our applied approach to synthesizing Martian regolith will aid in creating suitable quantities of material that can be used for a variety of research applications such as assessing aggregates for use in the production of construction materials.

1. Introduction

Martian regolith is an essential consideration for future Mars colonization operations either to be used as building material or as a surface cover for vehicular travel. In order to begin assessing how to utilize in situ resources such as regolith on Mars, simulants need to be recreated on Earth for testing and development purposes. Major objectives of past and current Mars surface missions have been directed towards characterizing the chemical, mineralogical and physical properties of the regolith on Mars. As demonstrated in these studies, Martian regolith has considerable chemical and mineralogical variation [1,2]. A single regolith simulant is not capable of representing the entire surface and while a number of simulants have been developed [3–7], there is a need to develop and produce a variety of other simulants representing other Martian terrains.

A wide range of possible applications for lunar regolith simulants have been identified and are summarized as follows [8]:

1. Physical regolith processing (drilling, excavation, handling and transport, crushing, beneficiation).
2. Testing of mobility systems such as rovers. The properties of the regolith are important not just for issues relating to traction but also the effects dust deposition and accumulation in joints, bearings and on other surfaces such as radiators and fenders which affects normal operation.
3. Resource processing – extraction and transformation of the regolith.
4. Radiation shielding and micrometeorite impact.
5. Dust mitigation.
6. Toxicity of dust.

While the development of the list of potential uses for regolith simulants was intended for lunar applications the list is equally useful for the study of Martian regolith simulants.

The proposed application of a regolith simulant, whether that be in a rover testbed or as a possible in situ construction material, will determine which properties of the material are the most important and suitability of the specific simulant. For example, Brunskill et al. [7] and Perko et al. [6] have investigated the mechanical properties and suitability of a number of simulants for possible use in a rover testbed. The specific mechanical properties of the regolith will have a greater influence on the traction and motion of the rover than the chemical or mineralogical properties of the regolith. Sullivan et al. [9] state that the two fundamental parameters relating to regolith mechanical behaviour are; (a) the friction angle, which is influence by the grain shape, angularity and sorting, and (b) the cohesion which can be affected by issues such as cementation, chemical bonding and electrostatic attrac-

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http://dx.doi.org/10.1016/j.actaastro.2016.11.024
Received 5 August 2016; Accepted 14 November 2016

tion.

When considering regolith as a construction material, particularly if used as an aggregate in the production of lunar [10] or Martian concrete, the chemical and mineralogical properties may be as important if not more so than the mechanical properties. Aggregate (regolith) when used in concrete construction is generally intended to act as inert fillers held together by a binding agent, typically a calcium silicate based cement. A number of types of aggregates, however, are known to be susceptible to alkali silica reaction (ASR) where the alkali present in the cement react with certain silica phases in the aggregate to cause expansive pressures, cracking and eventually failure of the concrete [11]. If a particular source of regolith is going to be used for in situ resource utilization some consideration must be given to possible reactions with the proposed binder. The regolith simulant used for the testing of various construction techniques, therefore, should be sufficiently representative of the intended in situ material to prevent unforeseen and potentially catastrophic failures.

The objective of our study is to develop an approach to create custom or targeted Martian regolith simulants and do so in quantities from 10 kg to several hundred kilograms that can be utilized for infrastructure development studies on the suitability of the target regolith as a construction material. The chemical and mineralogical characteristics of the simulant, in addition to grain size distribution which can influence the binder requirements, are the primary factors under consideration in this investigation. In this study we have chosen to produce Martian regolith simulant representative of material identified in the Columbia Hills region of Gusev Crater using olivine basalt and volcanic glass from Banks Peninsula, New Zealand. The chemical composition of three existing simulants; JSC-Mars1, Mojave Mars Simulant (MMS) and Jining Martian Soil Simulant (JMSS-1), along with Martian regolith results from the Spirit rover are provided in Table 1.

The Gusev Crater was chosen as the target for the regolith simulant partially due to the variety of minerals found in the area. Some of these minerals may prove particularly valuable in the production of future Martian habitats and infrastructure. For instance, carbonate concentrations in the range of 16–34% have been identified in the Columbia Hills region [14]. With some processing these carbonated may be useful as a feedstock in the production of binders for construction applications.

The subsurface soil in the Gusev crater, determined from disturbed soil exposed by the Spirit rover's tracks, is considered to be composed of approximately 45% pyroxene, 40% sodic to intermediate plagioclase and 15% olivine (Fo_{45}) [15]. Additionally, the mineralogy of the three specific rock samples investigated at the Spirit landing site in the Gusev crater are basalts containing olivine, pyroxene, and plagioclase in addition to iron titanium oxides. Mini-TES spectra suggest the dark portions of the Adirondack and Humphrey rocks are intermediate olivine with a forsterite composition between 30% and 60% [12].

Table 1
Range of chemical composition of Martian rocks and soil investigated by the Spirit rover in the Gusev crater along with three existing regolith simulants.

	Average rock values[a]	Average soil values [13]	JSC-Mars1 [3]	MSS [4]	JMSS-1 [5]
SiO_2	45.5	45.8	43.5	49.4	49.3
TiO_2	0.48	0.81	3.8	1.09	1.78
Al_2O_3	11.0	10.0	23.3	17.1	13.6
Fe_2O_3			15.6	10.9	16.0
FeO	15.3	15.8			
MgO	12.1	9.3	3.4	6.08	6.35
CaO	7.60	6.10	6.2	10.45	7.56
Na_2O	2.9	3.3	2.4	3.3	2.9
K_2O	0.06	0.41	0.6	0.48	1.02
Cl	0.12	0.53			
SO_3	0.75	5.82		0.1	

[a] Average rock values based on reported data by McSween et al. [12].

2. Materials and methods

Rock samples were collected from a number of areas in the Banks Peninsula located on the South Island of New Zealand. These rocks were examined by petrological microscopy and Energy-Dispersive X-ray spectroscopy (EDS) analysis at the University of Canterbury to identify crystal properties and measure their composition. The measurements were acquired using an Oxford Instruments X-Max EDS detector mounted upon a JEOL 6400 Scanning Electron Microscope. Settings include 45× magnification, 15 mm working distance, a 20 nA beam current, and 20 kV accelerating voltage. The major elementals were determine by X-ray florescence spectroscopy.

The particle size distribution (PSD) for particles greater than 300 µm were determined by sieve analysis while the PSD for the smaller particles was obtained from a HORIBA LA950 particle analyzer. A refractive index of 1.60-0.00i was selected which was in the range of 1.55-0.004i [16] and 1.8-0.02i [17] reported by Mariner 9 during a dust storm.

A hydraulic press was used to break the large rocks into sizes (< 50 mm) capable of being processed in a Boyd jaw crusher. The crushed rock samples were further processed with a Van Gelder 200 mm disk pulverizer (plate mill) operating at 850 rpm with a capacity of up to 30 kg/h.

3. Results and discussion

The Banks Peninsula in the South Island of New Zealand was formed from the twin volcanoes of Lyttelton and Akaroa in a series of eruptions starting approximately 32 m yr ago [18]. There are a variety of rocks types available for selection in the Banks Peninsula including: basalt, hawaiite, mugearite, benmoreite, trachyte and volcanic glass in addition to rhyolite which was not associated with the main volcanic dome building eruptions. The major elemental and mineralogical components of representative rocks are provided in Table 2. This range of rock types (including crystalline to glassy material) available in the Banks peninsula is representative of much of the geological diversity found on Mars and provides an ideal base to recreate a wide

Table 2
Major element oxide and mineralogy of the representative Banks Peninsula rocks [18].

Element	1 Mugearite	2 Hawaiite	3 Rhyolite	4 Basalt	5 Trachyte	6 Volcanic glass[a]
SiO_2	58.3	56.8	76.2	44.2	69.4	74.3
TiO_2	1.7	1.8	0.1	3.0	0.2	0.1
Al_2O_3	15.3	14.1	12.3	13.3	13.7	12.3
Fe_2O_3	2.7	3.8	0.5	4.5	2.5	1.2
FeO	5.9	4.1	0.7	8.6	1.4	
MnO	0.1	0.1	0.0	0.2	0.1	0.1
MgO	2.2	2.0	0.1	9.2	0.1	0.1
CaO	4.8	5.0	0.3	10.7	0.4	0.4
Na_20	4.2	2.8	3.5	3.3	5.8	3.5
K_20	3.0	1.6	4.7	0.9	4.9	4.9
P_20_5	0.5	0.5	0.1	0.7	0.1	< 0.1
$C0_2$	0.3	0.3	0.3	0.2	0.2	3
Total	99.0	92.9	98.9	98.6	98.8	99.9
Mineralogy						
Orthoclase	17.7	9.5	27.8	5.6	29.1	
Plagioclase	49.7	44.4	30.0	37.0	42.8	
Pyroxene	13.8	6.6	1.1	22.9	0.6	
Olivine	0.0	0.0	0.0	11.7	0.0	
Magnetite	3.8	5.5	0.8	6.5	0.9	
Total	85.0	66.0	59.7	83.7	73.4	

[a] XRF values for volcanic glass measured separately, not reported by Price and Taylor [17].