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ScienceDirect

Advances in Space Research xxx (2018) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Study of the rheological properties of water and Martian soil simulant mixtures for engineering applications on the red planet

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Received 12 September 2017; received in revised form 14 December 2017; accepted 27 December 2017

Abstract

The rheological properties of mixtures of water and the Martian soil simulant *JSC-Mars-1A* are investigated by preparing and testing samples at various solids concentrations. The results indicate that the dispersion is viscoelastic and, at small timescales (~0.1 s), reacts to sudden strain as an elastic solid. At longer timescales the dispersion behaves like a Bingham fluid and exhibits a yield stress. Hysteresis loops show that rapid step-changes (2 s duration) of shear-rate result in thixotropic behaviour, but slower changes (>10 s duration) can result in rheopexy. These observations are explained with the breakdown and recovery of the packing structure under stress. The rheological information is used to generate practical tools, such as the system curve and the Moody chart that can be used for designing piping systems, and calculating pump sizes and pressure requirements.

Keywords: Rheology; Thixotropy; Solid dispersion; Martian regolith simulant; In situ resource utilization (ISRU)

1. Introduction

As humans look towards the future of space exploration, the question of becoming a multi-planetary species emerges. This feat will require extensive technology development in order to create habitats that can sustain human life. One of the barriers to long term space exploration is the enormous expense and difficulty of transporting mass out of Earth's gravity well. In order to minimize the mass transported from Earth during these missions, the utilization of local resources (known as in situ resource utilization) must therefore be maximized. In this context, building materials deserve special attention since they are intrinsically heavy and usually required in large quantities.

A promising solution involves utilising local regolith for the production of construction material. A number of studies focus on the production of cementitious materials from Lunar regolith simulants (e.g. Happel, 1993; Cesaretti et al., 2014; Montes et al., 2015; Alexiadis et al., 2017) or Martian regolith simulants (e.g. Mukbaniani et al., 2015; Lin et al., 2016; Alexiadis et al., 2017). In the case of the Martian simulant in particular, alkaline suspensions of the JSC Mars-1A simulant are known to form aluminosilicate gels that, upon curing, result in a hard solid with a compressive strength comparable to that of normal construction bricks.

However, the actual production of these materials necessitates handling the regolith in slurry or paste form, and so the rheology of water-regolith dispersions must be understood for optimal design of associated transport and process equipment such as pipes, pumps and mixers. Additionally, 3D printing is the latest trend in the

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https://doi.org/10.1016/j.asr.2017.12.037
0273-1177/

Please cite this article in press as: Taylor, L., et al. Study of the rheological properties of water and Martian soil simulant mixtures for engineering applications on the red planet. Adv. Space Res. (2018), https://doi.org/10.1016/j.asr.2017.12.037

construction industry and it has been proposed for constructing off-Earth habitats (Leach et al., 2012; Cesaretti et al., 2014). A good understanding of the rheology is paramount also in this case. The fresh geopolymer must be extruded smoothly and each bead must hold its shape during the printing process. Moreover, the bead should also hold its shape when another bead is printed on top of it.

The behaviour of solid-liquid dispersions, especially when the solid phase is present in high concentrations, can be quite complex and includes occurrences such as shear-history dependent rheology (e.g. thixotropy or rheopexy), stick-slip, non-uniform packing distribution, and other phenomena, which have been collectively defined as *granulo-viscous* phenomena (Cheng and Richmond, 1978).

In this work, we study the properties of dispersions of water with the Martian dust simulant JSC Mars-1A. In particular, we focus on (i) the extent and timescales of history-dependent phenomena over a range of solids contents and shear rates, (ii) the existence of other time-dependent influences on viscosity (i.e. ageing), and (iii) characterize the underlying slurry rheology over a range of solids contents. As a high pH induces geopolymerization, a preliminary investigation into the rheology of an alkaline suspension is also undertaken.

These data are then converted into the *system curve* and the *Moody chart* of the fluid, which can be used to optimise the design and operation of slurry handling equipment.

2. Materials and methods

This section is organized as follows. Section 2.1 describes the preparation and composition of the samples used in rheological testing. Since geopolymerization of JSC-Mars-1A requires milling to reduce the particle size, all the rheological tests were carried out with milled simulant; the size distribution after milling is shown in Section 2.2, while the methodology of the rheological tests performed are described in Section 2.3.

2.1. Samples

The Martian simulant used is *JSC-Mars-1A* (Orbitec, USA). It is mined from the Pu'u Nene cinder cone in Hawaii, and was designed to be a spectral analogue of the 'bright regions' of Mars. The elemental oxide composition of the simulant as measured by Allen et al. (1998) is shown in Table 1 and is compared to a typical Martian regolith composition (Taylor and McLennan, 2008). During this study, the simulant was first milled, and then water was added to form a suspension. The standard procedure used for rheological testing required that these samples were tested shortly after preparation. However, some samples were tested after a number of days of exposure to water, to study ageing effects as discussed in Section 4.4. The samples used in the experiments are reported in Table 2. The concentration range was chosen on the basis of our previous work on geopolymerization (Alexiadis et al., 2017). For the geopolymer experiments (Section 4.5), sodium hydroxide pellets were dissolved into the $\phi = 0.39$ sample to form an 8M NaOH suspension.

Table 1
Comparison of elemental oxide compositions of JSC-Mars-1 (Allen et al., 1998), and the average Martian regolith composition (Taylor and McLennan, 2008).

Oxide [wt%]	Martian Simulant JSC Mars-1A	Martian Regolith
SiO_2	43.7	45.41
TiO_2	3.8	0.91
Al_2O_3	23.4	9.70
Fe_2O_3	11.8	–
FeO	3.5	16.73
MgO	3.4	8.35
CaO	6.2	6.37
Na_2O	2.4	2.73
SO_3	–	6.16

Table 2
Composition of the samples investigated.

Dry solids [g]	Total water [g]	Solids content [wt%]	Volume fraction ϕ [–]	Density ρ [kg m^{-3}]
50	20	71.4	0.49	1769
50	21	70.4	0.48	1750
50	22	69.4	0.47	1732
50	23.5	68.0	0.45	1706
50	25	66.7	0.44	1685
50	27	64.9	0.42	1652
50	31	61.7	0.39	1601

2.2. Milling

A *Pulverisette 5* planetary ball mill (Fritsch, Germany) was used for comminution. For each grind, 100 g of powder was loaded into a 250 mL grinding vessel with 500 g of 3 mm stainless steel media. The grind was run at 200 rpm for 30 min. This was repeated until around 700 g of dust was acquired, which was subsequently mixed together. The particle size distribution of this mixture was measured using a *Malvern Mastersizer 2000* laser diffraction particle size analyser (Malvern Instruments, UK), the results of which are shown for both the unground and ground simulant in Fig. 1a ($d_{50} = 10.1$ μm). Fig. 1b shows a representative SEM image of the milled regolith.

2.3. Rheological measurements

An AR-G2 rheometer (TA Instruments) was used for rheological testing. A vane spindle geometry was used since it mitigates jamming from large particles, and wall slip in yield stress fluids is less problematic than in other geometries (Barnes and Nguyen, 2001; Saak et al., 2001). A number of alternative tests were carried out with both parallel-plate and cone-and-plate geometries, but results were not reproducible as for the vane spindle and, therefore, disregarded.

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