



Geopolymers from lunar and Martian soil simulants

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Abstract

This work discusses the geopolymerization of lunar dust simulant JSC LUNAR-1A and Martian dust simulant JSC MARS-1A. The geopolymerization of JSC LUNAR-1A occurs easily and produces a hard, rock-like, material. The geopolymerization of JSC MARS-1A requires milling to reduce the particle size. Tests were carried out to measure, for both JSC LUNAR-1A and JSC MARS-1A geopolymers, the maximum compressive and flexural strengths. In the case of the lunar simulant, these are higher than those of conventional cements. In the case of the Martian simulant, they are close to those of common building bricks.

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1. Introduction

Plans for long-term planetary or lunar outposts require the creative use of the available resources for sustainable human existence outside our planet. In this context, building materials deserve special attention since they are intrinsically heavy and usually required in large quantities. Therefore, their on-site production would reduce the amount of payload sent from Earth considerably.

As a building material for lunar structures, researchers have proposed Lunarcete (Happel, 1993); a concrete where lunar regolith, instead of sand, is used as an aggregate. An even more radical solution – because both the aggregate and the binder come from the regolith – would be the on-site production of building material by geopolymerization. With some notable exceptions (e.g. Montes et al., 2015), however, little attention has been given to the geopolymerization of the lunar regolith, and no attention at all has been given to the geopolymerization of the

Martian regolith. NASA has a renewed commitment to human missions to Mars, including investments in planetary research, enabling life support technologies, as well as the development of spacecraft and launch systems capable of carrying humans to Mars. Living and working on Mars is considered a solvable challenge, and the ability to construct human-habitable structures using planetary resources is a significant aspect of the problem.

This study focuses on the geopolymerization of both lunar (JSC LUNAR-1A) and Martian (JSC MARS-1A) dust simulants. In fact, the geopolymerization of JSC LUNAR-1A has generated new scientific questions. Can JSC MARS-1A geopolymerize as well? How high are the compressive and tensile strengths of the Martian geopolymer compared to that of the lunar geopolymer? How do they compare to commercially available cement?

2. Geopolymerization

Geopolymers are a class of cementitious materials formed by the reaction of an alkaline solution with an aluminosilicate source such as fly ash or red mud, which today

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are considered as a potential alternative for replacing traditional structural materials (Davidovits, 1994).

The process of geopolymerization starts with silalate ($-\text{Si}-\text{O}-\text{Al}-$) or silalate-siloxi ($-\text{Si}-\text{O}-\text{Al}-\text{O}-\text{Si}-$) monomers in solution that join together to form inorganic polymers with properties similar to those of Portland cement. In general, geopolymerization is a complex process, involving three main steps: (i) alkali activation, which consist in the dissolution of amorphous aluminosilicates by alkali to produce monomers; (ii) reorientation, which consists in the transportation, orientation, and condensation of monomers into oligomers; and (iii) polycondensation, where the whole system hardens into an inorganic polymeric structure (Xu and Van Deventer, 2002).

Any material with high fractions of silica and alumina in amorphous (glassy) form could, in principle, geopolymerize. The composition of both JSC LUNAR-1A and JSC MARS-1A is shown in Table 1 (Allen et al., 1998; Gustafson, 2009); in both cases, the major components are SiO_2 and Al_2O_3 . Moreover, both simulants are collected from glassy volcanic ashes and have a high amorphous content. Ideally, geopolymers should have a stoichiometric Si/Al ratio of 1, 2 or 3 (Davidovits, 1994): the lunar simulant has a Si/Al ratio around 2.5, the Martian around 1.6. All these considerations suggest that, at least in theory, both Lunar and Martian simulants should react with alkaline solutions to form geopolymers.

We prepared six samples (three with JSC LUNAR-1A and three with JSC MARS-1A) following the method given by Xu and Van Deventer (2002):

Sample 1, 30 g of simulant, 7 mL solution of water 8 M NaOH.

Sample 2, 20 g of simulant, 10 g of K_2SiO_3 , 7 mL solution of water 8 M NaOH.

Sample 3, 50 g of simulant, 10 g of K_2SiO_3 , 20 mL solution of water 4 M NaOH.

In Samples 2 and 3, K-silicate (K_2SiO_3) was added to obtain samples with various Si/Al ratios. NaOH solutions with different concentrations were used to obtain samples at various pH. After blending the different materials, a viscous fluid was obtained. The final mixture was dried at constant temperature of 80 °C for 3 h in a silicone stamp

(8 × 20 × 40 mm) and cured at room temperature for another 28 days.

The resulting product, for all three samples containing JSC LUNAR-1A, was a rock-like solid as expected in the case of geopolymerization. On the contrary, none of the samples containing JSC MARS-1A agglomerated, but produced a loosely cohesive assembly that easily crumbled when dry.

2.1. Effect of milling

Does this negative result imply altogether that geopolymers from Martian simulant cannot be produced? JSC MARS-1A has a good content of aluminosilicates, the Si/Al ratio is acceptable, and volcanic ashes with composition similar to JSC MARS-1A are known to geopolymerize producing materials with high mechanical strength (Tchakoute et al., 2013).

The lack of geopolymerization could originate from the larger size of JSC MARS-1A particles. The mean (volume averaged) particle size of the lunar simulant is around 190 μm, while that of the Martian is 295 μm. This indicates a lower contact area between the NaOH solution and the JSC MARS-1A particles and, therefore, slower alkali activation.

In order to test this hypothesis, the dust was milled to reduce the particle size and, at the same time, enhance reactivity by mechanical activation (Terzić et al., 2014). A planetary mill Pulverisette 5 by Fritsch GmbH was used for 30 min at 200 rpm followed by a 125 μm sieve to remove any larger particles left. This procedure was adopted for both simulants, and the new size distributions measured with a Malvern Mastersizer Particle Size Analyzer. Milling produced a tenfold reduction of the mean particle size, which decreased to 19 μm in the case of JSC LUNAR-1A and to 28 μm in the case of JSC MARS-1A. After milling, the particles of the two simulants present a very different morphology as indicated by Fig. 1 (images obtained with a SEM microscope Hitachi TM3030). The lunar particles have very sharp and jagged edges, the Martian particles tend to be more round.

The same procedure used before was applied to the milled simulants and, this time, both JSC LUNAR-1A and JSC MARS-1A samples produced solid blocks (Fig. 2).

2.2. FTIR data

To verify that the hardening of the material is actually due to geopolymerization, FTIR spectra of the original JSC LUNAR-1A and JSC MARS-1A dusts were compared with the corresponding agglomerated samples. Absorbance profiles were obtained with a Bruker Tensor 27 FTIR Spectrometer.

The peaks highlighted in Fig. 3 are typical of geopolymers (Montes et al., 2015; Zhang et al., 2012; Arioza et al., 2013; Cătănescu et al., 2012; Lee and van

Table 1
Chemical composition of JSC LUNAR-1A and JSC MARS-1A.

Oxide	JSC LUNAR-1A (wt%)	JSC MARS-1A (wt%)
SiO_2	46.7	43.7
Al_2O_3	15.8	23.4
CaO	9.9	6.2
MgO	9.4	3.4
FeO	8.17	3.5
Fe_2O_3	12.5	11.8
Na_2O	2.8	2.4
TiO_2	1.7	3.8
K_2O	0.8	0.6
P_2O_5	0.7	0.9
MnO	0.19	0.3

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