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Lunar regolith can allow the synthesis of cement materials with near-zero water consumption

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ABSTRACT

With the continuous development of science and technology and the human understanding of the moon, many scientists have planned the creation of a space station on the moon using lunar building materials. Environmental factors mainly include large temperature differentials, and the presence of a hard vacuum on the surface of the moon is a huge challenge for the performance of lunar building materials. Geopolymer materials have the following properties: approximately zero water consumption, resistance to high- and low-temperature cycling, vacuum stability and good mechanical properties. Additionally, they meet most of the requirements for use in the lunar environment. Here, we present a potential lunar cement material that was fabricated using volcanic ash and sodium hydroxide solution as activator, based on geopolymer technology. The compressive strengths of the volcanic ash geopolymer specimens processed for 24 h under vacuum conditions and 30 freeze-thaw cycles in liquid nitrogen are 45.53 and 44.95 MPa, respectively. Additionally, 98.61% of water could be recycled, in consistence with the water recycling-simulated lunar environment in the lab. Although volcanic ash is not equivalent to the lunar soil, we speculate that the alkali activation of lunar soil could be very close to that of volcanic ash because of their similar chemical and mineralogical composition. In summary, this study provides a feasible approach for the development of near-zero water consumption lunar cement materials based on geopolymer technology.

1. Introduction

The human exploration of the moon consists of three stages: “unmanned lunar probe”, “manned lunar-landing” and “establishing a base on the moon”. At present, the first two stages have been achieved; returning to the moon, development of the moon resources and establishing a moon base have become the competitive focus in the world's space activities. Considering the growing interest for space exploration, the moon will play a crucial role as a staging post for the next generation of human space exploration missions. The Chinese lunar exploration project has the same vision. The project is now in the manned landing stage, with a plan to establish a lunar base by 2030 (Ouyang, 2005). However, the surface environments of the moon and of the Earth are quite different; hence, establishing a lunar base is very challenging (Taylor, 2014; Wang et al., 2016). These lunar building materials will be designed and prepared based on the following primary considerations (Benaroya and Bernold, 2008): [1] resistance to severe lunar temperature cycles (102.4 K to 387.1 K), [2] stability in a vacuum environment, and [3] minimal water requirements.

Some scientists and engineers propose using cement concrete as building material of the lunar base, which was first reported by Beyer (1985). In general, cement materials develop hydrates and attain their bonding strength after mixing with a quantity of water of approximately 20% to 30% of the cement mass (Lea, 1971). However, the Lunar Prospector Mission team indicated that the moisture content in the regolith at the bottom of the crater might be between 0.3% and 1% of the mass (Chua and Johnson, 1998). Therefore, the utilization of material with high water demands, such as conventional concrete, is not realistic, and the cost is high. To address the water problem, sulfur concrete was also studied (Toutanji et al., 2012). However, the strength, durability and refractoriness of sulfur concrete are not good. Therefore, one of the important challenges is to find a type of lunar cement material that does not use or uses very small quantities of water and has an excellent mechanical performance under extreme conditions.

Geopolymers, introduced by Davidovits (1991) are a class of amorphous structural material synthesized using alkaline, alkali-silicate or phosphoric acid with solid alumina- and silica-containing precursor materials at or above ambient temperatures (Cui et al., 2011; Davidovits, 2008; Liu et al., 2010; Wang et al., 2015). Geopolymers have a 3-dimensional framework consisting of tetrahedral silica and alumina units linked by shared oxygen atoms. Geopolymers have received burgeoning attention during the recent decades due to their

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excellent physical, structural and thermal properties (Cui et al., 2011; Davidovits, 2008; Wang et al., 2015). Compared with traditional cement materials, the structure of geopolymers is formed via the dehydration–polycondensation process as opposed to combining with water to form a molecular structure. Additionally, the final geopolymer structure does not rely on the presence of water (Davidovits, 1991). Furthermore, geopolymers are materials that shield radioactivity (Montes et al., 2015). Geopolymers can be synthesized from a wide range of reactive aluminosilicate powders including lunar simulant regolith (Montes et al., 2015). A study was reported on the development of geopolymers from volcanic ash (Lemougna et al., 2011) with compositions close to lunar regolith (Table 1).

The major components of the lunar regolith are glasses and fragments of rocks and minerals, mainly consisting of silicates, such as olivine, pyroxene and plagioclase, and non-silicates such as ilmenite (Liu and Taylor, 2011; Ray et al., 2010). Some volcanic scoria/ashes were identified having a close resemblance to lunar regolith and have attracted interest for the development of lunar soil simulants (Liu and Taylor, 2011; Ray et al., 2010; Taylor, 2014). The first lunar soil simulant standardized by NASA, named JSC-1 (Johnson Space Center), was issued by a volcanic tuff/ash mined just north of Flagstaff, Arizona. JSC-1 contains abundant volcanic glass of (49 mass%) and its bulk chemistry resembles several Apollo14 soils (Liu and Taylor, 2011; Ray et al., 2010). A Chinese lunar simulant CAS-1 (Chinese Academy of Sciences) was also obtained from volcanic scoria with 20–40 vol.% of glass from Sihai pyroclastics at the Jinlongdingzi Volcano in China (Sun et al., 2015; Yu et al., 2017). The scoria was crushed to produce the desired approximate lunar grain size (Liu and Taylor, 2011). Table 1 presents the chemical composition of several lunar regoliths (Ray et al., 2010; Zheng et al., 2009), lunar simulants (Montes et al., 2015; Zheng et al., 2009) and a reactive volcanic ash (Va) used for the production of structural materials using geopolymer chemistry. The compositions of the volcanic ash (Va) are similar to that of lunar regoliths; therefore, we speculate that the geopolymerization of volcanic ash likely has characteristics similar to that of lunar soil.

The objective of this research is to determine the compressive strength using X-ray diffraction (XRD) and if Va has an alkali-activated activity. The water consumption for the geopolymerization of Va was determined using water mass loss and DSC from the residual water content measured in a vacuum. The cement material from the geopolymerization of Va was checked for its durability and resistance to high- and low-temperature cycling and its vacuum stability under liquid nitrogen and vacuum conditions.

2. Material and methods

The primary raw materials used in this study were provided by local suppliers. The volcanic ash, a type of black and gravelly particles, is from Petponoun (N Latitude: 5°37′46″; E Longitude: 10°37′56″; Altitude: 1145 m) in Cameroon and was ground and passed through a sieve with a mesh size of 74 μm. The alkaline activator used was sodium hydroxide, which was produced by the Xilong Chemical Company.

2.1. Geopolymer synthesis

Inorganic polymer formulations were obtained by stirring powder of volcanic ash into a solution obtained by dissolving pellets of NaOH in distilled water to get mixtures of Na_2O_3/Al_2O_3 molar ratios ranging from 1.00 to 1.50, with intervals of 0.25. The water/ash mass ratio was maintained at 0.27 for all compositions. However, we changed the water/ash mass ratio to 0.30 and 0.33, respectively, for the DSC experiments.

2.2. Sample characterization

The chemical compositions of the volcanic ash were obtained by energy dispersive X-ray fluorescence (XRF) spectrometry using an Axios instrument. The sample preparation involved fusion with a 65:25:10 lithium tetraborate:lithium metaborate:lithium fluoride flux in platinum crucibles at 1050 °C for 8 min to produce a glass bead.

XRD experiments were performed using a Rigaku MiniFlex 600 instrument with Ni-filtered and Cu (Kα) radiation operating at 40 kV and 15 mA with a dwell time of 3 s, a 2θ range of 5 to 70° and a step size of 0.020°.

Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) were carried out to analyze the polished surfaces of the specimens using a S-3400N device (Japan Hitachi Limited Company) with an acceleration voltage of 20 kV. Specimens were impregnated using absolute ethyl alcohol, polished with SiC paper and then gold was used as a conductive coating.

In a single freeze-thaw cycle, the specimens were placed in liquid nitrogen (−196 °C) for 0.5 h and then held at 25 °C for 0.5 h. One complete cycle took approximately 1 h. The compressive strength of the specimens was determined after 30 freeze-thaw cycles. The compressive strength testing was conducted on specimens using a DNS100 universal testing machine. The displacement rate was 0.5 mm per minute.

Table 1
Chemical composition, mineral and percentage of amorphous phase of some lunar regoliths, lunar simulants and a reactive volcanic ash used for the production of structural materials using geopolymer synthesis.

Oxides(mass%)	Lunar soil regolith, Apollo 14(McKay et al., 1972)	Lunar soil simulant CAS-1(Ray et al., 2010)	Lunar soil regolith, Apollo 17, sample 70,051(Hill et al., 2007)	Lunar soil simulant JSC-1A(Montes et al., 2015)	Volcanic ash used for geopolymer synthesis (Va) (this work)
SiO_2	48.08	49.24	42.2	42.95	43.4
Al_2O_3	17.59	15.8	15.7	14.53	15.3
CaO	11.12	7.25	11.5	9.11	11.1
MgO	9.27	8.72	10.3	8.64	6.8
FeO	10.45	11.47	12.4	7.52	9.75
Fe_2O_3	–	–	–	11.5	2.75
Na_2O	0.65	3.08	0.2	2.6	4.5
K_2O	0.54	1.03	0.1	0.71	1.7
TiO_2	1.77	1.91	5.1	1.57	2.9
P_2O_5	0.58	0.3	–	0.65	0.9
MnO	0.14	0.14	0.2	0.17	0.2
Mineral observed	Basalt, anorthosite, breccia, olivine, pyroxene, plagioclase	Pyroxene, olivine and a small amount of plagioclase	Cristobalite, plagioclase, pigeonite, augite, olivine, ilmenite, chrome spinel, troilite	Olivine, pyroxene, ilmenite	Augite, ferroan forsterite
Estimated percentage of amorphous phase	60.5–70.0	20.0–40.0	32.5	–	58.0