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Formation of polymer micro-agglomerations in ultralow-binder-content composite based on lunar soil simulant

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Abstract

We report results from an experiment on high-pressure compaction of lunar soil simulant (LSS) mixed with 2–5 wt% polymer binder. The LSS grains can be strongly held together, forming an inorganic-organic monolith (IOM) with the flexural strength around 30–40 MPa. The compaction pressure, the number of loadings, the binder content, and the compaction duration are important factors. The LSS-based IOM remains strong from −200 °C to 130 °C, and is quite gas permeable.

Keywords: Binder content; Lunar regolith; Structural material; In-situ resource utilization

1. Introduction

In the next a few decades, building large-scale lunar bases and/or research facilities on the Moon will probably be one of major breakthroughs of manned or unmanned lunar exploration missions (Toklu, 2000). Previously, the study in this area was focused on the first-generation lunar habitats, by using lightweight alloys or composites (Happel, 1993; Khoshnevis et al., 2005). Since the distance from the Earth to the Moon is longer by three orders of magnitude than to the Low-Orbit International Space Station (ISS) (Kitmacher, 2010), with the limited space transportation capacity, if all the materials and components are transported from the Earth, the construction would be expensive and time consuming. It is, therefore, highly desirable that locally harvestable resources, such as lunar regolith, can be utilized (Benaroya, 2002).

A major component of lunar soil is silica. While, once heated to above 1200 °C, silica grains can be fused together, the thermal processing consumes a large amount of energy (Taylor and Meek, 2005). No low-melting-point salts or salts capable of lowering the melting point of silica, e.g. soda, have been discovered on the Moon (Schrader et al., 2010). Many other options, including production of cementitious materials (Beyer, 1985) and utilization of byproducts of lunar mining activities (Schrunk et al., 2007), demand sophisticated machinery and the final products may not survive the harsh lunar environment.

A promising concept is to bond lunar regolith grains by a small amount of binder. The binder should be lightweight, strong, and easy to handle. Some binder materials used on the Earth, such as sulfur (Meyers and Toutanji, 2007), are not compatible with the wide temperature range at lunar surface. Among all the materials — metals and alloys, ceramics, and polymers, high-temperature polymers, e.g. advanced epoxy, are attractive candidates.

Previously, we conducted research on JSC-1a lunar soil simulant (Qiao et al., 2007a), and fabricated lunar-soil-

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simulant (LSS) based organic-inorganic monolith (IOM), using polyethylene (PE) or unsaturated polyester resin (UPR) as the binder (Chen et al., 2015a, 2015b, 2017). In an IOM, the organic binder holds together the inorganic LSS filler grains (Qiao et al., 2007b). The processing technique was similar to conventional compression molding. The experimental data demonstrated that LSS-based IOM could be stronger than typical steel-reinforced concrete.

In a regular compression molding procedure of particulate composite, full dispersion and wetting of polymer binder with filler particles is achieved prior to the compression, through extensive mixing. The binder content must be higher than 10–15 wt%; otherwise the mixture is too "dry", causing a high defect density (Figovsky and Beilin, 2013). In the work of Chen et al. (2017), we began with an initial binder content of 15 wt% and used a high densification pressure to squeeze out the redundant binder and to crush and close-pack the LSS filler grains. The lower limit of the binder content was 8.6 wt% (Fig. 1a). To minimize the burden on space transportation, we aim at an ultra-low binder content below 5 wt%. In order to reach this goal, major improvement must be made.

In Fig. 1a, not all the polymer phase is equally important. The portion of binder at the direct contact points among the filler grains is most critical, and the portion in the interior of interstitial sites does not directly contribute to the load-carrying capacity. A more efficient binder distribution is depicted in Fig. 1b. The binder forms polymer micro-agglomerations (PMA) that bridge the filler grains together; the free space among filler grains is empty. In such a configuration, all the binder is utilized to carry load, and the binder content may reach a much lower level. For an order-of-magnitude assessment of the theoretical lower limit of binder content, we assume that the PMA size is ~1/5 of the size of interstitial site and the PMA form an ideal body center cubic (BCC) structure. The total PMA volume would be only ~1/60 of the free space. With this perfect PMA structure, the binder content can be reduced by ~60 times from that of Fig. 1a, to around 0.15 wt%.

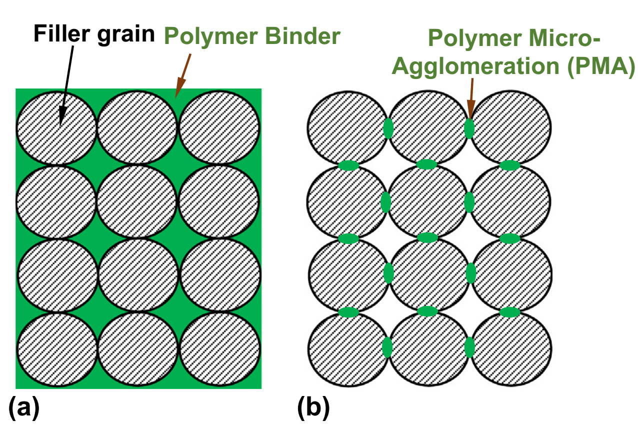

Fig. 1. Schematics of (a) close-packed filler grains, with the interstitial space being filled by ~8.6 wt% binder; and (b) polymer micro-agglomerations (PMA) that bridge the filler grains together, with the interstitial space being empty.

2. Experimental

In the current study, the filler was JSC-1a lunar soil simulant obtained from Orbitec. JSC-1a was upgraded from JSC-1 lunar soil simulant, with the composition and grain size and shape similar to those of Apollo lunar soil samples; it has been commonly accepted for lunar scientific research (e.g. McKay et al., 1994). The binder was Epon-828 epoxy resin provided by Miller-Stephenson, with the hardener being m-Xylylenediamine from Sigma-Aldrich. First, the epoxy resin and the hardener were mixed thoroughly, with the mass ratio of 5:1. Then, a small amount of epoxy-hardener mixture was dropped onto ~5 g of air-dried JSC-1a LSS filler grains (Fig. 2a). The binder content ranged from 2 wt% to 8 wt%. In a 50-ml beaker, the filler and the binder was mixed by a spatula for 5 min, and transferred to a stainless steel cylinder (Fig. 2b). The height of the steel cylinder was 50.8 mm and the inner diameter was 19.1 mm. The cylinder was capped from the top and the bottom by two stainless steel pistons, respectively. The piston diameter was 19.0 mm, loosely fitting with the inner surface of the steel cylinder. The filler-binder mixture was quasi-statically compacted by a type-5582 Instron machine, with the loading rate of 0.3 mm/min. The maximum compaction pressure, P_{max}, ranged from 20 MPa to 350 MPa. The maximum pressure was maintained for 1 min, and the piston was fully unloaded with an unloading rate of ~0.3 mm/min.

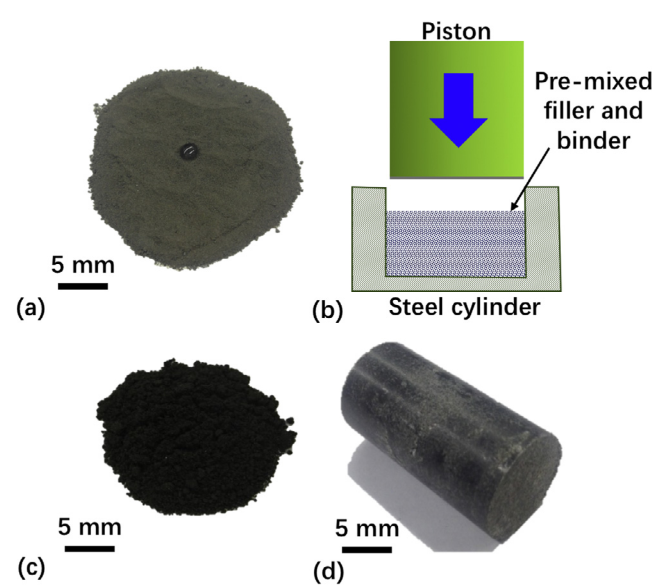

Fig. 2. (a) Photo of 4 wt% binder dropped onto ~5 g of air dried JSC-1a simulant filler. (b) Schematic of the compaction setup, wherein pre-mixed simulant-binder mixture is compressed by a steel piston in a steel cylinder. (c) Simulant-binder mixture after the first loading, which has been taken out of the steel cylinder and broken apart. (d) After the second loading and curing, the hardened IOM sample is taken out of the steel cylinder.