Developing Moonquake-Proof Structures Based on Locally Harvestable Resources.

Yu Qiao,* Vistasp M. Karbhari, and Gilbert A. Hegemie.
Department of Structural Engineering, University of California at San Diego
9500 Gilman Dr. MC 0085, La Jolla, CA 92093-0085, USA (Email: yqiao@ucsd.edu)

Summary: Based on findings of moonquake science and lunar regolith study in the past a few decades, it is now feasible to develop technology of moonquake-proof structures using raw lunar soils. The developed lunar soil based materials and structures should be strong, water-free, thermally nonconductive, durable (radiation-proof and low-cycle-fatigue resistant), energy-efficient, and airproof. They should have optimized damping properties to mitigate vibrations, which is important since the durations of moonquakes are much longer than that of earthquakes.

Introduction: While moonquake has been discovered by Apollo astronauts [1]. and studied thereafter for more than three decades, its influence on structural integrity and reliability is still a relatively uninvestigated area. This has become a "bottleneck" limiting the scale of lunar exploration missions as human beings are returning to and, more importantly, staying on the Moon, for which durable large scale bases and outposts must be built.

If only pre-fabricated habitats would be used in lunar exploration missions, moonquake may not be a major concern since these structures are often made of sufficiently strong lightweight materials. However, due to the limitation of space transportation capacity, it would be highly desirable that, after the first-generation habitats are installed, the expansion of lunar bases can be based on techniques using locally harvestable resources, such as lunar soils [2]. In the long run, for Mars exploration missions, such techniques will be even more critical.

The feasibility of using lunar soils as construction materials has been investigated for many years. It is, theoretically, possible that, as lunar dusts of different chemical compositions are appropriately mixed together, through complicated heating and curing procedures, "lunar cements", materials that can react with water or other liquids to form load-bearing components, can be obtained [3]. However, to achieve this, massive and energy-consuming "cement plants" must be built on the Moon, before the "lunar cements" are available. Even if this could be done, the "lunar cements", as any other ordinary cements, are of low tensile strengths, and therefore a large amount of metal/composite reinforcements must be used [4]. Their long-term reliability, especially in vacuum or high/low-temperature environments, is also problematic. Furthermore, the water or reactive chemicals necessary for the cementing process is about 30-40 wt.%; that is, in additional to the facilities and devices of the "cement plant", for every 10 parts of "lunar cement", 3-4 parts of liquid need to be transported from the Earth. In view of these limitations, over the years, a few alternative techniques, such as direct sintering of lunar soils [5] and water-free sulfur cements [6], have been proposed. However, these techniques either do not have much supporting data, or are energy consuming or can only yield poor-quality materials, and therefore are still far from being directly useful for space construction.

PIE Treated Lunar Cements: In a study on organic-inorganic nanohybrids, we developed a novel, high-performance polymer intercalation-exfoliation (PIE) cement-like material using JSC-1 lunar soil simulant [7], in which the lunar simulant grains are strongly bonded by a polymeric nanointerphase, as depicted in Fig.1. Due to the barrier effect of the sili-

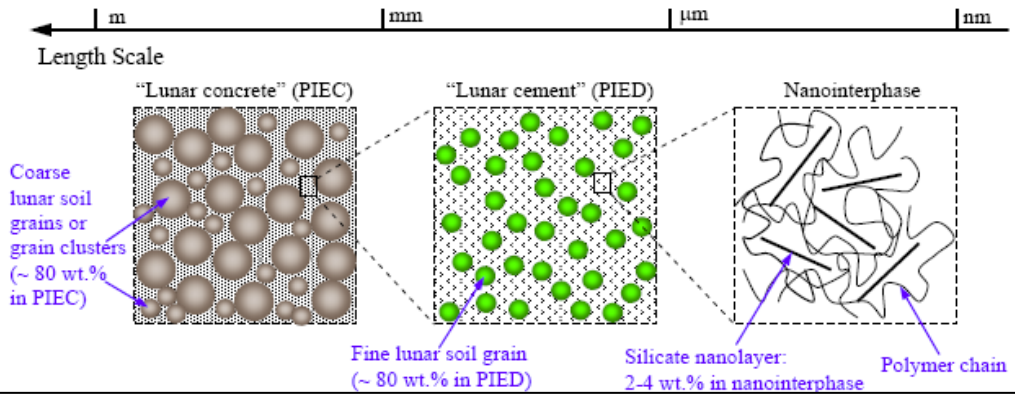

Fig.1 Schematic diagram of the microstructures of the polymer intercalation/exfoliation treated lunar concrete (PIEC). The content of the nanointerphase, which is the only component that needs to be transported from the Earth, is 2-4 wt.%.

cate nanolayers in the nanointerphase, the permeability of this material is very low, resulting in the superior air/water-proofness. The tensile strength is 75 MPa (compared to 3-5 MPa of a portland cement), comparable with that of aluminum alloys. It is envisioned that when the lunar soil simulant is replaced by real lunar soils, the material properties should be at the same level. Using the PIE-treated-cement-like lunar dust (PIED), PIE-treated lunar concretes (PIEC) can be developed, in which the PIED is employed as the binder to hold together coarse lunar soil grains. The only component that needs to be transported from the Earth is the nanointerphase (less than 4 wt.%), and the facilities are small-sized and lightweight.

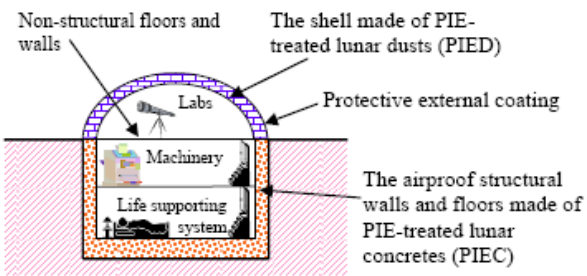

Fig.2 A schematic diagram of a permanent base consisting of the walls, the floors, and the shell (the roof). About 96 wt.% of the construction material would be raw lunar soils that can be harvested locally. The only component that needs to be transported from the Earth is the binder (the nanointerphase).

Considerations for Moonquake-Proof Structures: Using the developed PIEC and/or PIED, moonquake-proof structures can be built on the lunar surface, as shown in Fig.2. The lunar construction technique must be fundamentally different from the conventional ones, because of (1) the limitation of materials supply, including infrastructure materials and water, prohibits the use of ordinary matrix and reinforcements; (2) the facilities and equipment must be simple and lightweight; (3) the hardening process must be fast; (4) the harsh environment demands high tensile strength and reliability; and (5) the airproofness must be superior.

The structures must survive all types of moonquakes. Usually, moonquakes can be classified as (1) deep moonquakes, which are related to behaviors of lunar crust 500 km below the surface, and (2) shallow moonquakes, which take place only 20-50 km below the surface and are probably related to crater slumping. In addition, there are (3) thermal moonquakes, which typically occur at the ends of lunar nights as the sunlight heats lunar crust non-uniformly, and (4) meteorite impact vibrations, which can be regarded extrinsic. Meteorite impacts probably can cause most pronounced lunar surface vibrations, but only in highly localized areas. Thermal moonquakes are relatively predictable. Deep moonquakes and shallow moonquakes can provide rich information of lunar crust structure, and therefore the past studies were focused on them. Deep moonquakes are usually mild, merely detectable by high-accuracy sensors. Shallow moonquakes, on the other hand, can be equivalent to magnitude 5.5 earthquakes on the Richter scale. Note that, even a magnitude 4 earthquake can cause considerable damages of structures, such as panel cracking and foundation misalignment.

Shallow moonquakes happen frequently. According to the Apollo data, averagely each year 2-4 of them could be measured [8], indicating that the lunar crust was quite active. This frequency is comparable with (actually higher than) that of earthquakes in seismological active zones (e.g. California). While no moonquakes larger than magnitude 6 were detected during the short Apollo program, there is no guarantee that they would not occur over a longer period of time, e.g. the lifetime of a lunar base.

On the Earth, the earthquake effects on structures are relatively well documented. The major portion of the earthquake energy is released in the form of body waves propagating through the Earth itself. The primary waves (P waves) are longitudinal, and their rates are higher than that of the secondary waves (S waves), which are transverse. By studying these waves, the structure under the surface can be analyzed, and it has become an important scientific method to understand the history and the nature of our planet. However, usually in an earthquake the structural damages are caused by surface waves. If the magnitude, the frequency, and the direction of surface waves vary, similar structures can behave entirely differently. On the lunar surface, the relationship between surface waves and body waves is still unknown. Even for the body waves, which were better investigated, the database are far from being complete, imposing tremendous difficulties for designing moonquake-proof structures. Moreover, even if the moonquake waves were fully characterized, the lunar infrastructure materials are different from that used on the Earth, and therefore the standard earthquake-proof building techniques established in the past 200 years are no longer relevant.

References: [1] Latham G., et al. (1971). *Science* **174**, 687. [2] Toklu YC (2000). *Proc. Space 2000*, Reston, VA, pp.822. [3] Cox RM (2000). *Proc. Space 2000*, Reston, VA, pp.805. [4] Boles W, Kirby K, Baird S (2002). *Proc. Space 2002*, Albuquerque, NM, pp.143. [5] Taylor LA, Meek TT (2005). *J. Aero. Eng.* **18**, 188. [6] Toutanji H, Schrayshuen B, Han M (2006). *Proc. Earth&Space*, League City, TX. [7] Qiao Y, et al. (2007). LPSC '07, League City, TX. [8] Nakamura Y, Latham GV, Dorman HJ (1982). *J. Geophys. Res.* **87**, A117.