SOLAR BRICKS FOR LUNAR CONSTRUCTION

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ABSTRACT: A novel brick manufacturing technique is described, whereby natural mineral soil and added thermoplastic polymer particles are mixed, heated, and allowed to cool, to enable polymeric bonding of the soil grains. Experimental results indicate that the gradation of the soil plays a significant role on the compression strength of the manufactured bricks. This is because gradation controls fabric in highly compacted granular soils. A fabric that features pore filling by progressively smaller grains results in an increased likelihood of added polymer localization at intergranular contacts and therefore high strength. A conventional convection oven and a solar oven were used independently to implement the heat treatment; the comparison reveals the potential use of the latter for low energy cost brick construction in remote locations and nontraditional environments such as the Moon.

INTRODUCTION

Many of the world's most significant civil works have been built with masonry, dating back to the Egyptian Pyramids, the Colosseum and Aqueduct system in Rome, India's Taj Mahal, and the Great Wall of China. Clearly, brick is one of man's oldest manufactured products, with sunbaked clay bricks used in building construction more than 6000 years ago, and the use of firing (vs. sunbaking) for brick manufacture emerging nearly 4000 years ago (Beall 2012). As are many disciplines, the construction realm is charged today with the need to develop sustainable techniques and materials with low energy production costs and that are environmentally friendly (IEA 2011). In this article we describe a novel brick manufacturing technique, whereby polyethylene powder and soil are mixed and heated to produce polymer-bonded bricks. Two features of the technology are salient from the sustainability standpoint: (1) the powder is recovered from recycled water bottle caps, and (2) the heat can be imposed effectively with solar radiation, as described later. An energy demand analysis published elsewhere (Valdes and Cortes 2014) indicates that polymer bonded sand specimens prepared using conventional heating ovens have a compressive strength to embedded energy ratio ≈ 0.02 , which is ≈ 3.5 times higher than that of clay bricks and ≈ 2.5 times higher than that of soils bonded with Portland cement. This means polymer bonded soils require significantly less energy to exhibit the same strength. Since polymer bonded soil bricks require comparatively lower temperature to form, the use of solar radiation in conjunction with recycled polymers could potentially produce bricks with essentially no carbon footprint.

SOILS

Four soils with tailored gradations were prepared by scalping, using standard U.S. sieves. Grain size distribution (GSD) curves are shown in Figure 1, and soil properties are presented in Table 1. Two plots are shown in the Figure 1, to enable descriptions of the comparisons targeted in this study. Figure 1a shows GSD curves for soils A5 and B5 (the number –i.e., 5– represents the percentage of fines, i.e., grains with $d < 0.075$ mm). Both soils share the same fines content (f_c); yet, the range of grain sizes, captured by the coefficient of uniformity $C_u = d_{60}/d_{10}$ in Table 1, is larger for A5, given that its largest grain size ($d_{100} = 2.0$ mm) is larger than that of B5 ($d_{100} = 0.85$ mm). The inset shows the two GSD curves in log-log space; to be addressed later. Figure 1b shows GSD curves for soils A0, A5, and A48. The three soils share the same d_{100} ; yet, C_u and f_c are different for the three soils. Note in Figure 1b that the GSD curve of A48 is bound by two dashed curves. Lunar soils sampled in the Apollo 11, 12, 14, and 15 expeditions fall within such curves (Carrier 1972); hence, A48 is presented here as a representative, i.e., mimic, lunar soil (scalped from a silty sand). Based on the Unified Soil Classification System, all soils used are classified as sands because the fines content is less than 50%; yet, the gradations lead to different compacted fabrics, which in turn render different brick strengths, as revealed later.

PROCEDURES

Bricks were manufactured as follows. The soil is first mixed dry with recycled polyethylene powder (Figure 2). Dry mixing was implemented in the spirit of evaluating the feasibility of the proposed technology for use in environments where water is scarce or altogether unavailable (e.g., the Moon). The mix is then compacted by manual tamping in a brass mold; such tamping causes the soil to pack to the highest density achievable (i.e., relative density $\approx 100\%$). The soil is then heated. The heat treatment softens the thermoplastic polymer powder, allowing it to coalesce and locate at contacts shared by soil grains. The polyethylene hardens upon cooling (at room temperature), enabling bonding between soil grains. The bricks prepared for this study are different than typical construction bricks in both size and shape. Cylindrical (rather than rectangular) mini-bricks (length ≈ 4.5 cm and diameter = 2.2 cm) were prepared in this study to facilitate manufacturing and to promote homogeneous heat treatment.

Bricks with two different polymer contents (C) were prepared (i.e., $C = 5\%$ and $C = 10\%$) to examine the role of C on brick strength, and in doing so, enabling examination of the role of fabric on brick strength (by comparing strengths for analogous bricks, as described later). The polymer content is defined as the mass of polyethylene powder divided by the mass of soil. Heat treatment was imposed for 60 minutes using either a conventional oven or a solar oven, each dialed to a temperature $T = 150^\circ\text{C}$ for one hour. Example bricks with $C = 10\%$ are shown in Figure 3.

The solar oven (Figure 4) was built using an insulated cardboard box lined internally with aluminum foil and covered with a glass sheet. A square solar funnel was built with foil-covered cardboard, and placed over the oven to collect solar radiation and direct it towards the oven

box (Figure 4). The solar oven was used to examine the possibility of eliminating energy costs by using solar radiation to implement the heat treatment. Such approach may be transformational for construction in terrestrial regions with difficult or no access, as well as in extraterrestrial regions with permitting environments. The Moon is an example of the latter: surface temperatures can be as high as 120°C on the sunlit equator and as low as -230°C on shadowed polar craters (Malla and Brown 2015). Only minimal supplies can be transported to the Moon; thus, the technique proposed herein could conduce to cost-effective lunar construction that utilizes no-cost solar radiation and lunar regolith, and relatively small quantities of low density polymer (hence the fake lunar soil utilized for brick manufacture; A48 in Figure 1b).

“Solar” bricks were manufactured using the solar oven. One hour was generally required to attain a treatment temperature $T = 150^{\circ}\text{C}$ in the 29°C weather at the San Diego State University campus in San Diego, California. Once the target temperature ($T = 150^{\circ}\text{C}$) was reached, the soil-and-polymer –filled molds were placed in the solar oven. During heat treatment, the temperature inside the solar oven was continuously monitored with a thermocouple; efficient temperature control was achieved by orienting the vertical axis of the solar oven towards or away from the sun to increase or decrease the temperature, respectively.

Unconfined compression tests on dry bricks were conducted to determine brick strength q_{uc} . Each brick was loaded axially at a constant deformation rate = 0.02 mm/sec with an Instron load frame with capacity = 100 kN . Most brick types were tested in duplicate to assess experimental repeatability. Clusters obtained from tested (i.e., broken) bricks were imaged with a Scanning Electron Microscope (SEM) to observe the polymer’s distribution within the pore space and to gain insight into the micromechanics underlying failure.

RESULTS

An SEM image of a cluster obtained from an A0 brick with $C = 10\%$ is shown in Figure 5a. The mineral grain surfaces are light grey, whereas the hardened polymer is dark grey. In general, the polymer distribution appears to be considerably homogeneous, manifesting as menisci at contacts and as droplets on surfaces. This is best observed in Figure 5b, which shows a zoomed portion of Figure 5a, where a surface droplet is denoted **A**, and the letter **B** denotes a polymer bridge, i.e., a bond created where there was no mineral grain contact. The image also shows a failed polymer bridge, broken in two locations, denoted by **C**. Notice that this bridge failed due to the breakage of the polymer, not the detachment of the polymer from the grain surface. Indeed, polymer breakage was observed widely during microscopy analyses of multiple images. This means that the breakage strength of the polymer (not the detachment resistance) gave rise to the breakage strength of the bricks.

Strength comparisons for brick types A5 and B5 are shown in Figure 6 (recall that these soils have the same fines content, but A5 has a larger range of particle sizes than B5; Figure 1a). Consider the first four bars, which correspond to bricks prepared in the conventional oven. Bricks with $C = 10\%$ are clearly stronger than bricks with $C = 5\%$; this reveals the role of polymer

content on strength. For A5 and B5, the increase in strength achieved with the extra 5% polymer content is proportionally similar. Yet, B5 bricks are stronger than A5 bricks, regardless of polymer content. Clearly, gradation plays a role. Notice from the insert in Figure 1a, that the GSD of B5 is almost linear in a log-log plot. A linear GSD generally implies that the soil fabric is self-similar and therefore, optimal pore-filling by progressively smaller grains leads to a tight, internally stable fabric (see analysis by Loebstoskov documented by Kenney and Lau 1985). From the perspective of seepage, a soil with such property disallows the release of grains from its matrix, rendering it self-filtering (Chapuis 1992; Skempton and Brogan 1994) and less prone to segregation. From the perspective of grain binding, such a soil exhibits optimal coordination throughout, meaning that each grain shares contacts that effectively hold it in place. Such contacts are potential bonding sites, which in turn support a strong network of bonds that give rise to the higher strength observed for B5 bricks. The rightmost two bars in Figure 6 point to the similarity in strength attained by using a solar oven vs. a conventional oven, and thus, reveal the potential of the former for unique applications of the proposed technology.

Strength comparisons for brick types A0, A5, and A48 (lunar soil) are shown in Figure 7 (recall that these soils have the same d_{100} , but different fines content; Figure 1b). A glance at the SEM images shown in Figure 8 allows visualization of the bricks' fabric and aids in the interpretation of the strength data. Consider the first two bars, which correspond to bricks prepared in the conventional oven with $C = 5\%$. Notice that the soil with no fines (A0) has a relatively low strength. A5, with 5% fines, is ~ 5 times stronger. A5 has a wider range of sizes (Figure 1b), which means that A5 can be packed denser than A0. The high density means that the distance between adjacent mineral grain contacts in A5 is small, thus promoting a high likelihood of softened polymer retention at contacts (Figure 8b). In contrast, A0 is poorly sorted, and therefore, the distance between contacts is nominally large, thus allowing some of the softened polymer to harden on particle surfaces far from contacts, where no contribution to brick strength is made (Figure 8a). These arguments are supported by the results of A0 and A5 bricks with $C = 10\%$ (4th and 5th bars in Figure 7). Clearly, $C = 10\%$ bricks are stronger than analogous $C = 5\%$ bricks. More importantly, notice that the strength of A0 with $C = 10\%$ is ~ 10 times higher than the strength of A0 with $C = 5\%$, whereas the strength of A5 with $C = 10\%$ is ~ 4 times higher than the strength of A5 with $C = 5\%$. The higher polymer content increases the likelihood of softened polymer retention at contacts during soil packing; yet, the effect is more pronounced for A0 because of its uniformity and therefore inherently low maximum attainable density.

LUNAR SOIL BRICKS

The 3rd and 6th bars in Figure 7 capture the strength results of A48 (lunar) soil bricks. The strengths attained are comparable to the rest of the bricks. However, although this soil is classified as sand, its packed fabric is inherently different than that of A0 and A5 (and B5). This is because a large percentage of fines implies that any non-fine grains ($d > 0.075$ mm) are essentially 'suspended' in a matrix of fines (Yang et al 2006); see Figure 8c. Here is where the size of the polymer particles (Figure 2) emerges as a relevant parameter. The particles that compose the polymer powder range between 0.01 and 0.06 mm. Thus, the size ratio is $d/d_{\text{poly}} \approx$

20 for A0, A5, and B5. In contrast, the ratio can be nominally approximated as $d/d_{\text{poly}} \approx 1$ for the lunar soil (A48). Indeed, during preparation of a brick composed of a predominantly coarse soil (such as A0, A5, and B5), polymer particles are adhered to the walls of the pore network via van der Waals attraction. Upon heat treatment, each particle softens into a droplet, which may coalesce with neighboring droplets. Each resulting droplet adheres to a contact in the form of a meniscus or remains on a grain surface (e.g., Figure 5). During packing of a soil with significant fines content, such as A48, the added polymer particles take part of the soil skeleton. Upon heat treatment, the resulting droplets—which also have the potential of coalescing—essentially become plumes within the mineral pore network. Therefore, one may expect that most if not all of the added polymer contributes to the strength of the resulting material; however, the surface area per unit mass available for polymer coating is significantly larger than that associated with a predominantly coarse grained soil, given the inverse proportionality of the specific surface and the particle size (Santamarina et al 2002), namely $S_s \propto d^{-1}$. Therefore, although brick strengths are comparable (Figure 7), a direct strength comparison amongst coarse grained bricks and lunar soil bricks cannot be made [yet] with respect to the mechanisms that give rise to the strengths of the latter. Additional work is thus needed to further understand the role that the size ratio d/d_{poly} plays on the heat treatment response and strength behavior of bricks composed of soils with d on the order of d_{poly} . Finally, the last two bars in Figure 7 are a testament to the promise of solar-powered brick construction with lunar soil, as they indicate that the strengths of the lunar soil achievable with solar radiation are similar to those achieved with a conventional oven.

The low gravity of the Moon and the low density of polymers (relative to that of soil minerals) give rise to a unique particle-level force balance, which in turn leads to an interesting implication for lunar soil brick construction. In general, soil grains and polymer particles can be mixed homogeneously in the dry state if the van der Waals attraction forces F_{VDW} shared by the polymer particles and the mineral soil surfaces are larger than the weight W of the polymer particles (this prevents segregation). On Earth, effective dry mixing thus requires the use of small polymer particles (Figure 2). However, the particle size beyond which a polyethylene particle would detach from a mineral surface due to gravity ($F_W > F_{\text{VDW}}$) is ~ 2.5 times larger on the Moon ($g = 1.62 \text{ m/s}^2$) than that on Earth ($g = 9.81 \text{ m/s}^2$; particle-level force formulations can be found in Santamarina et al 2001). This means that on the Moon, effective dry mixing with little to no segregation could be performed with relatively large polymer particles (i.e., $d_{\text{poly}} \leq 700 \text{ }\mu\text{m}$). This translates to an added benefit with respect to the transport of polymer blocks that could be ground to relatively coarse powder in-situ; a benefit, as the energy demand for grinding is inversely proportional to the size of the resulting grains.

CONCLUSIONS

The experimental results presented support a novel technique for brick construction, whereby soil grains are bonded by heat treatment of added polyethylene particles. The bricks produced with the proposed technology exhibit significant compressive strength (1 to 2 MPa for bricks with polymer content $C = 5\%$ and 3 to 8 MPa for bricks with $C = 10\%$), which are comparable or

measurably higher than those of compressed earth blocks (0.7 to 3 MPa; Lima et al 2012), adobe (1.2 to 1.8 MPa; Tanacan 2011), and bio-bricks (1 MPa; 14-day treatment; Bernardi et al 2014). Moreover, the embedded energy –to– strength ratio associated with the proposed brick fabrication technology is significantly lower than those associated with other types of brick production, particularly when recycled polymers are used as the additive, and when heat treatment is imposed by solar energy (whereby sun-aided lunar brick construction emerges as an attractive possibility).

From the micromechanics perspective, strength variations attributed to the tested bricks are borne primarily from the grain size distribution of the soil with which the bricks are made. Soils that can be compacted to a dense packing (such as sorted soils) sustain a large proportion of the added polymer at intergranular contacts, where polymer bonds are created and thus contribute to strength. In contrast, considerable proportions of added polymer remain on surfaces and far from contacts in the case of poorly sorted soils, which inherently possess relatively large voids, and a relatively low maximum possible density.

This work offers the proof of concept for a new soil-polymer brick manufacturing technology. Yet, additional research regarding the durability and performance of polymer bonded bricks under a variety of loading (e.g., constant, cyclic, thermal) and environmental (e.g., wet, low/high temperature) conditions is required to unravel the full potential of the technology.

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FIGURE CAPTIONS (8)

Figure 1. Grain size distribution curves for (a) A5 and B5 soils, and (b) A0, A5, and A48 (i.e., lunar) soils. Lunar soils sampled in the Apollo 11, 12, 14, and 15 expeditions have gradations that fall within the gradations shown by dashed curves.

Figure 2. Polyethylene particles.

Figure 3. Examples of bricks manufactured with different soils.

Figure 4. Side view illustration of the solar oven.

Figure 5. SEM pictures of clusters obtained from an A0 brick with $C = 10\%$. A zoom of image (a) is shown in image (b). **A**, **B**, and **C** denote a hardened polymer droplet, a polymer bridge, and breakage sites of a failed polymer bridge, respectively.

Figure 6. Unconfined compression strengths: comparison based on coefficient of uniformity (same fines content, $f_c = 5\%$).

Figure 7. Unconfined compression strengths: comparison based on based on coefficient of uniformity and fines content (same d_{100}).

Figure 8. SEM images of clusters obtained from (a) A0, (b) A5, and (c) A48 (lunar) bricks with $C = 5\%$.

Table 1. Properties of soils used for brick manufacture.

Sand	d ₁₀₀ (mm)	fines (%)	C _u (d ₆₀ /d ₁₀)	G _s
A0	2.0	0	3.0	2.66
A5	2.0	5	5.3	2.66
A48	2.0	48	13 ^[1]	2.67
B5	0.85	5	4.1	2.66

^[1] Estimated with d₁₀ = 0.01 mm (Figure 1)

Figure 1a

Figure 1b

Figure 2

Figure 3

A0

A5

A48 (lunar)

B5

Figure 4

Figure 5a

Figure 5b

Figure 6

Figure 7

Figure 8a

Figure 8b

Figure 8c