Building a Vertical Take Off and Landing Pad Using *in situ* Materials

Hintze, P. E.
Materials Science Division, NE-L2, NASA Kennedy Space Center, FL, United States

ABSTRACT

This paper describes the ongoing work at NASA Kennedy Space Center (KSC) investigating methods of stabilizing lunar regolith for dust mitigation and utilizing the regolith in building materials. Several methods for stabilizing lunar regolith have been investigated. Sintering, a method in which powders are heated until fusing into solids, has been proposed as one way of building a Lunar launch/landing pad. Polymer palliatives are currently used by the military to build helicopter landing pads and roads in sandy areas. This technology can be adapted to the lunar environment by identifying solvent free polymers that cure under lunar conditions. A solar concentrator was constructed and used to stabilize JSC-1A lunar simulant. Various heat-cured polymers have been evaluated. A rover mounted sintering device was designed and tested at the 2010 ISRU field demonstration at Mauna Kea, HI. Physical testing results of field and laboratory prepared samples will be presented. Recently, KSC has performed tests where simulated rocket exhaust was fired on surfaces of lunar simulant stabilized using different methods. NASA KSC is also overseeing multiple Small Business Innovative Research (SBIR) programs on microwave sintering of regolith and the use of polymers to stabilize and make building blocks from lunar regolith, performed by Ceralink Inc. (Troy, NY) and Adherent Technologies (Albuquerque, NM) respectively. Both SBIR projects seek to advance the technologies to points where they can be utilized by robotic systems. Results and lessons learned from the laboratory experiments and field demonstrations are given. Future directions will be discussed.

INTRODUCTION

A sustained human presence on the Moon, Mars, or other celestial bodies, is a broad mission that will require numerous disciplines to create technologies, solve current known problems and anticipate new ones. One problem that has been identified from the past Apollo missions is the issue of dust mitigation to protect people and infrastructure. [1, 2] There have been numerous papers describing and cataloging dust problems during the Apollo missions that pertain to human health and operations. [2-6] Dust ejecta from a rocket plume can affect visibility during landing, erode nearby coated surfaces and get into mechanical assemblies near the landing site. Videos taken during landing of the Apollo missions, show regolith erosion during the landing process and astronauts have seen large amounts of regolith ejecta during take off and landing (see videos at NASA image gallery, nix.nasa.gov). During the Apollo 12 landing, visibility of the local topography was so obscured that there was concern that the lander could have touched down on a boulder or crater. [2] Dust erosion during landing can cause damage to nearby infrastructure, as shown by the recovery of Surveyor 3 lander parts. The Apollo 12 lander landed 155 m away from the robot lander. There was considerable dust accumulation on the craft and evidence of "sandblasting" and pitting, as a result of dust ejecta during landing, on the returned tubing and optics. [5, 7, 8] A vertical take off vertical landing (VTVL) pad will be needed in a location that has repeated launch and landings near any permanent infrastructure of an outpost.

Dust transport has been caused by other human activities besides the launch and landing. There have been reports of dust being kicked up by the rovers. When riding the Lunar Roving Vehicle (LRV) with a damaged fender(s), dust was kicked up so badly that it immediately began to affect the space suits. [2] Dust was also observed around the ankles of the astronauts after walking. The dust is extremely persistent and adheres to all surfaces. Dust caused some acute health issues for the astronauts. Cases of eye, nose and sinus irritation were reported during several missions.[4, 5] The dust made it into the crew modules and caused problems with space suits and seals, and other mechanisms. Zippers, connectors and helmets all experienced some degree of dust-caused malfunction. Roads and stabilized areas can help mitigate the dust problem in high traffic areas.

A way to minimize the dust problem and build a VTVL pad or roads on the moon is to stabilize the loose regolith of the surface into a form strong enough to be used as a building material. There are many ways to stabilize regolith. Technologies that will eventually be chosen should be evaluated by various parameters including power needs, need for consumables, mass, strength of stabilized regolith, ease of use, and reliability. This paper describes work on two methods for converting the lunar regolith into building materials: 1) methods of sintering the regolith into a solid and 2) using solvent free polymers to stabilize the surface. In addition, the stabilization methods have been demonstrated in field-testing and tested by firing a small thruster on them.

POLYMER SURFACE STABILIZATION

The military currently uses polymers to stabilize sandy surfaces for helicopter pads and roads [9]. The technology is relatively simple and uses a water-soluble polymer that is sprayed over the area to be stabilized. The water evaporates leaving a durable polymer surface. Although polymers dispersed in a solvent are not practical for use in this way on the Moon or other bodies, there are many solvent free polymers that cure with the application of heat, ultraviolet (UV) light or the mixing with a catalyst. These polymers come in either solid or liquid form. Initial studies employed solid polymers to minimize any difficulty that might occur when spraying a liquid in a vacuum. The solid polymers come as a powder, with particle sizes approximately a micron, and can be distributed on a surface in a number of ways including by electrostatic spray. The polymers can be mixed with lunar regolith to form a composite. Many commercially available solid polymer powders are available for use. They include organic and inorganic polymers that are tailored with different desirable properties such as flexibility or temperature resistance. The drawbacks of polymer surface stabilization are the mass and issues dealing with curing and applying the polymer in a vacuum. Work on this technology has focused on minimizing the amount of polymer needed to cover an area or to build a block and solving the other problems.

At KSC, the solid heat cured polymers have been evaluated by curing in a laboratory oven, with a solar concentrator, and in a vacuum chamber. The laboratory effort involving oven-cured samples was focused on finding the minimum amount of polymer needed to achieve stabilization and evaluating different ways of applying the polymer. Strength measurements on different polymer application rates of 75 – 300 g/m^2 have been reported earlier[10]. All application rates resulted in a surface covered by a thin layer of polymer/regolith composite, but the 75 g/m^2 application did not improve the strength.
A few demonstrations showed that the polymer could be cured with a solar concentrator. Both 1:2 and 1:1 polymer: JSC-1A mixes have been cured with the solar concentrator. The cure temperature for these polymers is 200°C for 10 minutes. This temperature was achieved by keeping the sample above the focal point of the solar concentrator and monitoring the temperature. A small area about 6 cm in diameter and 0.5 cm deep was solidified in this way. This demonstration showed the ease with which the polymers can be used to form a solid surface.
The three commercially available polymers used in this testing program were evaluated for curing in a vacuum (5 x 10-6 torr). Initial tests showed that the polymers flow and form a film under vacuum. However, the film was found to be more brittle and seemed to take longer to flow than when the same experiment was performed under ambient conditions. The degree of curing under vacuum was found, by differential scanning calorimetry, to be about 60% of the curing that occurred in normal atmospheric conditions. It is not known why the vacuum affects the curing process in these polymers, but it is possible that the commercial products contain small amounts of flowing or curing aids that are affected by vacuum.
Adherent Technologies Inc (Albuquerque, NM) is performing a small business innovative research (SBIR) project, managed by KSC, investigating polymers for stabilization. Adherent Technologies is pursuing two approaches, one in which regolith is used to build solid blocks and the second where a thin layer of polymer is sprayed on a surface to provide dust stabilization. Both approaches have proven successful. Blocks made using a 1:20 mix of polymer to regolith were found to have compression strengths of 185 psi. Sprayable resins have successfully stabilized lunar simulant when applied at rates of 25 g/m2. They have identified and demonstrated a spray system that can be operated in a controlled fashion under vacuum.

STABILIZATION BY SINTERING

Sintering is a method in which loose particles are heated, but not fully melted, until they bond together and form a solid. Ceramics, from ancient clay pots to modern materials and composites, are made via the sintering or firing process. Ceramic materials are traditionally made from local, natural products including silica and silicate materials, with little or no pre-processing.
Most ceramic objects, except for some glasses, are made by forming the fine ceramic particles into a shape and performing a heat treatment to cause the particles to adhere. The sintering process proceeds as shown in Fig. 1. As the particles are heated, grain boundaries begin to form, growing and filling the pore space and forming the bond.

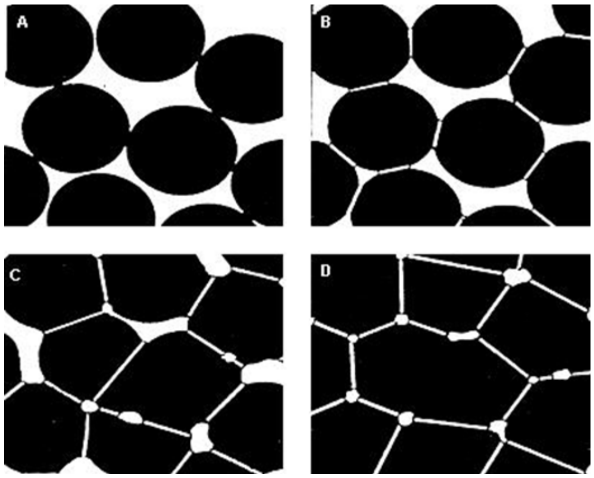

Fig. 1. Interparticle bond formation during the sintering process. Plate A shows the loose powder with initial contacts. Plates B and C show the progression of the interparticle bonds, grain boundary growth and pore shrinkage. Plat D shows the final product with minimal pore volume

Sintering is an ideal method for surface stabilization because it uses *in situ* materials and only requires a heat source. Solar concentrators [11, 12] and microwave heating [13-17] are the most commonly discussed heat sources. A resistive heater was used at the Hawaii field demo as discussed later. The lunar regolith has many properties that lend themselves to processing to form ceramics, and consequently, there have been many ideas on how to use the lunar regolith as structural ceramics. Lunar rocks are made up mostly of silicate minerals (>90% by volume). These silicate minerals are some of those traditionally used in the manufacture of ceramics.[18] In addition, the glass portion of the regolith can aid in densification during sintering.[19] The lunar regolith has been found to be a strong microwave absorber[13], indicating it is well suited for microwave sintering.

Similar to sintering, melting the regolith can be used for stabilization. When molten regolith is formed, all or some of the phases may melt. The rate of cooling determines the form of the final product. If the cooling rate is fast, the product may be an amorphous glass. If the cooling rate is slow, recrystallization of new species may occur. Fig. 3 shows SEM micrographs of JSC-1A lunar stimulant heated to 1100 and 1200 °C, with elemental analysis of different phases shown. At 1100 °C, many of the individual grains are still intact and the elemental analysis of these grains is similar to the material prior to heating. However, the elemental analysis of the lighter area of the image showed a new phase that consisted of iron, magnesium, silicon and oxygen that was not present in the material initially. JSC-1A heated to 1100 °C has sintered and not fully melted, although there a new phase was formed. The sample heated to 1200 °C resulted in a mostly glass-like substance. There was still evidence of some grains that

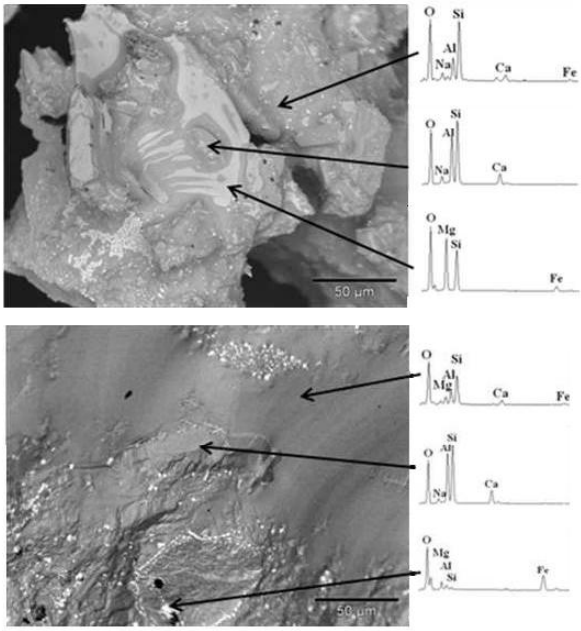

Fig. 3. SEM images and EDS spectra of JSC-1A lunar simulant after heating to 1100 °C (top) and 1200 °C (bottom).

did not melt, as seen in the middle of the image. There was additional recrystallization, as evidenced by the iron and oxygen rich crystals that appears as light spots on the image.

A solar concentrator, Fig. 2, with a 1 m^2 collection area was constructed for field testing at KSC. The solar concentrator consisted of a large Fresnel lens mounted on a frame that allowed the lens to move and follow the sun. The focal point of the lens is pointed downward to allow for rastering across a surface. The highest measured temperature generated by the solar concentrator was 1350°C, higher than is necessary to melt JSC-1A lunar simulant. Solar sintering is a promising technique since it gets its power from the sun (1380 W/m2). A more advanced solar concentrator system has been built and was recently tested for sintering [12].

Fig. 2. The 1 m^2 solar concentrator built at NASA KSC.

Initial experiments using the solar-concentrator focused on evaluating how thick a surface can be sintered and how best to sinter large areas. The first tests involved simply focusing the light on a bed of JSC-1A. When this was done, the top surface of the simulant quickly melted at the focal point. Within two to three minutes, a combination of melting and sintering occurs to a depth of about 6 mm. Continued heating after this time does not increase the thickness of the sintered area at the same rate. Fig. 4 (top) shows a cross section of solidified regolith. The top portion is a glass phase. Away from the surface, the simulant melted and sintered. There was evidence of new chemical phases in each area. The focal point of the solar concentrator was rastered back and forth over the surface of a bed of lunar simulant. At the focal point, JSC-1A quickly melts, but the thickness of this melted product is only 1 or 2 mm. In addition, the density of JSC-1A decreases on melting and the melted area contracts on itself, resulting in a weak bond between the melted areas formed on successive passes. Fig. 4

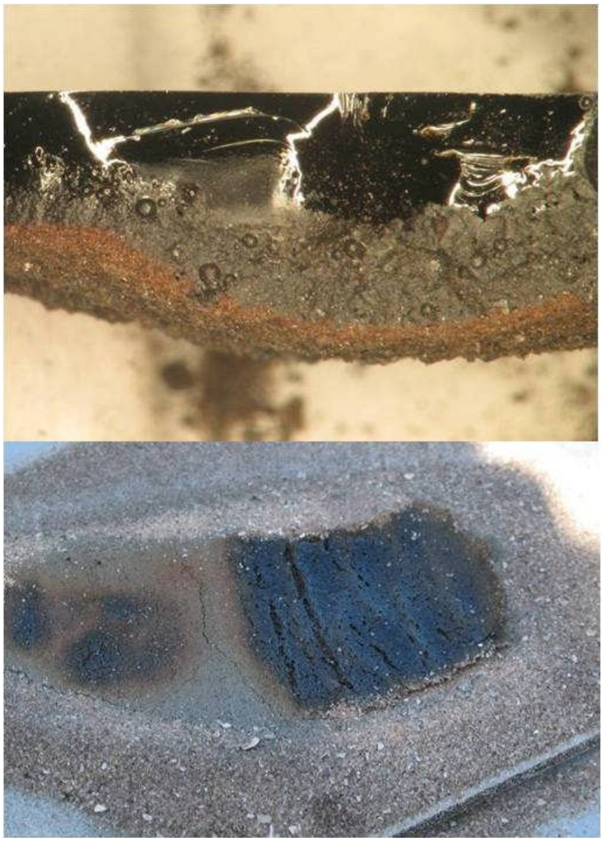

Fig. 4. Cross section of lunar simulant heated with solar concentrator (top) and surface image showing cracking between solar concentrator passes of sintered simulant (bottom).

(bottom) shows the cracks that can occur between raster passes.

At present, using a solar concentrator as a heat source for sintering must be considered promising because it is capable of achieving high temperatures in a short time, without any electrical power. Two main problems that require future work have been identified: 1) a solar concentrator consisting of a single lens must move to follow the sun while keeping the focal point at the desired area and 2) it is difficult to heat to great depths or wide areas. To address the first problem, a solar concentrator that has the collector and applicator decoupled from each other could be used [12]. Greater depth of sintering could be achieved by sintering the surface layer by layer, or continuously adding regolith on top of a heated area. This has been successfully performed and solid forms greater than 15 cm^3 have been made. Sintering wider areas would be facilitated by better temperature control. There is a large temperature gradient between the melted area and the surrounding areas when the simulant melts. The temperature gradient causes cracking between passes of the solar concentrator. Keeping each pass of the solar concentrator at the same temperature would help ensure that the sintered product produced on each pass was the same.

Microwave heating for sintering is a promising technology [13, 14]. Ceralink Inc. (Troy, NY) recently completed a Phase I SBIR with the goal of advancing technologies that could be used to microwave sinter the lunar surface. Their project was the first to demonstrate sintering by applying microwaves only from the top surface of a bed of lunar simulant, in this case JSC-1A. They solidified a 17 by 17 cm square to depths of 4-5 cm. In addition, they were able model the heating process for different microwave configurations and should be able to model microwave heating for different simulants and actual regolith, which has different microwave heating properties than JSC-1A. Ceralink found that their solidified product had a modulus of rupture ranging from 1700 – 3200 psi buy ASTM C1161.

FIELD DEMONSTRATIONS

Two field demonstrations have been undertaken to help improve these technologies and identify the best concepts for landing pad construction. The Large Area Surface Sintering System (LASSS) was built and operated during the January 2010 ISRU field demonstration at Mauna Kea, HI. LASSS, shown in Fig. 5, was designed to incorporate automated layered sintering into a system that could be moved on a rover. The second field demonstration consisted of simulate rocket exhaust firings on different potential launch pad materials.

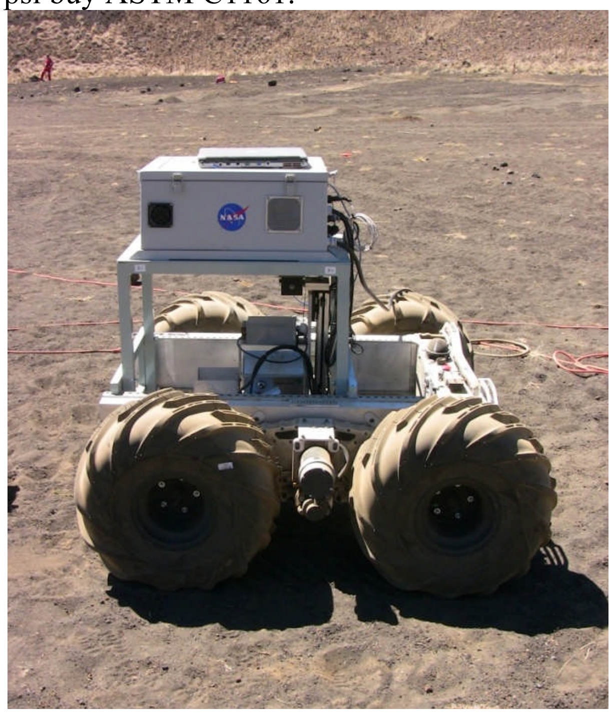

Fig. 5. LASSS mounted on a rover at the Mauna Kea ISRU field demonstration in January 2010.

LASSS attempted to improve on the initial KSC solar concentrator testing by increasing the thickness of the sintered/melted product and improving temperature control of the system, two problems identified in initial solar concentrator tests. LASSS consists of a hopper, heater, motion controller and associated control electronics. The stabilization occurs by depositing a layer of lunar simulant over an area and then passing the heater (directed downward) over the simulant to sinter it into a solid. The process can be repeated over the area again, resulting in a thicker sintered pad. An infrared thermocouple was used to monitor the temperature during system. The temperature can be used in a feedback loop that changes the movement rate of the heat source. LASSS was remotely controlled and could be mounted on a rover.

LASSS did not use a solar concentrator as heat source, but rather used a molybdenum disilicide (MoSi2) resistive heating element. This element was chosen because it simplified the overall system, in spite of the increased power requirements. The heating element had a serpentine shape and nominally provided near 140 W/in2. The heater was operated at 1000W of power.

The goals of this demonstration included showing that layered sintering was possible, positioning LASSS using a remotely operated rover, and firing a rocket nozzle on the sintered area. Layered sintering and positioning with a rover were demonstrated, but there was room for improvement.

The efficiency in the field was considerably less than laboratory tests. Efficiency losses were due to environmental conditions, such as wind, and increased thermal conduction. Laboratory tests were done on dry samples that were placed on top of an insulated tray or crucible. In the field, the tephra (volcanic ash) at the field site was slightly wet below the surface and it seemed that the thermal conductivity was greater than occurred in the lab. This led to a much slower sintering rate, a variable strength product, and the need to operate the heater extremely close to the surface. The heater was so close to the surface, it was difficult to align the thermometer, and therefore, the feedback loop was not effective. The temperature feedback loop worked in the laboratory tests.

Fig. 6 shows the completed sintered area, about 8 x 16 inches, before and after thruster firing. This area consisted of two layers of sintered tephra. The area in the figure was sintered in two segments, with the joint highlighted by an arrow. LASSS was moved by the rover between sintering the two areas. The joint was slightly lower than the other areas that had received multiple layers and was therefore weaker.

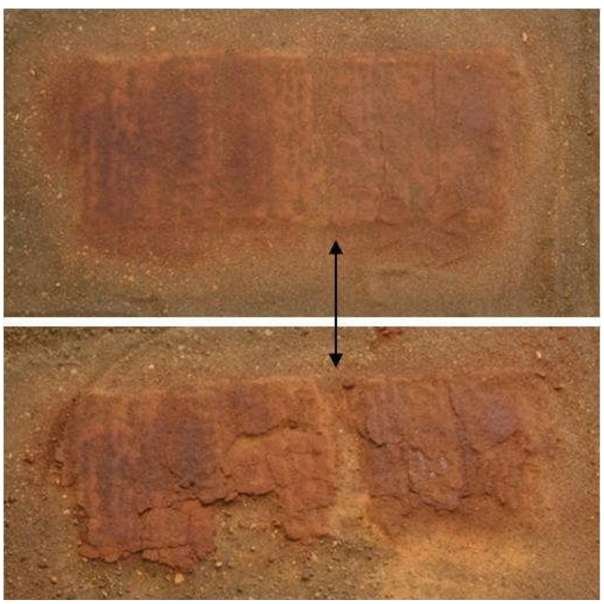

Fig. 6. The sintered area made with LASSS, before (top) and after (bottom) thruster firing. The arrow indicates the joint between two sintered squares.

The thruster was about 13 lbf. Much of the area survived the exhaust, but there was damage.

Although the layered sintering worked, the layers delaminated in some areas. After firing, penetrometer measurements were taken on this sintered area and others done during the field campaign. The strength was variable, ranging from 30 – 240 psi.

Future implementations of a field sintering system should include a method for monitoring the height of the ground. Since the heat source had to be so close, the tephra had to be smoothed and leveled prior to sintering. Unevenness resulted in the heater being different distances from the ground at different points causing the sintering to be weaker in areas were the heater was too far from the ground, such as occurred at the joint between the two squares.

At KSC, a simulated thruster was fired on different surface preparations. The thruster pushed high pressure nitrogen thru a nozzle onto the surface. No heat was applied. This was done to see how the exhaust plume would erode regolith after different surface stabilization techniques had been employed. The beds subjected to thruster firing are shown in Fig. 7. The bed consisted of a steel dish filled with JSC-1A lunar simulant. The surface stabilization method was applied on top of the lunar simulant. Investigated stabilization methods include tiles, polymers, gravel and textiles. Results of tile and polymer testing will be given here.

The tiles were made of JSC-1A lunar simulant that had been sintered in a furnace at 1125 °C. The tiles, cut from larger tiles, were 7.6 cm squares and 0.6 cm thick. The tiles were placed in three different patterns for firing: a square pattern, an offset square and a diagonal pattern. No matter the pattern, if there was any gap between the tiles the underlying material eroded. Fig. 7 shows the three patterns before and after firing, as well as the underlying simulant after the tiles were removed. Each pattern was fired on twice. The square and diagonal patterns each lost a tile during one of the firings.

The offset square pattern never lost a tile and seemed to do the best at preventing erosion in between tiles. The square pattern seemed to perform the worst, probably because the gaps between tiles were continuous in the direction of the exhaust flow.

Results from the polymer stabilization firing are shown in Fig. 7. The polymer surface was prepared by spreading a mixture of 1:2 polymer to JSC-1A over the surface at a rate of 300 g polymer/m^2 and then heating in a 200°C oven for 15 minutes. The polymer surface was fired on three times. The entire polymer surface shifted slightly during the first firing; however, it was not damaged, except at the edges. Although this surface could not stand a large load, it was resistant to the exhaust and could be used in areas that see rocket exhaust but do not receive high loads.

PHYSICAL TESTING

Various physical test methods and results used to evaluate the surface treatments have been previously reported [10]. Load bearing strength measurements were made by placing a three inch diameter area of treated JSC-1A on top of a bed of the simulant. A ¾ inch piston was used to apply force until the surface treatment failed. The strengths of laboratory prepared specimens ranged from 125 psi for a 2.5mm thick sintered specimen to over 600 psi for a 6 mm thick microwave sintered sample. The microwave sample is stronger than the sample made in a conventional furnace even though it has the same thickness. This is probably because the microwave sample reaches a higher temperature. Solar sintered samples, made with the KSC solar concentrator, are relatively weak having strengths of about 85 psi. The penetrometer measurements performed on the LASSS sintered samples, which were only 3-4 millimeters thick, have similar values to the 2.5 mm thick lab sintered samples. With increased efficiency, LASSS should be able to produce a thicker sintered surface that should have strengths similar to the lab-sintered samples.

An abrasion test was performed to evaluate different stabilization methods resistance to traffic.

A Taber abraser (model 5150) was used for the measurement. The Taber abraser employs a turntable for the sample and two rotating abrasive wheels. In this way, the sample is exposed to a twisting abrasion much like a rotating and turning wheel. The test results give a relative measure of the abrasion resistance of different materials. The sintered samples performed well, but the pure polymer was most resistant. The abrasion resistance of polymer/simulant mixes decreased as the amount of polymer increased.

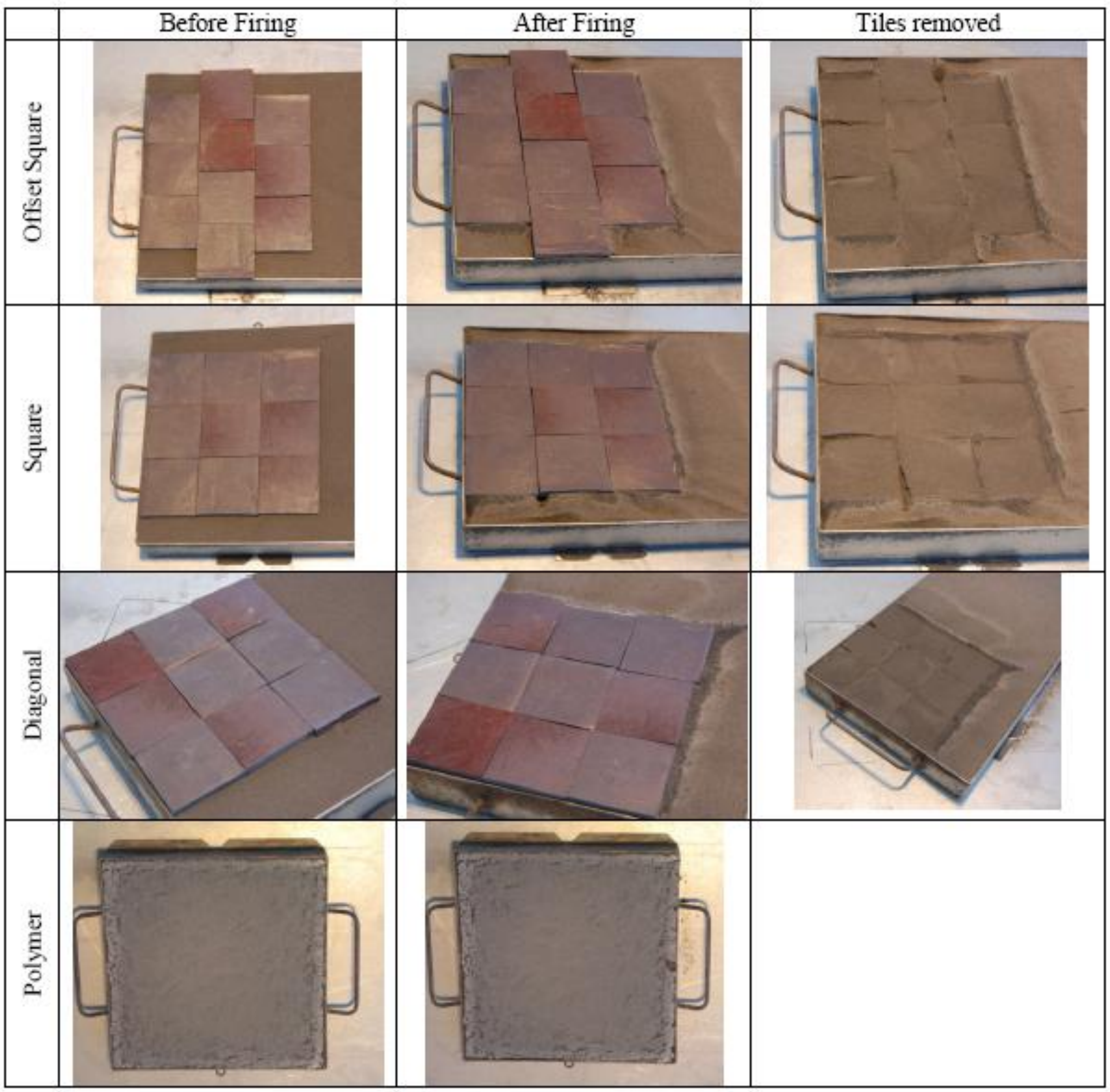

Fig. 7. Tile and polymer configurations used during the KSC thruster tests.

CONCLUSIONS

There are many different methods for using in situ materials to build a VTVL pad, each having advantages and disadvantages. A pad may in fact employ multiple techniques. Sintering and polymer stabilization can produce a strong surface, but suffer from the disadvantages of time and mass, respectively. If the pad can be made using multiple techniques, a center strong area could be combined with a quicker, yet less robust, stabilization method on the outsides of the pad that do not see large loads. For example, sintering could be used on the inner area of a VTVL, while polymer or general stabilization could be used on larger areas that only receive exhaust gas.

The choice of a technology should be based not only on the mass, power and cost of the technique as applied to a VTVL pad, but also on if the technique can be applied to other stabilization or building methods. Some applications may be so crucial that the cost of launching a polymer or fabric is worth it to ensure the reliability and ease of application that these techniques possess. For sintering, a system that can sinter a pad should have the flexibility to adapt components of the system to other systems that might build blocks for habitats or parts for spacecraft.

As these technologies are advanced in the laboratory, it is important to scale up and demonstrate the techniques in the field. This allows all the parts of the system to work as one. Field demonstrations show how a system will adapt to different environments and the results can give the researcher a more accurate assessment of the strengths and weaknesses of a particular technology.

The stabilization methods used for roads and landing pads can also find uses for other construction or manufacturing projects. The heat source used in sintering could be used in other fabrication processes to make parts for landers or rovers. Berms, trenches or mine walls may need stabilization. Habitation structures can be built from a combination of bricks made from regolith and/or regolith that is moved on top of a structure and stabilized, acting as radiation shielding. Areas used for science activities, or other sensitive operations, may need regolith stabilization to create a dust free zone. The technology that is chosen for surface stabilization should have adaptable or common parts with other systems used at the outpost.

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