In-situ Lunar Launch and Landing Pad Construction with Regolith-Thermoset Polymer Composite Materials

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ABSTRACT

Lunar launch and landing pads are necessary to mitigate risks to lander/ascent vehicles and surrounding surface assets from rocket plume ejected regolith. The current state of the art of landing and launching from the lunar surface is to land/launch on unprepared regolith surfaces. Significant risks exist for the larger landers proposed for the Artemis Program due to higher thrust levels leading to increased ejecta and cratering, presence of co-located assets in the ejecta path, and potential strict surface levelness requirements for tall vehicles.

Regolith-thermoset polymer composite materials were developed and evaluated for off-Earth launch and landing pad applications. Performance under methane-oxygen rocket engine firing conditions was assessed for two simulated Starship lunar launch/landing environments, one targeting thermal conditions and the second targeting pressure conditions. Paver test articles were prepared at 20% and 11% polymer mass fractions. Sintered regolith paver test articles were prepared with 20% polymer grouting filling the seams between pavers. Though significant erosion was experienced during the more extreme thermal testing conditions, all test articles successfully mitigated regolith ejecta from plume effects.

The mass of polymer required to be landed on the moon constitutes a primary risk for the application of regolith-thermoset polymer composites as a lunar launch/landing pad. Estimates for imported polymer mass were calculated based on assumed pad dimensions and polymer mass fraction. A Starship with planned 100t payload capacity to the lunar surface could provide enough polymer mass for all but the largest pad sizes.

A concept for preparing and emplacing the materials was developed and tested in laboratory conditions. The testing evaluated the feasibility of using screw extruder technology to mix, convey and deposit materials. Screw extruders were capable of processing and extruding the composite with a maximum of 90% mass fraction of regolith achieved.

The feasibility of the regolith-thermoset polymer composite based construction approach was proven in three critical areas: performance under engine firing simulating launch/landing conditions, fitting within the planned lunar payload capacity, and demonstration of a mixing and depositing concept. The materials must be proven to be compatible with lunar environments. It is recommended that development continue to TRL 6 for a small-scale lunar demonstration.

INTRODUCTION

This project directly addressed gaps in the NASA Excavation, Construction and Outfitting Roadmap, specifically construction of off Earth launch and landing infrastructure. The current state of the art of landing and launching on the lunar surface is to land/launch on unprepared surface sites. Though this has been a successful approach for Apollo and other unmanned missions, significant risks exist for the Artemis Program due to the increased thrust of the landers, presence of co-located assets, and potential strict surface levelness requirements for tall landers. Construction of launch and landing infrastructure is meant to address these risks for the Artemis Program. Although many concepts of LLP construction have been investigated, none have reached a high enough Technology Readiness Level (TRL) to be considered a viable option for a small-scale flight demonstration mission. The overall TRL level of the technology is approximately TRL-2 to 3. Much of the research has focused on materials development and strength characterization rather than development of the necessary material handling/processing and construction/emplacement systems and overall operations.

This project addressed technology gaps by assessing the feasibility of Room Temperature Vulcanizing (RTV) bound regolith materials and associated processing equipment for lunar launch/landing pad applications. This approach has the potential to dramatically reduce the power, process control and system complexity of construction systems because no bulk material heating is required, regolith mineralogy has minimal effects, and mixing/curing processes are far simpler than sintering and cementitious processes. The benefit is that the development timeframe could be significantly shorter resulting in a viable near-term solution for lunar launch and landing pads. The feasibility of this technology hinges on the amount of RTV payload mass required to be delivered to the moon since RTV cannot be produced in-situ. Additionally, the materials must be proven to be compatible with lunar environments in follow on work.

PROJECT OBJECTIVES

This project built off the "Regolith Derived Heat Shield for Planetary Body Entry and Descent Systems with In-Situ Fabrication" NASA Innovative Advanced Concepts (NIAC) work. The NIAC Phase 1 study demonstrated that a RTV bound regolith composite material was suitable for use as a reentry heat shield. Figure 1 shows an RTV-regolith test article under simulated re-entry conditions.

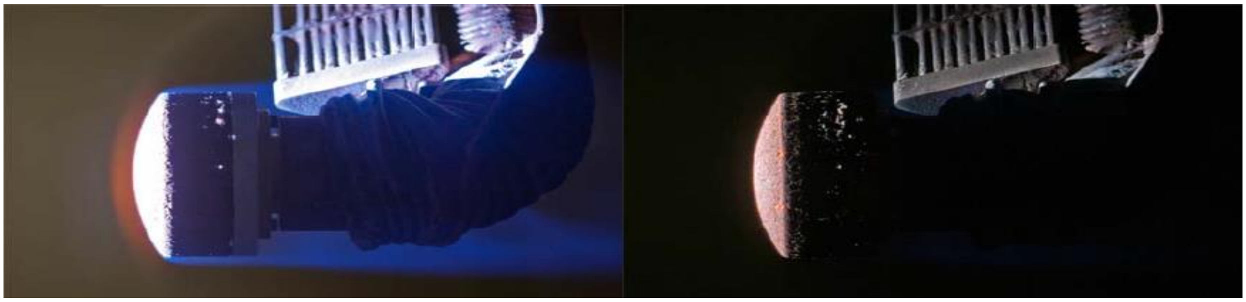

Figure 1. An RTV bound regolith heat shield prototype is exposed to simulated reentry conditions at Ames Research Center's Arc Jet Facility

This Center Innovation Fund (CIF) project adapted the NIAC materials and processes to landing/launch pad applications.

The purpose of this CIF was to demonstrate the feasibility of RTV bound regolith materials and construction systems for lunar launch/landing pad applications. Three key components of a first order demonstration of feasibility for this technology are:

1. Characterization of lunar payload mass requirements.
2. Demonstration of performance in launch/landing plume environments.
3. Demonstration of a construction implement concept for material processing and emplacement.

Each of these items are discussed in the following sections.

Assessment of material performance under the full range of lunar environments was not possible during the execution of this project due to resource constraints. Follow on work must be performed to characterize effects of lunar thermal, radiation, and gravity environments on the materials. It is thought that materials can be designed to accommodate the full range of lunar environments.

CHARACTERIZATION OF LUNAR PAYLOAD MASS REQUIREMENTS

The required payload mass for construction of a lunar launch/landing pad depends on three primary factors: pad diameter, pad thickness, and RTV-regolith mixture ratio. Each of these dependencies can be decomposed further.

The pad diameter depends on accuracy of landing systems. Reductions in landing pad diameter requirements reduces the RTV payload mass by a factor of (D/2)^2. The application of terrain relative navigation, landing aids, or other technologies that shrink the landing ellipse have a significant positive effect on the feasibility and payload mass of RTV bound regolith-based technologies (and others that rely on materials from Earth).

The pad thickness is a function of the plume environment. The higher the gas temperatures, velocities, and pressures, the thicker the pad must be to prevent burn though. The configuration of the launch and landing thrusters on the spacecraft (e.g., distance to the pad, thrust levels, number of thrusters) dramatically affects the plume environment that pads must be designed to withstand. For example, landers with high mounted thrusters will create a benign environment when compared to traditional landers with low aft mounted engines.

The RTV-regolith mixture ratio defines how much RTV must be provided per volume of pad. Minimizing the RTV mass percentage reduces the payload mass requirement, but factors such as erosion rate, strength properties, and material processability can also be affected and must be balanced to determine an optimum mixture ratio. Initially materials were created with 20% and 15% mass percentage based on the work that was completed in the NIAC. An experiment was performed to qualitatively assess the minimum possible mass percentage of RTV that would yield a consolidated sample. Samples were prepared by mixing the materials in a "Kitchen Aid" style mixer, transferring to molds and then manually pressing the materials into the molds. RTV mass percentages of 12%, 11.5%, 11%, 10.5%, 10%, 9.5% and 9% were created and all successfully formed consolidated samples, see Figure 2.

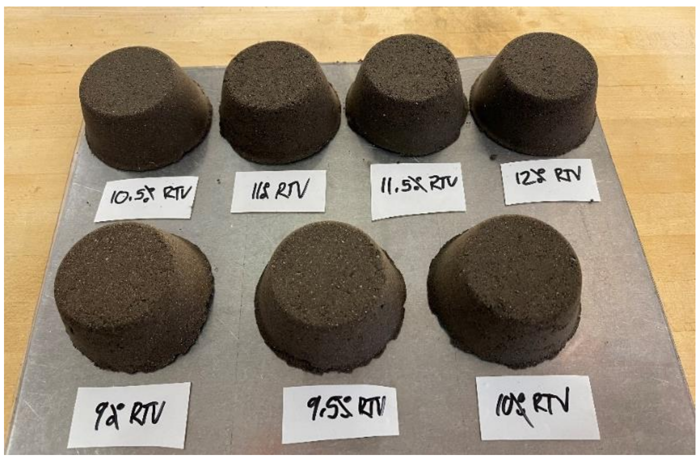

Figure 2. RTV bound regolith samples from 12% to 9% RTV by mass.

Material strength properties for each mixture ratio will be characterized later. Strength properties could affect the pad thickness requirements due to nominal and off nominal dynamic landing loads. These loading conditions have not yet been considered for pad designs. An assessment of the Apollo era landers showed that the landing footpads were designed to apply a static pressure of 0.7 psi. This led the project to consider erosion rate as the driver for pad thickness rather than dynamic landing loads.

MathCAD calculations were performed to determine RTV payload mass based on input diameter, thickness, and mixture ratio. The current Artemis Program landing pad diameter requirement is 200m, but discussions with the NASA Entry, Descent and Landing Principal Technologist have yielded an effort to reduce it to 100m. Table 1 provides reasonable estimates for mixture ratio, diameter, and thickness along with the resulting payload mass. SpaceX's Starship is targeting 100-200t payload to the lunar surface. A 200m diameter pad is not feasible with a single Starship payload, however 100m or less could be accommodated.

Table 1. RTV payload mass required for assumed pad characteristics.

Mixture Ratio (wt% regolith)	Diameter (m)	Thickness (mm)	Required RTV (t)
85%	200	25	282
85%	100	25	70
85%	50	50	35
80%	50	25	22
85%	15	50	3

DEMONSTRATION OF PERFORMANCE IN PLUME ENVIRONMENTS

A Masten Space Systems partnership with the SpaceX Large Vehicle Lunar Landing Surface Interaction Announcement of Collaboration Opportunity (ACO) project was leveraged by this CIF to provide hot fire simulated lunar launch/landing conditions to expose test articles. The Large Vehicle Lunar Landing Surface Interaction ACO final report provides full details of the testing that was performed. An overall summary of that project is provided in Mueller et al (2012). Information on the tests using RTV bound regolith materials is provided below.

Testing was performed during two test campaigns, one in December 2020 and the second in March 2021. All testing was completed using the Masten "Switchblade" engine. This is a gaseous oxygen/methane heat sink engine capable of firing for two seconds at a chamber pressure of 5,170 kPa and varying O_2/CH_4 mixture ratio in the range of 2.5 – 3.2. Nominally this engine has a thrust of 444 N. The engine is displayed in Figure 3 below.

Figure 3. 444 N heat sink "Switchblade" (Masten Space Systems).

During Campaign 1, a paver composed of Black Point 1 (BP-1) regolith simulant and RTV-655 thermoset silicone polymer at 20% RTV by mass was exposed to plume conditions. The 20% RTV paver size was 39.25" x 39.25" x 1.5" (length x width x height). The mixture loading of

20% was chosen to simplify fabrication and to ensure that the paver would not crumble due to inadequate binding of BP-1 grains. Figure 4 shows a 20% RTV paver on the test stand.

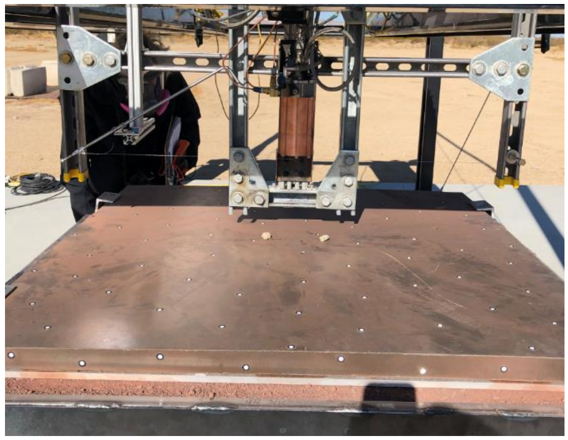

Figure 4. 20% RTV-Regolith paver installed on the test stand prior to testing.

During Campaign 2, a second RTV bound regolith paver was tested with the same specifications as the one in Campaign 1. An 11% RTV paver was also tested with dimensions of 12.5”x12.5”x1.5”. The 11% binder mixture loading was chosen because it was thought that additional BP-1 content would improve the paver performance. The 11% paver was smaller than the 20% pavers because not enough RTV 655 was available to produce a full-scale paver within time constraints. Figure 5 shows the 11% paver.

Figure 5. 11% RTV-Regolith paver before (left) and after installation on the test stand (right).

The 11% RTV-Regolith paver was installed inside a 13” cutout of one of the 20% RTV-Regolith pavers so that the overall geometry of the 11% and 20% test articles was the same. The gap between the 11% and 20% pavers was filled with Loctite High Temperature RTV Silicone Sealant, -75 to 600°F Temp. Range, Full Cure 24 hr, Red, as shown in Figure 5.

Campaign 2 also included a test article composed of nine sintered pavers (~12”x12”x1”) in a 3x3 pattern with a gap of approximately 0.5” between the pavers. The gap was grouted with RTV-regolith material with a 20% RTV binder mass percentage. The test was configured so that the rocket plume impinged directly on the grout line between pavers. Figure 6 shows a sintered paver test article on the test stand.

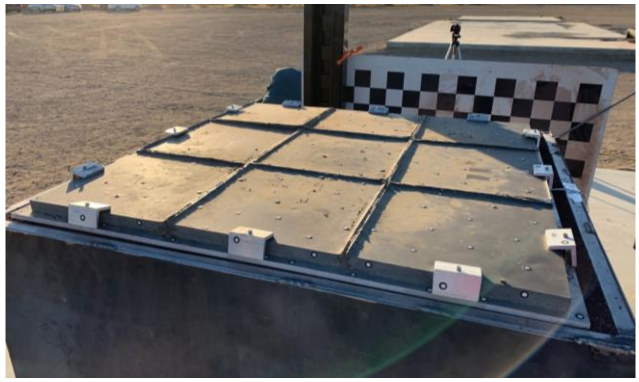

Figure 6. *The sintered paver test article installation onto the test stand.*

The RTV-regolith paver tested in Campaign 1 contained 20% RTV mixed with regolith. The sequence of images displayed in Figure 7a show a top down view of the engine and test article at various times throughout the test sequence. Figure 7b exhibits a concentric circular pattern of the high-temperature plume impinging on the RTV-regolith paver. It is thought that this feature corresponds to the inner and outer extents of the shock diamonds created in the plume. Figure 7d shows RTV-regolith material ablating radially outward from the center point of the impingement. The paver was discolored but dimensionally unchanged outside of the ablation streaks. A cylindrical cavity with a diameter of 3.07 cm and a depth of 3.2 cm was created resulting in ~23.7 cm3 of material eroded from the paver. The bottom of the eroded cavity displayed a small hole indicating that the test article had been pierced, however no regolith ejecta was observed. A likely explanation is that the test article survived the engine plume exposure and then the hole was produced either by the pressure of the 100 ms oxygen trail or from residual burning that occurred right after engine shutdown (Figure 7e). The creation of the hole was likely a post-engine shutdown event because no regolith simulant erupted during engine firing and the cardboard sleeve directly below the eroded cavity was found unaffected after the test.

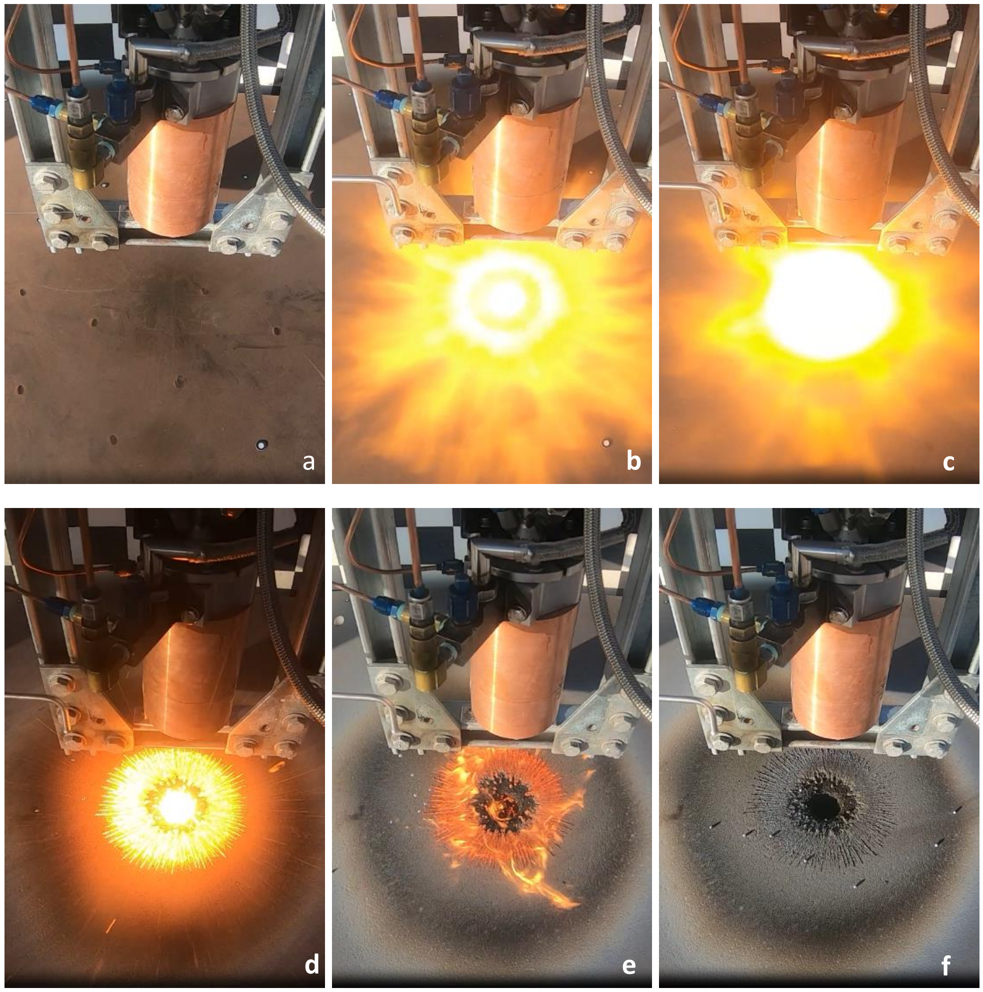

Figure 7. 20% RTV paver installed on the test stand (a) just prior to testing, (b) less than 0.5 seconds into the test exhibiting the concentric rings feature, (c) at approximately mid-point during the engine plume test, (d) glows brightly directly after engine shutdown, (e) burns immediately after the 100 ms oxygen trail, and (d) seconds after the hot fire test has concluded.

Campaign 2 changed the testing configuration from a static engine 16 cm above the test article to a dynamic engine that started at approximately 1.02 m above the test article and lowered to 0.6 m above it during the 2 second run time.

Sequential images from the high-speed video during Campaign 2 testing of the 20% RTV paver are displayed in Figure 8. Figure 8c shows the surface of the paver glowing with the engine at its closest position of 60 cm above the paver surface. The paver showed heat scaring, but little to no erosion of material was observed on the test article.

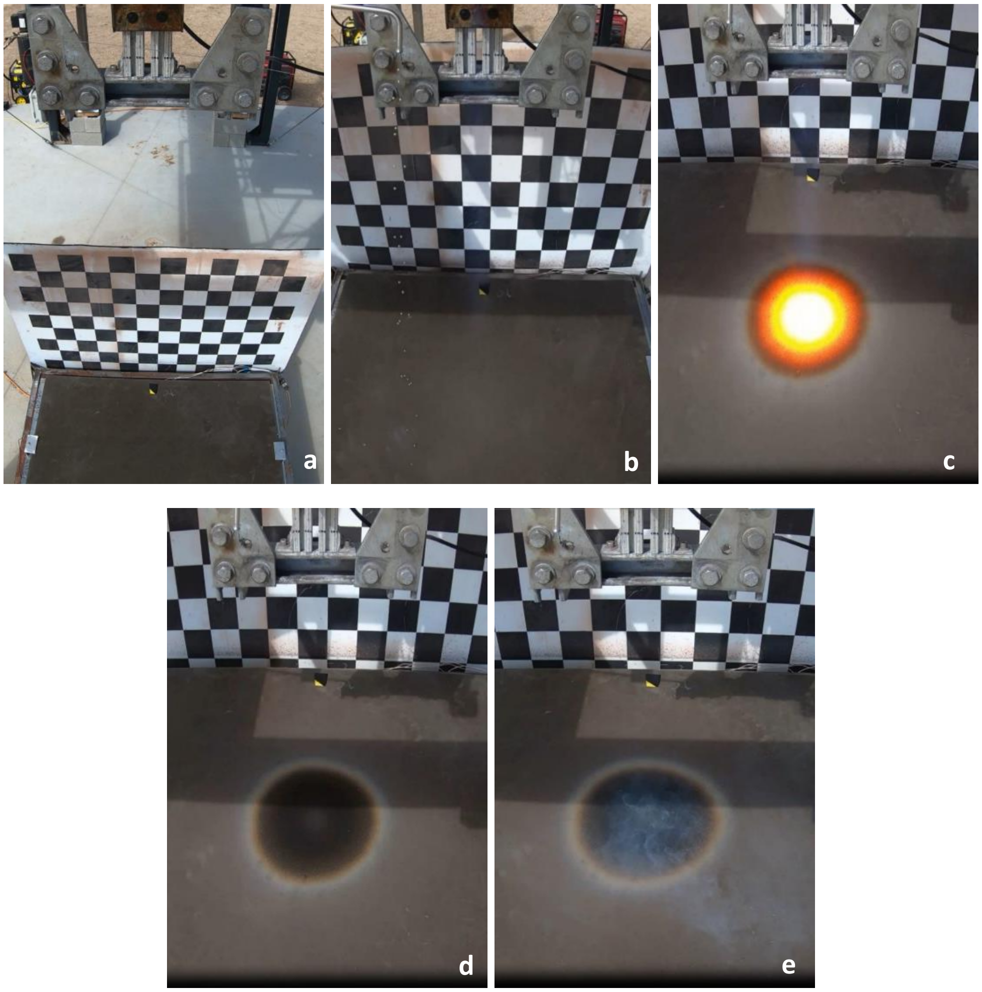

Figure 8. The 20% RTV paver (a) just prior to test initiation, (b) as the engine descends approximately halfway to the stops, (c) glows while the engine is at its closest position (60 cm above test article), (d) just after engine shut down, and (e) less than a second after engine shut down.

Sequential images from the high-speed video of the 11% RTV paver test are displayed in Figure 9. The camera field of view was not set correctly during this test, but the test article comes into view once the lift descends. Figure 9c shows the surface of the paver glowing with the engine in its closest position of 60 cm. The paver exhibited heat scaring, but little to no erosion was observed on the test article. The plume was not centered on the paver for this test due to misalignment during test set up operations, as seen in Figure 9e.

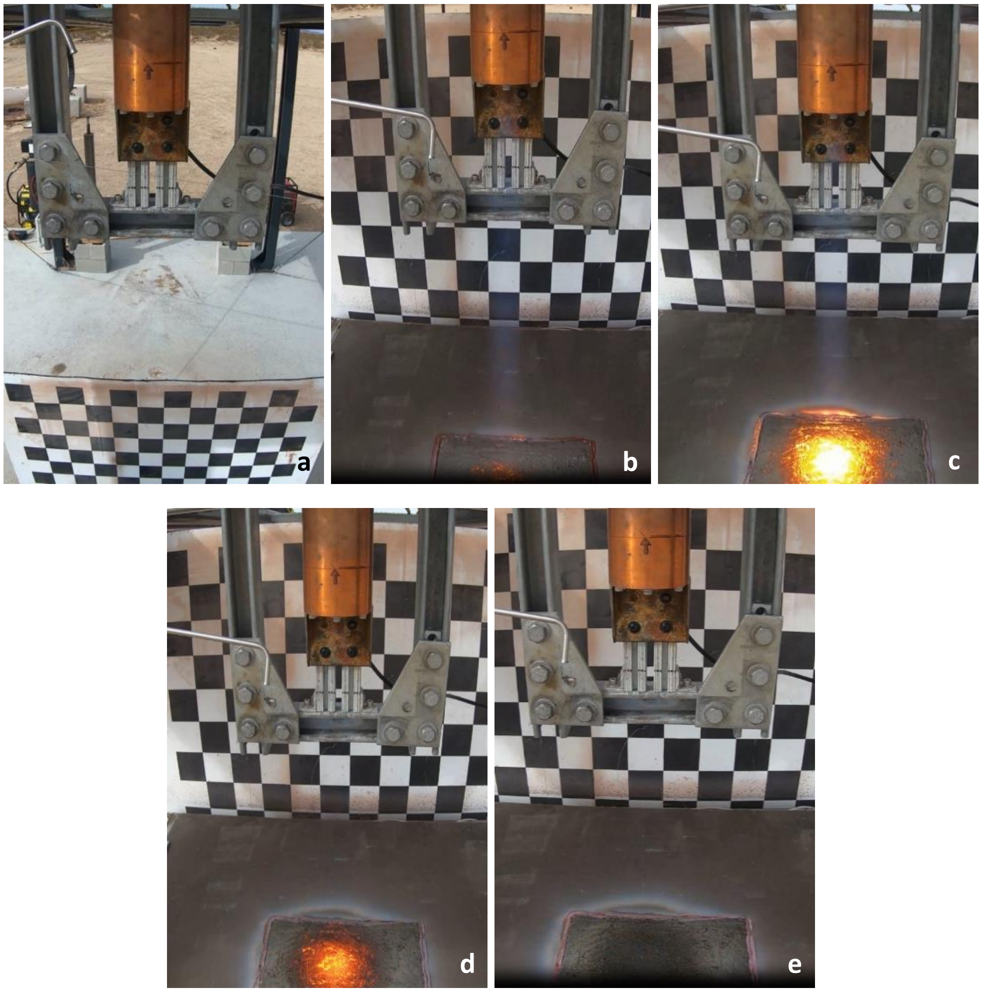

Figure 9. The small 11% RTV paver installed on the test stand (a) prior to engine ignition, (b) first enters the field of view when the engine is near its lowest point (60 cm above test article), (c) glows while the engine is at its closest position on the stops (d) just after engine shutdown, and (e) less than a second after engine shutdown.

Sequential images from high-speed videos for the sintered paver grouting test are displayed in Figure 10. Figure 10c shows the surface of the grout and paver glowing with the engine at its closest position of 60 cm. The paver and grout showed heat scaring, but little to no erosion was observed on the test article.

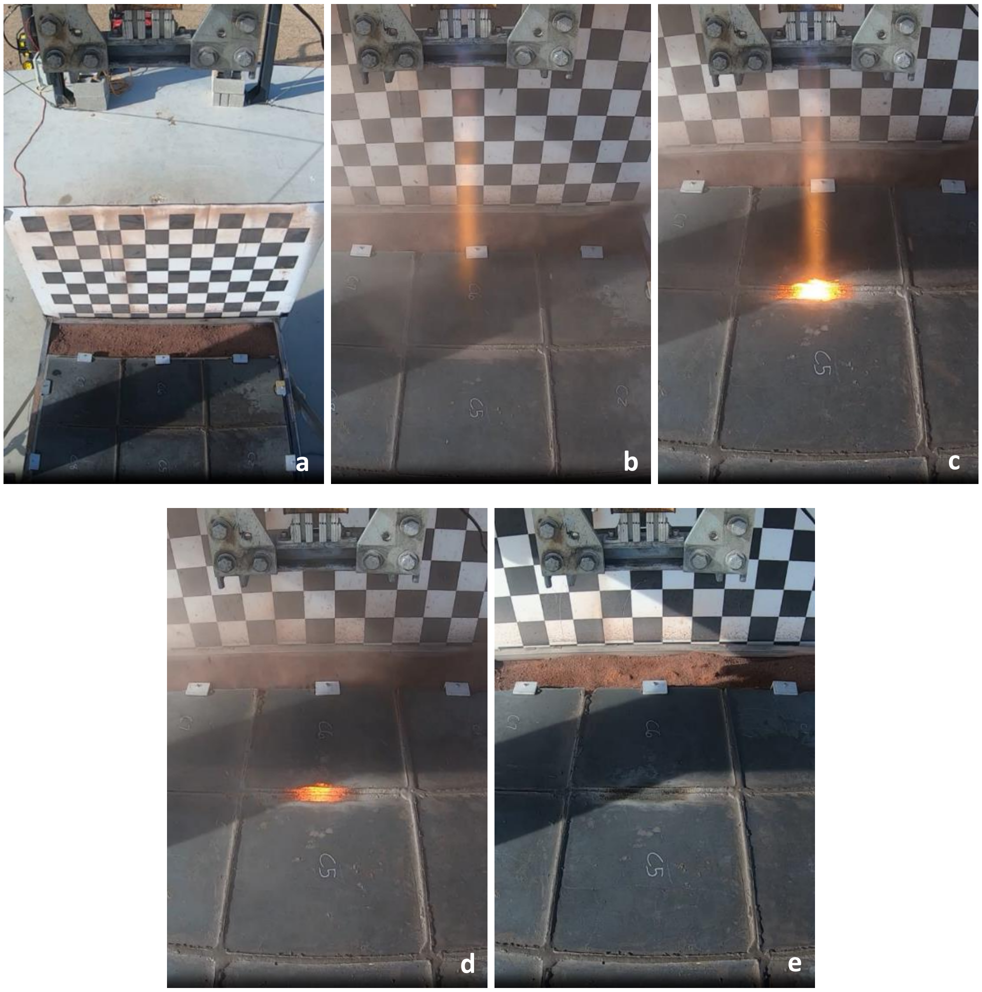

Figure 10. Set of sintered pavers installed over regolith (a) just prior to testing of grout exposure to engine plume, (b) as the engine descends approximately halfway to the stops, (c) glowing while the engine is at its closest position on the stops (60 cm above test article), (d) at engine shutdown, and (e) less than a second after engine shutdown. The offset position of the paver assembly is revealed by the presence of uncovered regolith.

CONSTRUCTION IMPLEMENT CONCEPT DEMONSTRATION

A concept for preparing and emplacing the materials was developed and tested in laboratory conditions. The testing evaluated the feasibility of using screw extruder technology to mix, convey and deposit materials. Testing was performed at CW Brabender facilities in South Hackensack, New Jersey. Black Point-1 (BP-1) regolith simulant and RTV-655 were used for the tests. The BP-1 was size screened to pass a 0.55mm sieve. The test set-up used a gravimetric feeder to deposit BP-1 into the feed inlet of the extruder. Two high viscosity Beinlich pumps were used to deposit each part of the RTV into the extruder feed inlet at set rates to match the mixture ratio of each part and to match the deposition rate of the BP-1 so that the desired overall BP-1 RTB mass percentage was achieved. Tests were run using both a single screw extruder and a twin-screw extruder. Single screw extruders typically have more torque capacity than twin screw extruders. This was a desirable feature because it was anticipated that the highly loaded materials would require large torque ranges to extrude. Twin screw extruders have superior mixing performance as compared to a single screw extruder. Barrel heaters were not employed during the test. The barrel air cooling system was used to reject the heat generated by friction. A conveyor take-up system was used to receive the extrusion as it exited the barrel.

Testing began with the 1 ¼” diameter, 25:1 Length/Diameter (L/D) single screw extruder. The screw had a feeding/conveying section with a 3:1 compression ratio, a “pineapple” mixing section, and a final conveying section. A die was not used on the outlet of the barrel. Figure 11 shows the test set up with the single screw extruder.

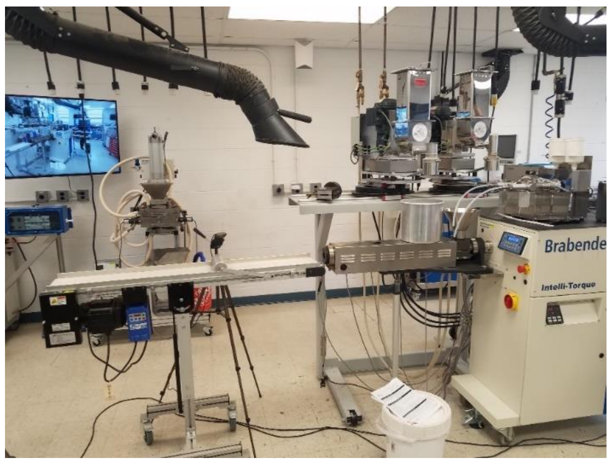

Figure 11. The single screw extruder equipment is configured for testing.

Testing started with only the RTV parts flowing into the extruder to lubricate the screw and barrel. BP-1 content was gradually increased while monitoring system torque and temperatures. Figure 12 shows extrusion at 80/20 wt% BP-1/RTV mixture ratio. Samples were collected for later analysis at 70/30, 80/20, and 85/15 BP-1/RTV mass percentages, see Figure 13.

Figure 12. 80/20 wt% BP-1/RTV material exits the extruder.

Figure 13. Samples of 70/30, 80/20 and 85/15 wt% BP-1/RTV materials are collected for future analysis.

Extrusion loading levels beyond 80% BP-1 caused irregular torque characteristics and flow conditions in the single screw extruder. Torques would rapidly peak and then drop off. Material flow surged and slowed intermittently. When loading levels of 90% BP-1 were attempted the torque spiked above 320 Nm which caused a safety shear pin to fail. When the screw was removed from the barrel it was observed that there was inconsistent flow occurring along the length of the screw and material was coating passive side of the flights. Figure 14 shows the screw after removal from the barrel. These conditions are evidence that the screw design was not optimal for the application. It is thought that the erratic behavior of the system was likely due to the 3:1 compression ratio of the screw which causes frictional increases as the volume in between flights is reduced along the length of the screw. A 1:1 compression ratio screw was not available for use.

Figure 146. The extruder screw has inconsistent residual materials along its length.

The twin screw extruder system was set up to continue testing. The extruder has two 20mm diameter co-rotating screws and a length of 800mm. The test setup is shown in Figure 15. The screws had a series of two conveying, metering, mixing sections followed by a final conveying and metering section.

Figure 15. The twin screw extruder is configured prior to testing.

Testing started with only the RTV parts flowing into the extruder to lubricate the screw and barrel. BP-1 content was gradually increased while monitoring system torque and temperatures. Samples were collected for later analysis at 70/30, 80/20, 85/15, and 90/10 BP-1/RTV mass percentages. Visually, the extrusion appeared to be uniform in makeup and did not exhibit the surging/slowing behavior as seen with the single screw extruder. Torque values remained much more consistent and well below the operating limits of the extruder. At 85/15 wt%, pressure readings at the tip of the barrel read an increase in pressure over ambient which indicated that the material was capable of building pressure and flowing. A 20mm die was attached to the barrel to form the material as it left the extruder. Figure 16 shows extrusion occurring at 85/15 BP-1/RTV mixture ratio before and after installation of the die.

Figure 16. Extrusion of 85/15 wt% BP-1/RTV without the die (left) and with the die (right).

Since the extrusion rate was consistent, the take-up conveyor was put into position to receive the materials as they exited the barrel. In concept, the conveyor simulated single degree of freedom motion of an extrusion system capable of tracing out material deposition trajectories for construction. Bonding and other characteristics of vertical and horizontal material deposition passes were not in scope for this testing but should be evaluated in follow on activities. Figure 17 shows materials deposited on the conveyor after the conveyor speed was set to match the extrusion rate. The extrudate appeared very consistent and promising for additive construction applications.

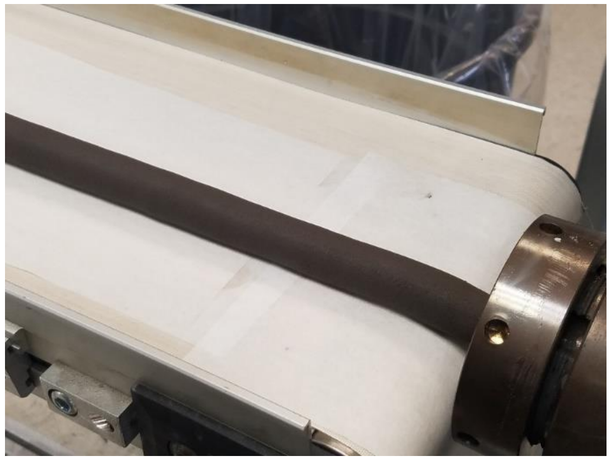

Figure 17. Extrusion onto the conveyor take-up system shows very consistent deposition characteristics.

A roller compaction concept was tested to determine if an asphalt-like deposition/construction process could be employed as opposed to an additive construction process. Asphalt is normally conveyed to the road surface, spread out over the width of the pass and then compacted by a roller to the desired lift height as it exits the equipment. The roller can span across an adjacent deposited layer and provide margin for positioning error since the materials are pressed into place against the previous adjacent layer. It is thought that this approach could reduce demands on autonomy for construction systems by allowing for more margin in positioning error as compared to an additive construction strategy. Figure 18 shows the roller attachment installed on the conveyor and compacting the materials. The conveyor and roller are covered with parchment paper in an attempt to prevent the BP-1/RTV materials from sticking to surfaces. Though the concept was successful, methods for mitigating material adhesion to the roller will have to be developed if this construction method is pursued.

Figure 18. A roller attachment is installed on the conveyor to compact the materials after deposition(left). Materials stick to the parchment paper after they have been compressed (right).

When the mixture ratio was lowered to 90/10 wt% BP-1/RTV, the behavior of the material changed. It exited the die in solid extruded rod form rather than a high viscosity fluid. Figure 19 shows that the extruded rod was self-supporting as it exited the die. Initially it was thought that the RTV may have cured, but further inspection showed that not to be the case. The extrusion was extremely dense, but still malleable. This behavior could be useful for extrusion of formed shapes such as bricks or other structural elements.

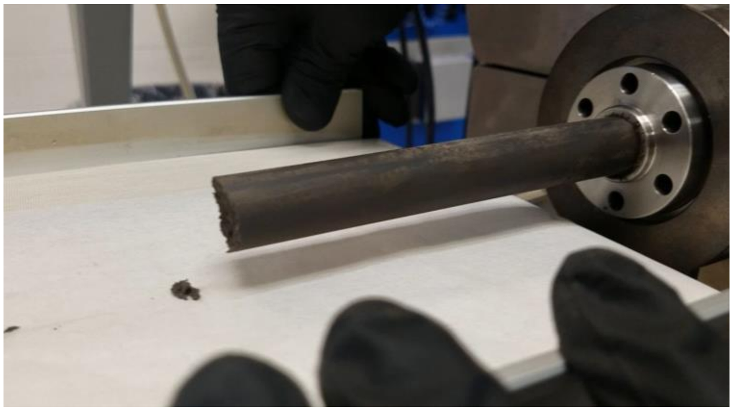

Figure 19. The 90/10 wt% BP-1/RTV extrusion is self-supporting as it exited the die.

After testing, the twin screw extruder was opened to inspect the materials and screws. Figure 20 shows the twin screw extruder in an opened configuration directly after testing. The first conveying, metering, mixing sections on the right-hand side of the screw were sufficient to fully mix the materials since no dry regolith exists further down the length of the screws. This implies that the extruder length can be significantly reduced and still yield the same performance. Reduction in extruder length will provide an overall mass savings and reduced torque and heat dissipation requirements since the area where friction occurs is reduced.

Figure 207. The twin screw extruder in an opened configuration directly after testing.

CONCLUSIONS

The feasibility of the regolith-thermoset polymer composite based construction approach was proven in three critical areas: performance under ambient engine firing simulating launch/landing conditions, fitting within the planned lunar payload capacity, and demonstration of a mixing and depositing concept. Follow on work must be performed to characterize effects of lunar thermal, radiation, and gravity environments on the materials and design the materials to accommodate the full range of lunar environments. It is recommended that development continue to TRL 6 for a small-scale lunar demonstration of emplacement of a launch/landing pad using a CLPS mission to support Artemis Program roadmap gap closure activities.

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