Extraterrestrial Construction Using Contour Crafting

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REVIEWED, Accepted August 15, 2012

Abstract:

Most proposals for construction of settlements on Moon and Mars are based on transporting structural elements from Earth and assembling them at the destination. A far less expensive and potentially practical approach is using Contour Crafting, a large-scale AM process, in conjunction with in-situ materials. Our trials with sulfur based concrete and sintered lunar regolith simulant made by NASA show strong promise. Our project ultimately aims at demonstration of lunar outpost infrastructure construction involving landing pads, blast walls, roads, shade walls and protective hangars. This paper reports on our very early efforts in the first stage of the project.

Keywords: Contour Crafting, Sulfur Concrete, Lunar Regolith

Introduction:

As interest in space exploration increases, human beings are to return to Moon and land on Mars in the future. To carry out experiments and live a longer time on extraterrestrial planets, permanent habitats are needed to shield heat, cold, cosmic rays and meteorite impact. Due to negligible lunar atmosphere or scarce Martian atmosphere, spaceship landing and launching off will cause frozen ice crystal from the fuel and gravels flying at a fast speed far away. High speed flying objects including micrometeorites threaten devices and inhabitants around. With solid landing pads and protective walls, landing and launching off will be much safer. Furthermore, hangars are needed to protect the landers and other equipment from radiation and micrometeorites and roads are needed to transfer the landers between the landing pads and the hangars.

Most proposals for construction on Moon and Mars are based on transporting structural elements from Earth and assembling them at the destination. Such approach is expensive and infeasible for large-scale implementation. Our approach is based on the use of in-situ material and digital fabrication techniques to construct the infrastructure elements. Intense research has been carried out in in-situ resource utilization (ISRU) and specifically lunar regolith characteristics have been extensively studied. In our research we are exploring the possibilities of using sulfur based concrete and molten regolith as construction materials to be processed by Contour Crafting.

Sulfur concrete is a mixture of pure sulfur with aggregate, which becomes strong as hydraulic concrete when heats up and cools down. Sulfur is extracted from Troilite soil (FeS) on the moon as a byproduct of iron. Toutanji [1] reports experiments, in which 35 % sulfur with 65% JSC-1 lunar regolith simulant by mass is mixed and heated up to 130-140 ºC, and then casted into 2-in cubes. The reported compressive strength is 2300 psi at -27 ºC, 2500 psi at room temperature. The performance under extreme temperature cycles has also been studied. Unlike hydraulic concrete, no chemical reaction takes place in the hardening process of sulfur concrete, and the material could be recycled indefinitely by heating up to sulfur melting point. Sulfur concrete cures very fast, reaching 90% of its ultimate strength in the first 6 hours by cooling to ambient temperature in terrestrial applications [2].

Researchers have also demonstrated building physical assets by geothermite reaction of lunar regolith and combustive metal powders. Using electrical wires to heat up the mixture and initiate the geothermite, metal powder will react with lunar regolith. Net shape voussoirs for domes have been fabricated in this way [3]. The compressive strength of fabricated parts ranges from 10-18 MPa (1450-2610 psi). These voussoir pieces could build up a dome structure which is geometrically stable and small cracks in the voussoir pieces will not threaten the whole structure. In this way, about 33 % of aluminum or magnesium powder by mass is needed for construction material.

A far less expensive and more feasible way is expected to be construction by Contour Crafting, a large scale AM process to be used in conjunction with in-situ materials. By using Contour Crafting the need for human intervention in extraterrestrial construction could be minimized, thus reducing the trouble for supplying food, oxygen and safety measures and saving huge amounts by eliminating the need for such resources. Our trials with sulfur concrete and molten lunar regolith simulant (JSC-1A) show strong promise.

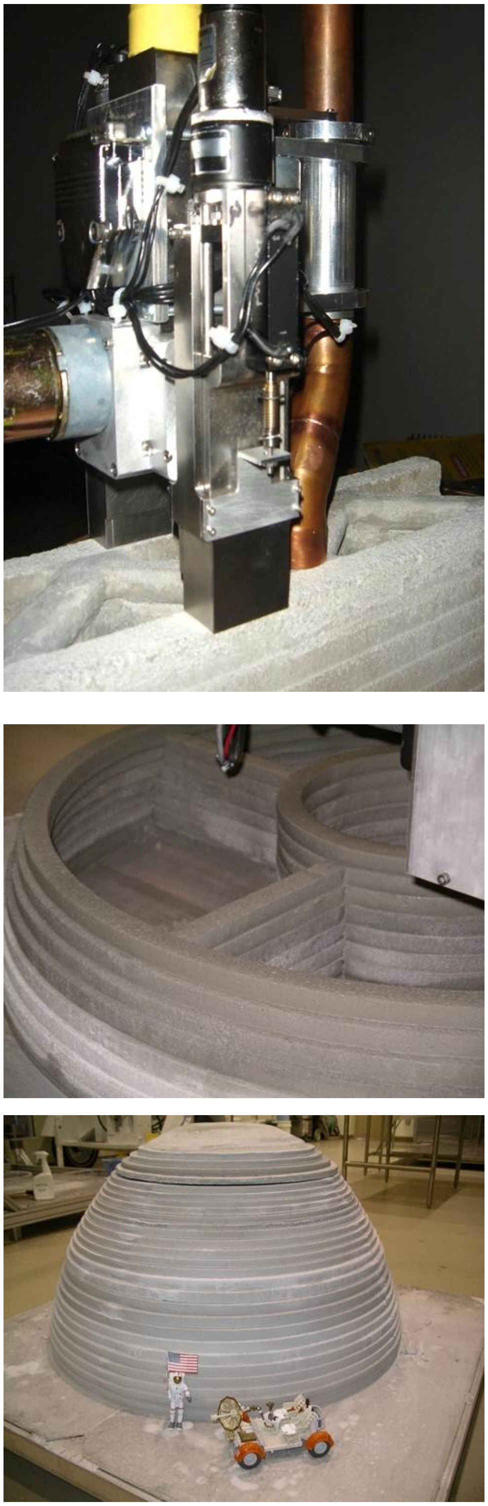

Figure 1. Top: Coextrusion by CC nozzle. Bottom: Dome structures built using Contour Crafting

Contour Crafting:

The basic CC technology works using layering of paste material extruded through a nozzle, which is maneuvered by a gantry or a mobile robot. The nozzle is equipped with computer-controlled trowels and other features that assure controlled surface geometry and possibility of hollow walls with intricate internal structures. The technology also allows integration with other robotic modules for concurrent placement of blocks, tiles and other external features such as plumbing, electrical and sensor modules in and around the extruded structures. The CC technology is currently at Technology Readiness Level (TRL) 6. Successful experimentations have been conducted on several materials, such as plastics, ceramics, composites and concrete. The CC technology as a building system tool has targeted the economic viability of the built-up environment and has demonstrated this capability for terrestrial applications. CC machines have produced full-scale structural elements such as walls with complex internal features (Figure 1, top). In fact, NASA has evaluated the CC technology and an elementary CC machine has been used to demonstrate dome construction with internal features at NASA MSFC (Figure 1, bottom) [4].

Automated building technology such as Contour Crafting is critical to improving astronaut safety in construction scenarios where conventionally several large and bulky components are proposed employing astronauts in risky EVA procedures. The assembly and building of roads and platforms are essential to setting up an initial operational capability base.

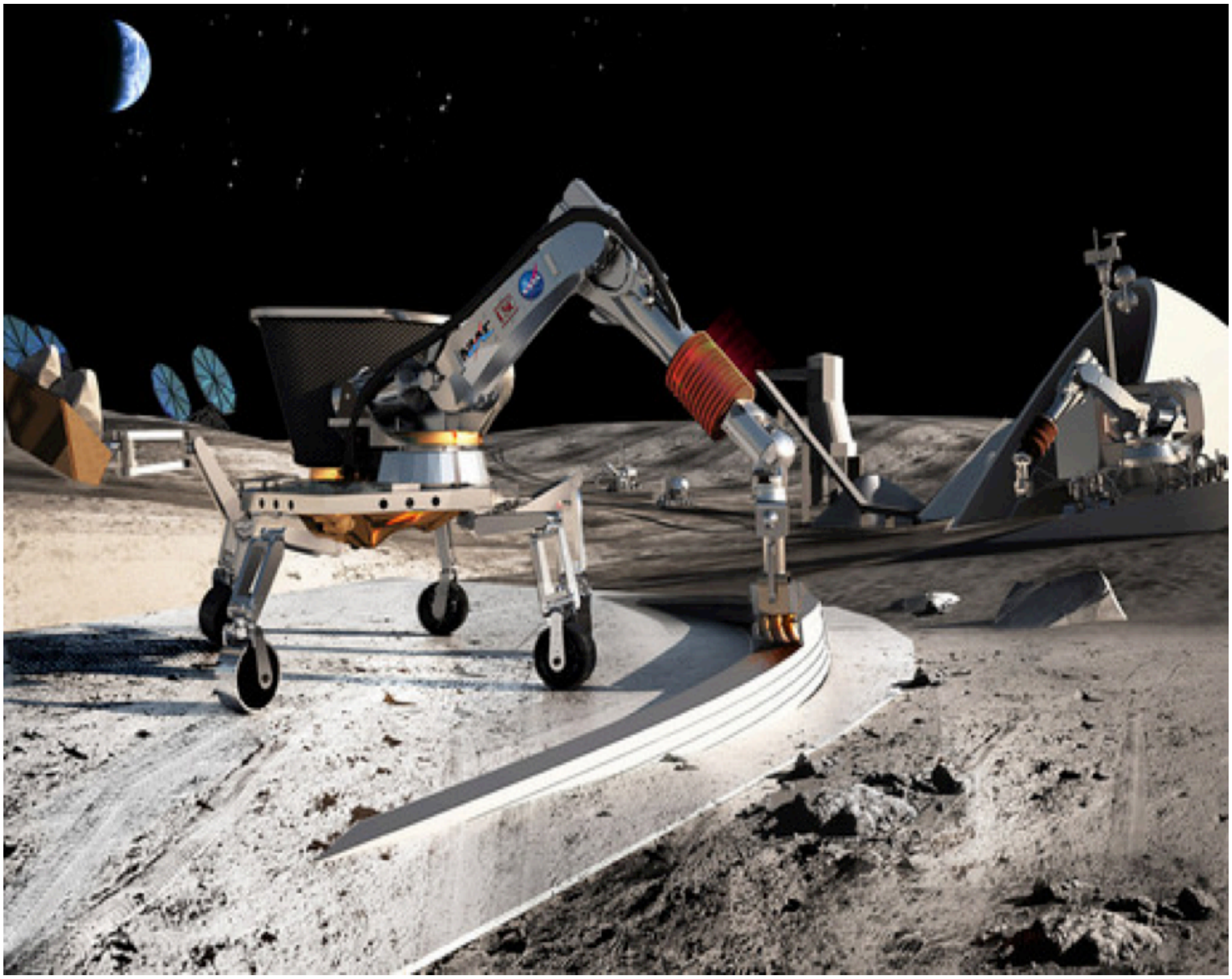

Figure 2. A Contour Crafting robot, housed on an 'ATHLETE' rover, is shown here printing a parabolic vault structure out of processed regolith. The structure is intended to house a lunar lander or other equipment, and is unpressurized. In the background can be seen an array of solar panels intended to supply power to the robot.

Using CC, it is possible to reduce or eliminate astronaut presence on site. We hope to conduct a series of activities to evaluate the merits and limitations of using CC in establishing an Initial Operational Capability (IOC) lunar base. Figure 2 illustrates a CC nozzle assembly and material delivery and melting system mounted on the JPL ATHLETE rover and constructing a lunar hangar by extruding molten regolith.

Sulfur concrete application:

Sulfur concrete is a relatively new construction material compared with hydraulic concrete. To use sulfur concrete, aggregates is mixed with sulfur powder and then is heated up to around 130 ºC then is cooled down to ambient temperature. The cooled down mix has a compressive strength as high as 17.24 MPa (2500 psi). Sulfur concrete cures faster than hydraulic concrete, and achieves 90% of its final strength within 6 hours. Sulfur concrete is more resistant to acidic and salt and hence it has been made into sewage pipes especially in food processing industries. Sulfur concrete also has better properties under large temperature cycles. The aggregate in our experiments is washed dry sand with a grain size below 1 mm, similar size distribution to that of JSC-1A. Loosely compressed sand has a specific gravity of 1.64g/cm^3, and that for regolith simulant is 1.73g/cm^3, and for sulfur and sand mixture is 1.68g/cm^3. Both sand and regolith simulant grains are irregular, and the chemical composition does not affect the binding strength.

Sulfur concrete extrusion could realize complete automation, high reliability and flexibility. We have demonstrated that sulfur concrete may be extruded from a nozzle. In the In terrestrial practice heated sulfur concrete mixture is poured into a mold to cool down, which takes time to cool down and move to the construction site to build up the desired structures. The shape of the mold is also limited. By extrusion, sulfur concrete could be extruded in arbitrary straight or curve forms at the construction site, fulfilling different design objects at a much faster rate and without needing molds.

A prototype extrusion system has been built in our lab and the concept is demonstrated. The system contains three main parts, feeding container, flow regulator, and heated extrusion elements. The feeding container stores raw materials and mixes them uniformly at a designed weight ratio. In the prototype system sulfur and aggregate are premixed with a weight ratio of 35% and 65%, respectively. The feeding container is a funnel with the narrow stem around a copper pipe of extrusion usage. While the system is in operation, the mixture flows into the copper pipe by means of vibration. In the real machine to be developed, a larger hopper will replace the funnel.

A flow regulator controls the flow direction of the heated paste mixture and exerts some pressure to the mixture to make it denser and smoother. Currently the flow regulator has a fixed shape and is only suitable for building certain structures of certain shape, like curved walls such as the one shown in Figure 3 is formed. In the new design a flexible regulator compatible to arbitrary shape is expected, and two heated trowels on both sides of the nozzle orifice will be adopted to smooth out the extrudate surfaces.

Figure 3. The Bridging effect

During the extrusion process the mixture is heated to around 135 ºC and is extruded from the copper pipe by the rotation of an auger. The copper pipe has an inner diameter of 0.96 cm (0.38 inch), and a length of 10.16 cm (4 inch). At the end of the pipe, there is an opening about 0.51 cm (0.2 inch) tall and 1.02 cm (0.4 inch) wide where sulfur concrete could flow through. The opening is connected to the flow regulator. An adjustable heating element of 40 Watts at maximum is closely coupled with the copper pipe and conducts heat to the mixture inside the pipe. An auger with a diameter of 0.95 cm (0.375 inch) rotates in the copper pipe to extrude the mixture out of the copper pipe as shown in Figure 4. A 12 volt gear motor of a ratio of 16:1 drives the auger by a coupler. A vibrator fixed on the auger generates and transmits vibration to the auger as well as to the mixture and the feeding container. The vibration in the auger breaks the arches that can be formed by the bridging effect shown in Figure 3. Without vibration the bridging effect frequently clogs the extrusion barrel.

Each section between two neighboring auger blades (auger pitch) is 1.27 cm (0.5 inch), and contains a mixture with a volume of

$$V = \pi(r_o^2 - r_i^2)h = 0.678cm^3$$

The heat needed for the sulfur to reach 135C from room temperature 25 ºC is

$$Q_s = 35\% * \rho_{mix} * V * (110K * C_s + H) = 96.2J$$

The heat needed for the sand to reach 135 C from room temperature 25 C is

$$Q_{sand} = 65\% * \rho_{mix} * V * (110K * C_{sand}) = 21.5J$$

The total energy needed is

$$Q = Q_s + Q_{sand} = 117.7J$$

In the equations r_o and r_i are the outer and inner diameters of the auger, h is the pitch of the auger, ρ_{mix} is the specific gravity of the mixture, C_s is the specific heat capacity of sulfur of 0.71J/g/K, and H is the sulfur heat of fusion of 54.0J/g, C_{sand} is the specific heat capacity of sand of about 0.80J/g/K.

During the extrusion process, the auger has an angular velocity of about 30 rpm. The copper pipe has a length of 4 inch, for this section to get out of the pipe, it takes 8 revolutions and 16 seconds. The actual generated heat from the heating element is 640J. The efficiency of the prototype system is 18.4%, which is quite low due to conduction of heat to the environment. The extrusion process is continuous without interruptions. In the lunar vacuum environment, the efficiency could be increased to above 50%, and to process 1 cubic meter of sulfur concrete a solar panel of 7 square meters would be needed to work for only 1 day.

Results:

The suitability for extrusion of different sulfur concentration is tested. Sulfur concentration of 35% by mass shows feasibility to extrude continuous and high quality walls. Single layer walls of different sulfur concentration have been built as shown in *Figure* 4.

At a sulfur concentration below 30% by mass, friction between the auger and the mixture might suddenly increase to a degree that the motor could not rotate even under the strongest vibration. The extruded wall is discontinuous and very loose. At a sulfur concentration above 40% by mass, melted sulfur will flow out from the nozzle, causing the material to be non-uniform and the structure to be weak because of sulfur dominance. For a sulfur concentration of 35%, the extruded process is smooth and the rotation can be maintained at a constant speed.

The distance between the bottom of the copper pipe and the platform also matters. When the distance is too large the mixture in the copper pipe has no support and will fall down to the platform directly without enough sulfur getting melted. A small distance is preferred if the platform is flat, since concrete flows out in all directions if there is a large gap between the nozzle outlet and the platform.

Figure 4. Extruded parts with 40%, 30% and 35% sulfur concentration (left to right)

Our measured compressive strength of extruded sulfur concrete is 7.79 MPa (1130 psi) at maximum and 3.65 MPa (530 psi) for average. This value is lower than that of the sintered cube in Toutanji's research. Sulfur concrete in this experiment is poorly pressed. Once a more powerful extrusion system is used to compact the sulfur concrete, the compressive strength is expected to increase significantly.

Experiments show that extruded sulfur concrete has promising properties, especially for lunar condition where gravity is 1/6 of that of earth. Here are the main advantages:

1. Sulfur concrete gets melted at 120 ºC, and the specific heat is low, reducing the energy demand. In practical applications heating the mixture to 130 ºC is sufficient for the process.
2. Sulfur concrete cures very fast. Experiments show that in about 2 minutes after extrusion sulfur concrete becomes hard and can sustain multiple layers.
3. No waste material is generated because all the solid material could be fixed in the sulfur net.
4. Material is recyclable. The built part could be recycled by crushing it into small pieces or melted into paste. Material recycling is favored on lunar construction.

5. The interlayer binding is strong. By building parts in multilayers it is proven that the above layer could adhere to the layer underneath.

From the photos of the specimens it can be seen that the fabricated parts contain porosities in the inner structure, mainly caused by expanded air bubbles in the mixture; such phenomena will not exist in the lunar environment where there is no atmosphere. Compaction immediately after extrusion could also reduce the porosity.

Lunar Regolith Sintering and Melting:

While sulfur concrete extrusion by CC is suitable for certain lunar structures that will not experience heavy loads and will not be exposed to direct sunlight (which could heat the structure above the melting point of sulfur), processes based on lunar regolith sintering and melting could be used to build landing pad, protective walls and other structures that undergo heavy loads and receive intense radiation by the sun. Sintered plain regolith has high compression strength. To sustain shock impact and tensile stresses, we have discovered that mixing metal powders before sintering significantly enhances the regolith tensile strength. We are also envisioning a variation of the CC method for sintering-based fabrication. Numerous experiments have been carried out to study regolith sintering. The JSC-1A lunar simulant used in our experiments has been obtained from Orbital Technologies Corp. This regolith simulant is designed to be chemically similar to mare regolith. This simulant has a grain size smaller than 1mm, and melts at 1100-1125 ºC.

Experimental Setup:

Lunar regolith and its mixtures with copper and steel are manually compacted in graphite molds. Compacted regolith mixture is put into a ceramic furnace (CeramPress Qex Porcelain and Pressing Furnace). The sintering temperature ranges from 975 ºC to 1100 ºC, lasting for 1 hour or 2 hours, in a vacuum condition of 1 torr. Temperature rising rate is 25 ºC/min starting from room temperature, and cooling rate to room temperature is decided by heat conduction to the platform in the same vacuum condition. The mold is 5.08cm*1.65cm*0.76cm (2 inch*0.65inch*0.3inch) in dimension.

Figure 5. Plain regolith sintered at 975 ºC for 1 hour

Results:

As the temperature increases from 975 ºC to 1100 ºC, compression strength increases first and then falls down due to porosity near melting temperature. At 975 ºC, regolith barely sinters, there is almost no shrinkage, and even a pencil tip could brush off the cooled block, as shown in Figure 5. For plain regolith sintering as shown in Figure 6, from 975 ºC to 1025 ºC the compression strength of sintered plain regolith increases and then drops down after 1050 ºC. The compressive strength at 975 ºC for sintered parts is denoted as 0. At 1000 ºC, increasing sintering temperature to 2 hours only slightly increases the compressive strength from 6.83 MPa (991 psi) to 10.34 MPa (1500 psi). From 1000 ºC to 1025 ºC the strength increases rapidly to 36.20 MPa (5250 psi) and 53.5 MPa (7760 psi), respectively. At 1050 ºC, sintered block contains large pores, significantly reducing the compression strength. At 1110 ºC, regolith melts and the powder swells out of the molds. The final parts contain large voids, which are visible at the surface as shown in Figure 7.

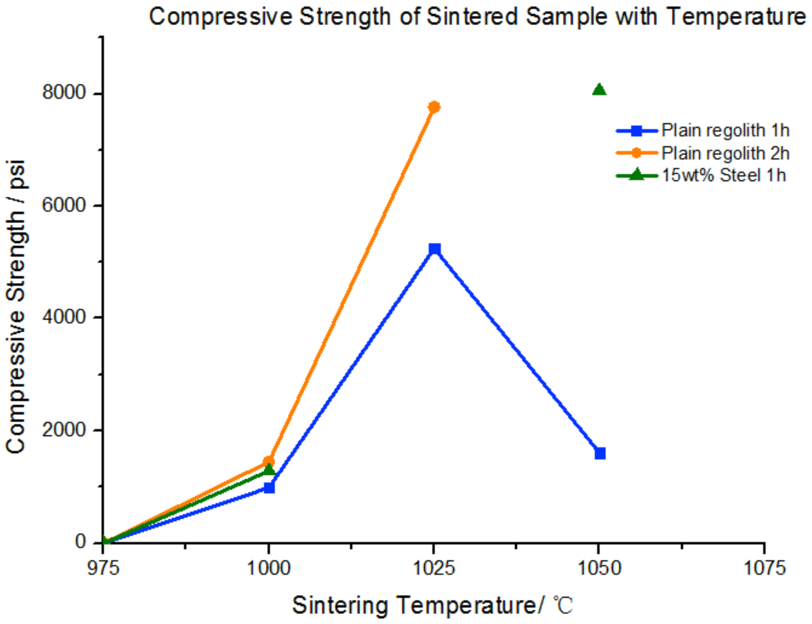

Figure 6. Compressive Strength of Sintered Sample with Temperature (The blue and orange dots denote plain regolith)

Figure 7. Plain regolith simulant sintered at 1100 ºC for 1 hour

Adding steel powder into the regolith could increase the quality of sintered parts at high temperature. The steel powder used is SS316H of 325 mesh size. Without addition of steel powder, plain regolith will swell and voids appear inside the sintered parts. At the temperature of 1050 ºC sintered blocks swell out of the molds as seen in Figure 8. With addition of steel powder with a weight ratio of 15%, the mixture has a high compressive stress of 55.57 MPa (8060 psi). The cracked sample after compression test also shows no visible voids in the sintered block.

Copper regolith mixture is also tested. Experiments show that copper could also increase the compressive strength but does not help at temperatures as high as 1050 ºC. Samples with copper also swell and contain vacancies inside.

(a) Plain sintered regolith (b) Sintered regolith steel mixture

Figure 8. Plain regolith and regolith steel mixture sintered at 1050 ºC for 1 hour

Conclusion:

CC technology combined with sulfur concrete and regolith sintering has proven feasible in the lab setup prototype systems. This approach could significantly save the energy and time used for extraterrestrial construction, and liberates astronauts from the heavy and hazardous work of onsite construction.

Experiments have shown the feasibility of the CC technology with sulfur concrete. In-situ material of regolith and sulfur could be obtained with ease; saving transportation cost from the earth proves feasibility for space exploration. Sulfur concrete requires much less energy than competitive construction materials and is 100% recyclable. CC will be able to automatically build complex shape structures with sulfur concrete.

Compressive strength of sintered plain regolith and mixture could reach 55.16 MPa (8000 psi), which is strong enough for building structures such as landing pads, blast walls and hangers. Sintering of regolith could be possibly used in two ways. First, regolith can be sintered with regular shapes like blocks and voussoirs, and regolith bricks. Faierson has showed that vousoirs with a compressive strength of 13.79 MPa (2000 psi) could sustain a self weight of 4259 m on the moon, since the dome structure is geometrically stable [3]. In this case regolith brick pavement might be combined with sulfur concrete extrusion. As sulfur concrete is extruded upon the previous layer of bricks, another layer of bricks may be paved upon it with a compression force. Such a combination could greatly speed up the construction rate and stronger buildings could be expected. Second, regolith sintering can be carried out on the construction site to yield the main construction material. A variation of the CC process may be used to deliver the regolith mix as a layer onto a selected area and keep it within the confines of three trowels (on sides and front) and expose the mix to sintering heat for certain time to complete the sintering process while slowly moving the delivery nozzle and trowels forward in a continuous sintering process.

Experiments are underway for layerwise fabrication using extrusion of molten regolith. These experiments will be best performed under vacuum as presence of air causes trapped gas expansion under extreme heat that result in voids in the extrudate.

Acknowledgement:

This research has been performed under a NASA Innovative Advanced Concept (NIAC) Phase I grant. We have received valuable guidance throughout the project from NIAC program officers and NASA researchers at various NASA centers.

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