# Additive Construction with Mobile Emplacement: Multifaceted Planetary Construction Materials Development

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## ABSTRACT

The National Aeronautics and Space Administration's Additive Construction with Mobile Emplacement (ACME) project is developing construction materials with which infrastructure elements, including habitats, will be additively constructed for planetary surface missions. These materials must meet requirements such as the ability to be produced from available in-situ resources to eliminate the cost of launching materials from Earth, the ability to be emplaced via three dimensional building techniques, the ability to resist aging in extreme environments including radiation and micrometeorite bombardment, and the ability to provide the necessary structural integrity for a given building.

This paper reviews the constraints placed on such planetary construction materials and details the work of the ACME team in characterizing materials that could one day construct planetary surface structures on Mars or the Moon. Material compositions, compressive strength, and requirements for additive construction on planetary surfaces are discussed. Due to the multifunctional requirements of the material, an optimization is necessary to balance between the site-specific regolith composition, emplacement via additive construction techniques, and characteristics of the final structure.

## INTRODUCTION

Additive construction is the process by which structures are built in three dimensions (3D) using a digital 3D construction model (Labonnote et al., 2016). The National Aeronautics and Space Administration (NASA) is studying this method for building structures including roads, berms, habitats, hangars, garages, and other infrastructure on planetary surfaces. The Additive Construction with Mobile Emplacement (ACME) project within NASA is funded by the Space Technology Mission Directorate Game Changing Development Program and the United States Army Corps of Engineers (USACE). NASA is interested in additive construction because it provides the ability to build different types of structures using a single robotic device with in-situ resources on planetary surfaces, thus saving the cost of multiple launches of construction equipment and materials from Earth. The USACE is involved because it also seeks to build structures from 3D models in theater from locally available concrete constituents.

To make additive construction feasible for planetary structure emplacement, materials must meet multiple requirements in multiple categories, such as the ability to be emplaced via additive construction techniques, the ability to be produced from available in-situ resources to eliminate the cost of launching materials from Earth, the ability to resist aging (degradation over time) in extreme environments, and the ability to provide the necessary structural integrity for a given building. The ACME team has identified numerous constraints that apply to each candidate material, and have begun evaluating materials based on their potential for use. Each material must have facets that meet minimum performance requirements in each category to be considered; a multifaceted, multifunctional construction material is critical to employ additive construction on planetary surfaces.

## ADDITIVE CONSTRUCTION TECHNOLOGY MATERIAL CONSTRAINTS

While the definition of additive construction allows for the layer-by-layer emplacement of solids (bricks), powders, and extrudable liquids/slurries (Labonnote et al., 2016), the ACME team is currently focusing on extrudable (slurry-type) materials for many reasons. First, there is little to no construction waste, unlike most powder 3D printing applications, as the slurry is simply deposited in specific locations layer-by-layer. Second, no mortar or adhesive is needed between bricks to form a single layer; ideally, the material chosen for additive construction will provide sufficient layer adhesion in order to eliminate the need for an additional adhesive material. Third, no formwork or any subsequent vibration is needed for the structures constructed. Fourth, a single feedstock delivery system and emplacement system can be used. Sintered regolith bricks, for example, require oven or microwave heating under very specific conditions. Slurry-type additive construction printing simply requires targeted deposition according to 3D models; it is a scalable process.

The ACME second-generation system at NASA's Marshall Space Flight Center (MSFC) is composed of a gantry mobility system, which dictates positioning of an extruder/nozzle, a concrete mixer and pump, hoses which run from the pump to the nozzle, and an accumulator, which accumulates concrete when the nozzle is not depositing in order to form a doorway or window gap. This system allows for continuous feedstock delivery to the nozzle and continuous deposition. The gantry system also dictates the allowable size of the structure by a defined print volume. A similar system exists at NASA's Kennedy Space Center (KSC), which uses a stationary robotic arm for positioning, a gravity-fed dry feedstock delivery system, and a heated nozzle to extrude polymers mixed with basalt rock regolith simulant.

For each system, the original mixture composition dictates the viscosity of the mixture at given temperatures, extrudability or workability of the mixture, the initial compressive strength of the deposited material in order to support subsequent layers, the initial setting time rate of the deposited material to ensure build ability and interlayer adhesion while considering the weather conditions under which the material can be deposited, as well as the environment the printed structure can function within. For example, Ordinary Portland Cement (OPC) Type III "high early strength classification for rapid construction cold weather applications" compositions and admixtures are available for high-latitude and high-elevation sites, which can allow setting of concrete at ambient temperatures as low as -7°C (Nmai, 1998).

An additive construction system consisting of a concrete mixer, pump, hoses, accumulator, and nozzle has its own limitations. First, a batch mixing system, such as a concrete mixer, limits the amount of material available by the defined volume of the mixer. Additionally, it can inadequately mix the material if not given sufficient time to mix properly. Second, using a pump system can add and redistribute air bubbles, pressurize the concrete so bleeding (settling) occurs, clog if not enough vibration is available to keep the slurry materials moving, and dictate how consistently the material flows. The pump also requires a certain viscosity in the mixture to make it pump-able. Third, the hoses used to transfer material can also affect air distribution, promote settling due to pressurization in the system that can occur if it is not sufficiently lubricated to allow the slurry material to pass, and change the continuity of flow due to friction, abrasion, or bridging of aggregate. This type of friction and abrasion can also occur in the nozzle of the system, causing tearing of the deposited slurry bead.

In the polymer concrete system, some of these challenges are eliminated since the ingredients are fed as a dry powder or in pellet form to the print head extruder nozzle, and the melted polymer slurry is produced "just in time". Other issues and challenges exist with this system, such as efficient conveying of each granular material ingredient, accurate dispensing and mixing ratios, temperature control, clean deposition and interlayer adhesion. Polymer materials tend to shrink when they cool so that warping and shrinkage must be assessed and mitigated to have accurate construction tolerances.

## PLANETARY MATERIAL COMPOSITION CONSTRAINTS

There are multiple constraints on materials based on the location of construction. For example, the building of structures on planetary surfaces will require a large quantity of feedstock. A single-story square structure with 20 meter long walls (400 square meter footprint), each 0.2 meters thick and 2.5 meters high requires 40 cubic meters of material (not including the foundation or roof). This puts a great requirement on the tools needed to excavate material, process the material into binder and aggregate, and mix the material into a usable form. It is for this reason construction waste is undesired. Thus, planetary construction materials should be optimized to be compatible with additive construction technology, to minimize construction material waste. A slurry material would fulfill this requirement. A slurry system is not limited to pastes or mortars composed of OPC. It is possible to use polymers, sodium silicate solutions, magnesium oxide-based cements, sulfur, metakaolin, and other binders.

The suite of available in-situ resources varies from site to site. This places additional constraints on the construction material chosen for a given site. For example, the state of Hawaii must import building materials such as asphalt and OPC from the continental United States for its structures. Whether NASA will build structures on the Moon or Mars, on the polar or equatorial regions, or if the exploration base is to be located on a basaltic or sedimentary rock site, the binder selection must reflect and complement the in-situ available materials. The mix should minimize the water consumption, as water is an important and precious resource for human life support, hygiene, growing plants, industrial processes, and making propellant. The construction materials mixture should not require a very precise mix because individual sites may have variations in geology that could affect a chemical mixture. For these reasons, mechanical binders are preferred over chemical binders, which can react with regolith added as filler.

To preserve energy for other exploration needs, the chosen regolith should require a minimal amount of power to mine (i.e., use loose surface regolith when possible), and the binder should require a minimal amount of processing to be produced from the available in-situ resources.

The creation of the construction material itself requires knowledge of the building site geology. Multiple sites are currently under examination as potential long-duration exploration sites on the Moon and Mars. These sites are not necessarily those that match currently available simulated regolith. Planetary scientists are continuing to characterize the potential exploration sites. Unfortunately, the volume of available in-situ resources is not well known. Thus, continued research into the amount of available material is necessary in order to assure that sufficient construction materials could be produced. Additionally, once a site selection is made, simulants must be created to match the bulk chemistry (including bulk mineralogy), grain size, grain shape, and density of the in-situ resource to provide assurances, through testing on Earth, that binder production technology will work efficiently on the selected planetary surface.

## EXTREME ENVIRONMENT CONSTRAINTS

The environment of deposition is the greatest constraint for materials chosen for additive construction on planetary surfaces. Conditions present on the Moon and Mars, referenced below from Williams (2017) must be considered in the material choices made for any structure on the surface of these planets.

**Gravity** is important in the settling of material, not only for the slurry itself which may reduce the height of the bead during emplacement, but for the aggregate/binder mixture. On Earth, aggregates found within slurry materials will settle to the bottom, while the binder material will often rise to the top of the bead (e.g., Petrou et al., 2000). This settling is not expected to occur in microgravity such as that of the International Space Station (ISS; e.g., Prater et al. 2016). The force of gravity is approximately equal to 38% that of Earth on Mars, and 16% that of Earth on the Moon. Settling is still expected to occur on the Moon and Mars, but the degree of settling would likely be less than that observed under Earth's gravity and more than that observed under the microgravity environment of the ISS; this aspect must be studied before the material can be reliably emplaced on the surface.

**Pressure at the surface** highlights the difficulties in the extrusion and emplacement of liquids. Vapor pressure becomes an issue, as fluids such as water sublimate at pressures of 0.01 of Earth's atmosphere on Mars, and the near total vacuum of the Moon. This sublimation effect must be well-studied, controlled or predictable as it can create vesicular material that will impact the durability and mechanical strength of the additively constructed structures.

**Temperatures** of the landing sites dictate not only how the material must be emplaced (i.e., with heaters; temperature also affects the setting time of thermosetting materials), but the temperature swings the materials must endure during the seasonal and day/night cycles on the planetary surfaces. Temperature swings are a factor in the aging process of materials. Each seasonal and day/night cycle will stress the material and likely degrade the material over time. Surface temperatures for the Viking 1 landing site on Mars ranged from -89°C to -31°C. On the Moon, near the equator, the day/night temperatures ranged from -178 to 117 degrees Celsius. Creating a material that can withstand these temperature swings, without degradation and shrinkage/expansion cycles outside of a specific tolerance for a given amount of time, is necessary for building durable and stable structures on the Moon and Mars.

**Radiation** from solar particle events and galactic cosmic rays is also a concern. The material created should offer some protection, either by design and composition of the material, or the capacity of the material to support a sufficient load of regolith to actively use the regolith as radiation shielding. On Mars, only a slight amount of protection from radiation is offered by the thin atmosphere (Hassler et al., 2013). For a particular exploration site, the radiation present must be characterized to place specific requirements on the construction material to ensure adequate radiation shielding for the crew.

**Surface bombardment and reactivity** is the property of planetary surfaces to potentially accelerate aging. On the Moon, the surface is being bombarded by hypervelocity micrometeorites and solar wind hydrogen which produces impact craters and glass, as well as a reducing environment evident by nanophase iron, respectively (Housley et al., 1974). Construction materials created for the Moon must be compatible with the reducing environment. On Mars, micrometeorites are not expected to form agglutinates due to atmospheric deceleration (Flynn and McKay, 1988), however perchlorates assist in creating a highly oxidizing environment (e.g., Hecht et al., 2008). Thus, construction materials created for Mars must be compatible with a highly oxidizing environment.

## PLANETARY STRUCTURAL CONSTRAINTS

Planetary structural requirements, like building codes on Earth, have not yet been completely fleshed out for a number of reasons. First, a permanent settlement on planetary surfaces where structures are built instead of inflated or merely positioned is not in relatively near-term plans (e.g., Mars Architecture Steering Group, 2009). Second, major strides in materials development continue to be made, thus the radiation protection properties, compressive and tensile strengths, and thermal properties of materials continue to be evaluated. In the Materials ISS Experiment (MISSE), materials are flown to the ISS and mounted outside the cabin to help assess aging of the materials in a well-characterized space environment (e.g., Robinson et al., 2006). Third, permanent habitats are still in the design phase, so there are no current guidelines for square footage, shape, and location of amenities. Fourth, the location of human landing sites on the Moon and Mars have yet to be determined and thus available in-situ resources have yet to be defined. Landing site workshops for the first human landing on Mars are underway (Bussey and Hoffman, 2016).

The Human Exploration of Mars Design Reference Architecture 5.0 document (Mars Architecture Steering Group, 2009) did not complete “a detailed assessment of Mars habitats”; instead, a comparison to the work of the Lunar Architecture Team was made. The lunar habitat architecture, cited within the Mars Architecture Steering Group (2009) document, included the assumption of a crew of four, incremental stay time (non-permanent), and emphasis on extra vehicular activity. The habitat architecture did not include the infrastructure for utilities, although needs for the habitats were estimated. The incremental stay time and extra vehicular activity emphasis provided the justification for a pre-built (Earth-made) central habitat, located on a lander platform, to be surrounded by two to three pressurized rovers and a logistics “train” – interconnected nodes with solar panels for power and other necessary life support systems. On Mars, these nodes could include such in-situ resource utilization devices as a carbon scrubber to produce oxygen from the carbon dioxide-rich atmosphere; the carbon could be used to create polymers from which habitats could be made.

To work with the current architecture and provide radiation shielding for longer-lived habitats, a “shell” for the habitat and rovers could be made using additive construction. If the shell is unpressurized and does not require a load other than the weight of the material itself, requirements for the material in terms of strength would be rather low. On the other hand, if a permanent habitat is desired, with three to four meters of regolith piled on top of the structure to provide radiation shielding (e.g., Vaniman et al., 1991), the compressive strength due to the load of the regolith and the tensile strength due to the pressurization of the habitat must be defined and accommodated.

**Compressive strength** of the material should be designed to accommodate a load of three to four meters of regolith, as well as the weight of superimposed habitat construction material. Considering only the weight of lunar regolith (1.5-2.0g/cm$^3$, Mitchell et al. 1972) on the Moon, and martian regolith (using 2.4g/cm$^3$, the measured solid density of JSC Mars-1A) on Mars, the pressure from the regolith load is less than 100 kPa. A factor of safety of three is assumed; the construction material must have a compressive strength of greater than 300kPa to withstand the lunar regolith load. This estimate does not include loads from equipment that will cover the structure in regolith.

**Tensile strength** of the material must be sufficient to withstand pressurization. If the pressure in the habitat was equal to one Earth atmosphere at sea level, the pressure would be approximately 100kPa. Assuming a 5m radius dome habitat is sufficiently bonded to the foundation, and the layer adhesion in an additively constructed 1m thick walled habitat is adequate to allow pressurization, and a safety factor of three assumed, the construction material must have a tensile strength of 7500kPa. If the construction material does not have the tensile strength needed, the structure may be designed to relieve the tensile stress by placing the structure into compression.

**Thermal conductivity** of the material needs to be sufficiently low to insulate the habitat from the extreme environments discussed above. Geologic materials are significant insulators. For example, Langseth et al. (1976) estimated the thermal conductivity range of 0.9-1.3 x $10^{-4}$ Wcm$^{-1}$K$^{-1}$ for lunar regolith at the Apollo 15 and 17 sites. The thermal conductivity of the construction material used will depend on the amount of regolith used as aggregate within the material, as well as any regolith cover.

**Radiation protection** from solar particle events and galactic cosmic rays is dependent on the composition of the construction material as well as any regolith cover. Additionally, radiation protection can be offered by designing a habitat with layers of “low z, high z” (low atomic number and high atomic number elements, Atwell et al., 2014) or potentially fiber-reinforced polymeric composites (Rojdev et al., 2009). Caution should be used when estimating and measuring the thickness of a regolith cover for radiation shielding. An insufficient amount of regolith will increase the amount of radiation received due to high energy particles creating a cascade effect of secondary sub-atomic particles (e.g., Vaniman et al., 1991).

## MATERIAL INVESTIGATION METHODOLOGY

Multiple materials are under study as planetary construction materials, including sulfur, various thermoplastic polymers, sintered and melted basalt, and cementitious materials (e.g., Bodiford et al., 2006; Toutanji et al., 2012; Mueller et al., 2014; Werkheiser et al., 2015; Khoshnevis et al., 2016; Mueller et al., 2016). Under the ACME project, sintering, polymer extrusion, and cementitious materials have been explored. The work completed at MSFC in the 2016-2017 timeframe with cementitious materials is highlighted here.

The current mixture used in the second-generation ACME additive construction system (ACME-2) at MSFC is composed of OPC, stucco mix, water, and a rheology control admixture. A mixture containing primarily the standard mixture but also containing the martian regolith simulant JSC Mars-1A has also been printed at MSFC, at terrestrial ambient conditions. It is from the standard and simulant mixes that a viscosity range was defined for the ACME system. To make the mix pump-able and still retain sufficient cohesiveness to make a smooth extruded bead, the viscosity range for a mortar (aggregate less than 0.64cm in size) must be between four and twenty Pa*s.

With this viscosity range and other requirements of the ACME-2 system in mind, two mortar mixes were investigated with OPC and magnesium oxide-based cements. Both binders require water for activation, which means the viscosity can be controlled by water addition and they are fairly easy to clean up with water provided setting has not occurred. Additionally, admixtures were added to keep the material from curing within the system prior to deposition.

In addition to the two types of cement, two simulants were evaluated for their contribution to compressive strength and hypervelocity impact resistance. The simulants used in these experiments were JSC Mars-1A martian regolith simulant – a weathered basaltic tephra (Allen et al., 1997) with a grain size of 5mm and less, and JSC-1A lunar regolith simulant – a crushed basalt (e.g., Rickman et al., 2007) with a grain size of 1mm and less. The grain size distribution of JSC-1A is known (e.g., Rickman et al., 2007). A 20kg portion of one bucket of JSC Mars-1A simulant was analyzed for grain size (Table 1). Grain size fractions of each of the simulants were evaluated for their contribution to the compressive strength of the mixtures.

**Table 1. JSC Mars-1A Regolith Simulant Average Grain Size.**

| *Size Fraction (µm)* | *Percent by Weight* |
|---|---|
| 4000-5000 | 10.84 |
| 2000-3999 | 20.69 |
| 1000-1999 | 10.25 |
| 500-999 | 10.51 |

| | |
|---|---|
| 250-499 | 15.29 |
| 125-249 | 23.11 |
| 63-124 | 7.53 |
| <63 | 1.78 |

## RESULTS AND DISCUSSION

Four samples were tested for resistance to hypervelocity impact: 1) OPC and JSC Mars-1A simulant, 2) OPC and JSC-1A lunar simulant, 3) magnesium oxide and monopotassium phosphate cement, and 4) a printed segment from an additively constructed wall using the standard JSC Mars-1A simulant-based mixture. The test parameters and results of the hypervelocity impact testing are included in Ordonez et al. (in press).

One issue that was highlighted during hypervelocity impact testing is layer adhesion. The sample sent for testing was printed using an OPC and JSC Mars-1A simulant mixture on multiple days, two layers per day. Thus, wet cement was emplaced upon dry cement. During shipping, the sample broke apart along one of the layer bonds in which a wet bead of mortar was emplaced over a dry bead (Figure 1). This illustrates the importance of continuous feedstock delivery, relatively rapid deposition, and a controlled setting rate modified by accelerators and retarders as it is easier for layers to adhere to one another if they have not had time to set.

**Figure 1. Additively constructed sample in which layer adhesion between a dry mortar layer and a wet mortar layer added the following day was proven to be weak compared to layer adhesion between two wet mortar layers emplaced on the same day.**

Compression testing was completed for numerous mixtures using standard 5.08cm cubes at 7 and 28 days from the time of mixing, which is common with OPC measurements as it indicates initial strength related to tricalcium silicate formation, and ultimate strength related to dicalcium silicate formation, respectively. Table 2 indicates the results of compression testing simulant-bearing mortars with a defined grain size. The effect of grain size has not been evaluated for magnesium oxide-based cements to date.

**Table 2. Average Compression Test Results for Simulant and OPC Mortars.**

| *Size Fraction (µm)* | *JSC Mars-1A (kPa)* | | *JSC-1A (kPa)* | |
|---|---|---|---|---|
| | 7-Day | 28-Day | 7-Day | 28-Day |
| 4000-5000 | 20339 | 32218 | | |
| 2000-3999 | 21146 | 35584 | | |
| 1000-1999 | 22111 | 32675 | | |
| 500-999 | 21335 | 33515 | 20554 | 28244 |
| 250-499 | 21949 | 35633 | 24728 | 34158 |
| 125-249 | 25628 | 31905 | 21089 | 26170 |
| 63-124 | 27802 | 34326 | 27820 | 37098 |
| <63 | 23939 | 29967 | 29367 | 37140 |
| Unsieved | 22826 | 24383 | 27796 | 36092 |

The highest compressive strength for the lunar simulant mortars occurs at grain sizes less than 63 microns, although a similar compressive strength is obtained from grains between 63 and 124 microns in size. Thus, grains below 125 microns would work well for lunar mortars. For martian simulant mortars, the 7-Day samples indicate similar results to the lunar mortars; the greatest compressive strength is obtained from the 63-124 micron samples. In contrast, the greatest compressive strength for the 28-Day samples is in the 250-499 micron samples. This indicates a greater ultimate compressive strength would be obtained from mixtures containing medium-size sand.

## CONCLUSIONS AND FUTURE WORK

Planetary construction materials, particularly those that are to be emplaced using additive construction techniques, have numerous constraints and must fulfill multiple requirements. The material chosen must have a balanced, optimized set of characteristics for a given environment and a given structural design. Ultimately, if these materials are to serve as habitat building materials, they must be compatible with human activities and must not be flammable, decompose, or become toxic when exposed to water, oxygen, or carbon dioxide unless a liner or skin is used. Characteristics such as these will be used in material trade studies in the future.

Each property of the construction material must be methodically studied. For example, the effect of grain size on the compressive strength of the material. The results from this study indicate smaller grains with a more unweathered basaltic material (JSC-1A) provide greater ultimate compressive strength, while relatively larger grains of weathered basaltic material (JSC Mars-1A) provide the best ultimate compressive strength. Given these results, multiple binders must be investigated with the same methodology to determine if this strength effect is a consistent, reproducible aspect of planetary construction materials for a given planetary environment.

In addition to the compatibility of the material with human activity and the grain size of the regolith used, trade studies will be completed that weigh the characteristics of a particular construction material composition with facets such as the cost to produce it, the time needed to produce it, the length of time the material will resist breakdown or embrittlement due to exposure to a planetary surface environment, the ultimate compressive and tensile strengths of the material to provide the necessary structural integrity, the ability to cure in pressures lower than that on Earth, and the ability to cure in a $CO_2$-rich atmosphere. An artificial neural network would assist in the efficiency of testing these multifaceted and multifunctional materials. Ideally, once analytical trade studies are completed, the promising construction materials will be fabricated to fly on the MISSE to more fully evaluate their resistance to damage in the space environment.

The first planetary landing site where additive construction technology will be used has not yet been identified. The ACME team will continue to monitor human landing site workshops for Mars and optimize planetary construction materials for those unique sites. The team will also encourage planetary scientists to quantify available in-situ resources through remote sensing to assist in identifying sufficient resources to build large-scale structures.

As additive construction technology matures and requirements for specific planetary structures become well-defined, planetary construction material development will continue. Complementary development of excavation and handling equipment for the regolith is necessary, as is the capability of size-sorting and beneficiating feedstock.

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