Manufactured Porous Ambient Surface Simulants

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ABSTRACT

The planetary science decadal survey for 2013-2022 (*Vision and Voyages*, NRC 2011) has promoted mission concepts for sample acquisition from small solar system bodies. Numerous comet-sampling tools are in development to meet this standard. Manufactured Porous Ambient Surface Simulants (MPASS) materials provide an opportunity to simulate variable features at ambient temperatures and pressures to appropriately test potential sample acquisition systems for comets, asteroids, and planetary surfaces. The original "flavor" of MPASS materials is known as Manufactured Porous Ambient Comet Simulants (MPACS), which was developed in parallel with the development of the Biblade Comet Sampling System (Backes et al., in review).

The current suite of MPACS materials was developed through research of the physical and mechanical properties of comets from past comet missions results and modeling efforts, coordination with the science community at the Jet Propulsion Laboratory and testing of a wide range of materials and formulations. These simulants were required to represent the physical and mechanical properties of cometary nuclei, based on the current understanding of the science community.

Working with cryogenic simulants can be tedious and costly; thus MPACS is a suite of ambient simulants that yields a brittle failure mode similar to that of cryogenic icy materials. Here we describe our suite of comet simulants known as MPACS that will be used to test and validate the Biblade Comet Sampling System (Backes et al., in review).

INTRODUCTION

The use of robotic spacecraft at the surface of a comet could enable access to some of the most pristine materials in the Solar System. We could learn about conditions of the early Solar System and the materials brought to early Earth by these primitive bodies from a returned comet sample. The planetary science decadal survey for the period of 2013-2022 (*Vision and Voyages*, NRC 2011) promotes mission concepts targeting small solar system bodies, including comets. To meet these requirements, a proposed mission, known as Comet Surface Sample Return (CSSR), would be the first to penetrate a comet surface and collect a sample. Achieving this standard requires tool design and testing with relevant simulants such that a comet sample from a depth of 10 cm can be obtained and returned to Earth for detailed chemical analysis. These requirements provided the essential inputs to the design of a new sampling system at Jet Propulsion Laboratory, the Biblade Sampler (Backes et al., in review). This sampler is a new technology that must be tested and validated in realistic comet simulant materials to achieve a high Technology Readiness Level.

Geological Earth analogs are normally used as proxies for the development of extraterrestrial sample acquisition systems. Finding terrestrial rocks that possess the appropriate properties can be challenging. On Mars, with the need to potentially provide samples that preserve geologic context, acquisition and handling of weakly lithified, brittle, low-density materials present challenges. Finding Martian sediment analogs on Earth is a non-trivial task. Deposited in one-third gravity and lying undisturbed in a world nearly devoid of weathering processes is vastly different than the deposition and environmental conditions found on Earth. Even if such materials existed, terrestrial dynamic weathering processes would quickly destroy these weak structures. Consider the surface of a comet, which was formed through accretion of dust and ice in a microgravity environment. Simply due to the effects of Earth's gravity, materials accreted in a similar fashion to that of comets is highly challenging, if not impossible to produce. Recently, Castillo et al (2012) has called out the need for development of a suite of simulants to support future primitive body missions. The development of such a suite of simulants requires a close look at the physical and mechanical properties of cometary nuclei.

The surfaces of cometary nuclei have been studied closely through flyby missions, such as Deep Space 1, Deep Impact, and Stardust. The Deep Space 1 spacecraft encountered comet 19P/Borrelly in 2001 and the Stardust spacecraft observed both comets 81P/Wild 2 and 9P/Tempel 1. The Deep Impact mission was successful in displacing cometary material from the surface of the nucleus of comet 9P/Tempel 1 for the purpose of studying the interior. Consisting of two parts, the Flyby spacecraft and the "Smart Impactor", the Deep Impact spacecraft converged on comet 9P/Tempel 1 in July of 2005. The "Smart Impactor" crashed into the surface of the comet and the resultant ejecta was studied by the Flyby spacecraft, as well as, ESA's Rosetta spacecraft and Earth-based telescopes.

It is from these missions that we make inferences regarding the physical properties of cometary surfaces. The surface shear strength of comets has been reported to be 1-100 kPa (Biele et al., 2009). Numerous reports on the low bulk density of comets, on the order of 0.4-0.8 g/cm^3, suggest that comets are highly porous in nature (Richardson et al., 2007; Thomas et al., 2007; Davidsson et al., 2007; Asphaug and Benz, 1996; Davidsson and Gutierrez, 2006; Davidsson and Gutierrez, 2004; A'Hearn et al., 2011). Additionally, comets are thought to contain a wide range of grain sizes (Tancredi et al., 2012). For the purpose of creating ambient comet simulant materials that mechanically represent the surface of comets, shear strength, grain size, porosity and homogeneity have been identified as key properties. Shear strength was initially chosen as the property of focus in the comet materials due to it being easily measured and compared with the current literature. With the recent results of the MUPUS instrument reporting a cone penetration resistance of at least 4 MPa (Spohn et al., 2015), we have broadened our study of the physical properties of MPACS to include cone penetration resistance.

To support the proposed CSSR mission, a suite of simulants was developed in parallel with the development of the Biblade Comet Sampling System. This set of simulants known as Manufactured Porous Ambient Comet Simulants (MPACS) is one flavor of a broader range of manufactured simulants known as Manufactured Porous Ambient Surface Simulants (MPASS). Applications for the MPASS suite of simulants range from cometary surfaces to Martian and asteroid surfaces. For the purpose of this manuscript, we will describe the development and physical properties of MPACS. The MPACS materials were required to meet the mechanical properties of cometary nuclei as they are described in the literature. The use of cryogenic simulants can be quite costly and tedious to manufacture, thus, we have developed MPACS as an ambient simulant that still mechanically represents what is currently known about cometary nuclei. A comparison between the physical and mechanical properties of comets with the MPACS materials will be described in a later section. Additionally, MPACS materials are an agglomeration of small particles held together with a binder, that fails in a brittle failure mode, much like that of cryogenic icy materials. Thus, MPACS is a repeatable, brittle, ambient comet surface simulant that will be used to test and validate the performance of the Biblade Comet Sampling System.

MIX DESIGNS

Formulation of the current mix designs of MPACS materials has been influenced by almost two decades of research. In 1996 the Extraterrestrial Materials Simulation Laboratory (EMSiL) was established by Dr. Jacklyn R. Green to develop mechanically relevant comet simulants. This was in preparation for the Champollion Deep Space 4 (DS4) Mission (Muirhead et al., 1997). The Champollion mission was labeled Comet Nucleus Sample Return (CNSR) as it was required to collect comet nucleus materials from up to one meter below the surface and return samples to Earth. To test such hardware requires relevant simulants that challenge the tool in the appropriate ways and accurately represent the properties of cometary nuclei.

Considering the hundreds of tests that must take place to develop a landed mission, the costs associated with the creation of simulated cometary surface environments, including vacuum and temperature scales below -100C, would be excessive for large scale testing. In the case of Champollion, this would have included testing of a two-meter long, ballistically deployed anchoring device and a one-meter drill. Instead of pursuing cryogenic testing for Champollion, emphasis was placed on ensuring that the mechanical properties relevant to the anchoring and sampling systems were properly manifest in simulants under ambient conditions. In order to anchor and sample, CNSR systems would be required to "fail" comet surface materials. The failure modes associated with minerals, including ice and icy composites is analogous to the brittle failure accompanying the hydrated minerals found in terrestrial concrete. This is advantageous, as concrete can be tailored for strength and internal composite structure. For CNSR testing, concrete mixtures stronger than 15 MPa in compressive strength were cast into cylindrical test articles 1-2 meters long and 0.6 meters in diameter. While these simulants represented potential worst-case scenarios for an anchoring system required to penetrate up to two meters into an unknown subsurface, the utility of Portland cement as a mineralizing binding agent for comet simulants became apparent.

The CNSR mission would have been an ambitious undertaking, but was cancelled in 1999. Since then, a series of comet missions have launched. These include STARDUST in 1999, Rosetta in 2004, and the ill-fated CONTOUR mission launched in 2002. Of these, only Rosetta's Philae lander required the use of surface simulants for spacecraft development. With the next logical step in comet science missions being potential sample return with subsurface sampling, MPACS was designed to be consistent with the composite structures produced in low-gravity, accretionary environments while retaining the ability to vary strength.

A baseline mix design of MPACS was developed using equal parts Quikrete® Quick Setting Cement and (< 40 µm) Pumicite combined, and added to water and a foaming agent. The wet and dry components were then whisked using a Hobart A-200 Stand Mixer for 120 seconds. It was then cast into the desired mold, ranging from small cylinders to various box sizes. The mix designs require a minimum of 21 days to cure and fully dry out. In this case, curing is a mineralization process that occurs between the water and the cement to generate a binder that cements the aggregate grains together (Figure 1). The MPACS material reaches its maximum

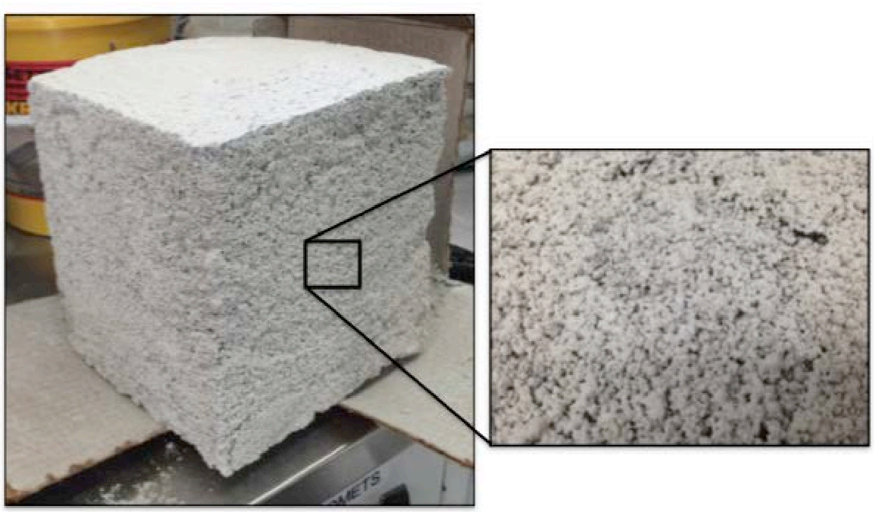

Figure 1. Image of an 8-inch cube of MPACS material showing the agglomeration of small particles held together with the cement binder.

strength after 7 days and requires an additional 14 days for evaporation of the excess water not mineralized with the cement.

The shear strength and density of the material was tuned by varying the amount of foaming agent within the mixture. It has been reported that the shear strength of cometary surfaces is within the range of 1-100 kPa (*Biele et al., 2009*). A relationship was found within the current mix designs between the amount of foaming agent and shear strength. This relationship was used to tune simulants at incremental strengths within the 1-100 kPa shear strength range.

CHARACTERIZATION

The characterization of MPACS material properties was conducted using the Geo-Tech lab facilities at Jet Propulsion Laboratory. Because the available strength measurement of comets in the literature was the 1-100 kPa shear strength (Biele, 2009), the initial measurements conducted on MPACS were shear strength and density. This measurement is also thought to be one of many important measurements to the Biblade Comet Sampling tool. To obtain a full picture of the mechanical properties of the MPACS suite, compressive strength and cone penetration resistance measurements were also conducted.

Density measurements were taken based on mass and volume of the cured samples and porosity was calculated based on those density measurements. Shear strength measurements were conducted using an actuated direct shear mechanism linked to a Mark-10, 7-Series force gauge to record the data at a rate of 1000 measurements per second. Comet Simulants were cast into 1.5-inch diameter cardboard cylinders and allowed to cure for 14 days. Once cured, the cardboard exteriors were carefully removed and the simulant was loaded into the shear tester. By actuating the lever, the comet simulant was sheared in half and the force gauge measured the force curve required to do this. To validate our shear testing apparatus, samples of the MPACS materials were sent to the California Testing and Inspection, a Los Angeles based geological materials testing laboratory. Multiple samples per mix design were tested and the results are shown in Table 1.

Table 1. Summary of MPACS Properties

MPACS	Density (g/cc)	Porosity	Shear Strength	Unconfined Compressive Strength	Cone Penetration Resistance
A	0.12-0.18	93-95%	30-40 kPa	40-50 kPa	0.25-0.75 MPa
B	0.27-0.31	88-90%	TBD	100-150 kPa	0.75-3 MPa
C	0.31-0.45	82-88%	100-120 kPa	200-500 kPa	3.5-6.5 MPa

Unconfined uniaxial compressive strength measurements were conducted using a Geotest Compression Machine. Similar to those of mortar strength measurements, 2-inch cubes of each mix design were compressed until failure, the maximum force required to fail the material was recorded and the yield strength of the material was calculated. In addition, cone penetration resistance measurements were taken in each of the mix designs. As shown in Figure 2a, a linear stage moves a force gauge with a cone penetration attachment at a constant rate until it penetrates the MPACS material to a depth of 10 cm. The raw data from this measurement is shown in Figure 2b and the maximum cone penetration resistance data is taken as an average of the region of the curve between 4-10 cm.

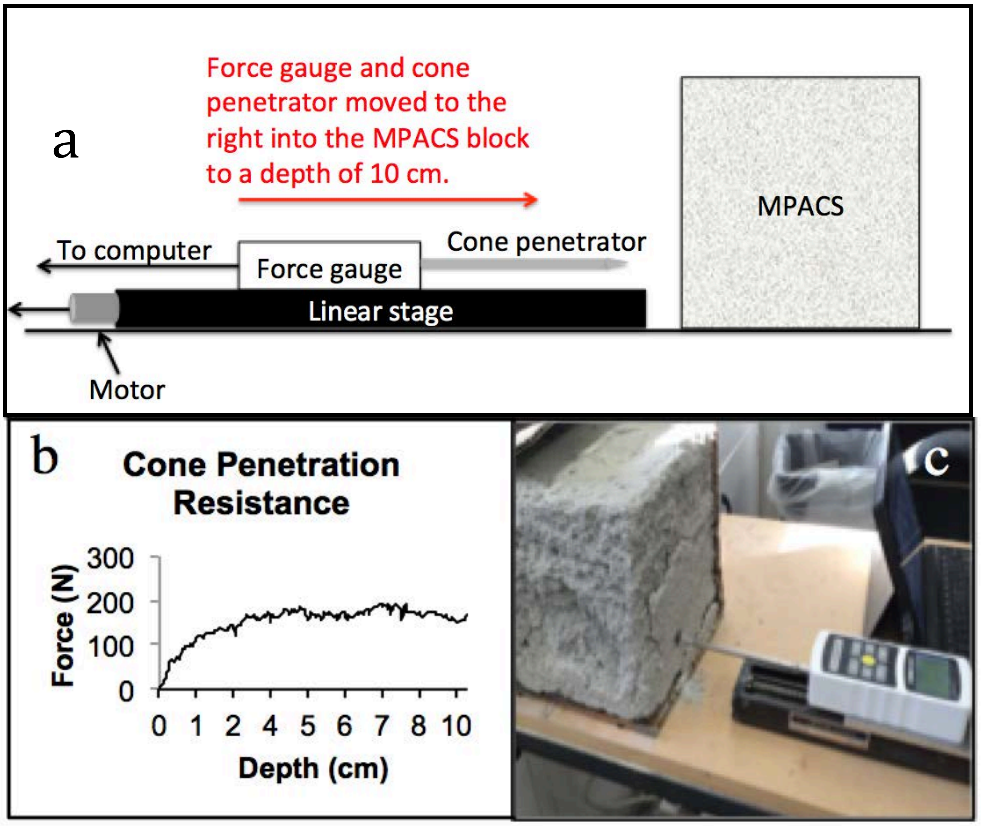

Figure 2. (a) A sketch showing howa cone penetration resistance measurement is obtained. The force gauge and attached cone penetrator are moved to the right by the linear stage and motor into the MPACS material. The force gauge measures and records force during penetration. (b) An example of the raw data obtained by the cone penetration resistance measurement. (c) This is MPACS materials being tested with the cone penetration resistance apparatus.

CONCLUSIONS

The planetary science decadal survey for 2013-2022 (*Vision and Voyages*, NRC 2011) has promoted mission concepts for sample acquisition from small solar system bodies. MPASS materials provide an opportunity to simulate variable features at ambient temperatures and pressures to appropriately test potential sample acquisition systems for comets, asteroids, and planetary surfaces. Here we have described MPACS, one particular "flavor" of the MPASS suite of materials, which are currently being used to test and validate the Biblade Comet Sampling System (Backes et al., in review). These simulants were invented to mechanically represent the known properties of cometary surfaces under ambient conditions thus allowing testing of hardware to be completed in a less tedious and more cost effective manner.

Previous testing of comet surface mechanical hardware has been conducted using Grill Brick and Foam Glas materials. These materials are difference from

MPACS in that both consist of a framework structure with unnaturally large pore spaces and a high bulk compressive strength. MPACS materials contain a composite structure of bonded grains and induced pore spaces. Thus, MPACS is the highest fidelity existing comet simulant for comet hardware mechanical testing applications.

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