Geotechnical Review of Existing Mars Soil Simulants for Surface Mobility

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ABSTRACT

The purpose of this paper is to provide a thorough review of the currently available Mars soil simulants and to determine those with geotechnical properties most appropriate for vehicle mobility studies. Sourcing and processing are considered since full-scale studies require bulk quantities of material on the order of tens of tons. This review identifies the top three simulants with the highest fidelity to Mars wind drift soils. These are M90, ES-2, and ES-1. In addition, recommendations to guide the development of future Mars simulants are made.

INTRODUCTION

It has long been the interest of the space community to send humans back to the Moon and beyond to Mars. The National Aeronautics and Space Administration (NASA) has laid out a multi-phase sustainable exploration plan to achieve the goal of placing humans on the Moon by 2024 and on Mars by 2030 [1, 2]. Much of this plan is dependent on lunar programs such as Artemis and Gateway—using the Moon as a proving ground for Mars. In parallel, the Mars 2020 mission and a potential Mars sample return campaign are considered essential to the transition from robotic to manned missions on Mars [3]. Mars 2020, scheduled to launch in July of 2020, will land a rover on the surface of Mars [4]. A core drill aboard the rover will be used to collect soil and rock samples which will be stored for future retrieval and return to Earth. The return of these samples will allow scientists to study the terrain of Mars, determining chemical, mechanical, and geotechnical properties of the soil and rock samples. Knowledge of these properties can help answer the long standing question of whether or not life previously existed on Mars. Additionally, these properties are integral to the successful design and development of future robotic vehicles and tools, which will interact with the Martian terrain. However, knowledge of these properties are only helpful for future missions—missions not likely to occur until the next decade. Without physical samples available for testing, the question becomes, "*How do engineers design robotic vehicles and tools for precursor missions to the Moon and Mars?*"

These precursor missions likely will include improved rover designs, more complex sampling and testing capabilities, and the traversal of previously unexplored regions—as is the nature of humans to push the design and exploration envelopes further. Regardless of the missions or location, it is imperative to thoroughly vet the design and performance of surface exploration vehicles and their components prior to flight. This requires Earth-based testing in analogue soils. These analogues, representative of the types of soil that a rover may encounter, must be utilized to develop the required parameters for simulation and to create appropriate test beds for component-level and full-scale mobility testing. Much information is known about the lunar surface as astronauts have physically explored the surface and terrain samples have been returned to Earth. Many lunar soil simulants have been developed and evaluated for the purposes of terrain-machine interaction [5, 6]. The development of Martian soil simulants is more complicated due to the fact that humans have not yet stepped foot on Mars. Thus, there are currently no Mars soil samples available to guide simulant development.

Nonetheless, there are several Mars soil simulants currently in existence [7]. All of these simulants have been developed from data retrieved by remote sensing and previous robotic missions to Mars including flybys, orbiters, landers and rovers [8]. As is typical, the various Mars simulants have been developed specific to an application. They are designed to match explicit properties such as chemical and mineralogical (JEZ-1, JMSS-1, MGS-1, MMS-1 and -2, Y-Mars), spectral (JSC Mars-1 and -1A), magnetic (Salten Skov 1), and physical or geotechnical (ES-X; KMS-1; MMS Mojave Mars Simulant; UC Mars1; M90) [7]. No two of these simulants is chemically or physically alike, which makes it difficult to determine which simulant is most appropriate for ground testing of simulated surface mobility or terrain-machine interaction on Mars. Moreover, these simulants can be difficult to obtain and may only be available in small quantities. For vehicle or component-level testing, quantities on the order of tens of metric tons are required.

The goal of this paper is to provide a thorough review of the currently available Mars soil simulants and determine those with geotechnical properties most appropriate for terrain-vehicle interaction or mobility studies. Physical and mechanical properties, along with sourcing and processing, will be considered. Properties such as grain size distribution, particle shape, bulk density, bearing strength, cohesive strength, and angle of internal friction are integral soil properties which control overall strength and influence vehicle performance. Chemical and mineralogical composition along with spectral and magnetic properties will not be reviewed in-depth as they do not directly influence soil strength. Ideally this review will identify a currently available simulant or guide the development of an appropriate simulant for verification of future robotic roving vehicles in addition to providing a central index for Mars simulants and their mechanical properties.

MARTIAN TERRAIN

Mars is a cold, dry planet with a thin atmosphere consisting primarily of carbon dioxide. Its surface consists of bedrock, which can be fractured, and can be covered by rocky outcrops and an unconsolidated sandy, and sometimes silty soil. The soil is composed primarily of igneous basaltic rock largely containing pyroxene and plagioclase feldspar with trace amounts of other minerals such as iron, olivine, and hematite [9]. The Martian landscape is well known for its windblown soil ripples and dunes. A wide range of soil and rock types have been identified across the Red Planet's surface making it crucial to identify which type of terrain may exist at proposed future landing sites and traversal routes.

Based on the Viking lander missions it was proposed the soil on Mars in the equatorial regions could be categorized into four major groupings [10]. These include: (1) drift materials, (2) crusty-to-cloddy materials, (3) blocky or duricrust materials, and (4) rock materials. Mechanical properties obtained from specific Mars missions for each of these materials are listed in Table 1. A brief description of each material is provided in the subsequent paragraphs.

Table 1. Typical mechanical properties of Martian terrain from various missions. *Caution should be used when referencing these values since they are engineering estimates and not the result of direct measurement.*

Mission	*Material Type*	*Particle Size (μm)*	*Bulk Density (g/cc)*	*Cohesion (kPa)*	*Angle of Friction (°)*
Viking Lander I [10]	Drift	0.1–10	1.0–1.3	0–3.7	15.6–20.4
	Blocky	0.1–1500	1.2–2.0	2.2–10.6	28.4–33.2
	Rocks	35k–240k	2600	1000–10k	40–60
Viking Lander II [10]	Crusty/Cloddy	0.1–10	1.2–1.6	0–3.2	29.8–39.2
	Rocks	35k–450k	2600	1000–10k	40-60
Pathfinder/Sojourner [11, 12]	Soil-like deposits	<40	1.29–1.52	0.21 *avg* 0–0.42	34.3 *avg* 30–40
	Crusty/Cloddy	--	1.5	0–0.36	33.6–39.8
MER – Spirit [13]	Drift	--	1.2-1.5	1–15	20–25
MER – Opportunity [14]	Surface Soil	--	1.3	1–5	20

Moore and Jankosky (1989) described drift material as providing a smooth relatively unfractured surface down to approximately 23 cm below grade and being very fine grained with low levels of cohesion. Brittle lumps were observed near disturbed drift areas of the landing site and consisted of amassed fine-grained particles. In general, drift material is very weak in strength and porous in nature [15]. Crusty-to-cloddy material also consisted of fine grained materials and behaved similarly to moderately dense soils. This type of material covered surfaces to a nominal depth of 14 cm. In disturbed regions pieces of broken crust material were observed to be mixed with fines. Even though the cohesion values of crusty-to-cloddy material were similar to that of drift material, Moore and Jankosky (1989) suggested that crusty materials behaved more like a material with a higher value of cohesion. The crusts appeared to be layered and were adhered to the edges of rocks, likely due to cementation [16].

Blocky soil or duricrust material was much shallower than drifts and clods, but was stronger and with higher values of cohesion, again, likely due to cementation [10, 16]. Although it was highly eroded during landing, the large cohesion values suggest that this material is not easily eroded by the Martian winds [16]. Finally, large quantities of dense rocks having diameters ranging from 3.5–45 cm were observed near both Viking I and II landing sites. Christensen and Moore (1992) stated that the rocks varied in nature from breccia to vesicular. In order of acreage, crusty-to-cloddy material was the most prominent, closely followed by blocky material. Drift material and rocks were sparse in comparison.

Additional surface information was obtained near the Pathfinder landing site near Ares Vallis. In this location, the terrain was covered by well graded, dense, crusty-to-cloddy material. This material consisted of dust, sand particles, soil lumps, sub-angular to sub-rounded pebbles and small rock fragments [11, 12]. Furthermore, very fine-grained compressible drift material with a sparse presentation of rocks larger than 3 cm in size were present [11, 12]. There was evidence that the drift material covered the cloddy material with a layering effect and that each layer was derived from a different process, with drift materials likely forming from Aeolian origin and clods potentially being derived from impact cratering. Moore et al. (1999) backed out estimates of friction angle based on parametric data from rotation of the Sojourner rover wheels. These values are reported in Table 1.

High resolution images and experiments performed at the Spirit MER landing site near Gusev Crater provided information that agreed with the classifications of soil previously mentioned [13]. Arvidson et al. (2004) summarized that, in general, the terrain is covered with rocks ranging in size and shape from 2–16 mm and angular to smooth, respectively. Drifts and crusty-to-cloddy soils with particles on the order of less than 1 mm were observed with a universal overlying thin layer of dust. Similar to the Pathfinder landing site, the drift materials were found to overly the cloddy materials. Results from trenching experiments indicated that the soil had small levels of cohesion capable of maintaining trench walls on the order of 65°. In addition, Arvidson et al. (2004) noted that observations of wheel-sinkage provided estimates of terramechanics properties such as bearing strength, cohesive strength, and angle of internal friction. These values range from 5–200 kPa, 1–15 kPa, and 20–25°, respectively, depending on location. These values are reported in Table 1 as well.

From these and other sources of information, it is obvious that in many respects the Martian terrain is similar to that of the Earth. Several terrain analogue locations that are favorited by the engineering community include Hawaii’s volcanic lava rock fields and Pu’u Nene’s cinder cone, which has similar spectral properties to the Mars soil [17, 18], California’s Mojave Desert which is a physical analogue to the Martian highlands, due to the weathering processes experiences in that location [18], and Australia’s rocky plains [17]. These terrestrial regions are the source of material for many Mars simulants as will be described in the subsequent section.

MARTIAN SIMULANT

A number of Mars soil simulants are currently in existence with varying chemical, mineralogical, physical, and mechanical properties. The more promising geotechnical analogues were selected for review based on their physical and mechanical similarities to the Martian terrain. These simulants are discussed in the subsections that follow. The geotechnical properties of each simulant and the particle size distribution (PSD) curves are provided in Table 2 and Figure 1, respectively.

JSC Mars-1

JSC Mars-1 is a heritage Martian simulant developed at Johnson Space Center that was prominent for many years. It was designed to match the spectral properties of Mars, but has been used as a general purpose Mars simulant. JSC Mars-1 is a well graded soil sourced from the Pu'u Nene cinder cone in Hawaii [16]. Particle sizes range from 0.1 to 1 mm in size with the soil containing up to 6% silt [19].According to Allen et al. (1998), this simulant was available free of charge from Johnson Space Center, but that supply has since expired. JSC Mars-1A was produced by Orbitec to replace the original supply of JSC Mars-1 when it ran out. However, neither simulant is currently available outside of NASA.

ES-X

ES-X Mars simulants or Engineering Soil Simulants-1 through -4 were developed by the European Space Agency as geotechnical simulants for use during the ExoMars program [7, 17, 20]. ES-1 was intended to replicate the fine dust portion of Martian soils. ES-2 was designed to replicate the very fine sandy soils in the windblown regions and ripples of Mars. ES-3 is a course sand replicate typically found near the base of ridges and ES-4 is a compact silty sand with gravel. ES-4 would typically be used as a "highway" type simulant to represent easily traversable regions on Mars. Though this type of consolidated soil exists on Mars, it is typically not a cause for concern in terms of mobility.

ES-1 through ES-3 have been procured from Sibelco UK Ltd and are generally available in bulk quantities, excluding ES-2 which is limited in quantity due to post-processing complications [17]. ES-1 was sourced from Sternjoy Nepheline Syenite powder in grade S7. Red Hill 110 silica sand was used to create ES-2, but the particle size distribution of this material was larger than desired without additional processing [17]. ES-3 was derived from Leighton Buzzard DA30 silica sand.

In addition, ES-1 and ES-3 are some of the few Mars simulants to have bevameter tests performed. The bevameter plate-sinkage and shear tests are heavily relied upon in terramechanics to determine the stress-strain characteristics of a soil in response to simulated normal and shear loading applied by the vehicle tire or wheel. Terrain parameters derived from these tests are highly empirical. Plate-sinkage tests lack considerable physical significance. The results of both tests are dependent on the contact area of the tire as well as the applied pressure and must precisely simulate that of the vehicle. The results of the bevameter plate-sinkage tests performed by Brunkill et al. (2011) are reported in Table 3, for reference, as there are no corresponding values available for the Martian terrain.

JMSS-1

Jining Martian Soil Simulant or JMSS-1 is a Chinese designed multi-purpose Martian simulant used to prepare for upcoming missions [7, 9]. As a general purpose simulant it was developed to match the chemical and mineralogical properties of Martian basaltic rock with the stipulation that the source material must be easily obtained in bulk quantities. A basaltic lava rock from Inner Mongolia was selected as the source material and post-processed to meet the desired particle size distribution. The post-processing included mechanical crushing representative of the impact weathering process on Mars. These particles were then mixed with additional minerals and then sieved to a final size distribution.

MGS-1

Mars Global Simulant, MGS-1, was developed with the goal of becoming a standard general purpose Mars simulant. Chemical and mineralogical properties from Rocknest windblown deposits at Gale Crater are replicated [21]. A complex process was used to create MGS-1 in which various minerals were formed into cobbles and then mechanically crushed back to particulate matter. The reason for this was to achieve a more natural formation of soil comparable to the erosion processes that occur on Mars (impact grinding and crushing; erosion by wind, water, lava; and chemical weathering). A final mixing of the particles with other minerals and sieving to less than 1 mm particle size completed the preparation of the simulant. Though the processing is quite involved, the benefit of MGS-1 is that that it follows a specific recipe of easily obtainable minerals.

MMS

Mojave Mars Simulant or MMS is a geotechnical Mars simulant developed at the Jet Propulsion Lab (JPL) in California. This simulant resulted out of a need for a better hygroscopic analogue material than JSC Mars-1 (the prominent Mars simulant) was able to provide [22]. The bulk material for this simulant was derived from Saddleback basaltic boulders in the Mojave Desert. Originally the boulders were mined and processed by Carlton Global Resources. They have been mechanically crushed and screened to meet the desired particle size and in the early 2000's were available in the forms of whole rock, sand, and dust [22]. Though it is currently not available outside of NASA, JPL is in the process of setting up a processing plant that will allow continued production of MMS variants.

A company called The Martian Garden sells two simulants, MMS-1 and MMS-2, which are advertised as an identical and enhanced version to the original MMS, however they are made from a cinder based source material. It is claimed that this company never had any communication with the originators of MMS [22, 21].

UC Mars1

UC Mars1, where UC stands for University of Canterbury, was developed to study the suitability of the Martian soils for use as construction materials [23]. This simulant is representative of the Mars soil near the Columbia Hills region of Gusev Crater. This location was selected, in part, due to its vast composition of minerals. The material for UC Mars1 was collected from the Banks Peninsula on the South Island of New Zealand. It consists of crystalline basalt and volcanic glass. The collected samples were cleaned to remove contaminants, mechanically crushed and milled, then washed again to remove a portion of the dust, and dried. The method of production currently results in 30 kg/hr.

MER Yard

MER Yard soil exists at JPL and was used for testing of the Spirit and Opportunity rovers. It is a poorly sorted (well graded), crushed volcanic rock, with a vast range of particle sizes from smaller than silt to greater than 0.5 cm [19]. MER Yard soil contains up to 6% silt.

Mars Yard

Mars Yard soil also resides at JPL and consists of decomposed granite dust and cinders mixed with washed sand [19]. It is a poorly sorted (well graded) soil with particle sizes ranging between 0.4 and 1 mm. Mars Yard soil contains up to 2% silt. This soil was used for Mars 2020 rover testing. It should be noted that this soil is stored outdoors in an unprotected area and is therefore constantly evolving. Dust, ash, and rock cuttings are constantly settling and mixing with this material and approximately 25 tons of MMS sand had been mixed into this material in the early 2000s (personal communication with Gregory Peters, JPL).

M90

M90 was obtained from a company called Soil Direct and is a fine grained, poorly graded, kiln dried sand which has been used by JPL in Mars 2020 rover wheel development and mobility testing. It was used as a conservative case for evaluating traction capabilities and is considered analogous to the Martian sand dunes and ripples.

The geotechnical properties of M90 have been measured by California Testing & Inspections Material Testing & Geotechnical Laboratory and are summarized in Table 2. The particle size distribution obtained from the vendor is shown in Figure 1. The narrow size distribution and sub-angular particle shaped create a flow response similar to wind drift soils. In addition, mobility parameters were obtained via bevameter tests performed by NASA Glenn Research Center (GRC) at Carnegie Mellon's Robotic Institute which currently houses the bulk M90 material for single-wheel testing. The empirical values for plate-sinkage and shear tests are shown in Table 3 for reference.

GRC-3

Although GRC-3 was developed for lunar excavation, it is being considered by NASA GRC as a Martian simulant for surface mobility studies. This soil was used for select Mars tire development tests due to it availability in bulk at NASA GRC. Single-wheel traction testing performed in this soil prepared to a loose state provided a response similar to that of M90 simulant, also, prepared to a loose state.

GRC-3 is composed of a mixture of commercially available sands from Best Sands Company in Chardon, Ohio and silt mined from a quarry in Colorado As shown in Figure 1, this soil has a wide size distribution which makes it a compressible material. It can exhibit very different strength properties depending on the relative density. Mobility parameters for loose GRC-3 were obtained via bevameter tests performed in NASA GRC's single-wheel traction test rig. The empirical values for plate-sinkage and shear tests are shown in Table 3.

Unfortunately the silt from Colorado is no longer easily sourced, a new GRC-3b version of the simulant was developed using silt from a quarry near Cleveland, Ohio. Thorough comparisons of GRC-3 and GRC-3b have not yet been completed.

Table 2. Physical and mechanical soil properties of Mars simulants.

Simulant	*Particle Shape*	*Particle Size (μm)*	*Bulk Density (g/cc)*	*Cohesion (kPa)*	*Angle of Internal Friction (°)*
JSC Mars-1 [16, 19]	--	<1 mm	0.85–0.89	0.06–0.09	40.8–41.4
ES-1 [17, 20]	Angular	<3-30	0.54–1.21	1.3–3.9	29.5–32.3
ES-2 [17, 20]	Angular to sub-angular	60-250	1.24–1.44	Negligibly low	38.2–41.4
ES-3 [17, 20]	Sub-rounded to rounded	300-800	1.46–1.64	0.3–1.4	34.3–35.8
ES-4*	--	--	1.8–2.2	0–4	38–44
JMSS-1 [9]	Angular to sub-angular	<1 (mm) 300 (median) 250 (mean)	1.45 (mean)	0.33	40.6
MGS-1 [21]	--	122 (mean)	1.29	--	--
MMS sand [22]	Angular	--	1.38 1.34	0.81 1.96	38 39
MMS dust [22]	Angular	--	1.08 0.91	0.38 0.53	31
UC Mars1 [23]	Angular to Sub-angular	--	2.7	--	35
MER Yard [19]	--	--	1.43–1.78	0.149	47.9–53.3
Mars Yard [19]	--	--	1.49–1.78	0.09–0.10	35.1–37.2
M90	Sub-angular	--	1.32–1.52	1.4–2.8	29–37
GRC-3 [24]	--	0.15 (median)	1.52–1.94	--	37.8–47.8

*Values obtained from electronic communication with JPL/ESA.

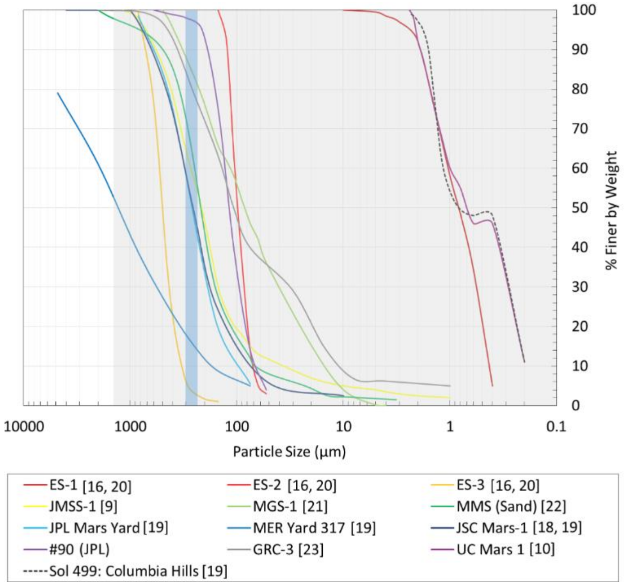

Figure 1. Particle size distribution curves for Mars soil simulants compared with that of the Columbia Hills region. Grey area shows the particle size range found on Mars according to Table 2. Blue area shows the nominal range on Mars [9].

Table 3. Bevameter terrain parameters for various Mars simulants.

Simulant	*Soil Density*	*n*	k_c *(kPa/m^n)*	k_Φ *(kPa/m^{n-1})*	Φ_b *(deg)*	c_b *(kPa)*	*K (mm)*
ES-1 [20]	--	0.67–0.75	67.3–142.4	0.68–1.66	--	--	--
ES-3 [20]	--	0.92–0.76	1727.5–2312.6	-(14.1–30.1)	--	--	--
M90	Loose	1.3	572.1	4915.3	32.0	0.27	25.4
GRC-3	Loose	1.0	23.2	606.7	36.7	0.13	23.5

DISCUSSION

After reviewing the available Martian soil simulants three things are directly apparent. First, no two simulants are alike and no standard simulant has been developed or accepted for mobility testing. Second, there is a lack of available geotechnical data for these simulants in which to compare their mechanical performance. Several gaps exist in the current datasets which need to be filled. Third, most simulants require a significant amount of processing in order to obtain a grain size distribution and particle shapes similar to that of Mars soil. This requires significant schedule and cost to produce quantities large enough for full-scale vehicle testing. The solution to these issues is outside the scope of this paper, however for the success of future missions these issues need to be resolved. In an effort to directly compare these simulants and determine their likeness to Martian soil for vehicle mobility studies, several charts were developed from the available datasets. These are discussed in the following subsections along with conclusions drawn from property comparisons.

Particle Shape

The particle shape on Mars ranges from very round to very angular depending on location. Round particles have the ability to “flow” over one another more freely creating a weaker soil whereas angular particles have a tendency to interlock amongst each other creating a stronger more “cohesive” soil. In terms of vehicle mobility a conservative soil simulant would have round to sub-angular particles. The simulants that align best with these particle shapes are ES-3 and M90. ES-2, JMSS-1, and UC Mars1 are also somewhat conservative having a range of angular to sub-angular particle shapes. ES-1 and MMS simulants are non-conservative having angular particles and would result in a material that is stronger than desired.

Particle Size Distribution

Figure 1 shows the PSD curves for all simulants compared with maximum, minimum, and nominal values on Mars. As shown most of the simulants fall within the range of particle sizes of the Martian soils. ES-1 and UC Mars1 are on the lower end of the Martian soil range while MER Yard and ES-3 are on the upper end. All other simulants fall somewhere between the max and min values found on Mars with most falling between 10 and 1000 µm.

Well graded soils typically hold a variety of particle sizes. As such, they tend to compact more efficiently as the smaller particles tend to fill the voids and create a solid structure. Poorly graded soils generally consist of particles of the same size. These soils tend to be loose in nature and are more challenging for a vehicle to traverse—this being the conservative case for mobility studies. Some of the more poorly graded simulants are JSC Mars-1, ES-1, ES-2, ES-3, MMS Sand, JMSS-1, JPL Mars Yard, and M90. Others have a wider distribution and may compact more easily creating an easier path to travel.

Bulk Density

The estimated in-situ bulk density of the Mars soil ranges from 1.0 to 2.0 g/cc with the majority of reported values falling in the range of 1.2 to 1.5 g/cc. Together with relative density, the bulk density of a soil can inform the amount of compaction a soil can incur as well as the volume of the voids in the soil structure. A wide range of bulk densities would imply that a soil can exist in either a compact (highway soil) or loose state (wind drift soil), i.e. it has a wide range of consolidation. The complete range of bulk density for the Mars soil is unknown, so it is difficult to interpret how dense or loose it might become after interaction with robotic vehicles or excavation tools, etc. Those simulants that best mimic the current estimates of in-situ bulk density of the Mars soil are the ES-2, MGS-1, MMS sand, and M90. JSC Mars-1, ES-1, and MMS dust are relatively low in density, while ES-3, ES-4, UC Mars1, MER and Mars Yard, and GRC-3 are relatively high. JMSS-1 has an average value within range, but not enough is known about the complete range of bulk density to determine its similarity to Mars soils.

Angle of Internal Friction

Figure 2 shows a comparison of the angle of internal friction and cohesion values obtained for Mars simulants versus those values determined for actual Mars soil. Looking first at angle of internal friction, there are no simulants which represent the soils found in the MER locations or the Viking I drift soils. Viking I and II clods and Pathfinder drift and clods are best represented by M90, Mars Yard, and the ES-1 through -3 simulants. MMS and UC Mars1 simulants are within the range of Mars friction angles, but only represent a small portion of that range. ES-4, GRC-3, MER Yard, JSC Mars-1, JMSS-1, and MGS-1 have friction angle values higher than the Mars soil. The implications of using a simulant with too high a friction angle for surface mobility tests would be developing a higher level of thrust and therefore better trafficability than what could be achieved in reality.

Cohesion

Looking at cohesion, there is a wide range of variability on the Martian surface—some areas with negligible levels of cohesion less than 1 kPa and others with moderate levels of cohesion up to 15 kPa. For surface mobility, the higher the cohesion the better the traction. Therefore to be conservative one would want to test to the soils with lower levels of cohesion. The majority of the simulants have cohesion values less than 3 kPa. JSC Mars-1, ES-2, JMSS-1, MMS Dust, MER Yard, and Mars Yard all have negligible levels of cohesion less than 1 kPa. These would agree well with the Mars soil in the Pathfinder location. ES-3 and ES-4 range from negligible cohesion up to 1.5 and 4 kPa, respectively. These align with soils from the Viking Lander locations. ES-1, MMS Sand, and M90 cover a mid-level range of cohesion which represent the MER soils as well as the Viking soils excluding cohesion values in the <1 kPa range. From a mobility perspective any of these simulants have acceptable levels of cohesion mimicking that of the Mars soil with those on the lower end being more conservative.

Sourcing and Processing

Sourcing refers to the availability of the source material used to create the simulants and how easy it is to process and produce in bulk amounts. JSC Mars-1 and MMS, two of the more popular simulants, are no longer available outside of the NASA community. Therefore these are currently not recommended for use as a standard Mars mobility simulant. The ES-X materials, excluding ES-2, appear to be available from an industrial supplier. The processing required to properly size ES-2 appears to be too involved to make it acceptable for production in bulk. The quantity in which these can be obtained and the lead time for acquisition is unknown. JMSS-1 claims to be easily produced in bulk quantities, but again the processing methods seem complex and involved. MGS-1 involves a complicated processing method as well and would be too costly to produce in large quantities. The availability of UC Mars1 is unknown. MER Yard and Mars Yard currently reside only at JPL in California. While these are available in bulk quantities it is unknown whether or not there is enough source material to reproduce this simulant. M90 is available from a commercial supplier and has previously been obtained in bulk.

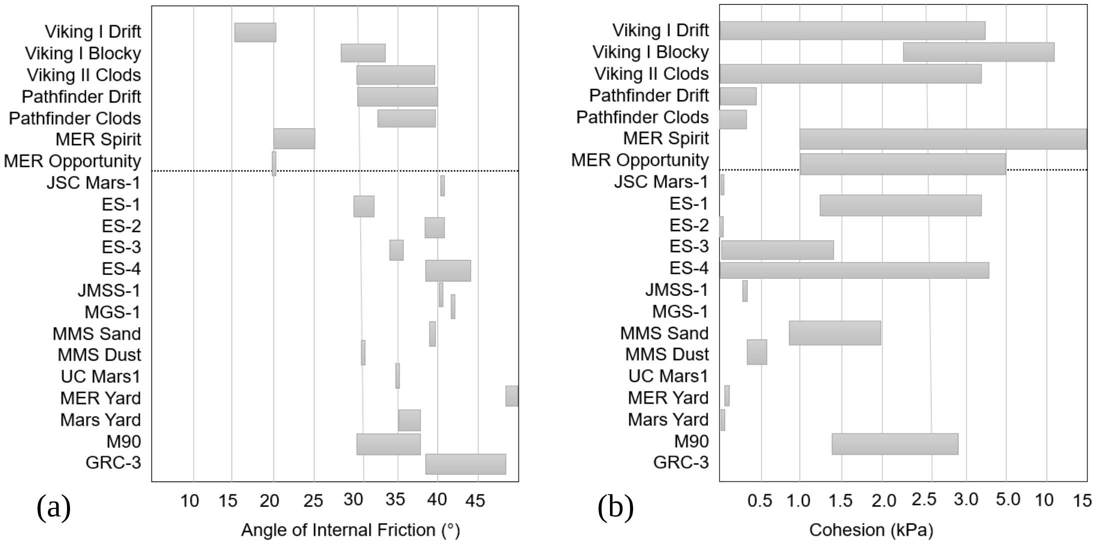

Figure 2. Comparison of (a) angle of internal friction and (b) cohesion for Mars soil and Mars simulants.

CONCLUSIONS

In order to determine the most analogous simulants to Mars soil for vehicle mobility studies, a set of parameters for the terrain most challenging in terms of surface mobility were defined as the criteria for evaluation. The criteria, defined in Table 4, were set to represent the mechanical properties of the Mars wind drift regions—a conservative soil when testing to mobility. Driving over wind drift soils increases the risk of entrapment, and may increase time and energy due to increased slip. A ranking system was devised based on these criteria. For each soil parameter, Figure 3 compares Mars simulant and ranks them as a “good analogue”, “good analogue, but with some limitations”, or as those with “no available data”. Each soil parameter was then weighted in terms of contribution to soil strength for vehicle performance. Angle of internal friction was given the heaviest weight followed by cohesion and particle shape, particle size, and lastly bulk density. Using these weighted values and a point system based on ranking, each simulant was assigned a fidelity value with a higher value representing a higher quality Mars wind drift simulant. Though ES-1, -3, and -4 were designed to represent soil types other than wind drift, they were included in the ranking for comparison. Sourcing and processing was considered separately since a high fidelity simulant may be worth the time and effort, but a low fidelity simulant may not be.

Table 4. Properties of wind drift Martian soils selected for simulant comparison.

Particle Shape	*Particle Size (μm)*	*Bulk Density (g/cc)*	*Cohesion (kPa)*	*Angle of Internal Friction (°)*
Rounded to sub-angular	0.1–10	1.0–1.5	0–3.7	15.6–25.0

	Particle Shape	Particle Size	Bulk Density	Angle of Friction	Cohesion
JSC Mars-1	✖				✔
ES-1		✔	✓	✓	✓
ES-2	✓	✓	✔		✔
ES-3	✔		✓		✔
ES-4	✖				✔
JMSS-1	✓		✓		✔
MGS-1	✖		✓		✖
MMS Sand		✓	✓		✓
MMS Dust		✖	✓	✓	✔
UC Mars1	✓	✔			✖
MER Yard	✖		✓		✔
Mars Yard	✖		✓		✔
M90	✔	✓	✔	✓	✓
GRC-3	✖				✖

✔ Good analogue
✓ Good analogue with limitations
✖ No data available

Figure 3. Comparison of Mars simulants in terms of how well they align with Martian soil properties pertinent to vehicle mobility.

Table 5. Ranking of Mars simulants in order of fidelity for surface mobility studies.

Simulant	*Score*
M90	30
ES-1	22
ES-2	22
MMS Dust	21
ES-3	20
JMSS-1	17
UC Mars1	15
MER Yard	14
Mars Yard	14
JSC Mars-1	12
ES-4	12
MMS Sand	12
MGS-1	8
GRC-3	6

Angle of internal friction, the highest weighted category, had the lowest number of simulants that could be considered “good analogues with limitations”. Looking at Figure 2(a), none of the simulants had friction angles within the range of 15–25°. Therefore those three with the lowest friction angles (ES-1, MMS Dust, and M90) were selected as analogue materials with limitations. On the other hand, examining Figure 2(b), all simulants met the 0–3.5 kPa criteria for cohesion. Those simulants with the lowest cohesion values of 0.5 or less were ranked as “good analogues” since lower cohesion creates a more conservative wind drift case.

As shown in Table 5, M90 was the highest ranking simulant followed by ES-1 and ES-2, which tied. It is surprising that ES-1 shared the same rank as ES-2 since ES-2 was designed specifically to represent wind drift soils. However, the requirements for the design of the ES-X simulants only included particle size, material, and particle shape. Friction angle and cohesion were not considered [17]. Looking at Figure 3, one can see that ES-1 outranked ES-2 in the category of friction angle—the most heavily weighted parameter. Considering sourcing and processing, it was previously noted that the processing required to obtain the correct particle size distribution of ES-2 was very involved and large quantities were difficult to obtain. For this reason, ES-1 may be the simulant of choice between the two for wind drift soils. Regardless, M90 is the strongest candidate for wind drift Mars simulant and is readily available with minimal processing. MMS Dust is the third ranked candidate that may be considered for use as Mars wind drift simulants for mobility studies. Though MMS Dust is not currently available, JPL is currently setting up a processing plant to resume production of this material in the near future.

Obviously, the simulants included in the ranking are already in existence. It may be of benefit to the science and engineering community to consider development of a new Mars simulant specific for mobility studies in wind drift soil since none of the existing simulants met the criteria for friction angle. These simulants were several degrees greater than the upper bound of the criteria, which could significantly increase soil strength. In addition, most simulants had particles that were sub-angular to angular while particles with a rounded to sub-rounded shape will likely exhibit less friction and therefore be more conservative in terms of strength.

With any simulant caution should be used as they typically are not a “one size fits all” and their specific properties or method of terrain preparation may represent one area of Mars better than another. It is important to know or at least have a good engineering estimate of the type of soil a vehicle will be traversing and test to those specific conditions prior to launch. As previously stated, there are many data gaps in existing Mars terrain data and simulant data that need to be resolved and will be the focus of future work in order to make this a more complete study. Another consideration for future work would be to consider testing mobility systems in a simulated Mars environment including lower atmospheric pressure and reduced gravity. Currently mobility studies are performed in Earth ambient environments, but it is important to consider that pressure and gravity can change cohesion and friction angle of a soil thus affecting its overall strength.

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