Geotechnical Engineering in the XXI Century: Lessons learned and future challenges
N.P. López-Acosta et al. (Eds.)

doi:10.3233/STAL190049

Assessment of the Geo-Mechanical Properties of Mojave Mars Simulant-1 (MMS-1) Soil

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Abstract. The development of unmanned rover space missions able to successfully explore the planet Mars requires suitable regolith simulants that accurately represent soils on the Martian surface and enable scientific studies to be performed in terrestrial laboratories. One such simulant is the Mojave Martian Simulant-1 (MMS-1), which is created from finely crushed or sorted granular basalt with slight surface weathering. This form of simulant has been found to closely match thermal and reflectance spectra, and some of the mechanical properties of Martian soils. What is currently absent from the literature are rigorous studies of the geo-mechanical properties of this type of material. This is of importance with respect to terramechanics applications (e.g. rover soil-wheel interaction). The main objective of this work is to provide high-quality data to better characterize the geo-mechanical performance of MMS-1 in states similar to those on Mars. Comparisons have also been made with Toyoura sand, a well-known benchmark sub-angular feldspar sand. The results of basic laboratory, direct shear and shear wave tests are presented. The aspect ratio and angularity of the crushed material plays a significant role in the packing states and subsequent compression, dilation and small-strain behavior, particularly for low densities and low pressures. Based on these results, the implications for laboratory testing and rover performance trials are also discussed.

Keywords. Mojave Martian Simulant-1 (MMS-1), stress-strain, Mars, rover performance, shearing, soil-wheel interaction.

1. Introduction

Similar to Earth, the Martian and lunar surface layers are covered with loose sediments (regolith), which consist of rocky debris, sand and dust particles. Terrestrial soils are subjected to various chemical and physical weathering processes that predominantly involve water. However, Mars lacks the water and biochemistry of Earth and the soil characteristics are therefore dominated by physical weathering. On Earth, the only similar materials are found in very arid/cold regions at the poles. Despite the success of recent Mars exploration programs (e.g. Mars Exploration Rover, Curiosity, Mars 2020 etc.), reaching and safely landing on Mars has proven to be a challenging task for many

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space programs. Further evidence about the physical and mechanical properties of the surface of Mars is useful for future mission planning. Therefore, to better prepare for landing missions on Mars, it is essential to carry out a programs of ground experiments using Martian soil before robotic missions are launched to explore the surface of Mars [1-2]. However, no soil has been returned to Earth, therefore soil simulants are often used for testing rovers, landers, and other equipment for the Martian surface [3].

Several Martian soil simulants have been reported in the literature {e.g. Mojave Mars Simulant (MMS), Johnson Space Center-1 (JSC-1), etc. [2, 4-6]}. These materials have been produced from various terrestrial sources (e.g. basalt, volcanic ash and cinders) and are mechanically crushed to create the simulants. This method is believed to closely resemble the physical weathering/communition processes of basaltic rocks on Mars (due to meteor impact and wind abrasion). The stimulants have been developed with similar chemical compositions, mineralogy, particle size distribution and physical properties to regolith on Mars. Although much effort has been expended to create these simulants and characterize their behavior in various ways, high quality geotechnical investigations are still lacking in the literature. In addition, since Martian regolith is known to have considerable chemical and mineralogical variation, a single simulant is unlikely to represent the entire surface of the planet. The aims of the study described in this paper are to investigate a typical simulant material (MMS-1) and describe its behavior based on a range of geotechnical tests, in an attempt to better characterize its mechanical response in states likely to be similar to Mars.

2. Testing procedures

2.1. Sample preparation and properties

Two different materials are used in this research: fine-grained basaltic Mojave Mars Simulant-1 (MMS-1 soil) and Toyoura sand, which is a well-known sub-angular feldspar benchmark sand [7]. MMS-1 contains small percentages of $MgSO_4$, Gypsum, and NaCl, which is similar to minimally altered volcanic-derived soil on Mars [5]. The physical properties and grain size distributions of these two soil samples are presented in Table 1 and Figure 1, along with a typical crushed silica flour for comparison. In terms of coefficients of uniformity (C_u) and curvature (C_c) values, MMS-1 soil has a wider range of grain size distribution than the other two soils. It is classified as a silty sand (SM) soil based on the Unified Soil Classification System (ASTM D-2487). It is observed from this Figure that the grain size distribution of the MMS-1 soil is located between the ranges of the Toyoura sand and the silica flour. The particles of MMS-1 are observed to be quite angular and have a high aspect ratio, as would be expected for a crushed material. It is noticeable that the minimum void ratio and spread between maximum and minimum void ratio of MMS-1, shown in Table 1, are higher than that of Toyuora sand, despite the much wider range of particle sizes.

Table 1. Physical properties of samples.

	Gs	e_{max}	e_{min}	D_{50} (mm)	C_u	C_c
MMS-1 soil	2.67	1.27	0.74	0.12	14.8	3.8
Toyoura sand	2.65	0.98	0.61	0.31	2.1	1.4
Silica flour	2.64	1.60	0.83	0.017	-	-

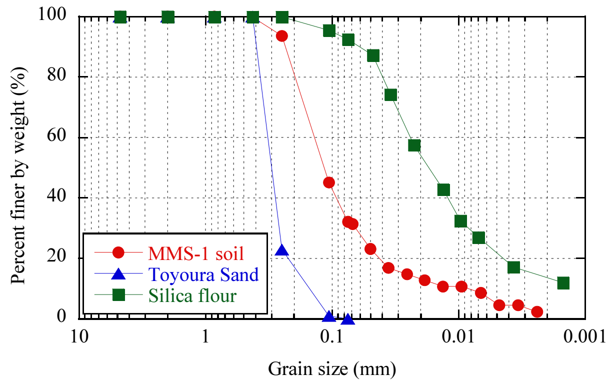


Figure 1. Grain size distribution curve of MMS-1 soil, Toyoura sand and Silica flour.

2.2. Experimental testing

A series of drained direct shear tests utilizing ASTM (D3080) were performed on the soil samples to investigate their mechanical properties. All soil samples were tested in a standard shear box with dimensions of 60 x 60 mm and 20 mm height. All tests were carried out at a strain rate of 0.2 mm/min under different normal applied pressures of 10, 20, 50, 100, and 200 kPa, respectively. Both horizontal and vertical displacements and shear force were recorded during the test, up to failure or 15 % shear strain. Table 2 shows the experimental program of direct shear tests. Table 3 shows the relationship between relative density (D_r) and dry density of MMS-1 soil and Toyoura sand, again demonstrating the differences between the packing states of the two materials.

Table 2. Program of direct shear tests for soil samples.

Sample	w (%)	D_r (%)	σ_n (kPa)	Shear speed (mm/min)
MMS-1 soil Toyoura sand	0	20 40 60 80	10 20 50 100 200	0.2

Table 3. Relationship between relative density (D_r) and dry density of MMS-1 soil and Toyoura sand.

Sample	Dr (%)	ρ_d (g/cm^3)	Sample	Dr (%)	ρ_d (g/cm^3)
MMS-1 soil	20	1.23	Toyoura sand	20	1.40
	40	1.30		40	1.46
	60	1.37		60	1.52
	80	1.45		80	1.57

Shear wave velocity (V_s) and small-strain shear modulus are important parameters used to evaluate the dynamic and stiffness properties of soil. A piezoelectric ring actuator (PRA) technique employed in an odometer setup developed at Sherbrook and Western University [8-10] was used to measure the shear wave velocity of the investigated soils. The shear wave arrival time was determined using frequency domain analysis methods. Once the arrival time and the height of soil specimen after normal loading were determined, the shear wave velocity could be found. Table 4 shows the testing program for the estimation of the shear wave velocity with different normal stresses.

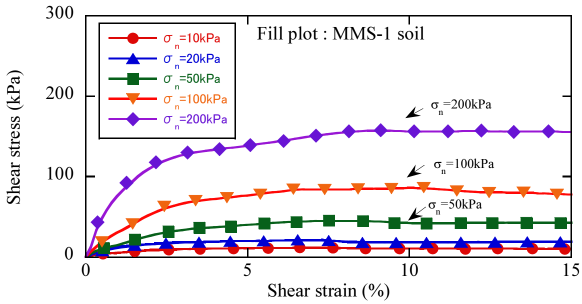
Table 4. Program of shear wave velocity tests for the soil samples.

Sample	w (%)	D_r (%)	σ_n (kPa)
MMS-1 soil	0	20 40 60 80	10 20 50 100 200 400 600
Toyoura sand	0	80	

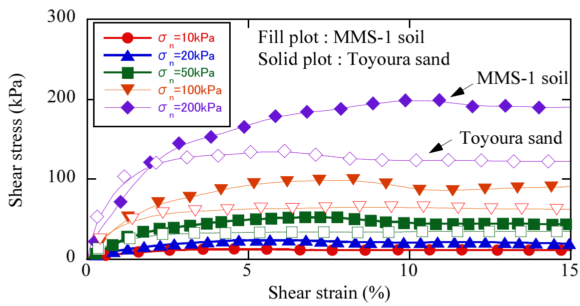
3. Results and discussion

3.1. Direct shear box results

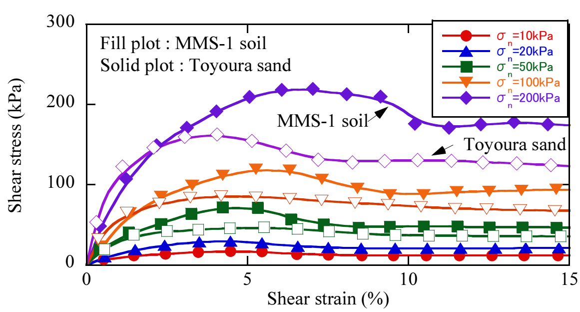
The direct shear tests were used to investigate the stress-strain behavior and the drained shear strength parameters during plane-strain shearing. In particular, the relationship between peak (ϕ'_{peak}) and critical state internal friction angle (ϕ'_{cs}) of the MMS-1 soil and Toyoura sand was sought for different densities and pressures.Figure 2 shows the results of the direct shear tests of MMS-1 soil and Toyoura sand. To simulate the situation of the ground on Mars, the soil specimens were initially tested at zero water content and 20% relative density. However, due to the difficulties of achieving a 20% relative density in the case of Toyoura sand, the majority of the comparisons in this paper are for 40% and 80% relative density. In the figure, the peak and critical state shear stress of the MMS-1 soil and Toyoura sand tends to increase with increasing vertical stress for all relative densities. In addition, although the initial stiffness increases with the increase of the vertical stress, the influence due to the difference in the relative density is not readily observed. The shear strains to peak stress in general for the Toyoura sand specimens seem to be lower. Also, the MMS-1 soil has a higher shear stress compared to Toyoura sand and has a clear peak with the increase of relative density. The post-peak strain softening also seems to be more significant for MMS-1, with higher differences between the peak and critical state strengths.



(a) Relative density Dr = 20%



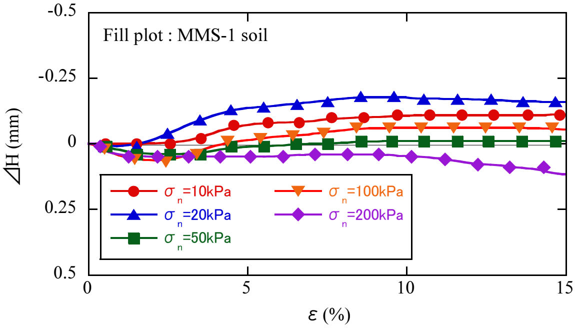
(b) Relative density Dr = 40%



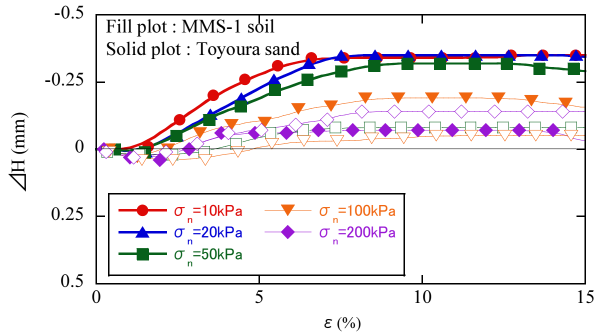
(c) Relative density Dr = 80%

Figure 2. Relationships between shear stress and shear strain of MMS-1 soil and Toyoura sand.

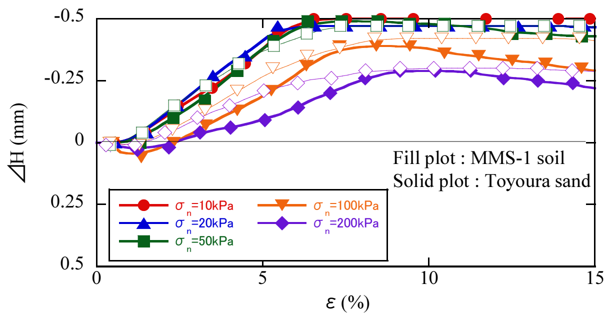
Figure 3 shows the relationships between vertical displacement and shear strain for the MMS-1 soil and Toyoura sand. It is observed from this Figure that for all cases, the applied normal pressure and relative density has a significant effect on the increase of volume change expansion, which is normally observed in the case of dense sand irrespective of relative density. For all specimens, the volume of the specimens contracted at the beginning of the shearing and after that the volume of the specimen tended to expand as the shear strain increased. Also, it can be seen that the volume change of both materials decreases as the vertical stress increases. In terms of the difference of relative density, it is observed that at D_r = 40%, there was a difference in the vertical displacement between MMS-1 soil and Toyoura sand. While in the case of high relative density $D_r = 80\%$, it was found that the vertical displacement of MMS-1 soil and Toyoura sand are almost equal. What is remarkable for the MMS-1 material is the tendency to still dilate significantly at the lowest relative density ($D_r = 20\%$).



(a) Relative density Dr = 20%



(b) Relative density Dr = 40%

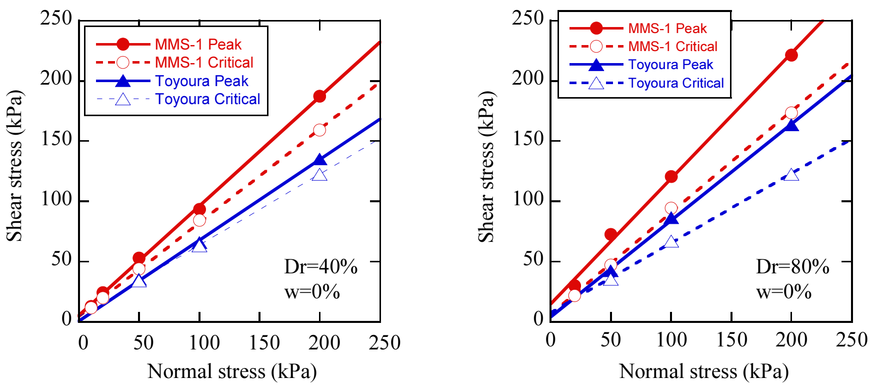


(c) Relative density Dr = 80%

Figure 3. Relationships between vertical displacement & shear strain of MMS-1 soil and Toyoura sand.

From the above shear box results, it can be concluded that MMS-1 soil has a higher shear stress and clear peak compared to Toyoura sand. In addition, all of the volume changes show a positive dilatancy behavior and tend to decrease with the increase of the vertical stress. When the relative density Dr = 60% or more, it was revealed that there is no significant difference between MMS-1 soil and Toyoura sand in terms of volume change characteristics.

Figure 4 shows the relationships between the shear and normal stress for peak and critical states for the two materials for different relative densities. Table 5 shows some of the derived strength parameters and compares these values with the previous results of Mars simulant soils and actual Mars 'field tests', which were obtained from in-situ tests from rovers. MMS-1 soil is seen to have higher peak internal friction angles and cohesions compared to Toyoura sand. The range of the internal friction angle (Φ'_{peak}) and cohesion of MMS soil obtained in this study were 37.1° to 46.0° and 3.8 to 15 kPa, respectively. The critical state friction angles of MMS-1 also seem to be considerably higher than for Toyoura sand. It was observed that the obtained range of internal friction angle and cohesion of MMS soil in this study is in agreement with the available values of other simulated soils, but is less convincing for actual Martian landing sites [4-5, 11-14].



(a) Relative density Dr = 40% (b) Relative density Dr = 80%

Figure 4. Relationships between shear stress and normal stress of MMS-1 soil and Toyoura sand.

3.2. Shear wave velocity results

Figure 5 shows the relationship between shear wave velocity and normal vertical stress of MMS-1 soil and Toyoura sand. It was found that shear wave velocity increases with the increase of pressure and relative density. The increase of shear wave velocity with the increase of applied pressure is related to the increase of the stiffness of soil samples. The average value of shear wave velocity of MMS-1 soil was found 100-180 (m/sec) in this study, which is lower than that of Toyoura sand. The main reason for the decrease of the average of shear wave velocity of MMS soil compared to Toyoura sand is probably related to MMS-1 having more angular, longer particles and more fines compared to Toyoura sand. Also, it is observed from Figure 5 that, the shear wave velocity increased significantly for lower applied pressures and after that the increase became less pressure sensitive.

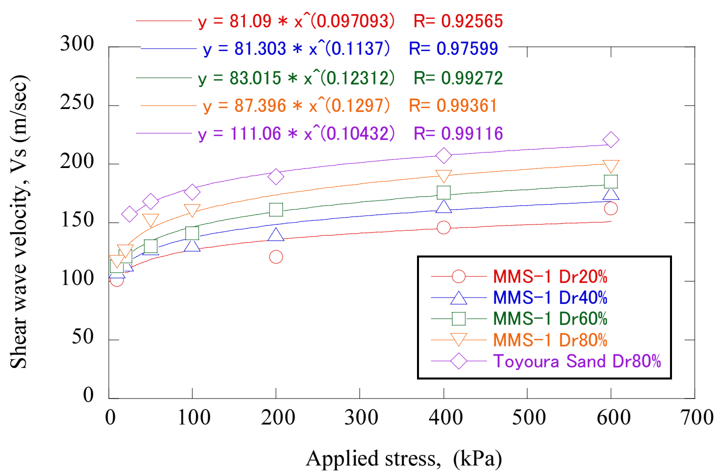


Figure 5. Shear wave velocity of MMS-1 soil and Toyoura sand.

4. Conclusions

To understand the basic mechanical properties of MMS soil, the shear characteristics and shear wave velocity were investigated. Based on the obtained results, the following conclusions can be drawn:

1. MMS-1 soil has higher shear stresses for given normal stresses compared to Toyoura sand, and it has a clear peak with increasing relative density.
2. Although it is quite dilatant at low pressures and densities, MMS-1 soil has similar volume change characteristics as Toyoura sand at higher relative density.
3. The range of the internal friction angle (Φ'_{peak}) of MMS-1 soil was 37.1° to 46.0°, and the range of cohesion was 3.8 to 15 kPa. These values are in agreement with the values obtained in previous works using different Mars Simulant soils, but appear to be higher those measured in-situ for Martian soil.
4. The particle shape and roughness of the crushed MMS-1 material seems to be having a significant effect on the packing, compressibility, shear strength and dilation of the material, particularly at low pressures and densities.

Although physical weathering is expected to be predominant on Mars, the use of purely crushed fresh rock materials with similar chemical/physical structures (i.e. basalts) needs to be further investigated. Since materials that present possible terramechanics hazards will likely be loosely packed and under very low self-weight stresses, the use of similar states in terrestrial rover trials with crushed rock derived soils will have significant dilative characteristics. This will have important consequences for the resulting mechanical response of the soils during soil-wheel interaction and the design of rover wheels. Comparisons with 'field' measurements of Martian soils seem to suggest less dilative soils and the root causes for these differences need to be investigated more thoroughly.

Table 5. Physical properties of the MMS-1 and Toyoura sand compared to material found at different Martian landing sites.

	Dr (%)	Bulk density (g/cm^3)	Friction angle φ'_{peak} (°)	Friction angle φ'_{cs} (°)	Cohesion c'_{peak} (kPa)
MMS soil (fine-grained basaltic)	20	1.23	37.1	37.1	6.3
	40	1.30	42.3	38.0	3.8
	60	1.37	45.2	39.7	10
	80	1.45	46.0	39.9	15
Toyoura Sand	40	1.46	33.6	30.0	0
	60	1.52	36.7	30.5	2.5
	80	1.59	38.8	30.0	1.3
Artificial soil (Toyoura Sand:Silica Flour =2:1)	20	1.49	34.4	34.2	1.2
	80	1.81	36.8	35.3	7.5
	Dr (%)	**Bulk density (g/cm^3)**	**Friction angle φ' (°)**		**Cohesion c' (kPa)**
JSC Mars-1[b] (simulant)		0.84	47		1.91
JMSS-1[c] (simulant)		1.45	40.6		0.33
Pathfinder[d]					
Drift material		1.29 to 1.52	34.3		0.21
Crusty material		1.42 to 1.64	37.0 ± 2.6		0.17 ± 0.18
Viking Landers[e]					
VL-1 drift material		1.15 ± 0.15	18 ± 2.4		1.6 ± 1.2
VL-1 blocky material		1.60 ± 0.4	30.8 ± 2.4		5.1 ± 2.7
VL-2 crusty material		1.40 ± 0.2	34.5 ± 4.7		1.1 ± 0.8
Spirit Rover[f]		1.20 to 1.50	20		1 to 15
Opportunity Rover[g]		1.30	20		1 to 5

[a]Peters et al. (2008), [b]Allen et al. (1998), [c]Xiaojia et al. (2015), [d]Moore et al. (1999), [e]Moore and Jakosky (1989), [f]Arvidson et al. (2004a), [g]Arvidson et al. (2004b)

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