

GEOTECHNICAL CHARACTERIZATION OF LUNAR REGOLITH SIMULANTS

By

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Geotechnical Characterization of Lunar Regolith Simulants

ABSTRACT

By

CHUNMEI HE

Many of the essential materials needed for the construction of permanent lunar bases and test beds for future missions to Mars can be produced from the resources on the lunar surface. Utilization of in situ resources on the moon will reduce the need and cost to bring everything from the earth. Therefore, it is essential to have a thorough understanding of the geotechnical behavior of lunar regolith. However, only a limited amount of information is available about the geotechnical properties of lunar soils. In addition, the amount of lunar regolith brought back to the earth is small. To execute the many small and large scale equipment tests planned for In-Situ Resource Utilization (ISRU), it is necessary to develop a simulant which is inexpensive and can be produced in large quantities. This dissertation presents the methodology behind developing such a lunar-like geotechnical soil, GRC-3, and compares the properties of this soil with that of lunar regolith to provide insight into the material's geotechnical properties. Results show that particle size distribution, specific gravity, relative density, friction angle and compressibility are similar to that of the lunar regolith. Additionally, the lunar regolith mare simulant JSC-1A and the lunar regolith highland simulant NU-LHT-2M were mechanically characterized and compared to those of the returned lunar regolith. The ASTM standard laboratory tests used in the studies of these lunar simulants were compared to the techniques used in the studies of lunar regolith.

CHAPTER 1 INTRODUCTION

1.1 PAST LUNAR EXPLORATION

Known since prehistoric times, the Moon is the brightest object in the sky after the Sun. It was Queen of the Night. The Moon's desolate beauty has been a source of fascination and curiosity throughout history. Observation and scientific investigation can be traced back to a few centuries BC, with the earliest observations being made by the Chinese Astronomers. In ancient China, the Moon's motion was carefully recorded as part of a grand structure of astrological thought. Early studies of the Moon's motion and position allowed the prediction of tides and led to the development of calendars.

For centuries, knowledge about the Moon accumulated slowly, driven by astrological and navigational needs, until the outburst of progress began in the Renaissance. In 1609 Galileo Galilei began the first telescopic observation on the Moon, which forever changed human understanding of the Moon. People believed that the Moon contained vast lakes of frozen water, which they called Maria, e.g. Maria Tranquilitatis, or Sea of Tranquility. Studying the Moon from thousands of miles away on the Earth wasn't like being there. People wanted to land on the Moon! Putting a person on the Moon was only possible through many discoveries and inventions. In 1943 the development of Rocketry by Von Braun, the father of the United States space program, following the use of rocketry by the Chinese as a military weapon from 1045, was the beginning of the Space Age (Anonymous, 1995). The Cold War-inspired space race between the United States of America and the Soviet Union accelerated with a focus on

the Moon. In 1957 the Russians successfully launched Sputnik 1, the first artificial satellite in space (refer to Figure 1.3). The explicit of lunar exploration began in 1959 with the Soviet Union's launch of the Luna satellites which obtained the first pictures of the far side of the moon. In the space of just two months the USSR and the USA had both sent missions to successfully fly past the Moon (Luna 1 and Pioneer 4 respectively). By 1964 Russia had put both Yuri Gagarin (the first man) and Valentina Tereshkova (the first woman) into outer space. In an effort to compete with Soviet successes, on 25th May 1961 President John F. Kennedy announced America's intention of "landing a man on the Moon and returning him safely to Earth". The US Ranger probes were followed by the Surveyor landers, whose mission was to establish suitable landing sites. Finally came the Apollo missions – a herculean effort involving over a million people and culminating in Apollo 11. Humans first landed on the Moon on 20th July 1969. Neil Armstrong stepped off the Apollo 11 and became the first man to walk on the lunar surface (refer to Figure 1.2). Five more successful manned landing missions followed, ending with Apollo 17 in 1972; at the completion of the program, a total of 12 astronauts had set foot on the Moon.

In summary, there were 65 moon landings (with 10 in 1971 alone) from the mid-1960s to the mid-1970s). However, only 9 of these total missions completed a round trip from Earth and successfully returned geologic lunar samples. This included three Luna missions (Luna 16, 20 and 24) and the Apollo missions 11 through 17 (excepting Apollo 13, which aborted its planned lunar landing). Table 1.1 below provides a complete summary of lunar exploration missions throughout the mid-1970s. In addition, Figure 1.3 and Figure 1.4 provide a map of the landing spots of lunar exploration missions.

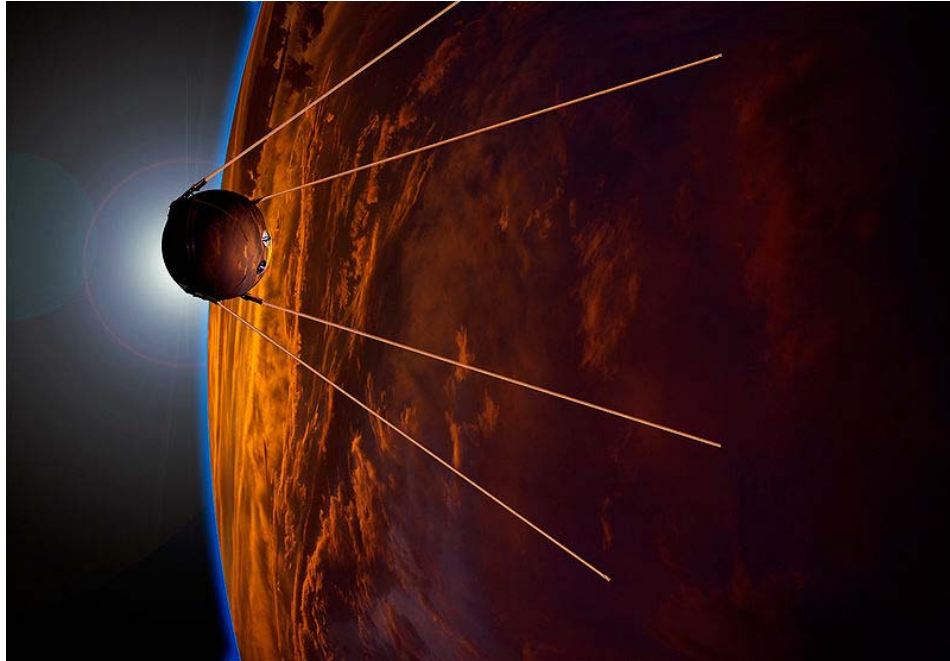


Figure 1.1 Sputnik 1 (credit Wikipedia)



Figure 1.2 Neil Armstrong's first moonwalk (credit NASA)

After the Apollo missions, lunar scientists continued to conduct multispectral remote-sensing observations from Earth and perfected instrumental and data-analysis techniques. In 1990 Japan launched Hiten orbiter and became the third country to orbit the Moon. NASA launched the Clementine mission in 1994 and Lunar Prospector in 1998. On 27th September 2003 the European Space Agency launched a small, low-cost lunar orbital probe called SMART1, whose primary goal was to take three-dimensional X-ray and infrared imagery of the lunar surface. SMART 1 entered lunar orbit on November 15, 2004 and continued to make observations until September 3, 2006, when it was intentionally crashed into the lunar surface in order to study the impact plume (Anonymous, 2006a). China has begun the Chang'e program for exploring the Moon and is investigating the prospect of lunar mining, specifically looking for the isotope helium-3 for use as an energy source on Earth (Leonard, 2003). China launched the Chang'e 1 robotic lunar orbiter on October 24, 2007. India's national space agency, Indian Space Research Organization (ISRO), launched Chandrayaan-1, an unmanned lunar orbiter, on October 22, 2008. The lunar probe would revolve around the moon for two years, with scientific objectives to prepare a three-dimensional atlas of the near and far side of the moon and to conduct a chemical and mineralogical mapping of the lunar surface (Anonymous, 2009a). The unmanned Moon Impact Probe landed on the moon at 15:04 GMT on November 14, 2008 making India the 4th country to touch down on the lunar surface.

Table 1.1 Lunar Exploration Timeline (Vaniman et al., 1991a, Anonymous, 2009b)

Mission	Date	Country	Task and Result
Luna 1	2-Jan-59	USSR	Flyby, 1 st lunar flyby
Pioneer 4	3-Mar-59	USA	Flyby, missed the Moon by 37,300 miles
Luna 2	12-Sep-59	USSR	1 st lunar impact near the Sea of Serenity
Luna 3	4-Oct-59	USSR	Probe, 1 st photos of lunar farside
Ranger 1	23-Aug-61	USA	Attempted test flight
Ranger 2	18-Nov-61	USA	Attempted test flight
Ranger 3	26-Jan-62	USA	Attempted impact
Ranger 4	23-Apr-62	USA	Impact, crushed on the lunar farside
Ranger 5	18-Oct-62	USA	Attempted impact
Luna 4	2-Apr-63	USSR	Flyby, missed the Moon by 5,282 miles
Ranger 6	30-Jan-64	USA	Impact, camera failed
Ranger 7	28-Jul-64	USA	Impact, 1 st close-up photos of the Moon
Ranger 8	17-Feb-65	USA	Impact, high quality photos of the Moon
Ranger 9	21-Mar-65	USA	Impact, high quality photos of the Moon
Luna 5	9-May-65	USSR	Impact, 1 st soft landing attempt
Luna 6	8-Jun-65	USSR	Lander, missed the Moon by 100,041 miles
Zond 3	18-Jul-65	USSR	Flyby, photographed lunar farside
Luna 7	4-Oct-65	USSR	Impact, crashed near Ocean of Storms
Luna 8	3-Dec-65	USSR	Impact, crashed near Ocean of Storms
Luna 9	31-Jan-66	USSR	Lander, 1 st soft landing, 1 st TV transmission
Luna 10	31-Mar-66	USSR	Orbiter, 1 st lunar satellite
Surveyor 1	30-May-66	USA	Lander, 1 st soft-landed
Lunar Orbiter 1	10-Aug-66	USA	Orbiter, lunar satellite
Luna 11	24-Aug-66	USSR	Orbiter, lunar satellite
Surveyor 2	20-Sep-66	USA	Attempted Lander
Luna 12	22-Oct-66	USSR	Orbiter, lunar satellite
Lunar Orbiter 2	6-Nov-66	USA	Orbiter, lunar satellite
Luna 13	21-Dec-66	USSR	Lander, soft landing on the Moon
Lunar Orbiter 3	4-Feb-67	USA	Orbiter, lunar satellite
Surveyor 3	17-Apr-67	USA	Lander, soft-landed robot laboratory
Lunar Orbiter 4	8-May-67	USA	Orbiter, lunar satellite
Surveyor 4	14-Jul-67	USA	Attempted Lander
Lunar Orbiter 5	1-Aug-67	USA	Orbiter, lunar satellite
Surveyor 5	8-Sep-67	USA	Lander, soft-landed robot laboratory
Surveyor 6	7-Nov-67	USA	Lander, soft-landed robot laboratory

Surveyor 7	7-Jan-68	USA	Lander, soft-landed robot laboratory
Luna 14	7-Apr-68	USSR	Orbiter, lunar satellite
Zond 5	15-Sep-68	USSR	1 st Return Probe
Zond 6	10-Nov-68	USSR	Return Probe
Apollo 8	21-Dec-68	USA	Crewed Orbiter, 1 st human to orbit the Moon
Apollo 10	18-May-69	USA	Orbiter, 1 st docking maneuvers in lunar orbit
Luna 15	13-Jul-69	USSR	Orbiter, crashed on the Moon
Apollo 11	16-Jul-69	USA	Crewed Lander, 1 st humans on the Moon
Zond 7	7-Aug-69	USSR	Return Probe
Apollo 12	14-Nov-69	USA	Crewed Lander, 2 nd human landing
Apollo 13	11-Apr-70	USA	Crewed Lander (aborted human landing)
Luna 16	12-Sep-70	USSR	1 st robot sample return (100 g)
Zond 8	20-Oct-70	USSR	Return Probe
Luna 17/Lunokhod	10-Nov-70	USSR	1 st robot rover
Apollo 14	31-Jan-71	USA	Crewed Lander, 3 rd human landing
Apollo 15	26-Jul-71	USA	Crewed Lander, 4 th human landing
Luna 18	2-Sep-71	USSR	Impact, crashed on the Moon
Luna 19	28-Sep-71	USSR	Orbiter, lunar satellite
Luna 20	14-Feb-72	USSR	2 nd robot sample return (30 g)
Apollo 16	16-Apr-72	USA	Crewed Landing, 5 th human landing
Apollo 17	7-Dec-72	USA	Crewed Landing, 6 th human landing
Luna 21/Lunokhod	8-Jan-73	USSR	Rover (139 days, 37 km)
Luna 22	2-Jun-74	USSR	Orbiter, lunar satellite
Luna 23	28-Oct-74	USSR	Lander, failed robot sampler
Luna 24	14-Aug-76	USSR	3 rd robot sample return (170 g)
Hiten	24-Jan-90	JAPAN	Flyby, Orbiter, and Impactor
Clementine	25-Jan-94	USA	Orbiter
AsiaSat 3/HGS-1	24-Dec-97	HKG	Lunar Flyby
Lunar Prospector	7-Jan-98	USA	Orbiter and Impactor
SMART 1	27-Sep-03	ESA	Lunar Orbiter
Kaguya (SELENE)	Sep-07	JAPAN	Lunar Orbiter
Chang'e 1	24-Oct-07	PRC	Lunar Orbiter
LRO	Oct-08	USA	Lunar Orbiter
LCROSS	Oct-08	USA	Lunar Orbiter
Chandrayaan-1	22-Oct-08	INDIA	Lunar Orbiter
Lunar-A	Cancelled	USA	Orbiter and Penetrators

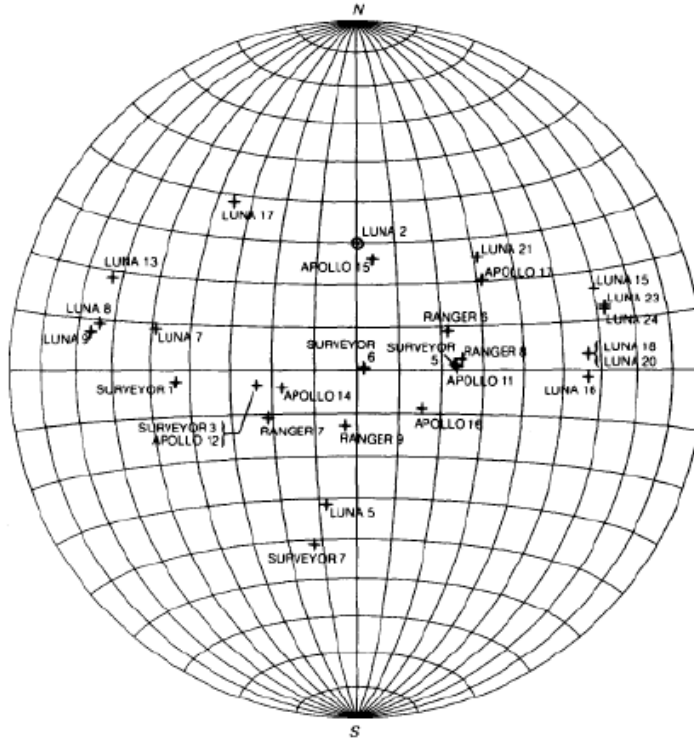


Figure 1.3 Landing spots of lunar exploration missions (Vaniman et al., 1991a)

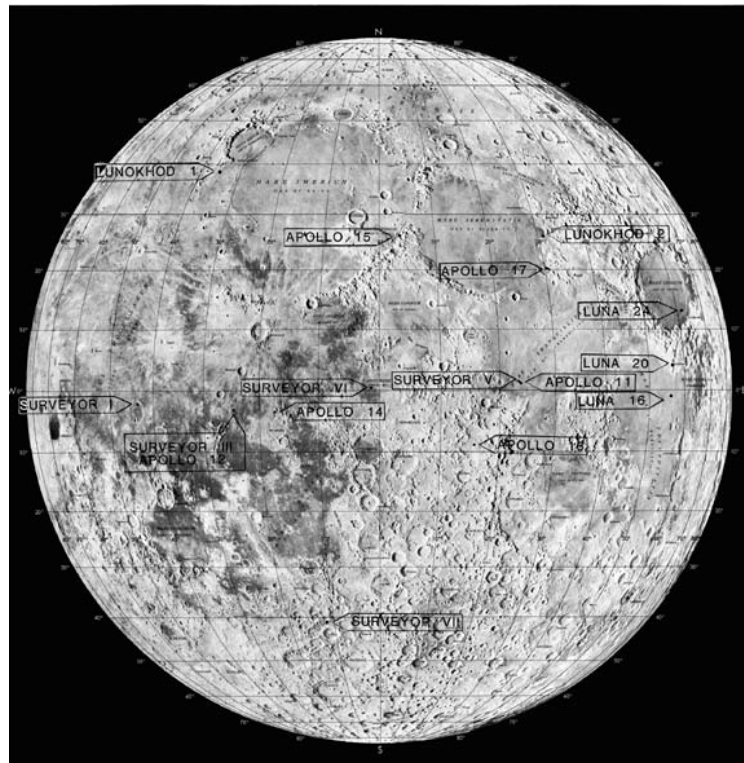


Figure 1.4 Landing map of Apollo, Surveyor and Luna Missions (Anonymous, 2008)

1.2 FUTURE LUNAR EXPLORATION

On January 14, 2004, President George W. Bush announced a new Vision for Space Exploration for the National Aeronautics and Space Administration (NASA) that would return humans to the Moon within a timeframe of 2015 to 2020 (refer to Figure 1.5). This vision encompasses a broad range of human and robotic missions, including the Moon, Mars and destinations beyond. It establishes clear goals and objectives, but sets equally clear budgetary “boundaries” by stating firm priorities and tough choices. It also establishes as policy the goals of pursuing commercial and international collaboration in realizing the new vision (Admiral et al., 2004).



Figure 1.5 President Bush announces plan for man’s return to Moon (Spudis, 2006)

This new program referred to as “Moon, Mars, and Beyond” includes sending a crew of 3-4 to the moon for several days even several weeks, constructing permanent

bases on the Moon, and building test beds for future missions to Mars and other destinations. Bush stated, "With the experience and knowledge gained on the moon, we will then be ready to take the next steps of space exploration: human missions to Mars and to worlds beyond." Present Bush described this program not as a race, but as a journey in which all nations were invited to participate for the benefit of mankind. Since then NASA has put much time and effort into recognizing, reconstructing, and remotivating space enthusiasts for a successful trip back to the Moon.

1.2.1 Why the Moon?

From April 2006 through December 2006, NASA worked with 13 of the world's space agencies to develop a Global Exploration Strategy, which includes input from more than 1,000 individuals representing 14 of the world's space agencies, as well as non-governmental organizations and commercial interests. The strategy explains why the global community believes we should explore space, how space exploration can benefit life on Earth, and how the moon can play a critical role in our exploration of the solar system. One of the primary activities the global space community pursued in 2006 was to answer the questions, "Why should we return to the Moon?" and "What do we hope to accomplish through lunar exploration?" (Wilson, 2007). The discussions generated agreement on six major themes for lunar exploration and almost 200 subcategorized objectives within those themes. These themes and objectives are shown in Table 1.2 and Table 1.3 , respectively.

Table 1.2 NASA lunar exploration themes

Topic	Details
Human Civilization	Extend human presence to the Moon to enable settlement
Scientific Knowledge	Pursue scientific activities that address fundamental questions about the history of the Earth, the solar system, and the universe with relation to mankind's role in them
Exploration Preparation	Test technologies, systems, flight operations, and exploration techniques to reduce risks and increase the productivity of future missions to Mars and beyond
Global Partnerships	Provide a challenging, shared and peaceful activity that unites nations in pursuit of common objectives
Economic Expansion	Expand the Earth's economic sphere, and conduct lunar activities with benefits to life on the home planet
Public Engagement	Use a vibrant space exploration program to engage the public, encourage students and help develop the high-tech workforce that will be required to address the challenges of tomorrow

Table 1.3 Subcategorized objectives for lunar exploration (Anonymous, 2006b, Oravec, 2009)

Objectives	Topics:					
	Human Civilization	Scientific Knowledge	Exploration Preparation	Global Partnerships	Economic Expansion	Public Engagement
<i>Astronomy and Astrophysics</i>		x		x	x	
<i>Heliophysics</i>	x	x	x		x	
<i>Earth Observation</i>		x			x	
<i>Geology</i>	x	x	x		x	
<i>Materials Science</i>	x	x	x		x	
<i>Human Health</i>	x	x	x		x	x
<i>Environmental Characterization</i>	x	x	x			
<i>Environmental Hazard Mitigation</i>	x		x			
<i>Operational Environmental Monitoring</i>	x	x	x		x	
<i>Life Support & Habitat</i>	x	x	x		x	
<i>General Infrastructure</i>	x	x	x		x	
<i>Operations, Testing, and Verification</i>	x	x	x	x	x	
<i>Power</i>	x		x		x	
<i>Communication</i>	x	x	x	x	x	x
<i>Position, Navigation & Timing</i>	x		x	x	x	
<i>Transportation</i>	x		x		x	
<i>Surface Mobility</i>	x		x			
<i>Crew Activity Support</i>	x	x	x		x	
<i>Lunar Resource Utilization</i>	x	x	x		x	
<i>Historic Preservation</i>	x	x			x	x
<i>Development of Lunar Commerce</i>	x		x	x	x	
<i>Commercial Opportunities</i>	x	x	x		x	x
<i>Global Partnerships</i>	x	x	x	x	x	
<i>Public Engagement and Inspiration</i>	x	x	x	x	x	x

“We leave as we came, and God willing as we shall return, will peace and hope for all mankind,” Eugene Cernan (Commander of last Apollo mission) said. Returning to the moon is an important step for NASA space program. Establishing an extended human presence on the moon could vastly reduce the cost of further space exploration. Lunar bases will be useful for spacecraft to be launched further into space from the Moon using less energy due to its reduced gravity field (Briggs et al., 1988). Utilizing the in situ resources on the Moon would vastly reduce the need and the cost to bring everything from the earth. The moon can and will be utilized to develop and test new approaches, technologies and systems that will allow us to function in other more challenging environments.

1.3 MOTIVATION FOR THE RESEARCH

Two components of the program “Moon, Mars and Beyond”, In-Situ Resources Utilization (ISRU) and vehicle mobility, require a thorough understanding of geotechnical properties of lunar soils and large quantities of equivalent soil to test systems. To satisfy the needs of the lunar research and development communities with large quantities of lunar regolith like soils, this research focuses on the development of new lunar simulants.

While the lunar samples returned by Luna and Apollo missions have revealed much about soil mechanics of lunar soils (Costes, et al. 1970; Scott and Roberson, 1968; Carrier, et al. 1973; and Gold et al., 1971), these priceless materials exist in too scarce quantities to be used for technology development and testing, and hence their use in the destructive testing is understandable very limited. Especially, some important

geotechnical properties of the lunar soils were not fully understood, e.g., the apparent cohesion of the regolith, the influence of vacuum on soil properties, etc. The amount of lunar soil samples is too limited to be sacrificed during destructive testing on the measurement of the mechanical properties of the lunar soil. And its scientific value is too great to be consumed by the destructive studies. The process of obtaining even the smallest quantity of lunar soil is extremely involved and must go through the lunar sample curator. Access to lunar samples is granted based on well defined and peer-reviewed research plan and only after all other possibilities of material use have been explored (Sibiille, 2005). Thus lunar soil simulant is needed to simulate the characteristics of lunar regolith. Besides, lunar exploration requires scientific and engineering studies using standardized testing procedures that ultimately support flight certification of technologies and hardware. Therefore, the techniques used in the evaluation of soil mechanics of lunar soil samples have to be reviewed.

Various lunar soil simulants have been developed for Earth based lunar soil studies, however, most were made from exotic materials using complex procedures, which can be hazardous, and so far they are no longer available or available in relatively small quantities. These small quantities are insufficient to execute the many small and large scale equipment test planned for ISRU. Other simulants are not affordable to obtain in large enough quantities for large scale testing. The need to supply lunar research community of large quantities of lunar simulant was identified at the *2005 Workshop on Lunar Regolith Simulant Materials*. A survey of potential users and estimates of needed simulant reserves, in the spring of 2005, indicated that the need for lunar simulant materials could fall between 125 and 250 metric tons over the next four years (Sibille et

al., 2005). Thus it is imperative to create a lunar soil simulant from readily-available soils which emulates the known mechanical properties of the lunar regolith. Soil mechanical properties, to the extent that we know for lunar regolith, can be matched even if the mineral and chemical properties of a simulant are not the same as the lunar soils. Thus the purpose of this research is to create a mixture of readily-available soils for ISRU operations sponsored by the NASA Glenn Research Center of Cleveland, Ohio.

Another objective is to use ASTM standardized testing procedures to determine the geotechnical properties of the lunar simulants developed by other agencies. The standardized tests are designed in such a way that the "questions, conditions for administering, scoring procedures, and interpretations are consistent" and are "administered and scored in a predetermined, standard manner" (Anonymous, 2009c). One of the main advantages of standardized testing is that the results can be empirically documented, therefore the test scores can be shown to have a relative degree of validity and reliability, as well as results which are generalizable and replicable (Popham, 1999). Most of ASTM laboratory tests require several hundred grams sample to properly evaluate the properties of soil. However, due to the limited amount of the lunar soil, the lunar soil properties were not determined by ASTM standardized tests. Therefore, the techniques used in the determination of lunar soil properties have to be reviewed.

1.4 SCOPE OF WORK

The focus of this research is on the development of a lunar-like geotechnical soil based on known physical and mechanical properties of lunar soil. The research describes and compares the results of past lunar missions including, but not limited to data obtained

by: astronauts' observations, in-situ lunar soils tests, returned lunar soil samples, and laboratory lunar soil tests. In addition, the composition and mechanical properties of past lunar soil simulants are considered in the development of a new lunar soil simulant. These lunar simulants include: MLS-1, JSC-1, JSC-1A, FJS-1 and GRC-1. Such a soil will be prepared to emulate various lunar terrain conditions, in order to validate the theoretical and numerical analysis of equipments for ISRU operations.

This dissertation presents the investigation of the geotechnical properties of lunar regolith simulants JSC-1A and NU-LHT-2M by using ASTM standardized testing techniques is to establish benchmark properties. This dissertation also presents methodology behind developing such a lunar-like geotechnical soil, GRC-3, whose geotechnical properties are similar to that of lunar regolith. The sub-objectives of this study are as follows:

1. To review the properties of the actual lunar soil and understand the conditions under which there properties were determined.
2. To review the properties of the current and past lunar soil simulants and understand the purpose and intent of creation and use.
3. To determine geotechnical properties of a new lunar regolith mare simulant, JSC-1A, and compare these properties to those of the lunar regolith and other lunar regolith simulants.
4. To determine geotechnical properties of a new lunar regolith highland simulant, NU-LHT-2M, and compare these properties to those of the lunar regolith and other lunar regolith simulants.

5. To develop a new lunar regolith simulant, GRC-3, and determine its geotechnical properties as well as compare these properties to those of the lunar soil and other lunar soil simulants.
6. To critically review the results of this study and develop suggestions for future work in this subject area.

1.5 OUTLINE OF THE DISSEATATION

Chapter 1 introduces past and future lunar exploration and presents the motivation and scope of this research.

Chapter 2 provides extensive literature review on geotechnical properties of lunar soil and lunar soil simulants as well as a review of laboratory test procedures used in the determination of the properties.

Chapter 3 introduces the development of JSC-1A and geotechnical characterization of JSC-1A and compares its geotechnical properties to those of lunar soil and other lunar soil simulants. It also describes the detailed standardized testing procedures used in the determination of the properties of JSC-1A. Finally, this chapter presents the study of particle size distribution of lunar dust simulant JSC-1AF.

Chapter 4 introduces the development of NU-LHT-2M and geotechnical characterization of NU-LHT-2M and compares its geotechnical properties to those of lunar soil and other lunar soil simulants.

Chapter 5 includes a detailed description of the development of GRC-3 and initial characterization of GRC-3 and compares its index properties to those of lunar soil and other lunar soil simulants.

Chapter 6 provides general conclusions and recommendations for further work.

CHAPTER 2 LITERATURE REVIEW

2.1 LUNAR ENVIRONMENT

The Moon is Earth's sole natural satellite and nearest large celestial body. Beyond Earth, the Moon is the only body in space that humans set foot and has been systematically sampled. It has become clear that the Moon holds keys to understanding the origin of Earth and the solar system despite the fact that many questions remain about its composition, structure, and history. The differences between the Earth and Moon appear clearly in comparisons of their physical characteristics (refer to Table 2.1). Some of the differences, such as gravity and escape velocity, provide unique opportunities for using the lunar environment and its resources in future space exploration. Despite all these differences, there are strong bonds between the Earth and Moon. Tidal resonance in the Earth-Moon system locks the Moon's rotation, so the nearside face of the Moon always faces toward Earth while the farside face always hides from the Earth. The moon has been slowly retreating from the Earth because the Permian Triassic boundary and the energy have been dissipating.

“On the moon the most obvious environmental factors that concern people are extreme temperature fluctuations, low gravity, and the virtual absence of any atmosphere. Other environmental factors are not so evident” (Vaniman et al., 1991b). Among all these factors, ionizing radiation is the most important.

Table 2.1 Properties of Moon and the Earth-Moon system (Vaniman et al., 1991b)

Property	Moon	Earth	Approximate ratio (Moon to Earth)
Mean distance from Earth (orbital radius)	384,400 km	--	--
Inclination of equator to ecliptic plane (Earth's orbital plane)	1.53°	23.45°	--
Inclination of equator to body's own orbital plane (obliquity to orbit)	6.68°	23.45°	--
Inclination of orbit to Earth's Equator	18.28°-28.58°	--	--
Eccentricity of orbit around Earth	0.0549	--	--
Recession rate from Earth	3.8 cm/year	--	--
Sidereal rotation time	27.322 days	23.9345 hr	--
Equatorial radius	1,738 km	6,378 km	1 : 4
Surface area	37,900,000 km ²	510,066,000 km ² (land area, 148,000,000 km ²)	1 : 14
Flattening	0.0005	0.0034	1: 6.8
Mass	0.0735×10^{24} kg	5.976×10^{24} kg	1 : 81
Mean density	3.34 g/cm ³	5.52 g/cm ³	1 : 1.7
Mean surface gravity	162 cm/sec ²	980 cm/sec ²	1 : 6
Escape velocity at equator	2.38 km/sec	11.2 km/sec	1 : 5
Mean surface temperature	day, 380 K (224 °F, 107 °C); night, 120 K (-244 °F, -153 °C)	288 K (59 °F, 15 °C)	--
Temperature extremes	396 K (253 °F, 123 °C) to 40 K (-388 °F, -233 °C)	331 K (136 °F, 58 °C) to 184 K (-128 °F, -89 °C)	--
Atmosphere	3×10^{-15} bar	1 bar	1 : 300 trillion

Atmospheric molecular density	day, 10^4 molecules/cm ³ ; night, 2×10^5 molecules/cm ³	2.5×10^{19} molecules/cm ³ (at standard temperature and pressure)	about 1 : 100 trillion
Moment of inertia	$0.395 I/MR^2$	$0.3315 I/MR^2$	1 : 0.84
Average heat flow	29 mW/m ²	63 mW/m ²	1 : 2.2
Seismic Energy	2×10^{10} J/yr	$10^5 - 10^{18}$ J/yr	
Magnetic field	0 (small paleofield)	24-56 A/m	

Lunar surface temperatures increase about 280 K from just before lunar dawn to lunar noon. The temperature at lunar noon varies about the year because of varying distance from the sun. The noon temperature increases about 6 K from aphelion to perihelion (Langseth et al., 1973). Because the Moon's axis is nearly perpendicular to the plane of the ecliptic, sunlight is always horizontal at the lunar poles, and certain areas, such as crater bottoms, exist in perpetual shadow. Under these conditions the surface may be relatively constant and as low as 40 K (−388 °F, −233 °C). Scientists have debated whether lunar polar ice exists over decades. The Lunar Prospector spacecraft, which carried a neutron spectrometer to investigate the composition of the regolith within about a meter (three feet) of the surface, gave clear indications of light-element concentrations at both poles, interpreted as proof of excess hydrogen atoms. The observed hydrogen signature may represent the theoretically predicted deposits of water ice. A high priority for future lunar exploration is to send an autonomous robotic rover into a dark polar region to confirm the putative ice deposits, find out the form of the ice if it exists, and begin assessing its possible utility. If lunar ice can be mined economically, it can serve as a source of rocket propellants when split into its hydrogen and oxygen components. From

a longer-term perspective, however, the ice would better be regarded as a limited, recyclable resource for life support (in the form of drinking water and perhaps breathable oxygen). Discovery of volatile substances anywhere on the Moon would be important both scientifically and for potential human habitation because all known lunar rocks are totally dry (Burke, 2009). Similarly, there may be continuous sunlight at the poles, where solar collector tracking the Sun from a high peak could provide essentially uninterrupted heat and electric power.

It is a requirement for astronauts to wear self-contained spacesuits to overcome the extreme lunar temperatures and the lack of air. Fortunately, due to the low lunar gravity, the mobility on the Moon with bulky awkward spacesuits was not much different from mobility on Earth without a suit. The Apollo 11 astronauts remarked that “the lunar gravity field ... has differing effects on Earth-learned skills. Although the gravitational pull on the Moon is known to be one-sixth of the gravitational pull on the Earth, objects seem to weigh approximately one-tenth of their earth weight. [Objects are] easy to handle in the reduced lunar atmosphere and gravitational field. Once moving, objects continue moving, although their movements appear to be significantly slower in the lunar environment” (Aldrin et al., 1969). The Apollo 12 astronauts stated that the characteristic “loping” gait seen in all the films of astronauts on the lunar surface was the most natural way to move; heel-to-toe “Earth” walking was more difficult and energy-consuming in the reduced lunar gravity. Energy consumption by the astronauts working on the lunar surface was high (about 1 MJ/hr) but not excessive (Bean et al., 1970).

Besides low gravity, the astronauts experienced difficulties in visibility due to the harsh sunlight without atmospheric filtering. “Walking in the up-sun direction posed no problem, although the light was very bright with the sun shining directly into the visor. While walking in the down-sun direction, most objects were visible, but the contrast was washed out. Varying shapes, sizes, and glints were more easily identified in the cross-sun directions” (Aldrin et al., 1969). In summary, the combination of low gravity, awkward suit mobility, and harsh sunlight without atmospheric filtering leads to significant disorientation in the unfamiliar lunar terrain. Spacesuit improvements and longer periods for acclimatization may improve this situation for future astronauts (Vaniman et al., 1991b).

The Moon is indeed an alien environment. Two very different terrains, the highlands and the maria, exist on the Moon (refer to Figure 2.1). Physically, the highlands are rough and intensely cratered while the maria are relatively smooth. High-velocity impacts and volcanism have controlled the moon’s terrain. The consequences of largest scale impacts are the ancient basins, which extend hundreds of kilometers across. The smaller scale impacts generated the craters ranging from the diameter of tens of kilometers to microscopic size (refer to Figure 2.2). Long and deep channels (rilles) produced by volcanic activities are shown in Figure 2.3.

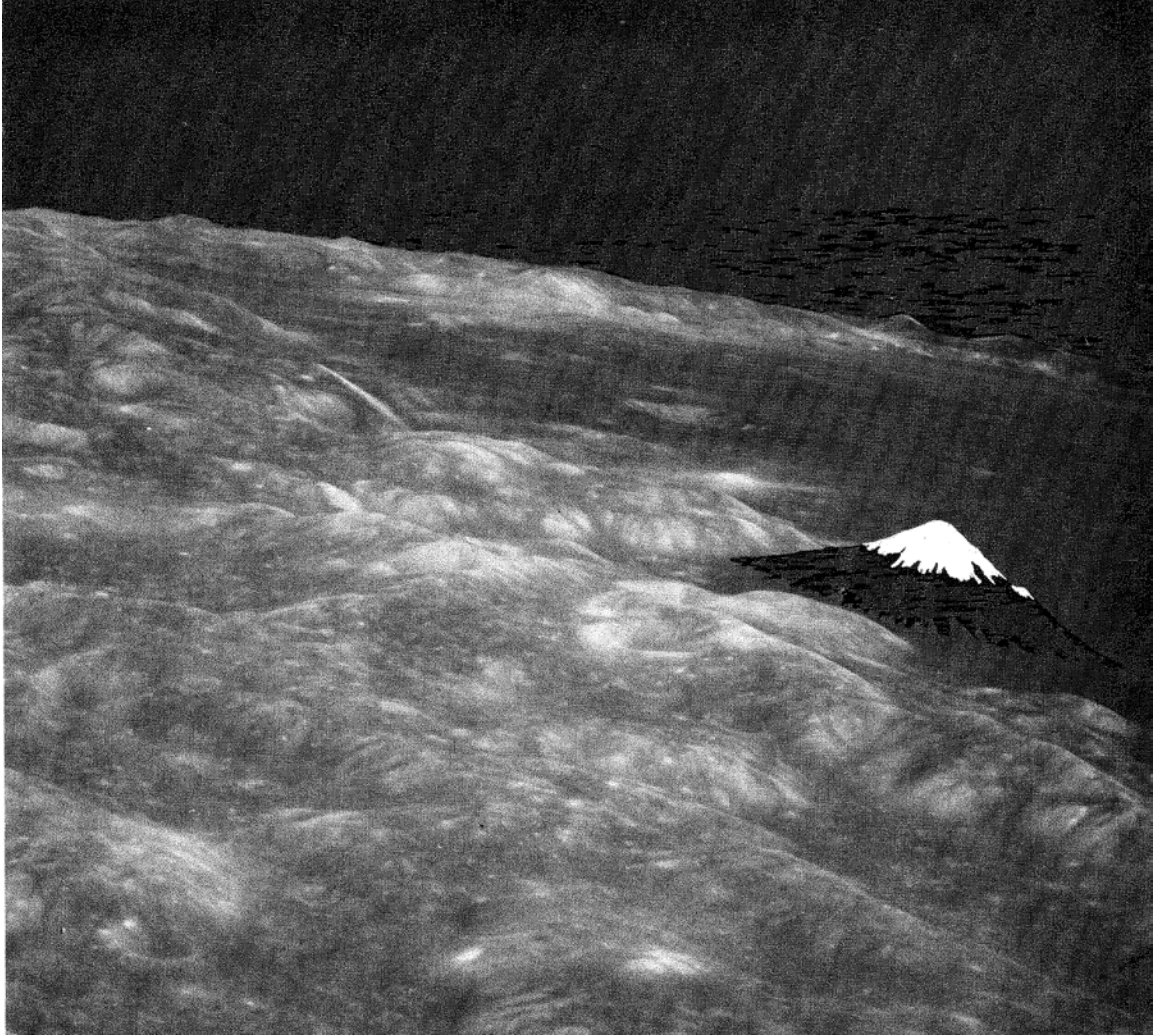


Figure 2.1 A view from orbit of the sharp terrain differences between mare and highland regions on the Moon. This is an oblique view of the rim of Mare Crisium. Mount Fuji, 3776 m high, has been drawn in scale (Vaniman et al., 1991b)



Figure 2.2 Craters



Figure 2.3 Rilles

2.2 LUNAR REGOLITH

Regolith has been defined as “a general term for the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land overlies or covers bedrock. It includes rock debris of all kinds, [including] volcanic ash...” (Bates and Jackson, 1980). Entire lunar surface, except perhaps on some very steep-sided crater walls and lava channels, is covered with several meters to tens of meters of loose regolith. The

lunar regolith is composed of five basic particle types: mineral fragments, crystalline rock fragments, breccias fragments, glasses of various kinds, and agglutinates. The regolith developed on the airless, lifeless Moon are produced from the continuous impact of large and small meteoroids and the steady bombardment of the lunar surface by charged atomic particles from the sun and the stars.

The lunar regolith is very important to understanding of the Moon and the space environment around it. The regolith is the source of virtually all our information about the Moon. All direct measurements of physical and chemical properties of lunar material have been made on the samples, both rocks and soils, collected from the regolith (McKay et al., 1991). Only the regolith layer has been conducted experiments by the astronauts on the Moon and by remotely monitored from the earth. Finally, because of its surficial, unconsolidated, and fine-grained nature, the regolith will likely be the raw material used for permanent lunar bases construction, mining, road building, radiation protection and resource extraction for oxygen, silicon, iron, aluminum, and titanium.

2.2.1 Formation of the Lunar Regolith

On the airless, lifeless Moon, there were no familiar terrestrial geologic processes of chemical weathering, running water, wind and glaciations. The regolith developed on the Moon is produced by uniquely different processes – the continuous impacts by meteorites and micrometeorites and the steady bombardment of the lunar surface by charged atomic particles from the sun and stars. The regolith results from a two stage process (McKay et al., 1991). During the early stage, both large and small impacts can penetrate the relatively thin regolith and excavate the fresh exposed bedrock. As more

meteors and meteorites impact the surface, the regolith layer builds up quickly. Once the regolith layers gets to a meter or more thick, only the larger impacts penetrate the regolith and yield new bedrock. In this later stage, the small impacts only cause the regolith to be churned and pulverized into smaller particles, and the regolith thickness increases more slowly. With these constant bombardments, the lunar regolith is constantly and gradually evolving. At any location and time, the combination of destructive and constructive mechanisms determines the nature and history of the regolith. The destructive mechanism means the excavation of existing regolith by impact craters. The constructive mechanism refers to the addition of layers of new material that is excavated from either newer or distant impact craters (McKay et al., 1991). In addition to the meteorite impacts, the particle irradiation and sputtering via solar wind, landslides various degrees, electrostatic particle transportation, and volcanic activity give minor influence on the formation of the lunar regolith (Oravec, 2009). In general, the thicker the regolith and the smaller the particle size, the older the lunar surface is. It is agreed that the regolith is generally about 4 to 5 meters thick in the mare regions but may average about 10 to 15 meters in older regions. Beneath this true regolith exists a layer called the megaregolith. The megaregolith is much thicker than the finely fractured lunar regolith and generally consists of fractured bedrock and large scale-ejecta typically larger than 1 meter. Currently the properties, characteristics, and behavior of the megaregolith layer are not well understood (Oravec, 2009). Figure 2.4 shows the upper crust of the Moon.

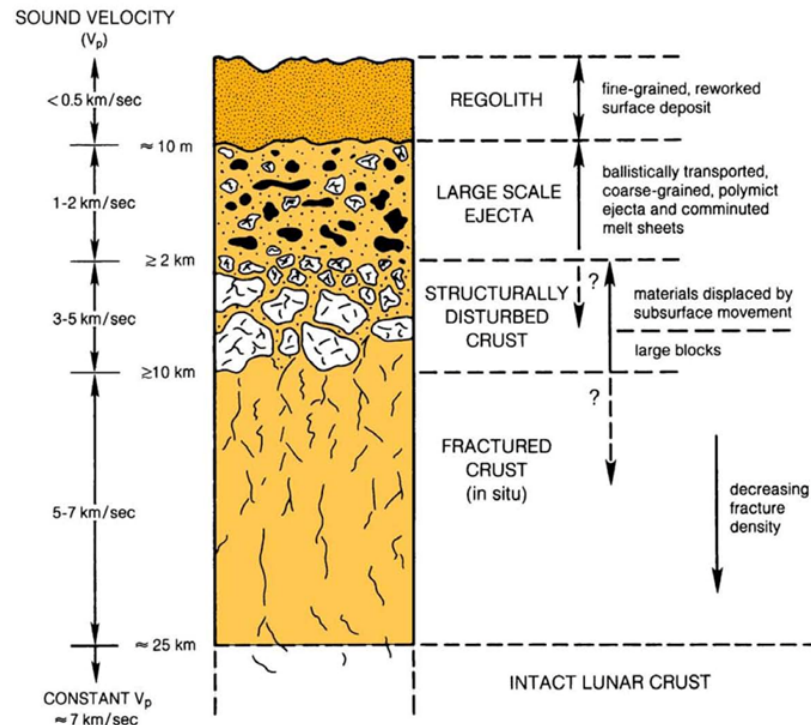


Figure 2.4 The upper crust of the Moon (Kring, 2006)

2.2.2 Lunar Samples

The principal source of data about the regolith is, of course, the samples returned by both manned Apollo missions and unmanned Luna missions to the moon. The lunar meteorites discovered on the Earth also attribute the data source about the regolith. All these three sources consist of the lunar sample inventory on Earth. The first and most significant are the Apollo samples, 381.7 kg of soil and rock fragments collected from the six Apollo landings including Apollo 11, 12, 14, 15, 16, and 17 (Vaniman et al., 1991a). Scott (1975) stated that “The Apollo lunar landing missions provided the first opportunity for direct collection of data relating to the physical characteristics and mechanical behavior of the surface materials of an extraterrestrial body by other than remote means”. Each mission some Apollo samples were packed in aluminum boxes designed to seal and

maintain the vacuum of the lunar surface environment during the trip to Earth and the Lunar Receiving Laboratory (LRL). However, some boxes did not maintain that low pressure for various reasons. After first mission, the Apollo astronauts also packed other samples in various closed but unsealed bags. According to Vaniman et al. (1991a), Samples in the leaking boxes and unsealed bags experienced limited exposure to the atmosphere of the Lunar module (LM) and command module (CM) as the containers underwent two or more decompression / compression cycles during the several days between their removal from the lunar surface and splashdown in the Pacific Ocean. At present the lunar samples are under the curation of LRL at the Johnson Space Center (JSC) in Houston, Texas. These samples are kept in the appropriate storage containers filled with nitrogen to protect further chemical alteration and contamination and are viewed and processed in glove boxes. The Lunar Sample Curator maintains thorough documents, both paper and electronic, on any activity involving the returned lunar materials. The second source of lunar samples is from USSR Luna missions 15, 20, and 24, which collected a total of 321 g soil and small rock fragments by drilling 35, 27, and 160 cm into the surface. These first two sources provide samples that can be imperative to known locations on the moon (Figure 1.3). Lunar meteorites collected on the Antarctic ice cap are the third source of lunar samples for study on Earth. Chemical studies of these meteorites have proved that their origin is the Moon, but from other locations than the nine sites sampled by the Apollo and Luna missions. A total of 10 meteorites have been recovered since the first recovery in 1979. "It is thought that the meteorites were blasted off the Moon and sent to Earth by large crater-forming impacts that took place thousands or possibly millions of years ago" (Vaniman et al., 1991a).

Apollo Soil Samples

Based on the collection techniques and/or types of equipment used, the Apollo samples can be categorized into: contingency sample, bulk sample, documented sample, selected sample, rake sample, and cores (Vaniman et al., 1991a). Contingency samples were collected at the first four Apollo landing sites by the first astronaut to set foot onto the lunar surface and scoop at several places with the contingency sampler. The contingency sampler comprised a combined scoop and bag on the end of a rod that allowed it to be quickly swept through the uppermost few centimeters of the lunar surface. Then the bag was removed from the sampler and stored in a pocket of astronaut's suit. These contingency samples were taken to ensure the return of some lunar material from the site if the surface exploration had to be terminated early. The majority of the contingency samples consisted of the loose, fine fraction of the lunar regolith. However, a few small rocks (generally smaller than 6.5cm) were present in the contingency sample. These rocks and fines of the sample only represented a small area of the lunar surface near the Apollo landing site.

During Apollo 11 mission, the astronaut also collected a total of 38.3 kg bulk sample from 22 or 23 locations a few meters northwest and west of LM. These small rocks and fine-grained regolith were placed into one of the two Apollo Lunar Sample Return Containers (ALSRC) that remained on the Modularized Equipment Storage Assembly (MESA) of the LM (Vaniman et al., 1991a). Johnson et al. (1995) stated that the bulk sample constituted highly disturbed soil samples which did not preserve stratigraphy or furnish a reasonable basis for determining bulk density of in-situ lunar soil.

Documented samples comprised of many rock and fine-grained regolith samples that were completely documented with down-sun and cross-sun photographs of the undisturbed area before collecting the sample and a down-sun photograph of the area after the sample was removed. Each sample was collected and placed in a numbered sample bag. The reflectivity of the sample before handling and packaging were measured by placing the gnomon within the area photographed. The “before” photographs presented the relationship of a sample and its surroundings before the surface was disturbed by the astronaut activity. The “after” photographs showed the influences of collection activity on the surface characteristics and provided the support for the identification of the collected sample (Vaniman et al., 1991a). By comparing the rock shape and shadow patterns recorded in the “before” photographs with the shape and shadows observed, the depth of burial and lunar surface orientation for many documented rock samples were determined by the Lunar Sample Preliminary Examination Team (LSPET). These rock orientations were necessary to determine the directions of micrometeoroid impacts and radiation effects on the surface samples.

Selected samples were collected by the astronaut teams without the full set of photographs required to document the sample in its lunar setting. It consisted of both many samples of rock and fine-grained regolith. Each “selected” sample was placed in a numbered bag with the written documentation of observations made by astronauts. Although these samples lacked the thorough investigation of documented samples, the astronauts could work independently while collecting a larger number and a wider variety of lunar samples.

Rake samples as described in Vaniman et al. (1991a) included a larger portion of rock material than soil material. During Apollo 15, 16, and 17 missions, the astronauts used the lunar sampling rake to collect the rocks larger than 1 centimeter, which were distributed through the upper few centimeters of the fine-grained regolith, and remain the finer material on the surface (refer to Figure 2.5). After the rock samples were placed in the individual bags, the astronauts also added one or more scoops of the fine-grained regolith taken adjacent to the rake sample location into the corresponding rock sample bags.



Figure 2.5 Lunar sampling rake (Kring, 2006)

Cores provided the only dependable information about the near-surface texture and stratigraphy of the lunar regolith. Hence, they are extremely valuable though they only occupied 5.2 percent by mass of the total returned lunar samples (Vaniman et al., 1991a). They also provided the information about the bulk and relative density of the soil

as a function of location and depth in the regolith. These samples were needed to evaluate the Moon's catering history, a record of solar activity and cosmic-ray flux, and structure of the lunar regolith. During Apollo 11, 12, 14, 15, 16, and 17 missions, a total of 21 core tubes were driven into the lunar regolith, pulled out and then returned to the Earth (Johnson et al., 1995). Ten were single length and 11 were double length. Depths of regolith sampled by coring range from 10 cm on Apollo 11 to 298.6 cm on Apollo 17 (Mckay et al., 1991). Drive tubes used in the first three missions were 2 cm in diameter and capable holding a core 31.6 cm long while improved tubes used in the last three missions were 4 cm in diameter and capable holding a core 34.3 cm in length (Vaniman et al., 1991a). The Apollo astronauts collected the first cores from lunar regolith by hammering the hollow drive tubes into the soil. These drive tubes provided little indication of the regolith sampled more deeply at other Apollo and Luna landing sites because of their short length (about 30 cm) and the incomplete sections they secured. A double drive-tube core sample, collected at the Apollo 12 site on the rim of a 10-m-diameter crater, gave the first clear indication that lunar regolith is layered (Mckay et al., 1991). Figure 2.6 shows an Apollo 12 astronaut driving a core tube into the lunar surface. The earlier Apollo core tubes, used during Apollo 11, 12 and 14 missions, were thick-walled by terrestrial standards and thus produced significant disturbance of soil during sampling (Carrier et al., 1971, Johnson et al., 1995). The true depths beneath the lunar surface were determined by driving test core tubes into a simulated lunar soil (Carrier et al., 1971, Johnson et al., 1995). Thin-walled aluminum core tubes started to be used from Apollo 15 to 17 missions. These tubes could be used individually or connected together to form double core tubes. A flat disk-like device termed a "keeper" which had the same

diameter as the inside the top end of the tube and pushed down to the top of the sample to keep it in place. Upon removal of the tube from the ground, the bottom end was covered with a Teflon cap (Oravec, 2009). These core tubes highly reduced the disturbance of soil during sampling, increased the size and amount of sample received, and created an easier sampling method for the astronauts (Costes et al., 1972). Experience with driving core tubes varied for each different location and missions. Driving the core tubes was reported to be easier during Apollo 11 and 12 missions than in Apollo 14 mission where the core tubes could only be driven to shallow depths. Observations from the core tubes of Apollo 17 missions revealed that the lower core tubes had higher density than in the upper tube. Mitchell et al. (1973) concluded that the lunar soil density generally increases with increasing depth. The same was found to be true for Apollo 15 and 16 core tube samples (Mitchell et al., 1973). In general, the core tubes with the larger diameter and thinner walled produced much less disturbed soil samples and more reliable source for measurements of in-situ bulk density.

In addition, a battery-powered rotary drill core tubes were drilled into the deeper layers of the lunar regolith at one point in Apollo 15, 16, and 17 missions. More than 4 kg of rotary drill core tube samples have been collected, from depths of up to 3 m.

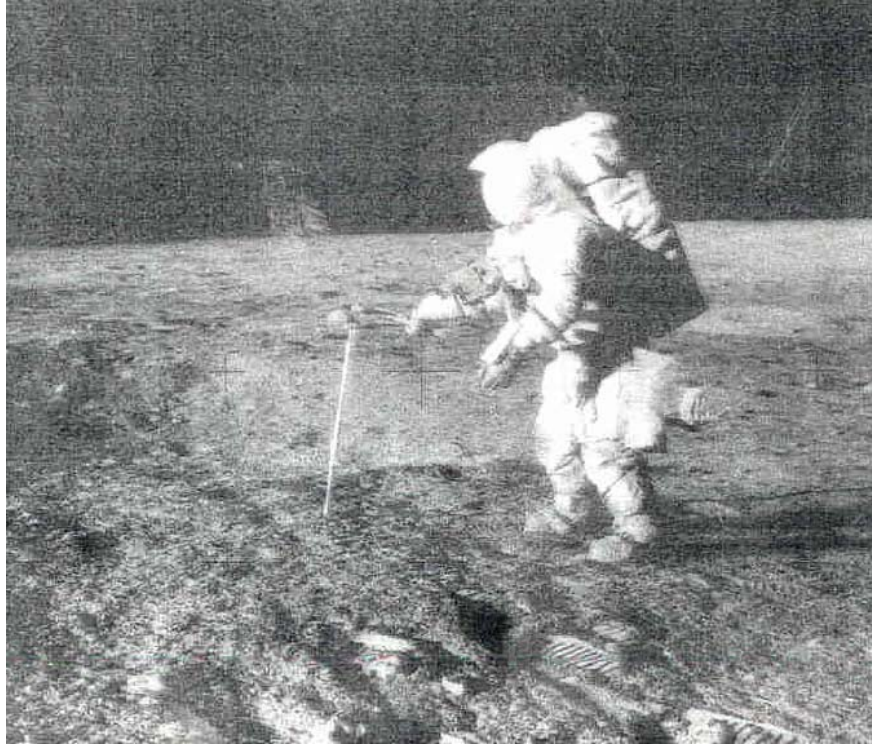


Figure 2.6 Apollo 12 astronaut driving a core tube into the lunar surface (credit NASA)

2.3 GEOTECHNICAL PROPERTIES OF LUNAR REGOLITH

The knowledge of geotechnical properties of the soil is of fundamental importance because it is the basic for engineering activity aimed at construction of lunar bases and for mineral resource exploration. Fortunately, the ranges of geotechnical properties of lunar materials are less than those that occur in surficial materials on Earth (Carrier et al., 1991). This is due to the three factors. First, no chemical weathering, running water, wind, and glaciations exist on the Moon. These processes tend to yield well-sorted sediments with uniform grain sizes. The primary lunar soil-forming process - meteoroid impact (see Figure 2.7) produces a heterogeneous and well-graded (poorly-sorted) soil. The second factor is the lack of water, clay minerals and organic materials, which produce unusual or “problem” soils on Earth. Third, the variety of minerals in

lunar soil is much less than found on Earth (Carrier et al., 1991). Therefore, the geotechnical properties of lunar soil tend to fall in a relatively narrow range.

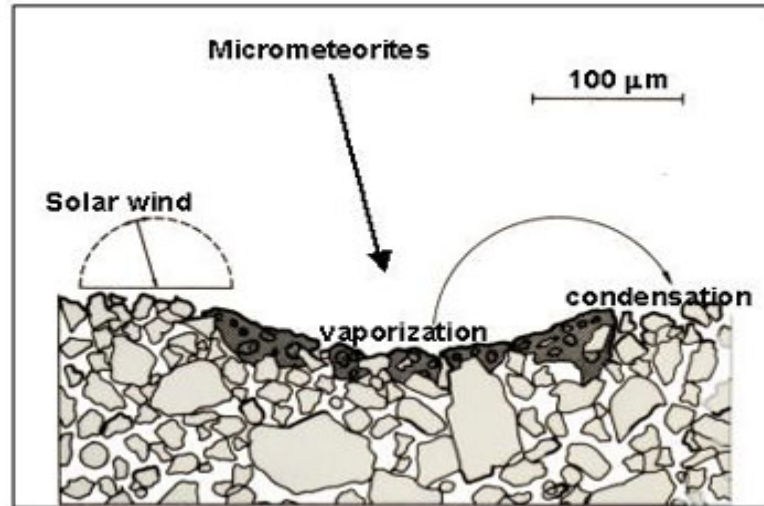


Figure 2.7 Cartoon of lunar space weathering process (credit NASA)

This section presents the geotechnical properties of lunar soils measured in situ by robots and astronauts, in the laboratory on returned samples, and by remote sensing from the Earth's surface and from lunar orbit. The chemical and mineral composition of the lunar soil will not be discussed in this dissertation since they are not pertinent to engineering studies. The chemical properties of lunar soil can be found in Haskin and Warren (1991) while the mineral properties of lunar soil can be found in Papike et al. (1991).

2.3.1 Particle Size Distribution

The particle size distribution is the most important geotechnical property which influences the strength and compressibility of the material, as well as its optical, thermal, and seismic properties (Carrier, 1973, Carrier et al., 1991). The particle size distribution is also related to the origin and mode of deposition of a soil (Carrier, 1973, Carrier et al., 1991). Tucker (1981) stated that particle size analyses of terrestrial clastic sediments, which are composed of broken fragments from preexisting rocks and minerals that have been transported some distance, are the basic descriptive element for any clastic material.

Carrier (2003) conducted a complete review on the particle size distribution of nearly 350 lunar samples measured by numerous investigations. These samples were taken in the vicinity of seven landing sites on the Moon: Apollo 11, 12, 14, 15, 17, and Luna 24. The results of Carrier's study were shown in Figure 2.8. In order to avoid clutter, the data points in Figure 2.8 have been plotted without the customary connecting lines. There are approximately 4,500 points in the Figure 2.8; roughly 90% of the data are from compilation by Graf (1993), and the remaining data are from the other sources: Duke et al. (1970a), Frondel et al. (1970), Hapke et al. (1970), Frondel et al. (1971), Heywood (1971), King et al. (1971), Lindsay (1971), LSPET (1971), Quaide et al. (1971), Sellers et al. (1971), Carusi et al. (1972), Clanton et al. (1972), King et al. (1972), LSPET (1972), McKay et al. (1972), Basu et al. (2001), as well as files sequestered in the Carrier's files (Carrier, 2003). The middle curve is the average particle size distribution of nearly 350 samples; the left-hand and right-hand curves show average ± 1 standard deviation. On average, it contains approximately 2% coarse sand (2.0 to 4.75 mm), 14% medium sand

(0.425 to 2.0 mm), 33% fine sand (0.074 to 0.425 mm), and 51% silt. Approximately 68% of the data points fall within the bounds defined by the left-hand and right-hand curves (Carrier, 2003).

As seen in Figure 2.8, the shape of the particle size distribution appears to be symmetrical; that is, the two halves of the “reverse-S” curve are very similar. Carrier (2003) determined the average graphic skewness to be -0.01 and the average graphic kurtosis to 1.07. These parameters imply that the lunar soil particle size distribution is nearly perfectly log-normal. That is, a plot of the logarithm of the particle size on probability graph paper is practically a straight line (Carrier, 2005).

The majority of the lunar soil particles fall in a fairly narrow range of particle distribution as seen in Figure 2.8. This is due to the meteorite impact, which is the primary lunar soil formation process (Carrier, 1973). In general, the lunar soil is a well-graded (or poorly sorted) silty sand to sandy silt, with approximately half the soil particle by weight irresolvable with the unaided eye (SW-SM to ML in the Unified Soil Classification System). The median particle size is 40 to 130 μm , with an average of 70 μm . There is roughly 10% to 20% of the lunar soil smaller than 20 μm and a thin layer of dust which adheres electrostatically to everything that comes in contact with the soil: spacesuits, tools, equipment and lenses (Carrier et al., 1991)

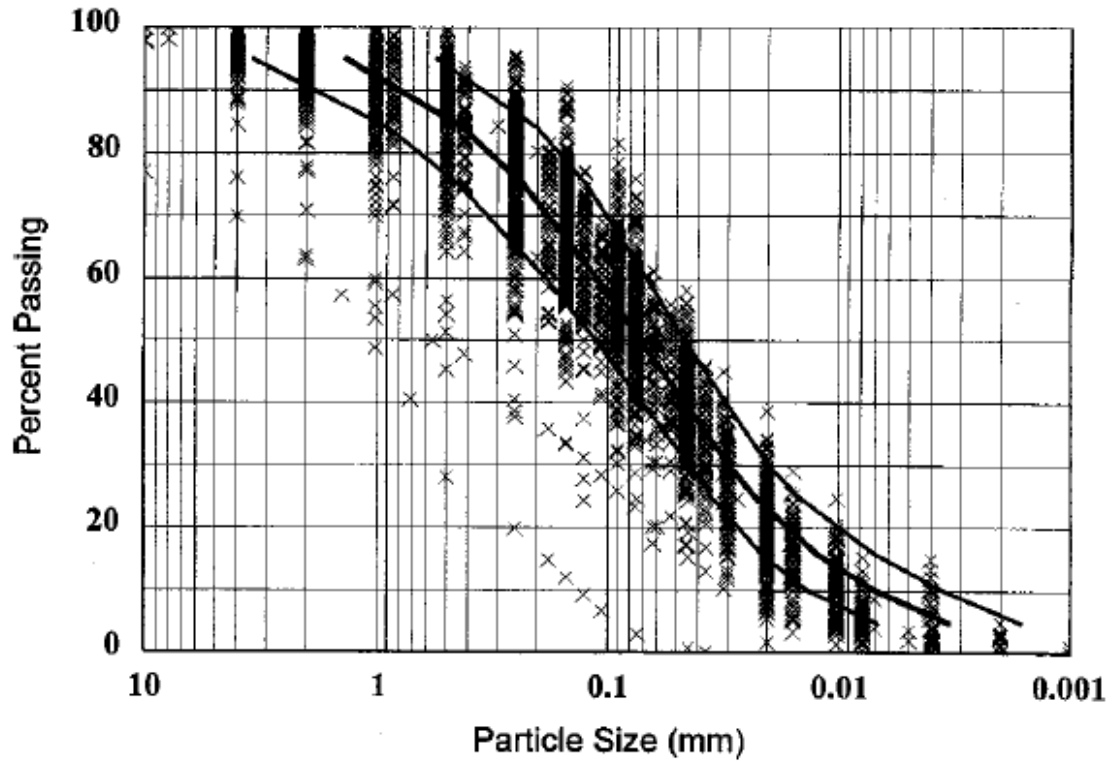


Figure 2.8 Geotechnical particle size distribution of lunar soils (Carrier, 2003)

Sample Sieving By the Investigator

The lunar particle size distribution data have been primarily determined by means of sieving, which is generally effective for particle sizes greater than about 10 μm (Carrier et al., 1991). A few investigators have also used sedimentation columns, Coulter electronic counters, computer-coupled television optical microscopes, and scanning electron microscopes for finer size fractions (Carrier, 1973). Various sieving techniques have been employed by different investigators: dry; dry with brushing; dry with sonic sifter; wet (freon) with vibration; wet (methanol) with sonic sifter; wet (acetone) with vibration (Carrier, 1973).

The lunar soils grain size catalog by Graf (1993) included 287 particle size analyses from 143 different lunar samples collected during the Apollo and Luna missions. Graf (1993) stated that “nearly every sample issued to a principal investigator (PI) has been prescreened by the curator with a dry sieve; the soil issued is $< 1\text{mm}$; samples from Apollo 14, 15, 16, and 17 missions were sieved into $> 1\text{ cm}$, 4- to 10-mm, 2- to 4-mm, 1- to 2-mm, and $< 1\text{ mm}$ fractions”. The size $> 1\text{ mm}$ were usually analyzed by the curator with a large sample. A smaller sample was sieved by the sample PI for sizes ranging from 1 mm to 20 μm . A still smaller sample, whose sizes smaller than 20 μm , was often optically analyzed by the sample PI. The range of lunar size data included in Graf’s catalog is from 10 mm to 1 μm . For at least two lunar soils, approximately 1 percent of the soil particles were smaller than 1 μm . Using the graphic methods, the data were normalized to 99 percent held at 1 μm . Whenever possible, the sizes of lunar soils range from 10 mm to 1 μm . These particle size analyses were conducted on the exceptionally small sample size, typically 0.1 to 0.5 g. There are concerns expressed in the literature that these subsamples were not always representative of the parent samples.

According to Graf (1993), most of the sieve tests were done at two laboratories: one is at the University of Houston with Butler and King et al.; the other is at NASA-JSC with Heiken, McKay, and Fruland et al. The following sample sieving procedure is from Butler and King (1974).

“Grain size-frequency distributions of 72 samples of lunar fines have been completed by sieving with an Allen Bradley sonic sifter and precision sieves; all sieves have square apertures. From 841 to 37 microns the sieves are woven mesh and from 30 to 10 microns the sieves are electroformed. Relative humidity was controlled in the sieving chamber so as to prevent clumping of the less than 30 micron fraction and the “thumping” action was minimized to preserve the delicate agglutinates. Visual

inspections under binocular microscopes did not reveal clumping of the finer fractions. Weight of sample retained on each of 14 sieves and the pan fraction was measured to the nearest 0.0001 g and grain size statistics were calculated according to the method of Folk (1968).”

The procedures performed at NASA-JSC are described in McKay, Fruland, and Heiken (1974).

“Methods for size analysis were similar to those previously described (McKay et al., 1972; Heiken et al., 1973). Soils were initially sieved in the Lunar receiving Laboratory at size intervals of > 1 cm, 4 mm, 2 mm and 1 mm. Our allocation, usually .25 g, was sieved at 500, 250, 150, 90, 75, 45, and 20 microns. Below 20 microns the soil was sized by analyzing a dispersed grain mount with a Millipore computer-coupled optical microscope which provided relative numbers of particles in the size intervals 20-16, 16-8, 8-4, 4-2, and 2-1 micron. The number of particles in each size interval as determined by the Millipore system was multiplied by an average particle volume for that size interval to determine the total volume in each size interval. The average particle volume for each size interval was taken as half the sum of the volumes of two spheres having diameters equal to the endpoints of the size interval. The total volume in each size interval was then converted to a vol.% of the sample from 1 to 20 microns. It was assumed that the average particle densities are equal from size interval to size interval so that the vol.% is equal to the wt.%. Finally, the weight percents were normalized to the entire sample by multiplying by the fraction of sample finer than 20 microns and the combined data from sieving and the Millipore system were plotted on probability paper as a cumulative curve. Graphical size parameters as defined by Folk and Ward (1957) were determined from the cumulative curve and Histograms were constructed at 1 ϕ size intervals.”

The particle size distribution of 10084, published by Duke et al. (1970a), is the only Apollo 11 size distribution included in Graf’s lunar soils grain size catalog. That is due to the confusion regarding the size distribution of Apollo soils. Carrier (1973) gave an excellent summary.

“The data for the Apollo 11 samples must be approached with caution. The Lunar Sample Preliminary Examination Team (LSPET) measurements immediately were recognized to be too coarse below approximately 0.1 mm, as a result of improper equipment and insufficient time to perform the analyses in the Lunar Receiving Laboratory (LRL). McKay et al report sieving times of 10 to 20 hours for 0.25-g samples; the LSPET was constrained to sieving 25-g samples in a few minutes. As the samples

were being sieved, it was obvious to the LSPET members that the finer particles were sticking to each other, to coarser particles, and to the sieves. As a result, the grain size distribution curves were biased to the coarser fractions. Conversely, it also was clear that the lunar soil was not nearly so fine-grained as some had predicted.

All other Apollo 11 samples listed are, in fact, subsamples of one large sample: 10084. Furthermore, this sample was passed through a 1-mm sieve in the LRL before distribution to the various investigators. Unfortunately, the weight of the soil coarser than 1 mm was never recorded; thus, it has not been possible to make a direct correction of the investigator data for determination of the lunar-surface grain size distribution. The data from these investigators fall together in a band, except for the sample analyzed by Hapke et al., which is significantly finer than the others. Because of this, the data from Hapke et al. have been neglected in the analysis that follows.

The samples analyzed by Lindsay, which came from core tube 10005, are the only samples besides the LSPET samples that include the plus-millimeter fraction. However, when the submillimeter portion of Lindsay's data is compared with the data from the other investigators, it is found that his distributions are consistently and significantly coarser. A similar comparison of Lindsay's data for Apollo 12 samples reveals the same trend; his distribution curves are always coarser than those of other investigators. It has been concluded that Lindsay's data have suffered from some of the same problems as the LSPET data, although to a lesser degree.

Consequently, we are faced with the fact that a complete grain size distribution is not known for a single Apollo 11 sample.

Nonetheless, indirect corrections of the submillimeter data are possible. For example, Duke et al. corrected their data by including the plus-millimeter portion of the LSPET data. These data indicated that the plus-millimeter fraction was roughly 10 to 12% of the total sample weight.”

In comparison to ASTM standard test method for soil particle size distribution, these methods use exceptionally small sample size and other equipments instead of hydrometer to analyze the finer size fraction. In this case, ASTM standard test method for soil particle size distribution requires at least 500 gram oven-dried test specimen. First the test sample should be washed through No.200 sieve. After oven drying, the coarse fraction of the sample should be analyzed by means of sieving while the fine fraction should be analyzed by using hydrometer.

2.3.2 Particle Shapes

The shapes of individual lunar soil particles are highly variable, ranging from round to extremely angular as shown in Figure 2.9. In general, the lunar soil particles are somewhat elongated and are subangular to angular (Carrier et al., 1991). The parameters of average particle shapes of lunar soil are given in Table 2.2. Elongation is defined as the ratio of the major to intermediate axes of the particle. An average value 1.35 indicates that the lunar particles are somewhat elongated. Volume coefficient is defined as the volume of the cube of the diameter of the circle that encloses the same area as the particle profile. An average value of 0.3 corresponds approximately to a prolate spheroid with a major-to-minor axis ratio of 3 to 1.

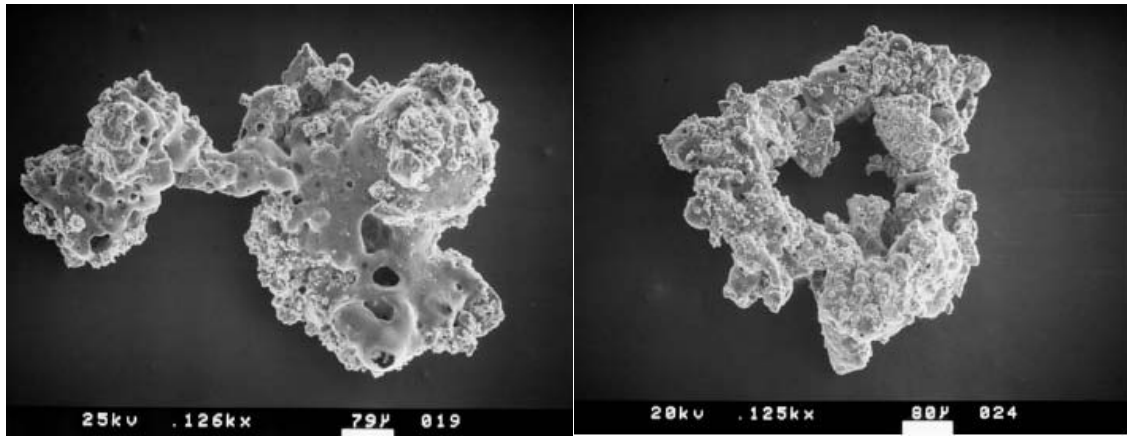


Figure 2.9 Irregular lunar soil particles (credit NASA)

Table 2.2 Average particle shapes of lunar soil (Carrier et al., 1991)

Parameter	Average Value	Description
Elongation	1.35	Somewhat elongated
Aspect ratio	0.55	Slightly-to-medium elongated
Roundness (Silhouette)	0.21	Subangular
Roundness (Direct light)	0.22	Angular
Volume coefficient	0.3	Elongated
Specific surface area	0.5 m ² /g	Irregular, reentrant

Carrier et al. (1991) stated that, the particles tend to pack together with a preferred orientation of the long axes because of the elongation. This effect has been observed in lunar core tubes and laboratory simulations. And because of the preferred orientation, the physical properties of the lunar soil in situ should be anisotropic.

Specific surface area is defined as the surface area of a particle divided by its mass. The average specific surface area of lunar particle is approximately $0.5 \text{ m}^2/\text{g}$. For a typical lunar soil, the surface area is nearly eight times that of equivalent-sized sphere. The relatively large specific surface area indicates that the lunar soil particles have the extremely irregular, often reentrant surfaces (see Figure 2.9). These particles are so irregular that they interlock with each other. Scientists used to wonder why the dry sand like lunar soil appears a cohesive behavior. Now it can be told that the cohesion is due to the mechanical interlocking of the irregular particles (Carrier, 2005). Carrier (2005) stated that “the cohesion (and the frictional shear strength) allowed the astronauts to dig trenches in the lunar surface with smooth, nearly vertical walls” (see Figure 2.10). Because of the high shear strength and low gravity, vertical trenches can be excavated in the lunar surface up to 3 m deep, with a safety factor of 1.5 (Carrier et al., 1991). From the Apollo missions’ results it can be confirmed that the drill core holes can remain open and stable to a depth of at least 3 m.



Figure 2.10 Smooth, nearly vertical walls by a trench (credit NASA)

2.3.3 Specific Gravity

The specific gravity of a soil is defined as the ratio of mass density of soil particles to the mass density of pure water at 4°C. Specific gravity is one of the most important geotechnical parameters. However, compared to other important geotechnical parameters, it has received much less attention in the lunar samples program. Carrier et al. (1973a) attributed it to an understanding unwillingness to commit the relatively large soil samples necessary for standard tests: at least 30 g air comparison pycnometer and 50 g for conventional 500-cm³ water pycnometer. Various techniques have been developed to investigate the specific gravity of lunar soil using much smaller samples.

Specific gravity values of lunar soils and rock fragments are summarized in Table 2.3 and range from 2.3 to greater than 3.2. These values are considerably higher than the typical value of 2.7 for many terrestrial soils. Carrier et al. (1991) recommends a value of 3.1 for general scientific and engineering analyses. This is due to the fact that the lunar

soil exhibits subgranular porosity which exists as voids enclosed within the interior of the lunar soil particles as shown in Figure 2.11. During the specific gravity test, the soil particles are immersed in a fluid to measure the volume that it replaces. Various fluids can be used, including water, air, or helium. The fluid can fill into the intergranular and intragranular voids, but not the subgranular voids. Thus, the average specific gravity of the lunar particles was underestimated. The detailed descriptions of various techniques used in the investigation of specific gravity of lunar soil will be discussed in the following sections.

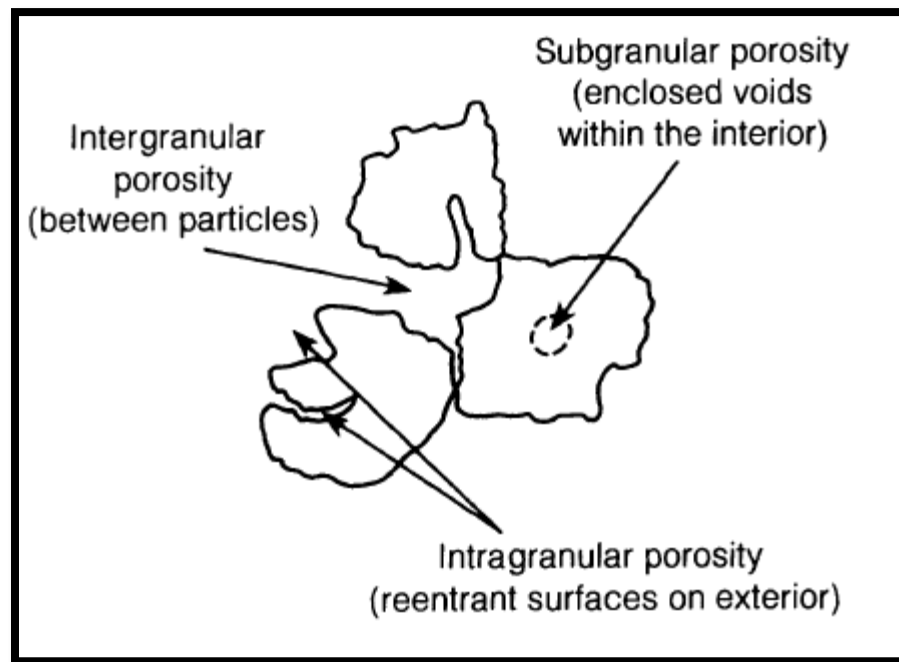


Figure 2.11 Carton displaying different porosities of lunar soil (Carrier et al., 1991)

Table 2.3 Specific gravity of lunar soils and rock fragments (Carrier et al., 1991)

Sample No.	Sample Weight (g)	Specific Gravity, G_s	Test Technique	References
10004 and 10005	49.1	3.1 ¹	Nitrogen pycnometry	Costes et al. (1970a)
10020, 44	5.94	3.25 ²	Water pycnometry	Horai and Winkler (1980)
10065, 23	4.48	3.12 ³	Water pycnometry	Horai and Winkler (1980)
10084	1.5	3.01	Suspension in density gradient	Duke et al. (1970b)
Apollo 12 (unnumbered)	56.9	3.1 ¹	Air pycnometry	Carrier (1970)
12002,85	2.32	3.31 ³	Water pycnometry	Horai and Winkler. (1975)
12029, 8	1.10	2.9	Nitrogen pycnometry	R. F. Scott, (1988)
12057,72		2.9	Unknown	Heywood (1972)
14163,111	0.65	2.9 ± 0.1	Helium pycnometry	Cadenhead et al. (1972)
14163,148	0.97	2.90 ± 0.05	Water pycnometry	Carrier et al. (1973a,b)
14259,3	1.26	2.93 ± 0.05	Water pycnometry	Carrier et al. (1973a,b)
14321,74		3.2 ± 0.1 ³	Helium pycnometry	Cadenhead et al. (1972)
14321,156		3.2 ± 0.1 ³	Helium pycnometry	Cadenhead et al. (1972)
15015,29		3.0 ± 0.1 ³	Helium pycnometry	Cadenhead et al. (1974); Cadenhead and Stetter (1975)
15101,68		3.1 ± 0.1	Helium pycnometry	Cadenhead and Jones (1972)
15601,82	0.96	3.24 ± 0.05	Water pycnometry	Carrier et al. (1973a,b)
70017,77	2.55	3.51 ²	Water pycnometry	Horai and Winkler (1976)
70215,18	4.84	3.44 ²	Water pycnometry	Horai and Winkler (1976)
72395,14	3.66	3.07 ³	Water pycnometry	Horai and Winkler (1976)
77035,44	3.68	3.05 ³	Water pycnometry	Horai and Winkler (1976)

¹ Total soil sample; others were performed on submillimeter fraction.

² Single basalt fragment.

³ Single breccias fragment.

Specific Gravity of Apollo 11 Samples

The first specific gravity test was on a lunar soil fraction, which had been removed from the combined splits of the two core tubes obtained in Apollo 11 mission for sieve analyses (Costes et al., 1970). The test technique is a gas comparison pycnometry. The specific gravity of this sample was determined to be 3.1. This high value indicated that the lunar soil was significantly different from typical terrestrial soils. Costes et al. stated that it may be attributed to the fact that compositional analyses have shown that the lunar soil to be composed mainly by the basic igneous minerals, e.g., plagioclase, olivine, and pyroxene, as well as relatively large amounts of titanium and iron oxides. The LRL preliminary examination team also performed the specific gravity analyses by means of the gas comparison pycnometry on several rocks from contingency sample obtained in Apollo 11 mission. Values from 3.2 to 3.4 were measured, slightly higher than the value obtained for the specific gravity of the soil from core tubes. Costes et al. commented that these values may not truly represent the specific gravity of the rock samples because the volumes of the rocks tested in this type of pycnometer were not large enough to provide accurate results. It was later found that the specific gravities for the individual particle types varied dramatically. Based on an examination of its suspension in a density gradient, which was produced by varying the proportions of a mixture of methylene iodine and dimethyl formamide, Duke et al. (1970b) estimated the mean specific gravity of the submillimeter fraction of lunar particles to be 3.01 and the following values of specific gravity: agglutinate and glass particles: 1.0 to > 3.32 ; basalt particles: > 3.32 ; and breccia particle: 2.9 to 3.1. The range of specific gravity is from 2.2 to greater than 3.32. Compared to the results obtained by Costes et al. (1970), the mean

specific gravity is lower. Duke et al. (1970b) attributed it to the increased amount of glasses in the submillimeter fraction. In 1980, Horai and Winkler determined specific gravities of the lunar samples 10020, 44 and 10065, 25 obtained during Apollo 11 mission from the difference between the sample weights measured in the atmosphere and in the distilled water with known temperature, which was called water pycnometry.

Specific Gravity of Apollo 12 Samples

Using the air pycnometry technique, Carrier (1970) determined the specific gravity of an Apollo 12 sample to be 3.1, which is same as the Apollo 11 samples determined by Costes et al. (1970a). In 1971, Heywood estimated the specific gravity of the lunar sample 12057, 72 to be 2.9 by unknown technique. The specific gravity of lunar sample 12002, 85 was reported to be 3.31 by Horai and Winkler (1975). The technique used in the specific gravity test is water pycnometry. Carrier et al. (1991) also mentioned a specific gravity test result of 2.9 obtained by R. F. Scott using the nitrogen pycnometry.

Specific Gravity of Apollo 14 Samples

Cadenhead et al. (1972) measured a value of 2.9 ± 0.1 on lunar sample 14163, 111 by using helium as part of their gas absorption studies in a classical BET system based on that of Faeth and Willingham (1955). This value agrees exactly the value of 2.90 ± 0.05 obtained by Carrier et al. (1973a) on another subsample of the same parent sample, 14163. Cadenhead et al. (1972) also measured the specific gravity of a fragment from a breccias rock, 14321, and obtained a value of 3.1 ± 0.1 . The helium pycnometry technique will be discussed in detail in the following section.

Instead of a standard conventional 500 cm³ volumetric flask, Carrier et al. (1973a, b) used 3 cm³ and 5 cm³ volumetric flasks to measure the specific gravities of three, 1-g submillimeter Apollo 14 samples. The average specific gravity of the particles in each sample was determined using the conventional water immersion micropycnometry techniques. Carrier et al. stated that the miniaturization required for small lunar samples was found to be practical and produced five reproducible results.

Compared to Apollo 12 and 15 soils, the specific gravities of the Apollo 14 soils were lower. Carrier et al. (1973a) attributed it to that the Apollo 14 (Fra Mauro region) soils contain a higher proportion of agglutinates and breccias and fewer mineral fragments and basalts than the Apollo 12 and Apollo 15 soils.

Specific Gravity of Apollo 15 Samples

Using the non-contaminating helium pycnometry technique, Cadenhead and Jones (1972) determined the specific gravity of lunar sample 15101, 68 to be 3.1 ± 0.1 . By water pycnometry technique Carrier et al. (1973a, b) obtained a value of 3.24 ± 0.05 for another lunar sample: 15601, 82. The latter is a remarkably high value. This is because this particular sample contains more basalts and mineral fragments, about the same proportion of agglutinates, and fewer glasses and breccias than the median Apollo 15 drill stem samples. Through the helium absorption on a modified high vacuum volumetric B.E.T. system, Cadenhead et al. (1974) and Cadenhead and Stetter (1975) also measured the specific gravity of submillimeter Apollo 15 basalt fragment 15015, 29 to be 3.0 ± 0.1 . The following pycnometry procedure is from Cadenhead and Stetter (1975).

“A classical volumetric gas-adsorption apparatus was used to determine the absolute density of the lunar samples by helium displacement. The basic technique for both the construction of the apparatus and the measurement of helium pycnometric densities has been detailed by Faeth and Willingham (1955). Typical sample lots of 0.5-1.0 cc were used. High (< 1 atm) pressures of helium were used in small volume pycnometers to minimize errors. Figure 2.12 illustrates two such glass pycnometers for rock fragments. Pycnometers for fines are relatively easy to design with "dead space" being kept to a minimum. The same is not true of rock fragments, particularly lunar rock fragments, which cannot be crushed. The fragment is placed in the male joint the residual dead space being filled with 16-20-mesh technical quality glass beads. A solid glass plug was then inserted into the female portion of the ground joint and the pycnometer assembled using Apiezon T grease (vapor pressure $\sim 10^{-7}$ torr at 50°C). The charged sample chamber was mounted on the vacuum adsorption apparatus and gently degassed at 45°C at 1×10^{-6} torr for not less than 16 hr. A water bath then was located around the sample and maintained at $25 \pm 0.1^{\circ}\text{C}$ throughout the remainder of the experiment. Ultra high-purity helium was admitted from the high vacuum manifold into the sample chamber. Through a series of compressions and expansions of helium, each time recording the pressure, the volume of the pycnometer, V_{pyc} , was calculated. The pressures were measured with the mercury manometer and a Cenco Universal Cathetometer to a precision of ± 0.04 torr. The data were then programmed and the computer (a CDC 6400) then performed not less than twenty-five calculations of each volume. Using this procedure densities of lunar rock fragments were obtained to better than 3%.”

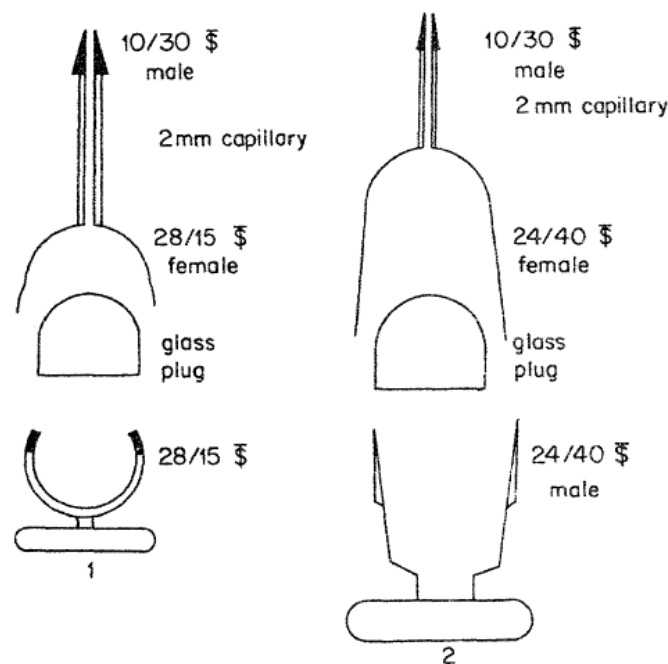


Figure 2.12 Glass pycnometers: 1) constructed for small rock fragments; 2) constructed to receive rock fragment 15015, 29

No specific gravity test is conducted on the Apollo 16 samples.

Specific Gravity of Apollo 17 Samples

Horai and Winkler (1976) measured the specific gravities of four Apollo 17 lunar samples: 70017, 77 (coarse-grained basalt), 70215, 18 (fine-grained basalt), 72395, 14 (breccias), and 77035, 44 (breccias). These samples are regular rectangular parallelepipeds except 70017, 77 which shows some irregularities of the shape due to its coarse-grain size and large porosity. The specific gravities of these samples were determined from the difference between the sample weights in the atmosphere and in distilled water of known temperature.

In comparison to ASTM standard test method for specific gravity of soils, these methods use exceptionally small sample size and small volumetric apparatus. In this case, ASTM standard test method for specific gravity of soils requires using at least 100 gram oven-dried test specimen and testing sample in a volumetric flask with a capacity of at least 100 mL or a stoppered bottle with a capacity of at least 50 mL. Distilled water or demineralized water should be used as the fluid in which soil particles are immersed.

2.3.4 Bulk Density and Porosity

The bulk density, ρ , of soil is defined as the mass of material contained within a given volume. The in situ bulk density is a fundamental property as it influences bearing capacity, slope stability, seismic wave velocity, thermal conductivity, electrical resistivity, and the depth of penetration of ionizing radiation (Carrier et al. 1991). Using the best estimates of the specific gravity of the lunar soil in combination with the best estimates for the bulk density of the lunar soil, the void ratio, which is equal to the volume of the void space between the particles divided by the volume of the “solid” particles, can be determined by the following equation,

$$e = G\rho_w/\rho - 1 \quad (2.1)$$

where G is the specific gravity of the soil, ρ_w is the density of water (1 g/cm³), ρ is the bulk density of the soil, and e is the void ratio of the soil. The void ratio can be used to estimate the degree of packing which is a main factor that determines the physical characteristics of a lunar soil sample. It is convenient in geotechnical engineering to also define another parameter, the porosity, which is the volume of void space between the particles divided by the total volume. Porosity, n , and void ratio are interrelated as

$$n = e/(1 + e) \text{ or } e = n/(1 - n) \quad (2.2)$$

The in situ bulk density has been studied well before the first lunar landing because of the need for data to solve engineering and operational problems. Based on remote sensing, a value of 0.3 g/cm³ was estimated by Jaffe (1964, 1965) while a value of 0.4 g/cm³ was estimated by Halajian (1964). When Surveyor I landed in June 1966,

Christensen et al. (1967) deduced a much higher density of 1.5 g/cm^3 by using records of the interaction between the lunar soil and the spacecraft footpads, combined with analysis of the television images, to determine the particle size distribution. Then Luna 13 landed in December 1966, and gave the first in situ bulk density: 0.8 g/cm^3 (Cherkasov et al., 1968). Carrier et al. (1991) provides a summary of estimated lunar bulk densities as shown in Table 2.4. The measurement of bulk density on returned core samples plays the most important role among various estimating and measuring techniques and is discussed in the following sections.

Measurements of Bulk Density on Returned Core Samples

The Apollo drive core tubes and rotary drill core tubes provide us unambiguous measurements of the in situ bulk density. Nearly 16 kg of drive core tube materials have been collected, using core tubes driven to depths of about 70 cm into the lunar surface; more than 4 kg of rotary drill core tube samples have been collected, from depths of up to 3 m.

Two single drive core tube samples, 10004 and 10005, were recovered on Apollo 11, and densities measured on the returned samples were 1.59 and 1.71 g/cm^3 , respectively. These density values were obtained on a basis of actual sample diameter of 1.97 cm. The internal volume of Apollo drive core tubes actually filled with lunar soil ranged from less than 47 % to greater than 48 %; so there was a problem in determining the original depth of lunar soil at various points in the core tube soil column (Carrier et al., 1971). The Apollo core tubes utilized a bit with an inward flare, opposite in shape to the standard terrestrial samplers. The internal area of the bit decreased from the leading edge

to the neck by a factor of greater than 2. Thus, if the soil were very porous, the shape of the bit would compress the in situ soil as it entered the core tube and cause it to shrink to a higher density. On the other hand, if the soil was densely packed, the shape of the bit would deform the soil and cause it to expand to a lower density. Therefore, Scott et al. (1971) concluded that the in situ bulk density of Apollo cores varied from 0.75 g/cm^3 to greater than 1.75 g/cm^3 .

Two single core tubes and a double (two tubes connected end to end) core tube were recovered during Apollo 12 mission. Based on a sample diameter of 1.97 cm, the measured bulk density on the returned samples ranged from 1.74 to 1.98 g/cm^3 . The Apollo 12 core tubes utilized a more conventional bit shape. However, the wall thickness was still relatively large compared to the internal diameter of the tube. The core samples recovered on Apollo 12 were a considerably improvement over the Apollo 11 samples but were still significantly disturbed. Taking into considerations of the disturbance in terms of the dimensions of the core tubes, the difference between the area of the bit at the cutting edge and the area inside the tube, and the measured bulk densities in the core tubes, Scott et al. (1971) estimated the in situ bulk density at the Apollo 12 landing site to be $1.8 \pm 0.2 \text{ g/cm}^3$. Through the performance of the Apollo 12 core tube on a simulated lunar soil, which is a mixture of League City sand (65%) and kaolinite clay (35%), Carrier et al. (1971) predicted that the lunar surface in situ density fell in the range of 1.7 to 1.9 g/cm^3 . Houston and Mitchell (1971) performed a core tube-sampling study using basaltic silty sand as the lunar regolith simulant and yielded additional estimate of 1.55 to 1.9 g/cm^3 .

Vinogradov (1971) estimated the density of lunar regolith in its natural deposition to be ~ 1.17 (1.20) g/cm^3 from the 101-g rotary drill sample returned by Luna 16. The Apollo 14 missions used the exactly same core tubes as the Apollo 12 tubes. Four core tube samples including two singles and a double were returned on Apollo 14 missions. The bulk densities in the upper and lower halves of the Apollo 14 double are 1.73 and 1.75 g/cm^3 , respectively; the bulk density for the Apollo 14 single is 1.60 g/cm^3 . Through the comparisons of bulk densities, specific gravities, porosities, and core recoveries between Apollo 12 and Apollo 14 core tubes, Carrier et al. (1972a) inferred the in situ bulk density at the Apollo 14 core tubes sites to be 1.45 to 1.6 g/cm^3 .

Carrier et al. (1991) stated that the shapes of the drive core tube bits used on the Apollo 11, 12 and 14 missions not only affected the measurements of the in situ soil density, they also complicated the interpretation of the relationships between density and depth. The depth in an early Apollo core tube sample does not truly correspond to the same depth below the lunar surface. Carrier et al. (1971, 1972a) conducted various laboratory simulations on the Apollo 11, 12 and 14 core tubes to evaluate the depth relationships.

A completely new drive core tube was used on the Apollo 15, 16 and 17. The sample diameter was more than double than the Apollo 11, 12, and 14 core tubes, and the wall thickness is reduced, resulting much less sample disturbance during collection. The comparison between the core tube bits for the different Apollo missions is shown in Figure 2.13. The depth-in-core-tube versus true depth in the regolith for the Apollo 15, 16 and 17 core tube samples is practically one-to-one. Sample recovery with this new core tube approaches 100%. Therefore, samples collected with the new tube yielded very

accurate measurements of the in situ bulk density. The Apollo 15 mission returned five core tube samples: one single and two doubles. Carrier et al. (1972a) calculated the bulk density of the lunar soil at the Apollo 15 site to be from 1.36 to 1.85 g/cm³ based on the samples collected on these new core tubes. These values for the returned samples were probably close to in situ densities. The Apollo 16 mission returned nine core tube samples: one single and four doubles. Mitchell et al. (1972b) estimated the in situ bulk density at the Apollo 16 site to be from 1.40 to 1.80 g/cm³. The Apollo 17 mission returned eight core tube samples: two singles and three doubles. The in situ bulk density at the Apollo 17 site was estimated to vary from 1.40 to 1.80 g/cm³ (Mitchell et al., 1973).

Besides the drive core tube, a rotary drill core tube was used on the Apollo 15, 16 and 17 missions. These three deep drill cores recovered on the Apollo 15, 16, 17 missions to the Moon are among the most valuable of all the returned lunar samples. As shown in Figure 2.13, the diameter of the rotary drill core sample was only slightly larger than that of the Apollo 11-14 core tube samples. However, the thickness of the drill core wall is much less, and the bulk densities of the recovered core samples are believed to reasonably represent the in situ conditions (Carrier et al., 1991). These drill cores are representative of the top 2 to 3 m of the lunar surface. Full scale drill tests similar to the drive tube tests were conducted to determine quantitatively the depth relationships for the drill cores (Carrier et al., 1974). The Apollo 15 drill stem consists of six sections. Each section, when full, contains 39.9 cm of sample, except for the bottom-most, or bit-end, stem which contains 42.5 cm; the total assembled length is 242.0 cm. The bulk densities of Apollo 15 drill cores were found to vary from 1.62 to 1.93 g/cm³. Carrier et al. (1974) stated that the in situ densities are probably $\pm 2\%$ of the sample bulk densities in the stem.

The Apollo 16 drill stem also consists of six sections, again with a total assembled length of 242.0 cm. The in situ bulk densities on the Apollo 16 landing site varied from 1.47 to 1.75 g/cm³ (Carrier et al. 1974). The Apollo 17 drill stem was longer than the two earlier stems, consisting of eight sections with a total assembled length of 321.8 cm. Carrier et al. (1974) found that the bulk densities in the stem varied from 1.74 to 1.99 g/cm³. They stated that with nearly 100% core recovery the original bulk densities in the stem were probably very close to the in situ values.

The returned core samples from the drive core tubes and from the rotary drill core tubes recovered on the Apollo 15, 16, and 17 missions provide the most accurate measurement of in situ bulk density of lunar soil at different discrete locations. Generally speaking, the density of the lunar soils tends to from the surface to a depth of about 70 cm; below that depth, the density profile is erratic (Carrier et al., 1991).

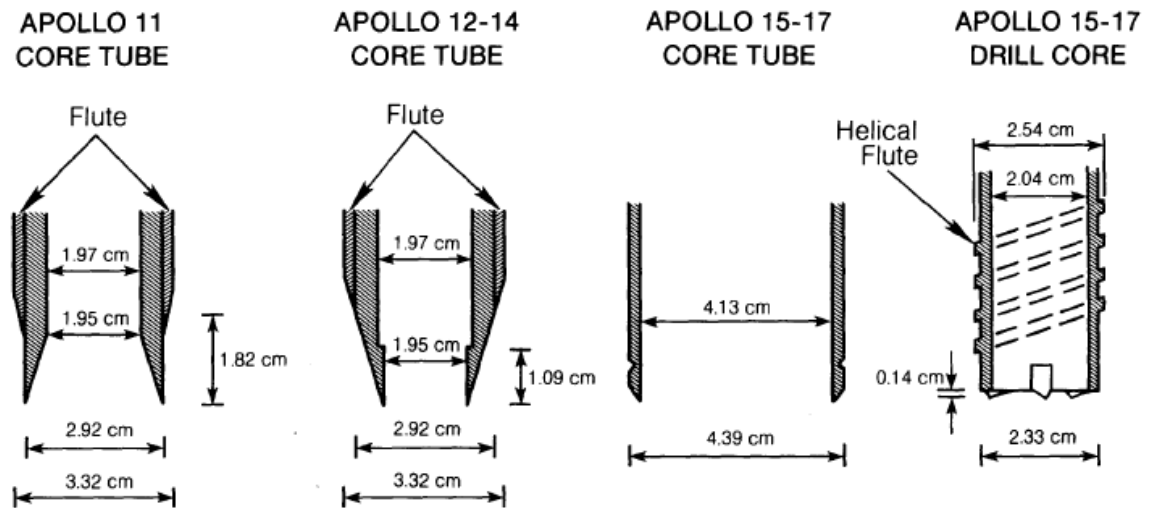


Figure 2.13 Comparison of different Apollo missions core tube sampling bits (Carrier et al., 1991)

Table 2.4 Estimates of lunar soil in situ bulk density

Source	Bulk Density (g/cm ³)	Investigator
Remote Sensing	0.3	Jaffe (1964, 1965)
	0.4	Halajian (1964)
Robotic Measurements on Surface		
Surveyor 1	1.5	Christensen et al. (1967)
Luna 13	0.8	Cherkasov et al. (1968)
Surveyor 1, 3, and 7	1.5	Scott and Roberson (1967, 1968 a,b); Scott (1968)
Surveyor	1.1 at surface; 1.6 at 5 cm	Jaffe (1969)
Lunokhod 1 / Luna 16	1.5 - 1.7	Leonovich et al. (1971, 1972)
Surveyor 3	1.7	Jaffe (1973)
Lunokhod 1 and 2 / Luna 16 and 20	1.5	Leonovich et al. (1974a, 1975)
Correlations with Simulated Lunar Soil		
Astronaut Bootprints		
Inter crater area	1.45 - 1.59	Mitchell et al. (1974)
Crater rims (depth 0 -15 cm)	1.34 - 1.57	Mitchell et al. (1974)
Vehicle Tracks		
MET and LRV (depth 0 -15 cm)	1.40 – 1.56	Mitchell et al. (1974)
Boulder Tracks (depth 0 -300 to 400 cm)	1.38 – 1.68	Mitchell et al. (1974)
Penetration Resistance		
Apollo 11	< 1.81 – 1.92	Costes et al. (1971)
Apollo 12	< 1.80 – 1.84	Costes et al. (1971)
Lunokhod 1 and Apollo 14 – 16 (depth 0 - 60 cm)	1.58 – 1.76	Mitchell et al. (1974)
Returned Core Samples		
Apollo 11	1.54 – 1.75	Costes and Mitchell (1970)
	0.75 - > 1.75	Scott et al. (1971)
Apollo 12	1.6 – 2.0	Scott et al. (1971)
	1.55 – 1.90	Houston and Mitchell (1971)
	1.7 – 1.9	Carrier et al. (1971)
Luna 16	1.2	Vinogradov (1971)
Apollo 14	1.45 – 1.6	Carrier et al. (1972a)
Apollo 15		
Core Tubes	1.36 – 1.85	Carrier et al. (1972a); Mitchell et al. (1972a)
Drill Tubes	1.62 – 1.93	Carrier (1974); Mitchell et al. (1972a)
Luna 20	1.1 – 1.8	Vinogradov (1972)

Source	Bulk Density (g/cm ³)	Investigator
Apollo 16		
Core Tubes	1.57 – 2.29	Mitchell et al. (1973)
Drill Tubes	1.74 – 1.99	Carrier (1974)
Luna 24	1.6 – 2.1	Florensky et al. (1977); Barsukov (1977)

Best Estimates of Bulk Density

Mitchell et al. (1974) provides the best estimates for the average lunar soil bulk density with respect to depth, which are shown in Table 2.5. These values are based on statistical average of Apollo 15-17 core tube densities. It is important to keep in mind that these values represent the best estimates for the bulk density of the lunar soil in the intercrater areas of the lunar surface values.

Table 2.5 Best estimates of average bulk density (Mitchell et al., 1974)

Average Bulk Density (g/cm ³)	Depth (cm)
1.50 ± 0.05	0 - 15
1.58 ± 0.05	0 - 30
1.74 ± 0.05	30 - 60
1.66 ± 0.05	0 - 60

Porosity and Void Ratio of Lunar Soil

Based on the best estimates of bulk density (above) and the recommended specific gravity value of 3.1, the in situ void ratio and porosity were calculated using equation (2.1) and (2.2), respectively. The results are presented in Table 2.6 below. In general, the porosity and void ratio of the lunar soil tend to decrease with increasing depth.

Table 2.6 Best estimates of lunar soil in situ porosity and void ratio (Mitchell et al., 1974)

Depth (cm)	Average Porosity, n (%)	Average Void Ratio, e
0 - 15	52 ± 2	1.07 ± 0.07
0 - 30	49 ± 2	0.96 ± 0.07
30 - 60	44 ± 2	0.78 ± 0.07
0 - 60	46 ± 2	0.87 ± 0.07

Best Estimates of Bulk Density

Carrier et al. (1991) proposed a hyperbolic relationship between density and depth:

$$\rho = 1.92 (z + 12.2)/(z + 18) \quad (2.3)$$

where z = depth in lunar surface (cm). On average, the bulk density, ρ , is approximately 1.30 g/cm^3 at the surface, increases rapidly to 1.52 g/cm^3 at a depth of 10 cm, then more gradually 1.83 g/cm^3 at a depth of 100 cm; and thereafter, the density asymptotically approaches a value of 1.92 g/cm^3 (see Figure 2.14). The hyperbolic density relationship falls with the bounds established by Mitchell et al. (1974) to a depth of 60 cm, and Carrier et al. (1991) stated that it is probably fairly reasonable to a depth of 3 m.

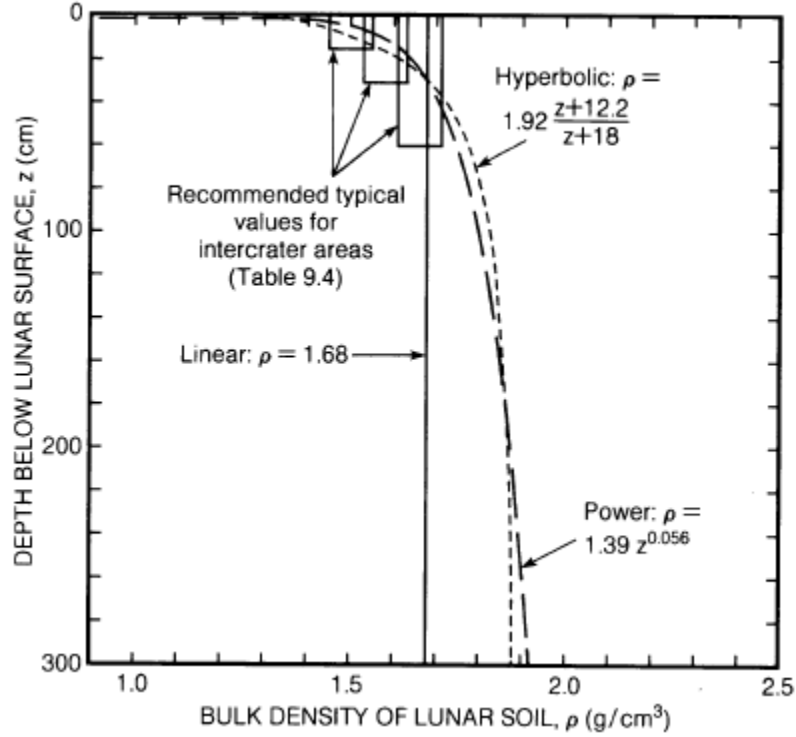


Figure 2.14 Hyperbolic relationship between density and depth (Carrier et al., 1991)

2.3.5 Relative Density

The relative density of the lunar soil is dependent on the sizes and shapes of the individual soil grains, and is determined based on the following relationship:

$$R_D = \frac{\rho_{max}}{\rho} \times \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}} \times 100\% \quad (2.4)$$

where ρ_{max} is the maximum bulk density, ρ_{min} is the minimum bulk density, and ρ is the bulk density of the soil sample. Relative density is important in both engineering and geological consideration. Based on the assumption of an average specific gravity of 3.1, $e_{max} = 1.7$ ($\rho_{min} = 1.15 \text{ g/cm}^3$), and $e_{min} = 0.7$ ($\rho_{max} = 1.82 \text{ g/cm}^3$), Mitchell et al. (1974) and Houston et al. (1974) converted the best estimates of bulk density shown in

Table 2.5 into the best estimate relative densities vs. depth. The results are presented in Table 2.7 with a description according to the theory of Lambe and Whitman (1969).

Table 2.7 Relative density of lunar soil (Carrier et al., 1991)

Depth Range (cm)	Relative Density, D_R (%)	Description
0 - 15	65 ± 3	Medium to dense
0 - 30	74 ± 3	Dense
30 - 60	92 ± 3	Very dense
0 - 60	83 ± 3	Dense

Laboratory Measurements of Minimum and Maximum Density

In order to calculate the relative density of the lunar soil, one has to obtain the maximum and minimum bulk densities first. A variety of methods have been developed by scientists and engineers to measure the maximum and minimum densities of lunar soil. Since the maximum density is dependent on the method, the values reported by different investigators cannot be compared directly. The results are summarized in Table 2.8. In those cases where the specific gravity is also known, the corresponding maximum and minimum void ratios have also been calculated using equation (2.1).

During a study of penetration resistance, Costes et al. (1970a, b) determined the minimum density of an Apollo submillimeter soil sample 10084 to be 1.36 g/cm^3 by placing the soil as loosely as possible into a sample can, 8.85 cm in diameter and 5.1 cm high. The corresponding void ratio and porosity were 1.28 and 56 %, respectively. In a second test series, the soil was placed in the sample can in several layers and was compacted by rodding, tamping, and compressing to a maximum bulk density of 1.80 g/cm^3 , corresponding to a void ratio of 0.72 and a porosity of 41.8 percent. It is important to keep in mind that the void ratios and porosities determined by Costes et al. were

calculated using a specific gravity value of 3.1 obtained on total soil sample. The values shown in Table 2.8 were corrected by Carrier et al. using the specific gravity of submillimeter soil determined by Duke et al. (1970a). Cremers et al., (1970), Cremers and Birkebak (1971), Cremers (1972), and Cremers and Hsia (1973) found only minimum densities of Apollo 11, 12, 14 and 15 samples as part of their investigation of thermal conductivity. These minimum densities were attained by loosely pouring the soil into the $25 \times 13 \times 13$ mm test cell constructed of teflon. During a study on penetration resistance, Jaffe (1971) obtained the minimum and maximum densities of a sample from the scoop of the Surveyor 3 soil mechanics surface sampler to be 1.15 and 1.93 g/cm³, respectively. For the minimum bulk densities, soil was gently brushed into the cup from its top, or spooned in with a spatula. The cup which contained the soil under the test had an inside diameter of 1.0 cm and depth of 1.1 cm and was made of poly (methyl methacrylate). For the maximum densities, the cup was tapped or vibrated. The density was determined by weighing on an analytical balance and measuring the depth optically or on radiography prints. Tests were made in air at 70 °C; the relative humidities were recorded at 40 - 50 %. Carrier et al. (1973a, b) developed a method for relative density determination that requires only one-gram samples. They used small graduated cylinders of 1.0 cm³ and 1.5 cm³ capacity to measure sample volumes after placement in loose and dense conditions. The loosest state was achieved by pouring the sample from a small height in a single, continuous operation. The densest state was achieved by dropping the cylinders filled with soil 4 to 5 cm in nearly free fall onto the table for 90 times. Gromov et al. (1971) determined the densities of Luna 16 samples as part of their penetrometer, oedometer and direct shear tests. The minimum density of the soil was determined from

weighing the soil poured into a weighing bottle 3 cm³ in volume. The average value of the minimum density was found to be 1.12 g/cm³ from twenty repeated measurements. In order to obtain the maximum density, the soil was packed layer-by-layer in the weighing bottle by a vibroshock method and by manual ramming. Later, Leonovich et al. (1974, 1975) also reported similar test results for Luna 16 and 20 samples.

In comparison to ASTM standard test methods for maximum and minimum densities of soils, these methods use exceptionally small sample size and small mold. According to ASTM standard test method for maximum density of soils, the maximum density of a given free-draining soil is determined by placing either oven-dried or wet soil in a standard mold, applying a 14-kPa surcharge to the surface of the soil, then vertically vibrating the mold on either an electromagnetic, eccentric, or cam-driven vibrating table. The shaking time and frequency of the sample in the mold depends on the double amplitude of vertical vibration (peak-to-peak) of the vibrating table. ASTM standard test methods for maximum and minimum densities of soils suggest the use of a mold having a nominal volume of 2830 cm³ or 14200 cm³.

Table 2.8 Measured minimum and maximum densities of lunar soil (Carrier et al., 1991)

Mission	Sample Number	Sample* Weight (g)	Density		Specific Gravity, G (Table 2.3)	Void Ratio		References
			ρ_{min} (g/cm ³)	ρ_{max} (g/cm ³)		e_{max}	e_{min}	
Apollo 11	10084	565	1.36 [†]	1.80	3.01	1.21 [†]	0.67	Costes et al. (1970a, b)
	10084,68	5	1.26		3.01	1.39		Cremers et al. (1970)
Apollo 12	12001,19	6	1.30					Cremers and Birkebak (1971)
	12029,3	6.5	1.15	1.93				Jaffe (1971a)
Apollo 14	14163,133	5	1.10		2.9 ± 0.1	1.64		Cremers (1972)
	14163,148	0.97	0.89 ± 0.03	1.55 ± 0.03	2.90 ± 0.05	2.26	0.87	Carrier et al. (1973a, b)
	14259,3	1.26	0.87 ± 0.03	1.51 ± 0.03	2.90 ± 0.05	2.37	0.94	Carrier et al. (1973a, b)
Apollo 15	15031,38	5	<1.30					Cremers and Hsia (1973)
	15601,82	0.96	1.10 ± 0.03	1.89 ± 0.03	3.24 ± 0.05	1.94	0.71	Carrier et al. (1973a, b)
Luna 16	-	~10	1.12	1.79				Gromov et al. (1972); Leonovich et al. (1974a, 1975)
Luna 20	-	~6 [‡]	1.1 - 1.2	1.7 - 1.8				Vinogradov (1972); Ivanov et la. (1973a, b)
	-	~10	1.04	1.80				Leonovich et al. (1974a, 1975)

* All tests performed on < 1 mm size fraction.

[†] May be in error.

[‡] Unsieved sample.

2.3.6 Shear Strength

Shear strength parameters (cohesion and friction angle) are mechanical parameters of a soil that have profound influence on ultimate bearing capacity, slope stability, and trafficability. The most common way to characterize the shear strength of a soil is the Mohr-Coulomb failure criterion, which can be expressed as:

$$\tau_f = c + \sigma \cdot \tan\varphi \quad (2.5)$$

where τ_f is the shear strength at failure on the failure plane, σ is the normal stress on the failure plane, c is the cohesion of the soil, and φ is the internal friction angle. Intensive researches have been focused on the estimates of lunar soil cohesion and friction angle, as summarized in Table 2.9. Some of the best pre-Apollo estimates of the lunar soil cohesion and friction angle are near the lower bounds of actual lunar soil shear strength. For example, the best available estimates prior to the Apollo 11 mission obtained by Scott and Roberson (1969) were values of 0.35 to 0.70 kPa for cohesion and values of 35 to 37 degrees for friction angle of the lunar soil derived from the Surveyor 3 and soil mechanics surface sampler. Later, Mitchell et al. (1972c, 1974) used a variety of data, including the data from the manned Apollo missions, to determine the more representative values of the shear strength of lunar soil. These values range from 0.1 to 1 kPa for cohesion and 30 to 50 degrees for friction angle. These parameters were determined as a function of relative density. The higher shear strength parameters correspond to higher values of relative density of the lunar soil.

Table 2.9 Estimates of lunar soil cohesion and friction angle (Carrier et al., 1991)

Sources	Cohesion, c (kPa)	Friction Angle, ϕ (degrees)	References
EARLY INFERRED: REMOTE SENSING	24 - 240	0	Halajian (1964)
	> 0.00	> 28	Jaffe (1964)
	> 0	> 25	Jaffe (1965)
INFEERED: BOULDER TRACKS	0.35	33	Nordmeyer (1967)
	0.1	10 - 30	Moore (1970)
	0.5*	21 - 55 (39 [†])	Hovland and Mitchell (1971)
Apollo 17 – North, East and South Massifs	1*	26 - 50 (37 [†])	Mitchell et al. (1973)
SURVEYOR: EARLY ESTIMATES			
1: TV and Landing Data	10	0	Halajian et al. (1966)
	0.15 - 15	55	Jaffe (1967)
	TV and Landing Data	0.4 - 0.13	30 - 40
TV and Landing Data			Christensen et al. (1967)
3: Soil Mechanics Surface Sampler, TV, and Landing Data		> 35	Scott and Roberson (1968a)
	0 for	45 - 60	Christensen et al. (1968a)
	10 for	0	
6: Vernier Engine	> 0.07 for	35	Christensen et al. (1968b)
Attitude Jets	0.05 - 1.7		Christensen et al. (1968b)
3 and 7: Soil Mechanics Surface Sampler	0.35 - 0.70	35 - 37	Scott and Roberson (1969)
SURVEYOR MODEL: BEST ESTIMATE	0.35	35 - 37	Scott and Roberson (1969)
APOLLO 11			
LM Landing, Bootprints, Crater Slope Stability	Consistent with Surveyor Model		Costes et al. (1969)
Core Tube, Flag Pole, SWC Shaft Penetration	0.75 – 2.1	37 - 45	Costes et al. (1971)
APOLLO 12			
LM Landing, Bootprints, Crater Slope Stability	Consistent with Surveyor Model		Scott et al. (1970)
Core Tube, SWC Shaft Penetration	0.56 – 0.75	38 - 44	Costes et al. (1971)

Table 2.9 (Continued)

Sources	Cohesion, c (kPa)	Friction Angle, φ (degrees)	References
LUNOKHOD 1			
Vane Shear - Lowest - Highest - Mode	3.9 - 4.9	N/A	Leonovich et al. (1971, 1972)
	0.26 - 1.1	50 - 25	Mitchell et al. (1972d)
	1.2 - 4.8	50 - 25	
	0.64 - 2.6	50 - 25	
Cone Penetrometer - Crater Wall (inner) - Crater Slope (outer) - Horizontal Ground			Mitchell et al. (1972d)
	0.17 - 0.10	45 - 25	
	0.52 - 2.7	45 - 25	
	0.34 - 1.8	45 -25	
APOLLO 14			
Soil Mechanics Trench	< 0.03 - 0.1	35 - 45	Mitchell et al. (1971)
Apollo Simple Penetrometer	Equal to or greater than Surveyor Model		Mitchell et al. (1971)
MET Tracks		37 - 47	Mitchell et al. (1971)
APOLLO 15			
SRP Data and Simulation Studies		47.5 - 51.5	Mitchell et al. (1972a)
SRP Data and Soil Mechanics Trench	1.0	50	Mitchell et al. (1972a)
APOLLO 16			
SRP: Station 4 (10-20 cm depth)	0.6	46.5	Mitchell et al. (1972b)
SRP: Station 10	0.37	49.5	Mitchell et al. (1972b)
SRP: Station 10	0.25 - 0.60	50 - 47	Mitchell et al. (1972b)
Drill Core Open Hole	1.3	46.5*	Mitchell et al. (1972b)

Table 2.9 (Continued)

Sources	Cohesion, c (kPa)	Friction Angle, ϕ (degrees)	References
APOLLO 17			
Drill Core Open Hole (Neutron Flux Probe)	1.1 - 1.8	30 - 50	Mitchell et al. (1973)
LRV	0.17	35	Mitchell et al. (1973)
APOLLO MODEL: BEST ESTIMATE	0.1 - 1.0	30 - 50	Mitchell et al. (1972d, 1974)
LUNOKHOD 1 AND 2 (AVE.)	0.4 [§]	40 [§]	Leonovich et al. (1974a, 1975)
RETURNED LUNAR SAMPLES			
Apollo 11: Penetrometer	0.25 - 0.85	42 - 38	Costes et al. (1969, 1970a,b); Costes and Mitchell (1970)
Apollo 12: Penetrometer (Surveyor 3)	N/A		Jaffe (1971a)
Apollo 12: Vacuum Direct Shear	0 - 0.7	28 - 35	Carrier et al. (1972b, 1973c)
Apollo 12: Direct Shear (Surveyor 3)	0.1 - 3.1	13 - 56	Jaffe (1973)
Apollo 12: Triaxial Shear (Surveyor 3)	0 - 1	51 - 59	Scott (1987)
Luna 16 and 20: Direct Shear and Coulomb Device	3.9 - 5.9	20 - 25	Leonovich et al. (1974a, 1975); Gromov et al. (1972)

* Assumed.

† Mean of 69 values.

‡ Mean of 25 values.

§ Estimated.

Carrier et al. (1991) provides a table of recommended typical shear strength parameters for the lunar soil of inter-crater areas as shown in Table 2.10. These values of cohesion and friction angle generally increase with the increasing density of the soil. The laboratory measurements of shear strength are described in detail in the following.

Table 2.10 Recommended typical values of lunar soil cohesion and friction angle (Carrier et al., 1991)

Depth Range (cm)	Cohesion, c (kPa)		Friction Angle, ϕ (degrees)	
	Average	Range	Average	Range
0 - 15	0.52	0.44 - 0.62	42	41 - 43
0 - 30	0.90	0.74 - 1.1	46	44 - 47
30 - 60	3.0	2.4 - 3.8	54	52 - 55
0 - 60	1.6	1.3 - 1.9	49	48 - 51

Laboratory Measurements of Shear Strength

The first laboratory measurements of lunar soil shear strength were made in 1969 at the Lunar Receiving Laboratory at the NASA Manned Spacecraft Center as part of the preliminary physical-chemical examination of Apollo 11 returned lunar samples (Carrier et al., 1991). The tests consisted of pushing a simple spring-loaded penetrometer into the compacted lunar soil finer than 1 mm particle size. During these tests the penetrometer was held normal to the surface of soil sample with either its front tip or its back end in contact with the soil. Then Terzaghi bearing capacity theory, with appropriate adjustments to account for circular contact areas as in the case lunar module footpads, was utilized to interpret the shear strength parameter of compacted lunar soil. The results of these penetration tests were reported in Costes et al. (1969, 1970a, b) and Costes and Mitchell (1970). Durgunolu and Mitchell (1975) determined the friction angle to be from 42° to 38° and the cohesion to be from 0.25 to 0.85 kPa for of Apollo 11 lunar soil by

utilizing the bearing capacity theory to reanalyze the data for the bearing test conducted on this Apollo 11 soil at the maximum density.

Jaffe (1971a) performed similar penetrometer experiments on a 1.3 g sample of lunar soil from the scoop of the Surveyor 3 soil mechanics surface sampler returned in October 1969 by the Apollo 12 astronauts. A commercial vertical, screw-driven, tension/compression testing machine equipped for recording load versus deformation was utilized. However, no shear strength parameters were interpreted in these penetration tests.

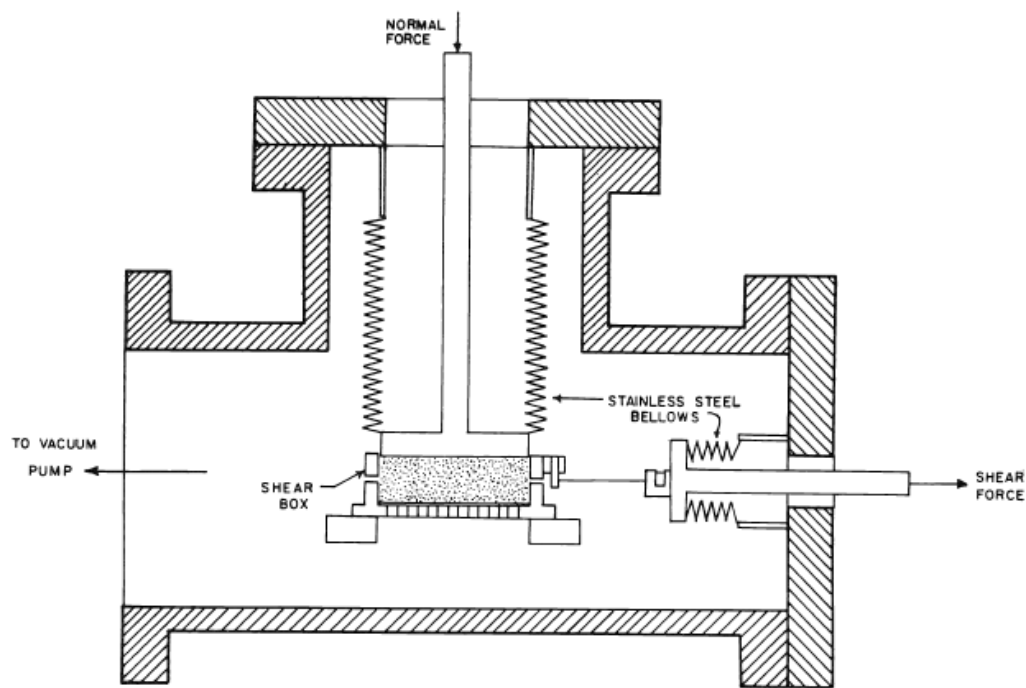


Figure 2.15 Ultra-high vacuum (UHV) test chamber (Carrier et al., 1972b)

Carrier et al. (1972b, 1973a) performed three direct shear tests in vacuum on a 200 g sample of lunar soil from Apollo 12 (12001, 119). The samples were placed in a shear box which was then inserted into a small ultra-high vacuum (UHV) test chamber

(refer to Figure 2.15). Then the UHV test chamber was sealed and transferred to a test bench where the sample was sheared at a pressure less than 5×10^{-8} Torr. The cohesion of the lunar soil sample ranged from 0 to 0.7 kPa and the friction angle ranged from 28° to 35° . The lunar soil sample had considerably less strength than a basalt simulant at the same void ratio, the lunar soil strength being only about 65% of the simulant strength. This was caused by the microbreccias, agglutinates, and other weakly cemented particles contained in the lunar soil. These particles were easy to break down into smaller particles.

Jaffe (1973) also performed miniature direct shear tests on 1.3 g of the lunar soil from the scoop of Surveyor 3 returned to the Earth by Apollo 12 astronauts. The tests were conducted in laboratory air at a approximate 20°C and 40-50 % relative humidity. A miniature standard soil mechanics direct shear box was used as shown in Figure 2.16. The steel cup to contain the soil was 5 mm in diameter and 5 mm deep inside, split horizontal halfway up. The upper and lower halves of the cup were separately supported, via upper and lower platens, by vertical flexures to avoid friction. To test, the lower half was motor-driven horizontally at constant speed; a dial gage was used to record the displacement of lower platen motion. The horizontal shear load transmitted through soil to upper half of the cup was measured by a strain gage and recorded continuously. Five initial bulk densities were achieved in the test, ranging from 0.99 to 1.87 g/cm^3 . Cohesion increased with bulk density from 0.1 to 3.1 kPa; internal friction angle increased from 13° to 56° . He also concluded that exposure and testing in air did not appreciably affect the shear strength properties of the lunar soil. Carrier et al. (1991) stated that most of the values of friction angle obtained by Jaffe (1973) were significantly lower than those determined in other experiments.

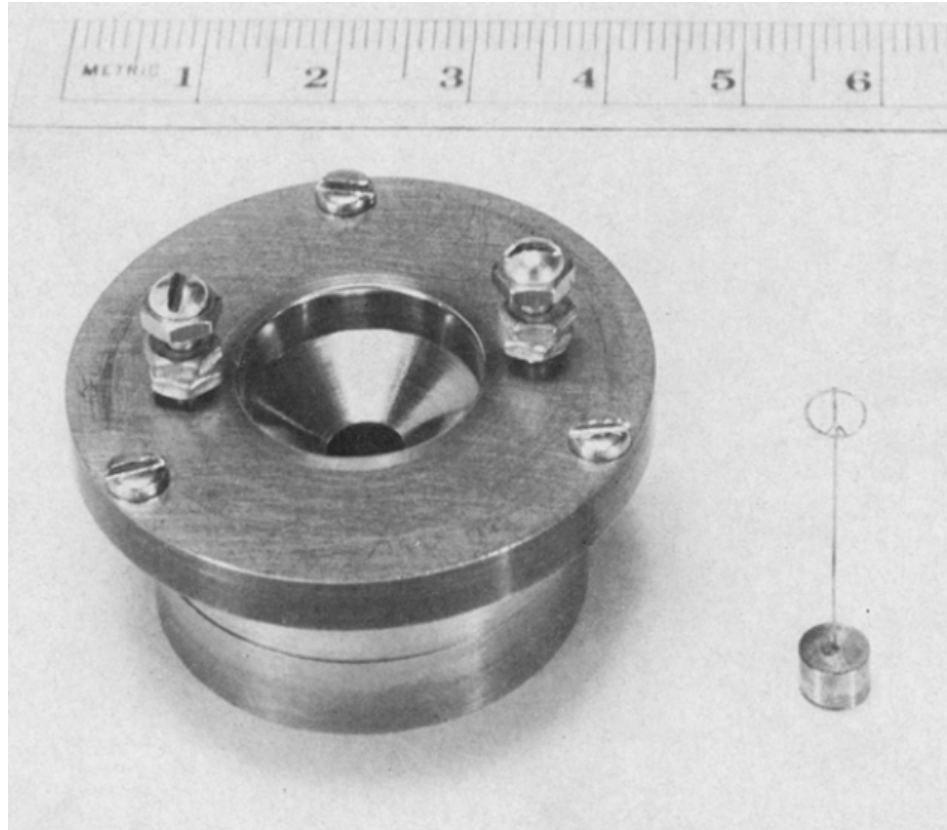


Figure 2.16 Miniature shear box apparatus (Jaffe, 1973)

Scott (1987) performed miniature triaxial tests on a 1.1 g sample of the soil from the Surveyor 3 scoop. The triaxial cylinder was only 0.25 inch (6.23 mm) in diameter and 0.5 in (12.7 mm) high. The confining pressure was imposed by subjecting the specimen to a vacuum to minimize disturbance to the material's natural state. The measured values of cohesion varied from 0 to 1 kPa and the friction angle from 51° to 59° .

Leonovich et al. (1974a, 1975) performed direct shear and coulomb device tests to determine the shear strength of lunar samples returned from Luna 16 and 20 missions. The shear device belonged to the class of flat single-shear instruments with a fixed surface of shear. The lunar soil sample for testing in this device is 25.2 mm in diameter and 12 mm in height. The Coulomb device had a movable partition whose shift permitted

one to observe the character of soil strain visually through the transparent walls of the device. The shear strength was determined by a method of overpacked soil. For this purpose the soil was preliminarily packed by a top which was used to plot the shear strength graph. For a range of cohesion from 3.9 to 5.9 kPa, the measured friction angle was 20° to 25° . Leonovich et al. stated that with the increase in packing pressure the initial cohesion and the internal friction angle increase due to the increase in the number of the contacts between particles and the increase in the number of particles sticking together. The initial cohesion and the internal friction angle approached constant values at packing pressures greater than 0.4 to 0.5 kg/cm². Soviet scientists: Leonovich et al. (1974b), Vedenin et al. (1974), Douchowskoy et al. (1974,1979), and Gromov et al. (1979) also conducted laboratory measurements of shear strength of lunar soil and reported their findings in Russian.

Various laboratory equipments have been employed by different investigators to determine the shear strength of lunar soil: penetrometer; vacuum direct shear; direct shear; triaxial shear; Coulomb device. Most of the tests use exceptionally small sample size and small device. Typically, the shear strength of a soil will be determined according to ASTM standard test method for either direct shear test or triaxial compression test. According to ASTM standard test method for direct shear test, the minimum specimen diameter for circular specimens, or width for square specimens, shall be 50 mm, or not less than 10 times the maximum particle size diameter, whichever is larger, and conform to the width to thickness ratio of 2:1. The specimens for triaxial compression test shall be cylindrical and have a minimum diameter of 3.3 cm. The height-to-diameter ratio shall be between 2 and 2.5.

2.3.7 Compressibility

The compressibility of a soil is a measure of the relative volume change of the soil in response to a pressure change. It is an important parameter in geotechnical engineering in the design of certain structural foundations whose settlement is a concern. If the load applied during trafficking and excavation is larger than the resistance the soil against the compressibility, compressibility of the soils occurs. Hence, it is also necessary to know the compressibility of a soil in the design of vehicle and excavation tools. In general, compressibility occurs in two phase. The first phase happens when the soil is under low initial confining pressures or exists a state of relatively low density. The intergranular slippage occurs and the particles reorient themselves to fill in void that previously existed in the honeycomb soil structure. The second phase happens when the confining pressure increases or if the initial density of the soil is considerably high. The particles themselves are deformed and / or fractured, generally breaking near the points of contact.

The soil compressibility parameters (compression index and swelling index) can be determined in an oedometer test. In the oedometer test, a soil sample is subject to a series of one-dimensional loads with a load increment ratio $\Delta p/p = 1$ and the corresponding deformation is measured. Then the results are plotted as void ratio versus logarithm of applied effective vertical stress. From the straight-line part of the relationship, the compression index, C_c is determined as

$$C_c = \frac{e_1 - e_2}{\log\left(\frac{p_2}{p_1}\right)} \quad (2.6)$$

in which e_1 and e_2 are the void ratios of the soil corresponding to effective vertical stress of p_1 and p_2 , respectively. Then, the vertical loading is gradually reduced with a load decrement ratio $\Delta p/p = 1$ and the resulting void ratios are measured. From the recorded data on the unloading line, the swelling index of the soil can be determined as

$$C_r = \frac{e_1 - e_2}{\log\left(\frac{p_2}{p_1}\right)} \quad (2.7)$$

Carrier et al. (1991) gave a summary of compressibility parameters as presented in Table 2.11. A typical value of 0.3 was recommended for loose lunar soil and 0.05 for dense lunar soil. In addition, the compression index of lunar soil typically decreases with increasing initial relative density (Carrier et al., 1991).

Table 2.11 Compressibility parameters of lunar soil (Carrier et al., 1991)

Parameter	Range	Recommended Typical Value
Compressibility Index, C_c		
Loose		0.3
Dense	0.01 - 0.11	0.05
Swelling Index, C_r	0.000 - 0.013	0.003

The compression index has been measured on soil samples from the Apollo 12 and Luna 16 and 20 missions (refer to Table 2.12). Carrier et al. (1972b, 1973c) performed two oedometer and three direct shear tests in vacuum on a 200 g sample of lunar soil from Apollo 12. The first sample was placed in a medium-dense condition in the shear box which was later inserted in the ultra-high vacuum test chamber (see Figure 2.14), compressed vertically in four increments, and then sheared. The top half of the shear cup was moved back into position and a small normal load was left on the sample. The sample was recompressed in four increments to a normal stress more than two times

of previous load, and then sheared. After the first test, the sample was removed from the shear box, and then replaced in the shear box as loosely as could be attained with the constraints of the vacuum system. After that, the sample was compressed in a series of increments and then sheared. The normal forces on the sample were controlled by removing or adding weights in the counterweight which was connected to the normal force through a cable-pulley arrangement. A Linear Variable Differential Transformer (LVDT) was mounted for monitoring the normal and shear displacements of the sample. The compression index was found to be from 0.01 to 0.11, depending on the initial density and the applied pressure. Jaffe (1973) also performed miniature compression and direct shear tests on 1.3 g of the lunar soil from the scoop of Surveyor 3 returned to the Earth by Apollo 12 astronauts. The test equipment was shown in Figure 2.16 and described in the section of shear strength. The normal forces were applied by deadweights through a disk on top of the soil as shown on the right of Figure 2.15. The compression index was estimated to be from 0.04 to 0.21. Leonovich et al. (1974a, 1975) performed oedometer tests on two 10 g samples from the Luna 16 and 20 missions. The sample was compressed in a series of increments, and then reduced the normal stress from the sample at each stage of loading. After that, the sample was recompressed to a normal stress multiple times of previous load, and then reduced the normal stress. The compressibility was found to be from 0.02 to 0.9. The average value of these data was about 0.3. However, these results are uncertain since no actual data points are presented, only a smooth curve with a curious shape (Carrier et al., 1991).

Except the tests conducted by Carrier et al. (1972b, 1973a), the other tests was performed on small sample size. According to ASTM standard test method for one-

dimensional consolidation properties of soils, the minimum specimen diameter shall be 50 mm; the minimum initial specimen height shall be 12 mm, but shall be not less than ten times the maximum particle diameter; the minimum specimen diameter-to-height ratio shall be 2.5; the standard loading schedule shall consist of a load increment ratio of one.

Table 2.12 Compressibility index of lunar soils (Carrier et al., 1991)

Mission	Sample Number	Sample Weight (g)	Density Range (g/cm ³)	Stress Range (kPa)	C_c	References
Apollo 12	12002,119	200	1.67 - 1.82	0.08 - 67.5	0.04 - 0.11	Carrier et al. (1972b, 1973c)
			1.84 - 1.92	0.09 - 31.2	0.012 - 0.062	Carrier et al. (1972b, 1973c)
			1.91 - 2.00	1.9 - 69.9	0.03 - 0.09	Carrier et al. (1972b, 1973c)
Apollo 12	12029,8	1.3	1.29 - 1.60	0.12 - 28.0	0.21 [*]	Jaffe (1973)
			1.4 - 1.64	0.14 - 28.0	0.11 [*]	Jaffe (1973)
			1.58 - 1.68	0.14 - 28.0	0.04 [*]	Jaffe (1973)
Luna 16	-	~10	1.03 - 1.51	0.05 - 98.0	0.3 [*]	Leonovich et al. (1974a, 1975); Gromov et al. (1972)
Luna 20	-	~10	0.98 - 1.51	0.05 - 98.0	0.3 [*]	Leonovich et al. (1974a, 1975)

^{*} Estimated.

2.4 REVIEW OF LUNAR REGOLITH SIMULANTS

Lunar regolith simulant is defined as any material manufactured from natural or synthetic terrestrial or meteoritic components for the purpose of simulating one or more physical and/or chemical properties of a lunar rock or soil (Sibille et al., 2005). The development of lunar regolith simulant stems from the fact that the current lunar soil sample inventory is insufficient in quantity to support lunar technology projects. Also, the scientific value of the lunar soil samples is too grand to be sacrificed during destructive testing. Hence, various lunar regolith simulants have been developed to replicate the physical and/or chemical properties of lunar soil for Earth based lunar soil studies. The lunar regolith simulants can be divided into two categories: root simulant and derivative simulant. A root simulant is composed of rock, mineral, or synthetic source materials. It is developed to represent the end-member in terms of physical, chemical, and mineralogical properties relative to the targeted regolith. It inherently approximates the predominant characteristics of the targeted regolith and does so with a minimum degree of processing. A derivative simulant was created by subjecting the root simulant to a variety process such as chemical and/or mineralogical modification, addition of physical components, or physical modification. It is better to replicate specific characteristics of the lunar regolith than a root simulant. Sibille et al. (2005) stated that, “The division between root and derivative simulants is dictated by the practical aspects of obtaining materials that in raw form are similar to targeted lunar soils, and can be obtained in tonnage quantities, compared to the needs for smaller amounts of simulant that would be utilized for specific applications.” In general, root lunar regolith simulant would serve the community needs for predominantly physical activities, such as drilling and excavation,

whereas a simulant produced by derivative processing would provide higher fidelity materials for chemical activities such as oxygen extraction. The following sections summarize some of the most reliable lunar simulants and the present status of these simulants.

2.4.1 MLS-1

Minnesota Lunar Simulant (MLS-1) was produced at the Space Science Center at the University of Minnesota in the 1970s. MLS-1 is a terrestrial material of basaltic composition that emulates its bulk chemistry of Apollo 11 lunar regolith. It was produced from an intrusive igneous rock of gabbroic composition mined from an abandoned quarry in Duluth, Minnesota. MLS-1 has a high composition of titanium which is similar to the Apollo 11 regolith. The mineralogy of this basalt contains coarse grains of plagioclase, olivine, ilmenite, titanomagnetite, and clinopyroxene grains as shown in Figure 2.17. However, this quarried basalt does not contain glass or agglutinates, which made up approximately the majority of Apollo 11 regolith. The lack of glasses has little impact on the engineering properties while the lack of agglutinates may have a significant impact on the stress-strain relationship of the soil since the particles tend to break in shear (Batiste and Sture 2005).

According to Perkins and Madson (1996), the basalt rock was quarried, crushed, and ground to match the particle size distribution of Apollo lunar regolith material (see Figure 2.18). It should be noted that the particle size distribution of MLS-1 as shown in Figure 2.18 is representative of MLS-1 which has been regraded to better represent the range of Apollo 11 sample grain sizes. Approximate 43 % of the reground MLS-1 is finer

than 75 μm . It is classified as highly angular, silty sand with nonplastic fines. The actual MLS-1 simulant has a fraction of larger grain sizes that is too great that will require regrounding by researchers in order to bring the distribution into agreement with Apollo soils. The coarse grain size of MLS-1 is due to the milling process during which the rock fragments break down and result in the release of large mineral fragments. In contrast, lunar soils consist of lithic fragments down to essentially the dust size fraction. Although these aspects are problematic for certain research projects, MLS-1 is considered as a successful lunar regolith simulant. However, it is no longer available for use as a lunar regolith simulant because the raw material was mined from an abandoned quarry. Sibille et al. (2005) addressed that “it is always desirable to utilize an active quarry where assistance from a mining operation is available and fresh rock material is guaranteed.”

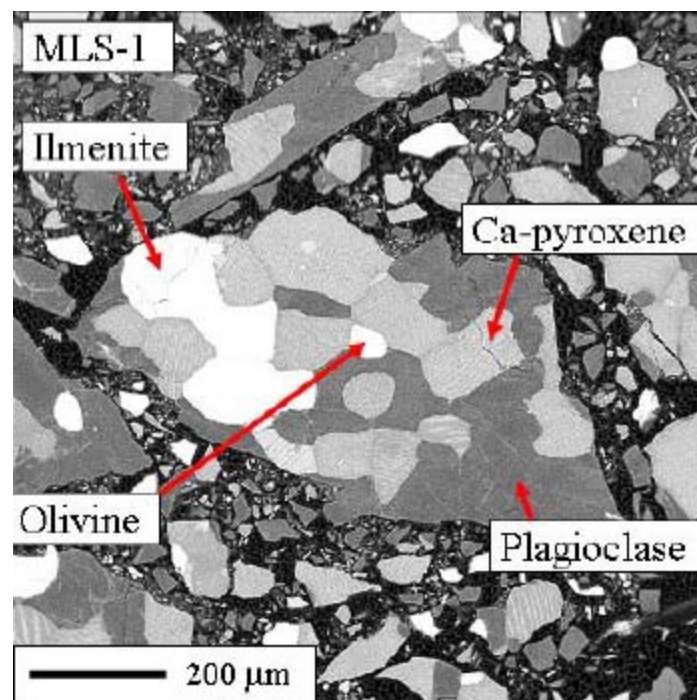


Figure 2.17 Backscattered electron image of lunar simulant MLS-1 (Sibille et al., 2005)

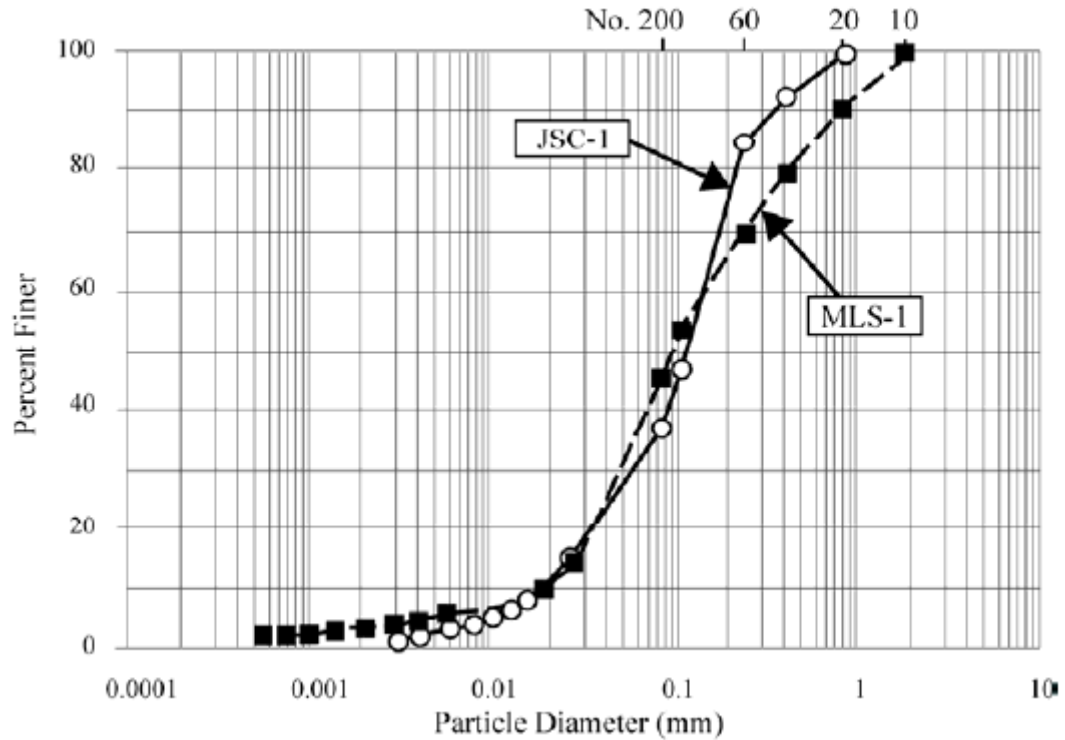


Figure 2.18 Particle size distributions of MLS-1 and JSC-1 (Perkins and Madson, 1996)

Table 2.13 Comparison of shear strength of lunar soil and MLS-1 (Perkins et al., 1992, Batiste and Sture, 2008)

Material	Density (g/cm ³)	Confining Pressure (kPa)	Internal Friction Angle (°)	Cohesion (kPa)
Lunar Regolith	1.50	-	42.0	0.52
	1.71	52.6	40.7	-
	1.75	-	54.0	3.0
	1.89	26.0	48.8	-
MLS-1	1.70	34.5	42.9	-
	1.70	68.9	41.4	0 - 0.1
	1.90	13.8	49.8	-
	1.90	34.5	48.4	-
	2.17	-	66.7	1.5

A quantity of MLS-1, without the particles processed to form glasses or agglutinates, was allotted to the Center for Space Construction at the University of Colorado at Boulder for geotechnical research. Since the original MLS-1 lacks of fine particles, it was first sieved into its respective sizes, then the larger particles were ground

in a rodding mill to create a sufficient quantity of fines. The soil was then recombined to produce a simulant which better represents the particle size distribution of all Apollo missions. The specific gravity of reggraded MLS-1 was found to be 3.2. The maximum and minimum densities were found to be 2.20 and 1.56 g/cm³, respectively. The minimum density was measured by spooning the simulant as loosely as possible into a 100 mL glass container. In order to determine the maximum density, the simulant was compacted inside a container 143 mm high by 80 mm in diameter. MLS-1 was placed in four equal lifts, with each lift compacted using a hand vibrator set to be highest compactive effort. The maximum and minimum void ratios were determined to be 1.05 and 0.454, respectively (Perkins and Madson, 1996). The low maximum void ratio was believed to result from lack of agglutinates. According to Batiste and Sture (2005), “An increase in maximum void ratios for Apollo 12 (Surveyor 3), Apollo 15, and Apollo 14 samples follows the trend of increasing average agglutinate contents of 15%, 33% and 52%, respectively.” The highly irregular shape of the agglutinate particles allocates a much looser density. In order to characterize the shear strength of MLS-1, a series of conventional triaxial compression test were performed. The test results are summarized and compared to the lunar soil in Table 2.13. As seen from the table, the internal friction angles of MLS-1 at the lower bound are similar to that of lunar soil, but MLS-1 show an increased upper limit on friction. Perkins et al. (1992) attributed it to the differences in testing conditions with respect to confining pressure. It should be noted that the cohesion of MLS-1 is low, which is believed to be caused by the absence of agglutinate particles as well as the lack of electrostatic charging.

Perkins and Madson (1996) conducted conventional triaxial compression tests. The MLS-1 was prepared to the densities of 1.70, 1.90 and 2.20 g/cm³ and tested under the confining pressures ranging from 1.7 to 649 kPa. The cohesion was assumed to be zero and the internal friction angle was found to be from 48° to 58°. Willman and Bole (1995) also conducted conventional triaxial compression tests. The MLS-1 was prepared to a density of 1.92 g/cm³ and tested at the confining pressures of 1.7, 3.44, and 6.89 kPa which were chosen to simulate the lack of overburden when physically digging the soil. The tests yielded a cohesion of 0.9 kPa and a friction angle of 37°. The lower friction angle can be attributed to different testing methods especially with respect to confining pressure.

2.4.2 JSC-1

A Lunar Simulant Working Group at the Space 1992 Conference recognized the need for large quantities of simulant material to be used in a variety of scientific and engineering tests. To meet this need, a new lunar regolith simulant JSC-1 has been developed under the auspices of NASA Johnson Space Center. JSC-1 is a glass-rich basaltic ash mined from a volcanic ash deposit located in the San Francisco volcano field near Flagstaff, Arizona. It simulates the chemical composition, mineralogy, particle size distribution, and engineering properties of lunar mare soil. More specifically, JSC-1 matches the composition of the average Apollo 14 mare basalt. Similar to MLS-1, the mineralogy of JSC-1 contains mainly plagioclase, pyroxene, ilmenite, and olivine (see Figure 2.19). In contrast to MLS-1, JSC-1 contains a low percentage of titanium and a high percentage of glass. Hence, JSC-1 is viewed as a complement to the MLS-1.

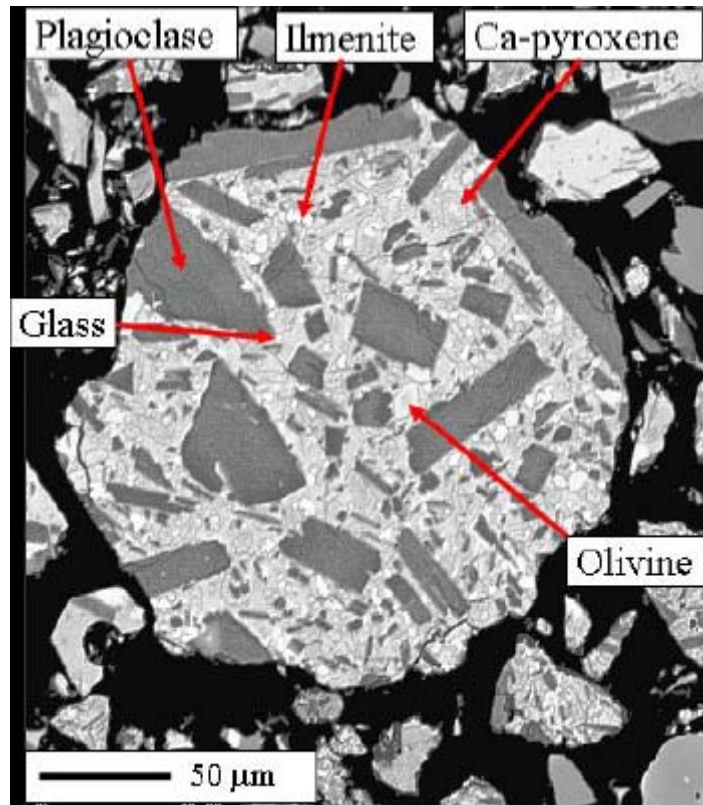


Figure 2.19 Backscattered electron image of lunar simulant JSC-1 (Sibille et al., 2005)

According to McKay et al. (1994), the volcanic ash was mined from a commercial cinder quarry near the south flank of Merriam Crater. Following mining, the ash was coarse sieved with the larger particles transfer to and crashed in an impact mill. The ash from several millings was partially air dried and was then mixed. The finish product was packed into plastic bags in 45 - 50 lb quantities and the bag were heat sealed. More than 12,000 kg of JSC-1 simulant was produced in early 1990s and has been widely distributed for various scientific and engineering investigations. JSC-1 has been a very successful simulant for the lunar regolith. However, due to poor recordkeeping and unsupervised distribution of this lunar simulant, it is unknown that how much of this material remains or what condition the remaining material is in. Currently, no JSC-1 is left for distribution (Oravec, 2008).

The particle size distribution of JSC-1 is compared to MLS-1 in Figure 2.18. Approximately 36 % of JSC-1 is finer than 75 μm . The coefficient of uniformity and coefficient of curvature are 7.5 and 1.12, respectively. JSC-1 is classified as a highly angular, silty sand with nonplastic fines (Perkins and Madson, 1996). Figure 2.20 shows the particle size distribution of JSC-1 compared to the average ± 1 standard deviation particle size distribution of lunar regolith (McKay et al., 1994). It was found that the median particle size for JSC-1 is between 98 and 117 μm and the mean particle sizes range from 81 to 105 μm . The specific gravity of JSC-1 was reported to be 2.9 by McKay et al. (1994) and Willman et al. (1995). Perkins and Madson (1996) measured the minimum and maximum densities of JSC-1 to be 1.33 and 1.80 g/cm^3 , respectively. The corresponding maximum and minimum void ratios are 1.18 and 0.61, respectively. The testing techniques used were exactly the same as described in the section of MLS-1. Klosky et al. (1996) measured the minimum and maximum densities of JSC-1 to be 1.43 and 1.91 g/cm^3 , respectively. Following the ASTM D 2049 (Annual 1991), Klosky et al. (2000) carried out six experiments to measure the maximum and minimum densities of JSC-1. The minimum and maximum densities were found to be 1.43 and 1.83 g/cm^3 , respectively. The differences among these results can be attributed to different equipments and techniques used in the testing.

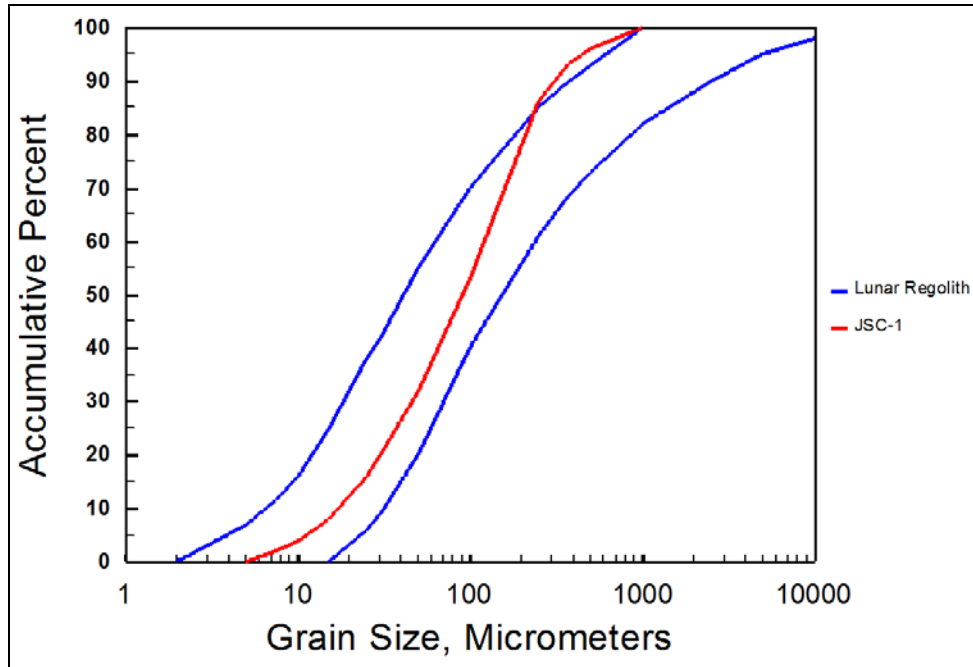


Figure 2.20 Particle size distribution of JSC-1 and lunar regolith (Carter et al., 2004)

Table 2.14 Shear strength parameters of JSC-1

Density (g/cm ³)	Relative Density, %	Internal Friction Angle (°)	Cohesion (kPa)	Reference
-	-	45	1.0	McKay et al. (1994)
1.50	-	45	≤ 1.0	Willman et al. (1995)
1.60	-	45	≤ 1.0	
1.65	-	45	≤ 1.0	
1.78	-	48 - 64	0*	Perkins and Madson (1996)
1.62	40	44.4	3.9	Klosky et al. (1996)
1.72	60	52.7	13.4	
1.62	53	44.4	3.9	Klosky et al. (2000)
1.72	75	49.5	6.2	
1.81	95	53.6	14.4	

* Assumed.

Various investigations have been conducted to study the characteristic of shear strength of JSC-1. The test results are summarized in Table 2.14. McKay et al. (1994) presented some preliminary finding for shear strength parameters of JSC-1. The internal friction angle of JSC-1 is 45° and the cohesion is 1.0 kPa, which is a good mechanical

analog to lunar soil. The tests were run in a triaxial cell and tested at confining pressures of 5, 10, and 15 psi. Using the same equipments, Willman et al. (1995) run triaxial tests on JSC-1 at the densities of 1.50, 1.60, and 1.65 g/cm³ under the confining pressures of 3, 5, and 10 psi. The friction angle was found to be 45° and the cohesion was found to be smaller than 1.0 kPa. The little change on the internal friction with different confining pressures and mass densities is most likely due to the mass densities employed by Willman et al. being close to or below the critical void ratio (Perkins and Madson, 1996). Bolton (1986) stated that, samples prepared at or above the critical void ratio tend to result in a similar friction angle as the critical state is approached, regardless of confinement. Perkins and Madson (1996) performed the same conventional triaxial compression tests on JSC-1 as on MLS-1. The JSC-1 was prepared to the density of 1.78 g/cm³ and tested at nine different levels of confining pressures ranging from 20 to 700 kPa. The cohesion was assumed to be zero and the internal friction angle was found to be from 48° to 64°. Klosky et al. (1996) also performed the triaxial compression tests on JSC-1 at densities of 1.62 and 1.72 g/cm³. These correspond to the relative densities of 40% and 60%, defined as loose and medium-dense, respectively. The samples were about 20 cm high and 10 cm in diameter. Mohr-Coulomb failure criterion was used to characterize the shear strength parameters. It can be seen from test results as shown in Table 2.14 that the values of friction angle and cohesion are strongly related to the relative density of JSC-1. The results are generally similar to the previous studies of McKay et al. and the reported values of returned lunar soils (Carrier et al., 1991). Klosky et al. (2000) performed the conventional triaxial compression tests again on JSC-1 at three densities levels: 1.62, 1.72 and 1.81 g/cm³. These correspond to the relative densities of 53%, 75%

and 95%, defined as medium, dense and very dense, respectively. The internal friction angle was found to be from 44.4° to 53.6° and the cohesion was found to be from 3.9 kPa to 14.4 kPa, which was similar to the previous studies of Klosky et al. performed in 1996.

2.4.3 GRC-1

In order to develop effective lunar vehicles and validate mobility models for future missions to the Moon, a lunar regolith simulant, GRC-1, is developed to be used as a standard vehicle mobility lunar simulant at the NASA Glenn Research Center for which it is named after (Oravec, 2008). GRC-1 has been used to test prototype wheels and vehicles under simulated terrain conditions. GRC-1 does not match both the compositional and textural features of the lunar soil, so it is considered as a low fidelity simulant.

TYPICAL SILICA SAND GRADES

Mesh	412	430	612	620	1020	1220	1635	2040	530	540	545	550	555	560	565	570	575	110
1/4"	1																	
4	20	T	T															
6	59	28	1	T					T									
8	18	59	43	13	T		T		1									
10	2	10	42	16	6	T	1		2									
12	1	3	11	16	18	7	5		2									
16	T	T	2	33	46	51	14	T	3	T	T							
20			T	18	25	35	16	12	3	3	2							
30				3	4	5	29	39	6	8	6	T	0	0	0	0	0	
40				1	1	1	32	45	11	17	12	8	7	5	3	3	3	0
50				1	1	1	3	3	26	40	28	34	28	23	12	12	12	0
70				1	1	1	1	T	31	27	34	41	42	43	43	35	40	1
100				T	T	T	T		13	4	15	15	19	23	29	26	20	15
140									3	1	3	2	4	6	9	13	12	40
200									T	T	T	T	1	1	4	9	8	31
270											T	T	T	T	1	3	3	11
Pan													T	T	T	1	1	3
AFS	N/A	N/A	N/A	9	11	12	20	25	43	40	47	49	53	55	64	73	72	124
E.S.	2.77	2.28	1.95	0.95	0.91	0.88	0.50	0.48	0.18	0.22	0.17	0.18	N/A	N/A	N/A	N/A	N/A	N/A
U.C.	1.46	1.38	1.26	1.82	1.56	1.52	1.52	1.40	1.89	1.63	1.84	1.62	N/A	N/A	N/A	N/A	N/A	N/A

Figure 2.21 Typical silica sand grades (Best Sand Corporation of Chardon, Ohio)

GRC-1 was created using four different types of sands provided by the Best Sand (BS) Corporation. These sands are denoted by BS 1635, BS 565, BS 530, and BS 110 and their grain size distribution characteristics are listed in Figure 2.21 (Best Sand Corporation of Chardon, Ohio). It was produced by mixing 32% by weight of BS 1635, 24% of BS 565, 8% of BS 530, and 36% of BS 110. Since these soils are commercially available at low cost, GRC-1 is available in large quantities for vehicle mobility tests.

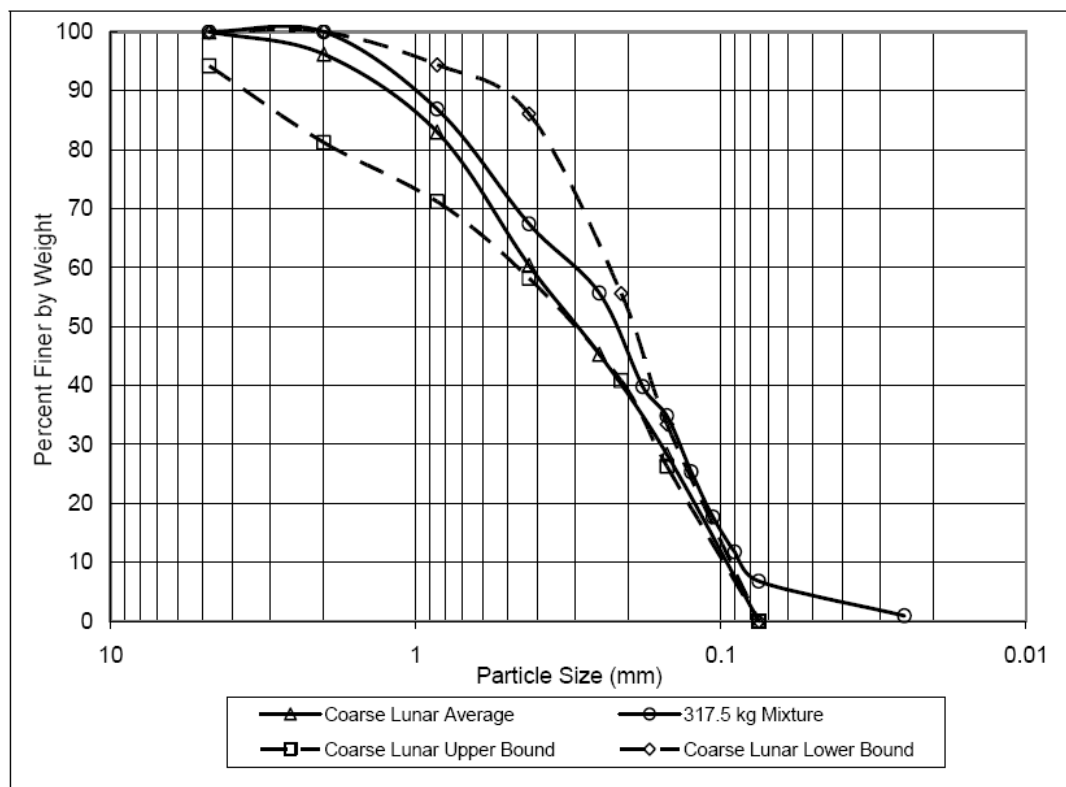


Figure 2.22 Particle size distribution of GRC-1

The particle size distribution of GRC-1 is shown in Figure 2.22 together with the average, upper and lower bounds of coarse lunar soil. It should be noted that GRC-1 does not simulate the fine fraction of lunar regolith. This is due to the safety precaution to prevent dust generation during testing. The coefficient of uniformity and coefficient of curvature of GRC-1 are 4.15 and 0.698, respectively. It is classified as a poorly graded

sand (SP) with little to no fines (Ovarec, 2008). The specific gravity is found to be 2.583 with a standard deviation of ± 0.004 . The maximum and minimum densities of GRC-1 are found to be 1.89 and 1.60 g/cm³, respectively. The minimum and maximum porosities are 0.267 and 0.380. These correspond to minimum and maximum void ratios of 0.364 and 0.613, respectively. Following ASTM D2435 (Annual 1991), two one-dimensional consolidation tests were performed by Ovarec (2008) to study the compressibility of GRC-1. The compression and recompression index was determined to be 0.03 and 0.008, respectively. Ovarec (2008) performed a total of 10 unconsolidated undrained triaxial tests on GRC-1 at 10 densities levels: 1.60, 1.62, 1.64, 1.66, 1.71, 1.73, 1.76, 1.78, 1.79, and 1.82 g/cm³. The tests were conducted at the confining pressure of 50, 100, and 200 kPa. The test results were summarized in Table 2.15. Ovarec (2008) also conducted 5 repeat Hele-Shaw cell tests to determine the angle of repose of GRC-1. The angle of repose of a soil is defined as the maximum angle at which the unconsolidated material can remain stable without sliding or crumbling. It is an engineering property of granular materials determined by friction, cohesion, and the shapes of the particles. The average angle of repose for GRC-1 is approximately 35.3° with a standard deviation of $\pm 0.711^\circ$.

Table 2.15 Shear strength parameters of GRC-1 (Ovarec, 2008)

Density (g/cm ³)	Relative Density, %	Internal Friction Angle (°)	Cohesion (kPa)
1.60	0.00	29.84	8.71
1.62	6.90	30.40	9.92
1.64	13.79	33.28	0.00
1.66	20.69	33.38	0.00
1.71	37.93	33.83	7.17
1.73	44.83	37.18	0.00
1.76	55.17	38.43	4.85
1.78	62.07	42.06	4.30
1.78	65.52	42.43	9.04
1.82	75.86	44.38	1.64

2.4.4 Other Lunar Regolith Simulants

Various lunar regolith simulants have been developed to support the Earth based lunar studies. Jansan Scientific, LLC in the United States developed a lunar regolith simulant called JS-Lunar Simulant to simulate a lunar mare basalt material (Sibille et al. 2005). This simulant was created by mixing 10% aged brecciated basalt from the Colorado Rockies near Duffey CO, 40% unweathered vesicular basalt from Hawaii, 40% basalt from Pullman WA, and 5% purest anorthite from the San Gabriel Mountains in California. This simulant was designed to serve primarily as a geotechnical material.

Shimizu Corporation in Japan developed two lunar simulants, FJS-1 and MKS-1, by mixing Mount Fuji basalt with olivine and ilmenite minerals (Kanomori et al., 1998). They were designed to match the bulk mechanical properties and chemical composition of Apollo samples in the mare region of the Moon. FJS-1 and MKS-1 are comparable to JSC-1, but have a higher SiO₂ and lower MgO content. They represent the material that is more quartz normative than lunar soils, in reflection of the source material used for simulant development.

Recently, a lunar highland physical simulant, OB-1, has been developed by the Northern Centre for Advanced Technology Inc. (NORCAT) in Canada (Richard et al., 2007). OB-1 is created by mixing anorthosite and olivine slag added to enhance abrasive qualities. Anorthosite is acquired from Avalon Ventures Ltd. Quarry located in Foley, Ontario. It is designed to replicate the particle size distribution of Apollo 16 highland samples for the support of geotechnical work.

Two lunar simulant, CAS-1 and NAO-1, have recently developed in China. The lunar mare regolith simulant CAS-1 is designed by the Chinese Academy of Sciences to support lunar orbiter, soft-landing mission and sample returned missions of China's Lunar Exploration Program (Zheng et al., 2009). It simulates the mineral and chemical compositions of Apollo 14 lunar soil sample. It is created by crushing a low-Ti basaltic scoria, which was obtained from the Jinlongdingzi Volcano in the Changbai Mountains of northeast of China, in an impact mill. CAS-1 is comparable to JSC-1, but has a higher Al_2O_3 and lower CaO content. It contains pyroxene, olivine, minor plagioclase, and about 20-40% modal glass. The lunar highland simulant, NAO-1, is created in National Astronomical Observatories (NAO), Chinese Academy of Sciences. This simulant is produced by gabbro quarried from the north bank of Yarlung Zangbo River in Tibet. It mainly contains pyroxene and anorthite. It simulates the chemical properties of Apollo 16 lunar soil. Its particle size distribution is similar to the Apollo 17 lunar soil.

These simulants developed outside of the USA have excellent properties. However, simulants cannot easily be imported and used in large quantities because of the availability of the simulants, transportation costs and period, quality control during transportation, etc. In addition, "there are also issues of proprietary development in the current business environment of space exploration" (Sibille et al., 2005).

CHAPTER 3 GEOTECHNICAL PROPERTIES OF JSC-1A

As can be seen from the literature review of Chapter 2, during the previous Luna, Lunakhod, Surveyor, and Apollo missions, several soil mechanics studies were carried out on both in-situ and returned lunar soil samples. However, due to the limited quantity of lunar soils that were brought back and the limitations of in-situ testing devices in these missions, some important geotechnical properties of the lunar soils were not fully understood, e.g., the apparent cohesion of the regolith, the influence of vacuum on soil properties, etc. Several lunar soil simulants have been developed for various small and large scale engineering investigations of the lunar soil. However, most of these simulants are no longer available or are too expensive for large scale investigations such as vehicle mobility and in-situ resource utilization testing. To satisfy the needs of the lunar research and development communities with large quantities of lunar regolith like soils, new standard lunar soil simulants have been developed. This chapter describes both the development and geotechnical characterization of a lunar regolith simulant, JSC-1A, which is intended to be used as a standard lunar mare regolith simulant for future lunar operations.

3.1 METHOD FOR CREATING JSC-1A

The 2005 Lunar Regolith Simulant Materials Workshop identified the need of large quantities of Standard Lunar Regolith Simulants (SLRS) to be used as lunar soil analogs in hardware development and testing. SLRS materials must be able to support both near term and long term needs and be accurately characterized and evaluated. In this

workshop, two main root simulants, a mare basaltic simulant and an anorthositic highland simulant, have been proposed. The mare basalt root simulant should be a low-Ti terrestrial basalt so that derivative simulants can be formed by addition of a Ti component such as ilmenite. The simulant must be produced from terrestrial rock and mineral sources that match those of lunar materials in terms of chemistry and mineralogy, as well as physical and geotechnical properties (Sibille et al., 2005).

To fulfill Agency near-term needs until a new generation of Lunar Regolith Simulant Materials (LRSMs) can be developed, NASA Marshall Space Flight Center (MSFC) has contracted Orbital Technologies Corporation (OBITEC) of Madison Wisconsin to produce and distribute 16 metric tons lunar regolith simulant. Known as JSC-1A (Johnson Space Center Number One-A), this new lunar regolith simulant is a replica of JSC-1 which was widely used and has now been depleted. Just like JSC-1, it is mined from a volcanic ash deposit in a commercial cinder quarry located in the San Francisco volcano field near the Merriam Crater just outside of Flagstaff, Arizona (see Figure 3.1). It approximates a low-titanium mare regolith and contains major crystalline silicate phases of plagioclase, pyroxene and olivine, with minor oxide phases of ilmenite and chromite, and traces of clay. JSC-1A has been approved to be a standard lunar mare regolith simulant to support NASA's future exploration and research of lunar surface. This material is available in three different forms: JSC-1AF, JSC-1A, and JSC-1AC. JSC-1AF is primarily 50 micro particle size and lower, JSC-1A is 1 mm particle size and lower, and JSC-1AC is 5 mm particle size and lower. The JSC-1A simulant family is a set of odorless powder/grand sand like material as shown in Figure 3.2.

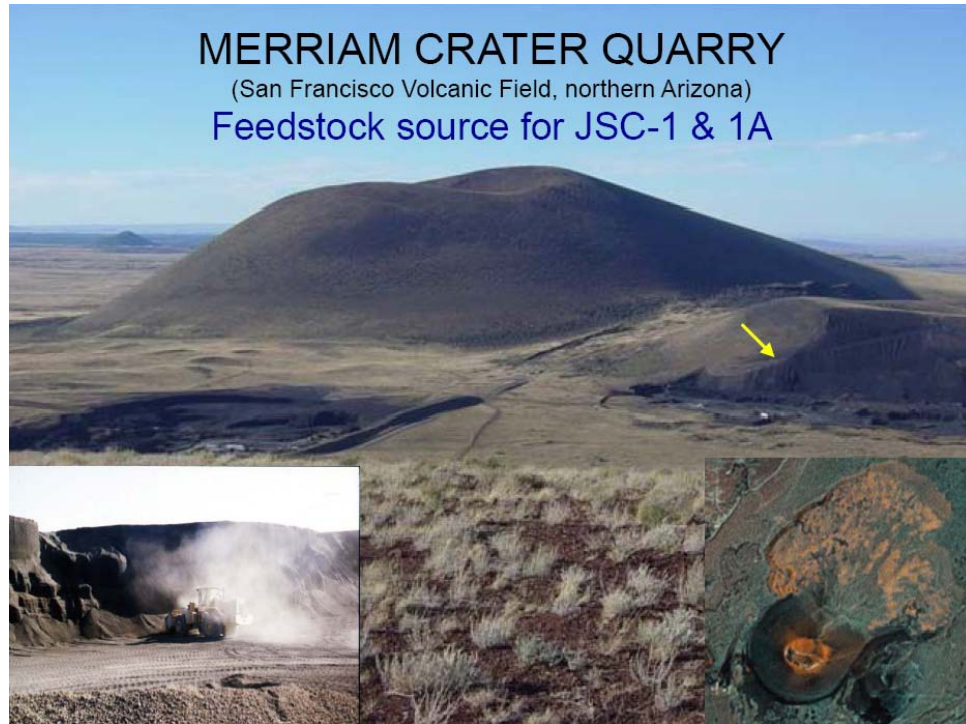


Figure 3.1 Feedstock source for JSC-1 & 1A (Stoeser, 2009)



Figure 3.2 JSC-1AF (left) and JSC-1A (right)

According to Gustafson (2009), the basalt cinders are first mined and then hand-picked to remove impurities or unwanted deposits. Tons of cinders are dried outdoor to remove excess moisture before milling. After drying, the cinders are ground into fine fraction and larger fraction. The finish product of JSC-1A is created by mixing fine and large fraction particles in predetermined quantities to match the composition and particle

distribution of the original JSC-1 simulant as closely as practical. More than 30 metric tons of JSC-1A simulant has been produced by the time of February 2009.

3.2 GEOTECHNICAL PROPERTIES OF JSC-1A

Many Earth-based studies of future lunar operations will involve the use of the JSC-1A simulant. Therefore, it is very important to characterize the geotechnical properties of this simulant. To that end, just as for benchmark soils like Nevada Sand, several groups have made independent measurements to establish benchmark properties. It should be noted that the JSC-1A lunar simulant discussed here is the material whose particle size is between 50 microns and 1 mm.

A group of laboratory tests were conducted at Case Western Reserve University and the NASA Glenn Research Center to measure the geotechnical properties of JSC-1A lunar regolith simulant (“Ton 2” Batch). The test procedures followed strictly the standards specified by ASTM (1991), which are the standards commonly used by the geotechnical engineering community, so as to ensure the comparability of the results. Several tests were repeated multiple times so as to check the repeatability of the data. These tests and the corresponding ASTM standards are summarized in Table 3.1.

Table 3.1 Summary of laboratory tests conducted on JSC-1A

Name of Test	ASTM Standard	Parameters Measured
Sieve Test	D421 & D422	Particle size distribution > 75 μm
Hydrometer Test	D421 & D423	Particle size distribution < 75 μm
Atterberg Limit Test	D4318	Liquid limit, plastic limit, plasticity index
Specific Gravity Test	D854	Specific gravity G_s
Relative Density Test	D4253 & D4254	Maximum and minimum dry densities
Compaction Test	D698	Dry unit density under compaction
Triaxial Test	D2850 & D4767	Internal friction angle and cohesion
Consolidation Test	D2435	Compression index and swelling index

3.2.1 Particle Size Distribution

The particle size distribution of a material is the most important parameter in determining its geotechnical properties. Based on the data from Apollo missions, the particle size distribution of lunar regolith had a quite significant variation with depth and from location to location (Carrier et al., 1991, Carrier, 2003). In fact, the spatial variation in lunar soils is more significant than that commonly seen on the earth. Based on all the available data on particle size distribution of lunar regolith, a band of average particle size distribution with $\pm$ one standard deviation has been established as shown in Figure 2.7. Therefore, the first step of the laboratory testing program is to investigate whether the particle size distribution of JSC-1A matches that of lunar regolith.

The tests to determine the particle size distribution of JSC-1A includes sample preparation (ASTM D421), sieve analysis for coarse particles (ASTM D422) and hydrometer tests for fine particles (ASTM D423). To check whether there is particle

segregation during the transportation process, one sample each of the simulant was taken near the top and bottom of the bucket, respectively. The soil separation test procedure using the standard sieves for the coarse particles and the hydrometer for fine particles are as follows:

1. Obtain exactly 500 g oven-dried soil and record the mass of this initial soil sample.
2. Wash the sample using the tap water through the No. 200 sieve and catch the washings in a weighed large dish. If the dish tends to overflow, temporarily stop washing and decant the clear top water. Continue washing until the water coming through the sieve is clear. When the wash water is clear, backwash the material retained on the sieve into a weighted dish. Oven dry this coarse fraction for sieve test, then weigh and record the mass of dry soil. Decant as much clear top water from the large washing dish and put the dish in the oven to dry for hydrometer test, then weigh and record the mass of dry fine fraction soil.

(Use the oven-dried coarse fraction for the sieve test)

3. Properly clean the sieves before conducting a new test. This involves emptying the sieves of any residual soil from past experiments via tapping the sides of the sieves to loosen soil particles and using a wire brush to clean the openings of the sieve mesh. Record this mass of each empty sieve, including the bottom pan, to the most accurate value possible (in this case 0.01g).
4. Stack the sieves in right order from top to bottom: No. 4 sieve, No. 10, No. 20, No. 40, No. 60, No. 140 and No. 200.

5. Pour the coarse fraction of the soil into the top sieve. Record the mass of this initial soil sample. Place the lid on the top sieve and secure crossbar.
6. Place the stack of sieves in a mechanical shaker shown as Figure 3.3 and shake for 15 minutes.



Figure 3.3 Humboldt Ro-Top testing sieve shaker

7. Remove the sieves from the shaker, carefully separate the sieves and put each one on a paper towel. From the top down weigh each sieve with the soil retained on it (sieve plus retained soil). If the sieving has not been done well, some particles may drop out of the mesh onto the paper towel during handling. Place this soil into the next lower sieve before it is weighed.
8. Obtain the mass retained on each sieve by subtracting the sieve mass from the sieve mass plus retained soil mass. Record these values and sum them including

the mass of retained soil in the pan. Ensure that this mass is not more than 2 percent by weight of the initial weight of soil that was placed in top sieve. If it is greater than 2 percent start over at Step 1.

9. Calculate the percent retained on each sieve by dividing the soil mass retained on each sieve by the original sample mass.
10. Compute the percent passing or percent finer by beginning with 100 percent and subtracting the percent retained on each sieve in a cumulative fashion.

(Use the oven-dried fine fraction for the hydrometer test)

11. Weigh exactly 50 g of oven-dry soil fines, which was washed through No. 200 sieve.
12. Mix the soil with 125 ml of 4% NaPO_3 solution in a small evaporation dish and cover with wet paper towels to minimize evaporation. A 4% sodium metaphosphate solution can be made by mixing 40 g of dry chemical with enough water to make 1000 mL. The solution should be freshly mixed.
13. Allow the soil mixture to stand for 16 hours. At the end of soaking period, transfer the mixture to a dispersion cup and add tap water until the cup is about two-thirds full. Mix the soil for 1 minute. While the soil is being dispersed prepare the control jar by adding 125 mL of same solution used in Step 12 and sufficient temperature stabilized water to produce 1000 mL. Be sure the water temperatures are adjusted so that the sedimentation and control cylinders are with 1°C . Put a thermometer and the hydrometer into the control cylinder so that both are temperature stabilized when needed. Obtain a “zero correction” using

hydrometer to correct for water impurities and for the use of a dispersal agent on hydrometer readings.

14. After mixing, transfer all the contents of the dispersion cup to the sedimentation cylinder, being very careful not to lose any material. Rinse any soil in the dispersion cup by using a plastic squeeze bottle or adding stabilized water and pour this into the sedimentation cylinder. Now add temperature-stabilized water to fill the cylinder to the 1000 mL mark.
15. Cap the cylinder of soil suspension with a No. 12 rubber stopper, carefully agitate for about 1 min. Agitation is defined as turning the cylinder upside down and back 60 turns for a period of 1 min. An upside down-and-back movement is 2 turns. Set the cylinder down and remove the stopper to check that no soil particles are on it or the cylinder above the volume mark. If there is soil, restopper the cylinder and agitate sufficiently to dislodge the particles back into solution and again set the cylinder down and unstopper. Take the first readings at an elapsed time of 2 after setting cylinder down. About 20 seconds before the reading time, insert the hydrometer for the first reading; also take a temperature reading. Remove the hydrometer and thermometer. Repeat this cycle for a second reading at an elapsed time of 4 min. Remove and place both the hydrometer and thermometer in the control jar (which should be within 1°C of soil-water suspension) between readings. Take a meniscus reading in the control jar on the hydrometer as shown in Figure 3.4.



Figure 3.4 Hydrometer test in progress for fine particles

16. At the end of first pairs of reading (2 and 4 min), replace the No. 12 stopper, reagitate the suspension, and take another set of 2- and 4-min readings. Repeat this step as necessary until two sets of readings agree within 1 unit of each other for both readings.
17. Continue take hydrometer and thermometer readings at approximate elapsed times of 8, 16, 30, 60 min and then 2, 4, 8, 16, 32, 64, 96h. These elapsed times are approximate but will usually give a satisfactory plot spread.
18. Apply the meniscus correction to the hydrometer readings, then use this meniscus corrected R_a to determine L using the equation (3.1). With specific gravity G_s and the test temperature T_i for each hydrometer reading, enter Table 3 (Values of K for Use in Equation for Computing Diameter of Particle in Hydrometer Analysis)

in the ASTM D422 to obtain the K value. With the values of K , L , and the elapsed time t_i for each reading compute the values of particle diameter D using the equation (3.2).

$$L = 16.3 - 0.1641R_a \quad (3.1)$$

$$D = K\sqrt{L/t} \quad (3.2)$$

19. With the test temperature T_i for each hydrometer reading, obtain the temperature correction factors C_T . Using corrected values of R_c from equation (3.3) together with the correction factor for G_s from Table 1 (Values of Correction Factor, a , for Different Specific Gravities of Soil Particles) in the ASTM D422, compute the percent finer for each test point using equation (3.4). Note in this equation M_s is the oven dry mass (50 g) from Step 1.

$$R_c = R_{actual} - \text{zero correction} + C_T \quad (3.3)$$

$$\text{Percent finer} = \frac{aR_c}{M_s} 100\% \quad (3.4)$$

20. Use the data from Steps 18 and 19 above together with the mechanical sieve analysis data to plot a composite particle-size distribution curve for this soil.

The results of the measurements are shown in Figure 3.5, together with the average, +1 standard deviation, and -1 standard deviation of lunar soils that were tested in the past. As shown in the figure, the results from the two samples taken near the top and bottom of the bucket are almost identical, suggesting there was no segregation of particles during the transportation process. In general, the particle size distribution of

JSC-1A falls between the +1 standard deviation and -1 standard deviation of lunar regolith but not at the average range.

In order to classify JSC-1A using the Unified Soil Classification System (ASTM D2481) it was necessary to determine the grain sizes D_{10} , D_{30} , and D_{60} where D denotes the size or apparent diameter of the soil particles and the numeric subscripts refer to the percentage that is smaller. For example, D_{10} is approximately equal to 0.017 mm for JSC-1A in Figure 3.5. This means that 10-percent of the sample grains are smaller than 0.017 mm. Continuing in this fashion for JSC-1A, D_{30} for JSC-1A is approximately equal to 0.042 mm and D_{60} is approximately equal to 0.11 mm. These values were used to determine the coefficient of uniformity C_U and the coefficient of concavity or curvature C_C for JSC-1A. The coefficient of uniformity is an indication of the range of particle sizes and is given by the following equation,

$$C_U = \frac{D_{60}}{D_{10}} \quad (3.5)$$

Typically, a large value of C_U is indicative that the D_{10} and D_{60} grain sizes differ considerably. The coefficient of concavity is a measure of the shape of the curve between the D_{60} and D_{10} grain sizes. It is defined by the following equation:

$$C_C = \frac{D_{30}^2}{D_{10}D_{60}} \quad (3.6)$$

where a C_C value much different from 1.0 suggests that there are particle sizes missing between the D_{60} and D_{10} grain sizes. The values obtained for the coefficient of uniformity and coefficient of curvature of JSC-1A was approximately 6.47 and 0.94, respectively. In

addition to particle size distribution tests, Atterberg limit tests (ASTM D4318) were also carried out to determine the plastic and liquid limits of the fines. The testing procedure will be described in the section 5.2.2. It was found that the soil has very little plasticity and the tests could not produce consistent results. Based on the particle size distribution and the fact that the soil has little plasticity, the soil is classified as a poorly-graded silty sand (SM) using the Unified Soil Classification System.

After a soil sample went through compaction test (using standard Procter device), its particle size distribution was studied again to investigate the effect of mechanical compaction on particle size distribution. In addition, the particle size distribution was measured once more after a sample was tested in a shear ring device up to failure to study the possible influence. The results of particle size analysis after soil samples were subjected to mechanical compaction and shear to failure are shown in Figure 3.6. It is obvious that these two processes after a single repetition had little impact on the particle size distribution of the JSC-1A simulant. Thus the simulant can be used more than once in most soil tests, as far as size distribution is concerned.

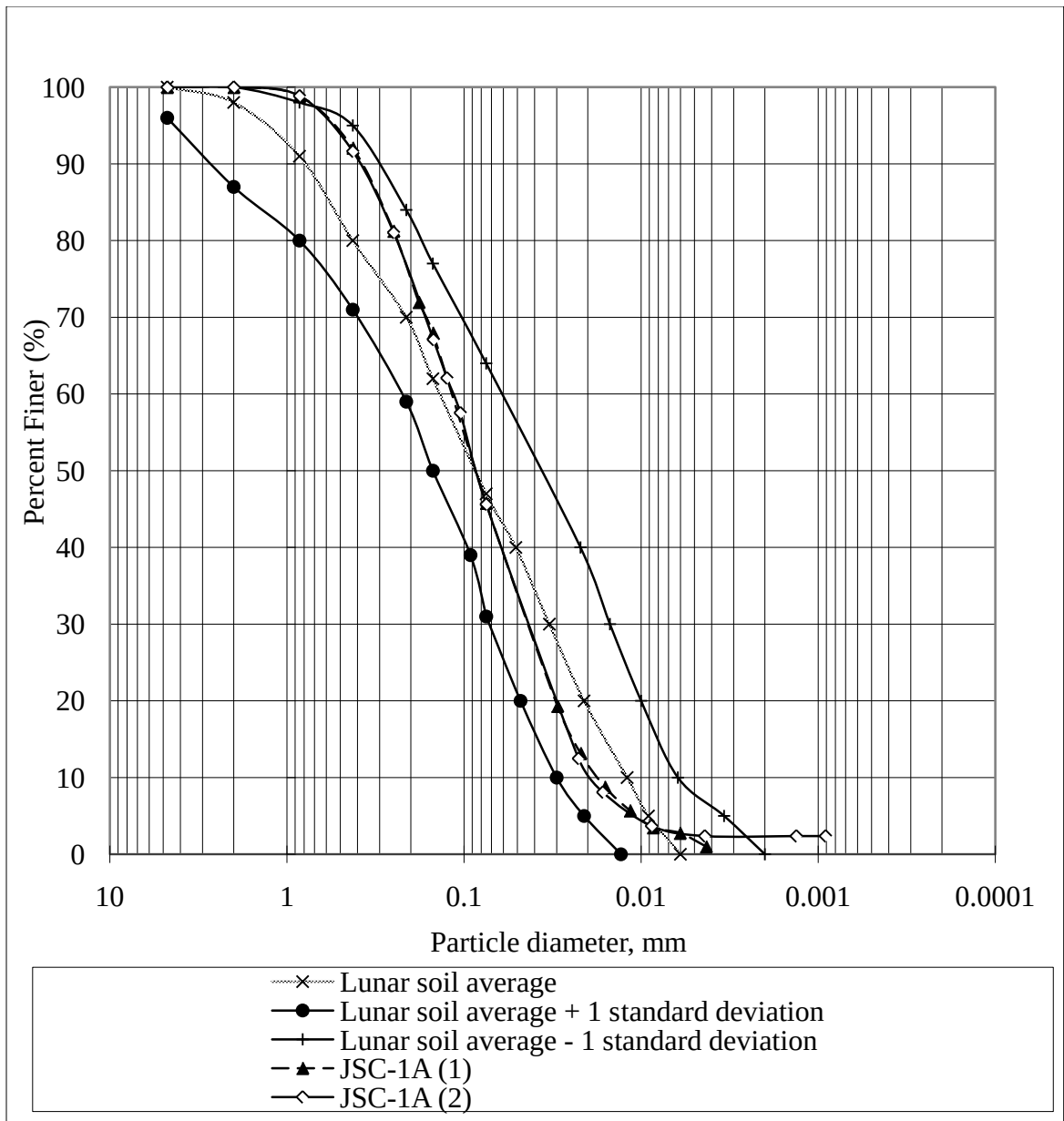


Figure 3.5 Particle size distribution of JSC-1A

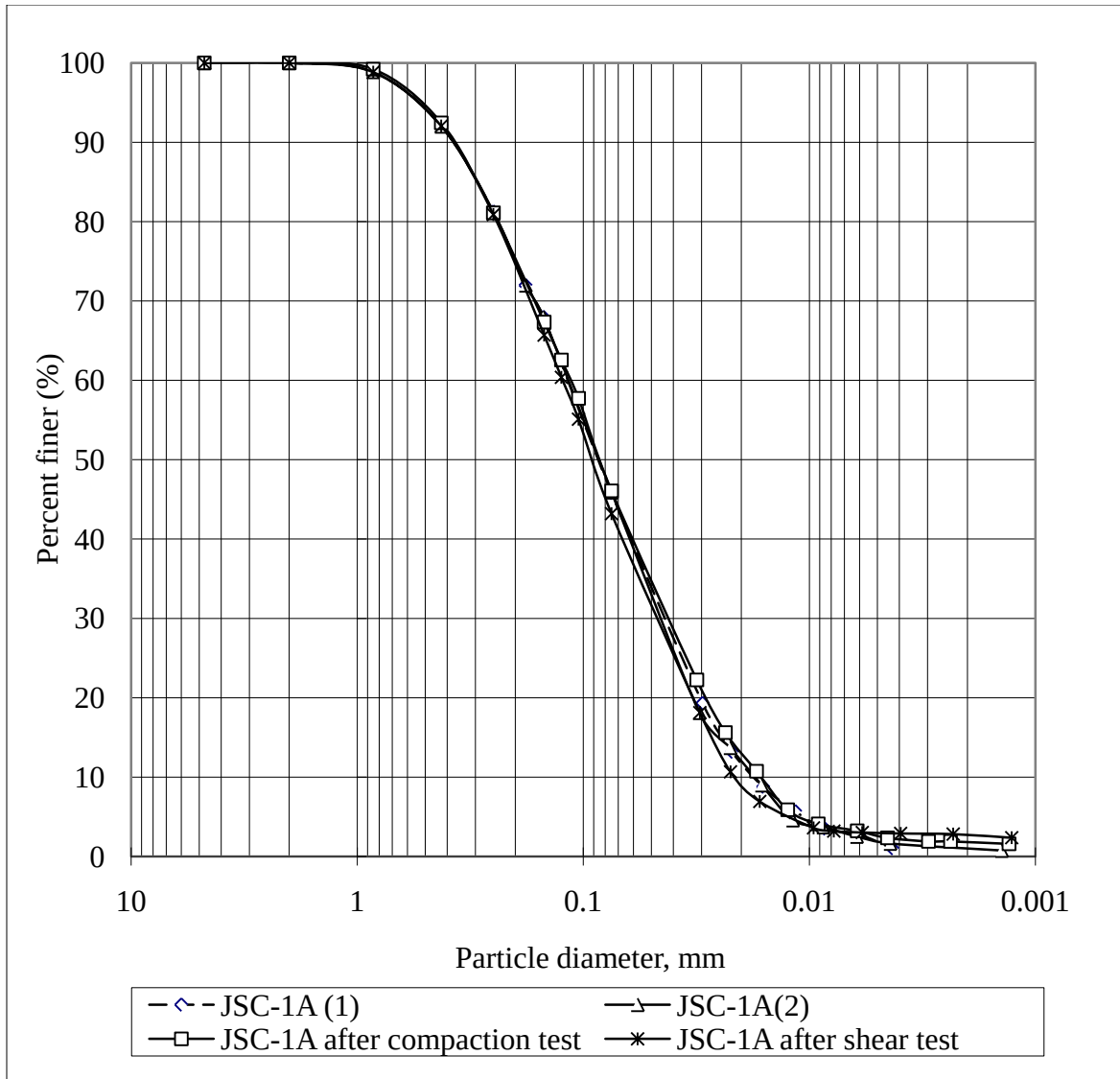


Figure 3.6 Particle size distribution of JSC-1A after compaction and shear test

3.2.2 Specific Gravity

The specific gravity of a soil is defined as the ratio of the mass density of solid particles to the mass density of pure water at 4°C. Values for lunar soils range from 2.3 to 3.2 and a value of 3.1 is recommended for general scientific and engineering analysis of lunar soils (*Carrier et al.*, 1991). In this test, two samples of JSC-1A were used following ASTM standard D854. The general test procedure is as follows:

1. Determine and record the mass of a clean, dry pycnometer (500 mL volumetric flask), M_f . Weigh about 100 g of air-dry soil. Break up lumps. Place the specimen in the flask. Add deaerated water to fill the flask about two-thirds full.
2. Attach the volumetric flask to a vacuum (air pressure not exceeding 100 mm Hg) for at least 30 minutes by connecting the flask directly to a vacuum pump (refer to Figure 3.7). Gently agitate the flask. Observe that the reduced air pressure in the flask causes the water to “boil”. This can take up to several hours. If the water level of soil-water mixture in the flask drops more than 3 mm when the stopper connecting to the flask is pulled to break the vacuum, deaeration is not complete and must be continued. Release the vacuum slowly.
3. Add deaerated water in the flask to the volume mark until the bottom of the meniscus is exactly at the volume mark. Add the deaerated water slowly and carefully to avoid the entrapment of air bubbles in the specimen. Carefully dry the outside and the neck of the flask above the volume mark with a clean, dry cloth. Determine the mass of the mass of flask filled with soil and water, M_{bws} , to the nearest 0.01 g. Insert a thermometer into the water, and determine its temperature to the nearest 0.5°C.



Figure 3.7 Specific gravity test at CWRU

4. Empty the flask and its content into a weighed dish. Put the dish in the oven for drying. Determine the mass of the oven-dry sol, M_s .
5. Repeat Steps 1 to 4 get another sample of soil, using the same flask.
6. Clean the previous used flask and fill it two-thirds full of deaerated water, apply vacuum for a short period then completely fill to the volume mark. Determine the mass of flask with deaerated water (M_{bw}) and insert the thermometer into the water to measure its temperature.
7. Come back to the lab next morning to determine the masses of the two oven dry dishes with and without soils so as to determine the masses of dry soil M_s .

8. Finish the calculations for specific gravity. If the two values of specific gravity are within 2% of each other, the test is a success. If the difference is more than 2%, explain the possible reasons. Rerun the test.

The specific gravity, G_s , of the JSC-1A is calculated using the following equation,

$$G_s = \frac{KM_s}{M_{bw} + M_s - M_{bws}} \quad (3.7)$$

where K is a temperature correction coefficient from Table 1 (Density of Water and Correction Factor K for Various Temperatures) in the ASTM D854 to account for temperature effects on the density of water. The results are summarized in Table 3.2. The average specific gravity of JSC-1A was found to be 2.875, which is lower than that of typical lunar soils at 3.1. In addition, there was the concern that the particles in different size range may have different specific gravities. Therefore, specific gravity tests were conducted on particles larger or smaller than 0.075 mm (or the opening of #200 sieve). The results are also listed in Table 3.2. The values show very little difference in their respective specific gravities.

Table 3.2 Results of specific gravity tests of JSC-1A

Specific Gravity	JSC-1A	JSC-1A (only fine particle)	JSC-1A (only coarse particle)
Test 1	2.880	2.865	2.907
Test 2	2.870	2.882	2.895
Average	2.875	2.874	2.900

3.2.3 Maximum and Minimum Densities

The state of density of a dry soil such as JSC-1A is typically measured as a relative term with regard to the maximum and minimum densities possible. Therefore, it is important to determine the maximum and minimum densities of JSC-1A. From the measured in-situ density of the soil, it is possible to calculate its relative density as

$$R_D = \frac{\rho_{max}}{\rho} \times \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}} \times 100\% \quad (3.8)$$

where, ρ_{max} is the maximum bulk density, ρ_{min} is the minimum bulk density, and ρ is the bulk density of a sample. The relative density generally refers to the degree of particle packing (which is particle size and shape distribution dependent) of a soil. It is probably the most important factor in determining the strength and stiffness of a soil.

A total of six tests were performed in the laboratory at CWRU in order to determine the maximum and minimum bulk density of JSC-1A (three repeat tests for maximum bulk density and three repeat tests for minimum bulk density). The tests followed ASTM D4253 and ASTM D4254 for maximum and minimum index densities, respectively. The general procedure used is as follows:

1. Find a standard compaction mold (see Figure 3.8). Determine the mass and inside dimensions of the mold with the base but without the collar.
2. Use an oven pan to get about 3kg of soil sample.
3. For maximum density test, place the sample in the standard compaction mold with a 14-kPa surcharge (dead weight) on the top of the sample and shake for 10 min at 60 HZ on the electromagnetic vibrating table (as seen on Figure 3.9).



Figure 3.8 Typical standard compaction mold



Figure 3.9 Compaction mold bolted on shake table

4. Measure the mass of the compaction mold full of soil. Measure the volume filled by compacted sample. Pour soil out and remix.
5. Repeat steps 2 to 4 for another two times. This gives 3 repetitions for maximum bulk density. Calculate the maximum density of the soil sample by dividing the soil weight by the volume it occupied in the mold.
6. Using a large spoon, carefully and slowly spoon soil into the mold until it extends over the top. Then use a straightedge to scrape smooth the surface. Determine the mass of the mold with soil.
7. Repeat step 6 for another two times. This gives 3 repetitions for minimum bulk density. Calculate the minimum index density of soil by dividing the soil weight by the volume it occupied in the mold.

The results of the maximum and minimum bulk density tests are summarized in Table 3.3. The average maximum and minimum dry densities of JSC-1A are 2028 kg/m³ and 1566 kg/m³, respectively. In comparison, the maximum and minimum densities of lunar regolith obtained from Apollo samples were 1930 kg/m³ and 870 kg/m³, respectively (Carrier et al., 1991).

Table 3.3 Results of maximum and minimum density tests of JSC-1A

JSC-1A	Maximum density (kg/m ³)	Minimum density (kg/m ³)
Test 1	2036	1574
Test 2	2029	1545
Test 3	2019	1578
Average	2028	1566

3.2.4 Porosity and Void Ratio

Based on the maximum and minimum densities and specific gravity of the soil, other engineering properties such as porosity and void ratio of the JSC-1A can be estimated. The bulk density, specific gravity, and porosity of a soil are related as:

$$n = 1 - \frac{\rho}{G_s \rho_w} \quad (3.9)$$

where ρ is the bulk density of the soil, G_s is the specific gravity of the soil, ρ_w is the density of water (1g/cc), and n is the porosity of the soil. This equation presents the ratio of the volume of the voids to the total volume of the soil sample. The void ratio of a soil in general is defined as a ratio of the volume of the voids to the volume of the soil solids. Mathematically it is related to the soil porosity by the following equation,

$$e = \frac{n}{1-n} = \frac{G_s \rho_w}{\rho} - 1 \quad (3.10)$$

Using equations (3.9) and (3.10) the porosity and void ratio of JSC-1A has been determined and is related to bulk density and relative density as shown in Table 3.4. The average specific gravity of 2.875 for JSC-1A was used to calculate the porosity and void ratio. It is important to note the porosity and void ratio as listed in Table 3.4 actually correspond to the densest and loosest conditions of JSC-1A. Therefore, the maximum porosity of JSC-1A is 0.455 while the minimum porosity is 0.295 and the maximum void ratio of JSC-1A is 0.836 while the minimum void ratio is 0.418. In comparison, the maximum porosity of lunar soil is 0.970 while the minimum porosity is 0.416 and the

maximum void ratio of lunar soil is 2.37 while the minimum void ratio is 0.670 (Carrier et al., 1991).

Table 3.4 Porosity and void ratio of JSC-1A

Condition	ρ (kg/m ³)	R_D (%)	n	e
Maximum	2028	100	0.455	0.836
Minimum	1566	0	0.295	0.418

3.2.5 Compaction Test

One of the objectives in this study is to find the best way, dry or wet, to achieve compaction for JSC-1A when preparing soil samples in a soil bin, in order to simulate extreme conditions that may be encountered on the moon. In geotechnical engineering, the Proctor compaction test is carried out by compacting the soil to be tested into a standard mold using a standardized compaction energy at several different levels of water content. The water content of the soil has a significant influence on the degree of compaction that can be achieved (*Proctor*, 1933). The water content that can achieve the best compaction or maximum dry density is called optimum moisture content. The tests reported here followed the standard described in ASTM D698. The general procedure used is as follows:

1. Weigh about 15 kg of air-dry soil, and then pulverize sufficiently to run through the No. 4 sieve. Prepare at least four specimens from the sieved soil to have contents such that they bracket the estimated optimum water content. A specimen having a water content close to optimum should be prepared first by trial additions of water and mixing. Typically, soil at optimum water content can be

squeezed into a lump that sticks together when hand pressure is released, but will break cleanly into two sections when “bent”. At water contents dry of optimum soils tend to crumble; wet of optimum soils tend to stick together in a sticky cohesive mass. Select water contents for the rest of the specimens to provide at least two specimens wet and two specimens dry of optimum, and water contents varying about 2 %.

2. Use approximately 2.3-kg of the sieved soil for each specimen to be compacted. To obtain the specimen water contents selected in step 1, add the required amounts by spraying it into the soil during mixing. Thoroughly mix each specimen to ensure even distribution of water throughout and then place in a separate covered container and allow standing for at least 3 hour.
3. Weigh the compaction mold and base plate. Determine the interior volume of the compaction mold, V_m . Assemble and secure the mold and collar to the base plate.
4. Using the standard hammer compaction method, compact a cylinder of soil in the mold (see Figure 3.10). Use three equal layers for compaction with each layer compacted 25 times by the hammer. The total amount of soil used shall be such that the third compacted layer slightly extends into the collar, but does not exceed 6-mm above the top of the mold.
5. Remove the collar and carefully scrape the top of the compacted cylinder of soil with a steel straightedge.
6. Weigh the mold and cylinder of soil without collar and record its mass. Calculate the moist density of each compacted specimen by dividing the interior volume of mold from the wet soil mass.



Figure 3.10 Standard compaction mold and hammer

7. Extrude the cylinder of soil from the mold. Obtain a portion by slicing the compacted specimen axially through the center and removing about 500-g of material from the cut faces. Determine the water content w of the portion.
8. Repeat step 2 to 7 for each specimen. Calculate the dry density ρ_d of each specimen using the equation (3.11).

$$\rho_d = \rho_m / (1 + w/100) \quad (3.11)$$

9. Plot dry density to the nearest 1 kg/m^3 and water content to the nearest 0.11% . From the compaction curve, determine the optimum water content and maximum dry unit weight.

The results of the tests are summarized in Table 3.5. The optimum moisture content was found to be 13.50% at the maximum dry density achieved by compaction, 1746 kg/m³. In comparison to the maximum dry density achieved by vibration, the maximum compacted dry density by adding water is much lower. Therefore, there is no need to use this method to achieve the maximum compaction. This is not surprising as the fines in the soil have low plasticity. Instead, the method of using vibration with vertical surcharge is more effective, and can produce a density closest to the maximum density.

Table 3.5 Results of compaction test of JSC-1A

Water Content	Compaction density (kg/m ³)	Dry density (kg/m ³)
9.30%	1852	1694
13.50%	1982	1746
18.04%	1978	1676

3.2.6 Shear Strength

Shear strength parameters (cohesion and friction angle) are mechanical parameters of a soil that have profound influence on vehicle mobility, and excavation. Therefore, laboratory triaxial tests were carried out to determine these parameters as a function of bulk density. The most common way to characterize the strength of a soil is the Mohr-Coulomb failure criterion, which can be expressed as:

$$\tau_f = c + \sigma \cdot \tan\varphi \quad (3.12)$$

where τ_f is the shear strength at failure on the failure plane, σ is the normal stress on the failure plane, c is the cohesion of the soil, and φ is the internal friction angle. Values of

cohesion and internal friction angle for JSC-1A were determined via the most commonly used laboratory test to determine the shear strength and stress-strain relationship of soil: the triaxial test.

A total of nine triaxial tests were conducted on JSC-1A samples of three different dry densities each at 100, 150 and 200 kPa confining pressure following the standards described in ASTM D2850. The procedures outlined below were generally followed for determining the shear strength of JSC-1A via triaxial tests under unconsolidated undrained (UU) conditions (drain-air conditions for dry sand).

1. Fasten the base platen to the base of the cell. Attach a rubber sleeve membrane of the proper diameter to the base platen using rubber bands.
2. Weigh a representative amount of dry soil in a glass beaker so that the bulk density can be obtained and approximately duplicated for succeeding tests.
3. Place a specimen mold around the rubber membrane and fold the top portion of the membrane down over the mold. Place a porous stone and filter paper into the membrane so that they enclose the bottom of the soil sample. Apply vacuum to evacuate the air between the rubber membrane and the membrane stretcher as shown in Figure 3.11.

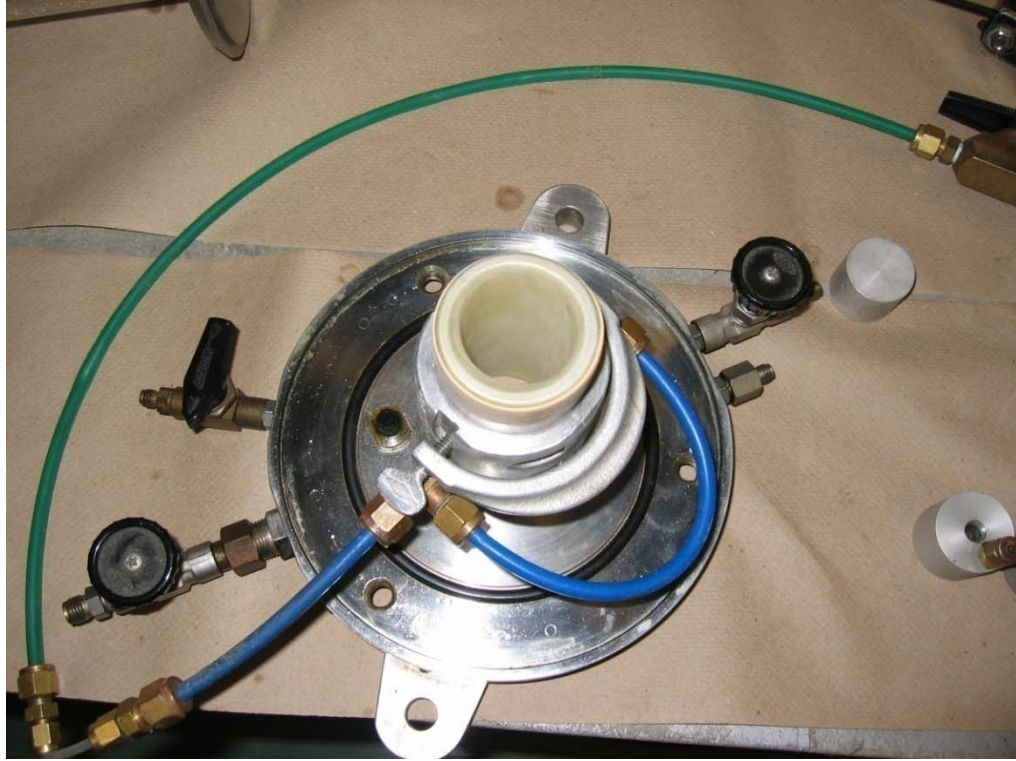


Figure 3.11 Membrane place in mold

4. Carefully pour the soil inside the membrane by means of a funnel as shown in Figure 3.12. The desired density may be achieved by tapping, tamping, or vibrating the specimen. It is important to note that a specimen which is properly formed will deform in a symmetric fashion upon loading.
5. Place a porous stone and then the top platen on the sample. Roll the membrane off the mold onto the top platen and seal with rubber bands. Take a small level and level the top platen. Weight unused soil to calculate the dry sample weight.
6. Simultaneously apply vacuum to the inside of the soil specimen while removing vacuum from the outside of the soil specimen. Keep the intensity of the vacuum relatively small to avoid consolidation of the specimen (approximately 200 to 250 mm of mercury). Now remove the specimen mold and examine the membrane for

holes and obvious leaks. If any are found, the sample must be remade using a new membrane. The sample now should be free-standing as shown in Figure 3.13.



Figure 3.12 Using a funnel slowly pour the soil into the mold

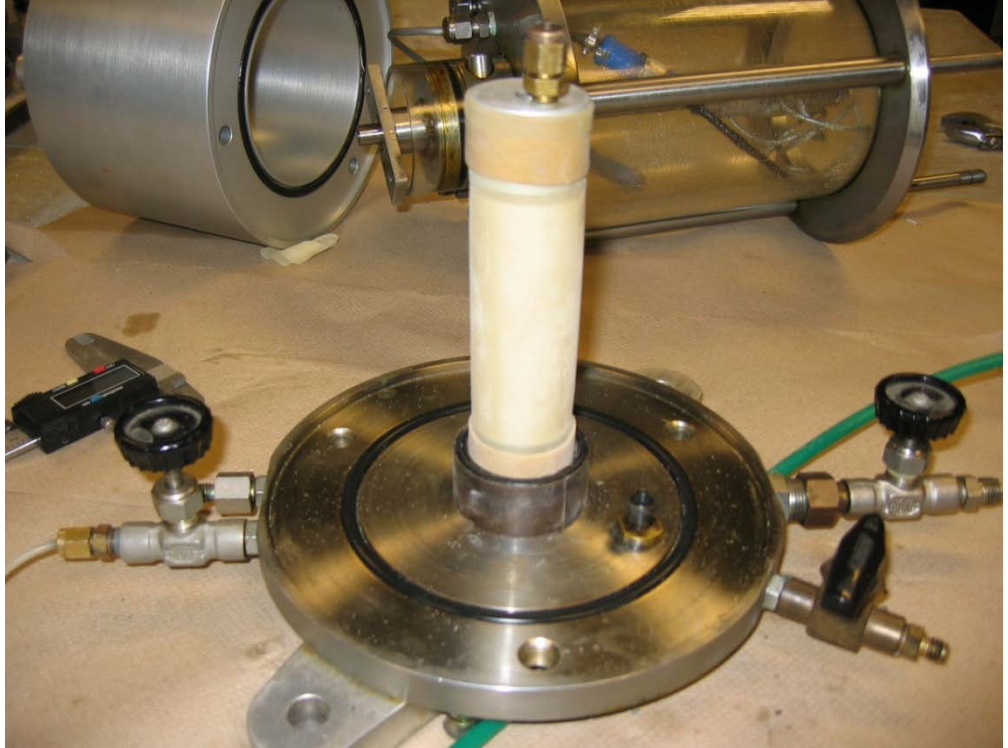


Figure 3.13 Standing-free triaxial sample

7. Obtain three height measurements approximately 120° apart, and use the average value for the initial specimen height. Using a pair of calipers to take three diameter readings 120° apart each at the top, at mid height, and at the base. Compute the average diameter of the specimen at each height and then compute a final average specimen diameter as

$$d_{av} = (d_t + 2d_{mid} + d_b)/4 \quad (3.13)$$

where d_t = average top diameter and other d_i are similarly defined. Compute the corresponding value of initial sample volume using the average height and the average diameter just computed. Determine the soil bulk density by dividing the mass of used soil by the initial sample volume.

8. Place the Lucite cylinder on the cell base, being sure the base is free of soil grains so that an airtight seal can be obtained. Place the cell in position in the axial loading device. Adjust the machine (raise or lower the cell) so that the load cell slightly above the specimen cap. Attach the pressure-maintaining and measurement device. Using compressed air to apply a predetermined lateral pressure to the cell and simultaneously reduce the vacuum on the interior of the sample to zero. Wait approximately 10 min after the application of chamber pressure to allow the specimen to stabilize under the chamber pressure prior to application of the axial load.
9. Attach a LVDT to the machine as shown in Figure 3.14. Check the compression machine is set to the desired strain rate (generally between 0.5 and 1.55 mm/min).
10. Start the test with the piston slightly above the specimen cap, and before the piston comes in contact with the specimen cap, measure and record initial piston friction and upward thrust of the piston produced by the chamber pressure and later correct the measure axial load. Record the simultaneous load and deformation by DAQ (data acquisition) device (as seen on Figure 3.15). Readings may be taking at until either
 - Load peaks and the falls off, or
 - Deformation is somewhat greater than 15 percent strain, or
 - Load holds constant.



Figure 3.14 Triaxial cell on the load frame connected with LVDT

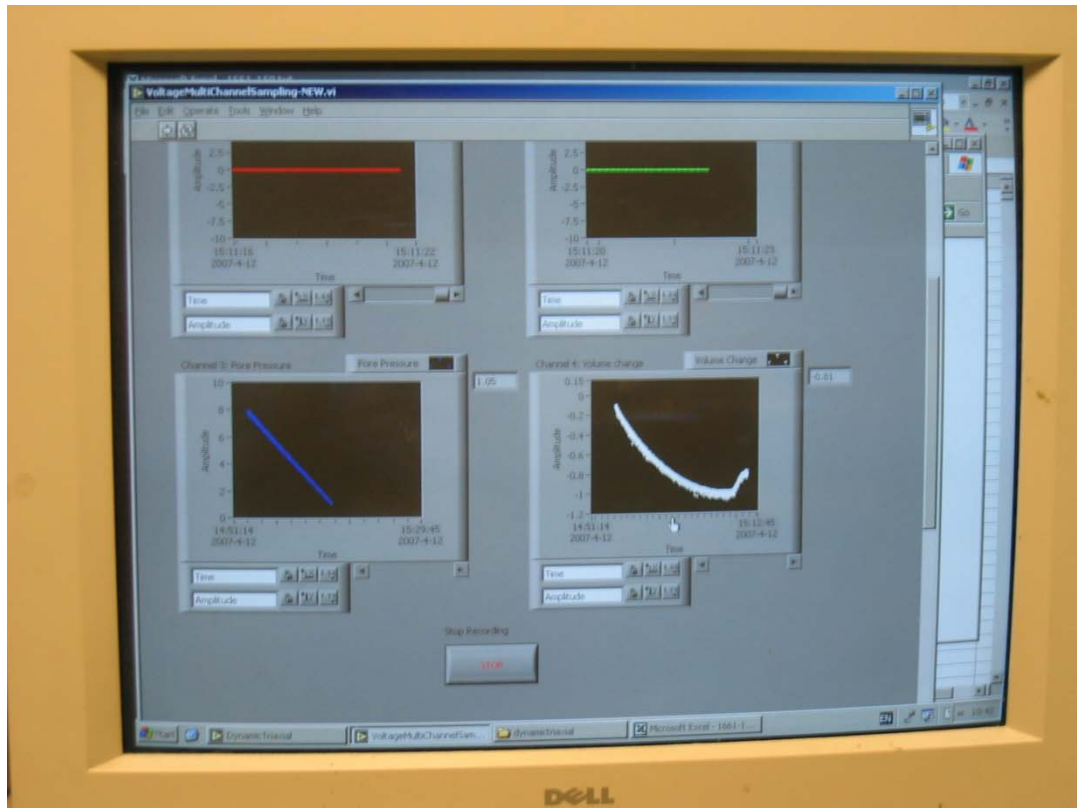


Figure 3.15 Data acquisition device

11. After the sample has failed, shut off and/or reverse the compression machine; release the chamber pressure, and remove the sample load.
12. Prepare a new specimen to the same approximate density and repeat steps 1 through 11 for at least two additional tests (a total of three).
13. Then do three repeats for each of two other bulk densities.

The principal stresses at failure of three samples at different confining pressures for each density are used to generate the Mohr's circles at failure, from which the failure envelopes can be drawn. Then the cohesion and friction angle of the soil can be determined. A typical result of triaxial tests is shown in Figure 3.16. It is clear that JSC-1A shows both peak and ultimate strength. Based on the peak strength recorded, the

Mohr's circles at failure can be drawn and the peak friction angle can be determined as shown in Figure 3.17. The results of triaxial tests are summarized in Table 3.6. As shown by the data, there is a gradual increase in the friction angle of the soil as the density increases. The friction angle is quite high, which is normal for angular soils such as JSC-1A. The range of the friction angle is similar to that reported for lunar soil (Carrier et al. 1991).

However, the measured cohesion was too low, as is consistent for typical silty sands, to make a meaningful conclusion here. The reason is that the triaxial tests were conducted with a pretty high effective confining pressure while to measure cohesion accurately, one needs to use a very low effective confining pressure. As pointed out by Das (1985), determination of cohesion from triaxial tests may be difficult as a straight line extrapolation of the failure envelope back to the normal stress of zero is not very accurate. In fact, the strength envelope is more likely to be curved near small confining pressure. However, due to the fact that there is neither an easy way to perform tensile test on a soil nor a reliable way to conduct triaxial test at a low effective stress (Mitchell, 1993), how to determine accurately the cohesion of a soil remains a challenge. There is also considerable uncertainty associated with the causes of the cohesion recorded, as stated by Willman et al. (1995).

Table 3.6 Results of triaxial test of JSC-1A

Average Bulk Density (kg/m ³)	Relative Density (%)	Friction Angle (°)
1659	24.6	41.9
1789	54.7	46.5
1940	84.6	56.7

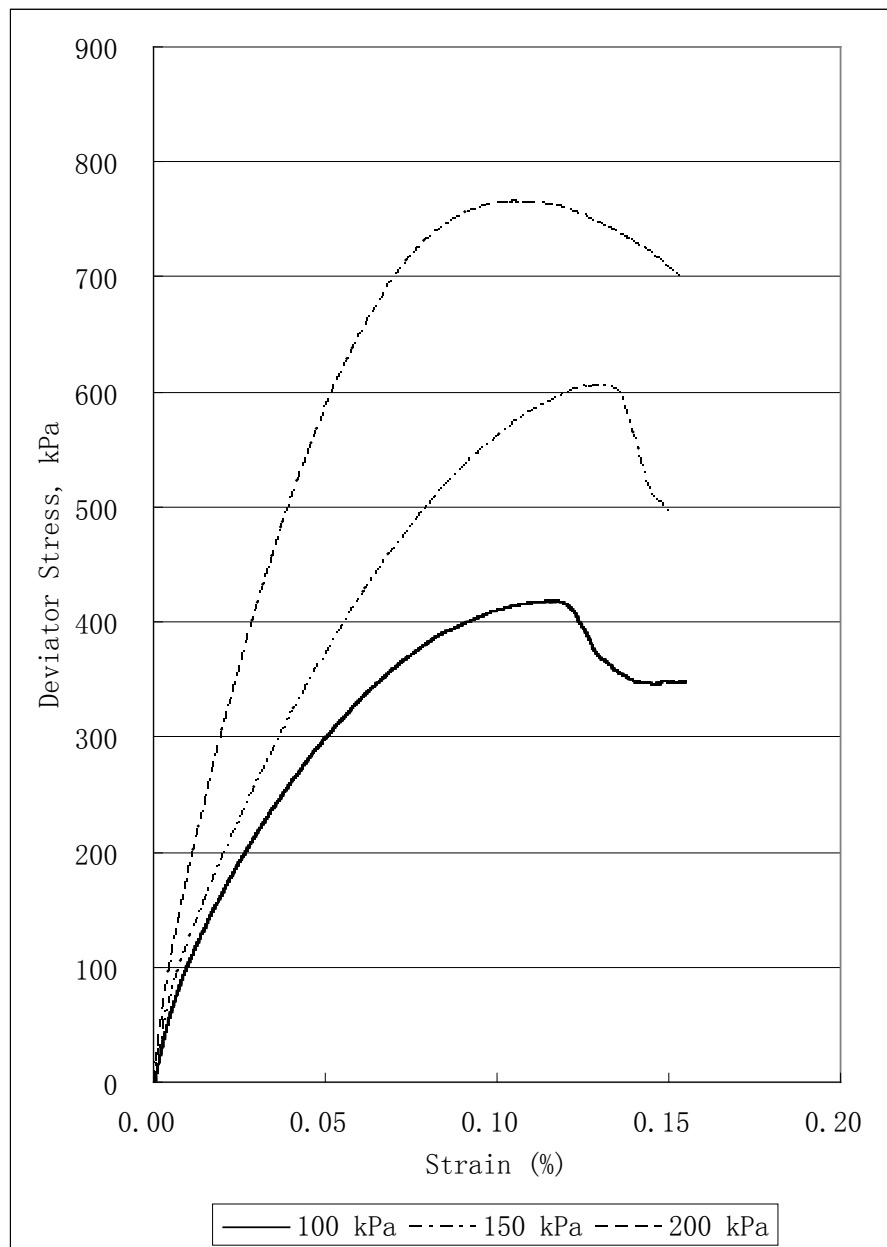


Figure 3.16 Deviator stress versus axial strain recorded in triaxial tests on JSC-1A (density = 1659 kg/m³)

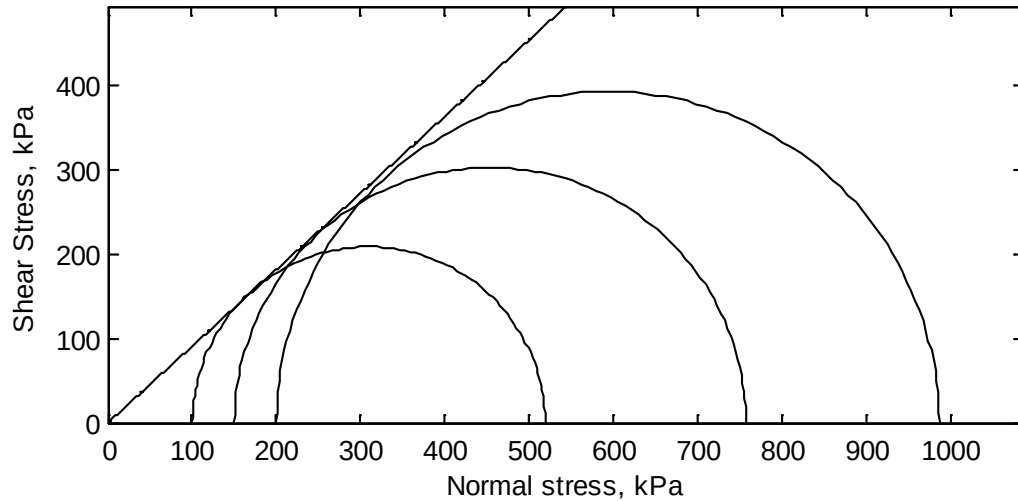


Figure 3.17 Mohr stress circles for JSC-1A (density = 1659 kg/m^3)

3.2.7 Compressibility

Compressibility describes the volume change, or densification, that occurs when a confining stress is applied to soil. It is an important concept in geotechnical engineering in the design of certain structural foundations whose settlement is concerned. If the load applied during trafficking and excavation is larger than the resistance the soil against the compressibility, compressibility of the soils occurs. Hence, it is also necessary to know the compressibility of a soil in the design of vehicle and excavation tools. The soil compressibility parameters can be determined in a consolidation test conducted in the laboratory following the standard procedures described in ASTM D2435. In a consolidation test, a soil sample is subject to a series of one-dimensional loads with a load increment ratio $\Delta p/p = 1$ and the corresponding deformation is measured. Then the

results are plotted as void ratio versus logarithm of applied effective vertical stress. From the straight-line part of the relationship, the compression index, C_c is determined as

$$C_c = \frac{e_1 - e_2}{\log\left(\frac{p_2}{p_1}\right)} \quad (3.14)$$

in which e_1 and e_2 are the void ratios of the soil corresponding to effective vertical stress of p_1 and p_2 , respectively. Then, the vertical loading is gradually reduced with a load decrement ratio $\Delta p/p = 1$ and the resulting void ratios are measured. From the recorded data on the unloading line, the swelling index of the soil can be determined as

$$C_s = \frac{e_1 - e_2}{\log\left(\frac{p_2}{p_1}\right)} \quad (3.15)$$

The following general procedure was used for consolidation tests on JSC-1A.

1. Weigh 1 kg of air-dry soil. Mix the soil by adding water in the mechanical mixer until the mixture appears a uniform color and consistency. Transfer the mixture in layers into aluminum tube. At each layer, vibrate the tube to eliminate the air bubbles. Air-dry the mixture in the tube for 2 days.
2. Prepare the consolidation equipment. Measure the diameter of sample ring and compute the area of sample ring A_r . Obtain the two porous stones, check their fit to the sample ring, and put them in a beaker of warm water to deaerate and saturate.
3. Carefully extract the soil sample from the tube, cut a short length for the test and trim it to fit the sample ring diameter. Trim the sample to the nominal height of 20 mm and record this value H_i . Also determine the initial mass of the sample + ring

and record this value. Next put a piece of filter paper on each face of the sample. Cover with a damp towel to avoid sample dehydration.

4. Calibrate the consolidometer by putting the loading block onto two porous stones with two pieces of filter paper between. As shown in Figure 3.18 fix the dial gauge to the cross-arm assembly and apply the load sequence to determine the equipment compression for each load increment. Record these ΔH_e values.



Figure 3.18 Typical consolidation setup

5. Apply a seating load of approximately 5 kPa and ensure that the porous stones do not hang on the sample ring. Within 5 minutes of load application, zero the deformation dial gauge (leaving the seating load on the soil).

6. Apply the first load increment which should be a sufficient additional load to develop the first desired load increment. Typically the load should be applied in a geometric progression with a load ratio of $\Delta p/p = 1$ equal to one. This is so that the soil does not build up internal resistance to the loads. If this happens the total deformation of the sample is usually less than obtained if the load increment ratio $\Delta p/p = 1$ is used. In this case, the load was applied in 2.5, 5, 10, 20, 40, 20, 10, 5, 2.5 psi in sequence. Simultaneously take deformation readings at pre-determined elapsed times. Typically 0.1, 0.2, 0.5, 1.0, 2.0, 4.0, 8.0, 15.0, and 30.0 minutes, and 1, 2, 4, 8, and 24 hours for each load are satisfactory. After the 15 or 16 min reading fill the saturation ring with enough water that it will not evaporate below the top porous stone and dehydrate the top of the sample. Check whether the sample is swelling and, if so, quickly remove the saturation water with a battery bulb. In this case put damp towels, wet cotton or other material around the sample to keep it from dehydrating.
7. After 24h, or when ΔH between two successive readings is sufficiently small, change the load to the next value and again take elapsed-time interval readings as in Step f above. If the saturation ring was emptied in Step f, fill it after the 15 min reading. No swell should occur under a 50 kPa pressure.
8. Continue changing loads throughout the desired load range and taking elapsed time vs. deformation dial readings through the load range of the consolidometer.
9. After the specimen has consolidated under the maximum load, remove the load in decrements equal to the loading increments. Take readings of the dial indicator as each decrement is removed to determine the rebound of the specimen.

10. For each load increment and decrement, plot the dial reading versus the time data on a semi-logarithmic plot. Plot the dial reading on the arithmetic scale and the corresponding elapsed time on a logarithmic scale. Determine the end of primary consolidation D_{100} by fitting a tangent line to the steepest part of the plot. At the intersection of the two tangent lines draw a horizontal line to the ordinate and read D_{100} .
11. Weigh a clean, dry evaporating dish for a water content container. Now carefully remove all the water from the saturation ring using a battery bulb, sponges, paper towels, and so on. Next remove the sample load and quickly remove the sample ring from the consolidometer. Push the wet soil cake out of the ring into the evaporating dish and rapidly weigh the dish + wet soil. Put these data on a water content sheet from this lab manual. Now put the sample in the oven to dry for 12 to 16 h. Also, if not previously done, determine the mass of the empty sample ring. Boil the porous stones to clean any clay particles out of the pores.
12. On the next day return to the lab and determine the mass of the oven dry soil cake + dish. Record on the data sheet and compute the mass of dry soil solids M_s and the mass water in soil cake M_{wf} .
13. Determine the final void height H_{vf} by dividing the mass water M_{wf} by the area of sample area A_r . Compute the change in sample height ΔH using equation (3.16).

$$\Delta H = D_2 - D_1 - \Delta H_e \quad (3.16)$$

where D_1 is the initial dial reading, D_2 is the final dial reading, ΔH_e is the final equipment calibration correction factor. Compute the height of solids H_s using equation (3.17).

$$H_s = H_i - \Delta H - H_{vf} \quad (3.17)$$

Determine the initial height of voids H_{vi} by subtracting initial sample height H_i from the height of soil solids H_s . Determine the initial void ratio e_0 by dividing the initial height of voids H_{vi} by the height of soil solids H_s .

14. Compute the void ratios of the specimen corresponding to different load increments and decrements. The void ratio is numerically equal to the height of the voids divided by the height of the solids and can be calculated via the following equation:

$$e = e_0 - \frac{(D_{100} + \Delta H_e)}{H_s} \quad (3.18)$$

15. Plot the void ratios obtained in the previous step versus the corresponding pressure on a semilogarithmic plot where the void ratio is on the arithmetic scale and pressure on the logarithmic scale. Determine the compression index using equation (3.14). Determine the swelling index using equation (3.15).

The results of consolidation tests on JSC-1A are shown in Figure 3.19. From the data it is found that the compression index of JSC-1A is 0.068 and the swelling index is 0.001. Both values are pretty low, indicating the soil is less compressible with lower

swelling than most terrestrial soils. This agrees with the information about lunar regolith provided in the Lunar Sourcebook (*Carrier et al.*, 1991).

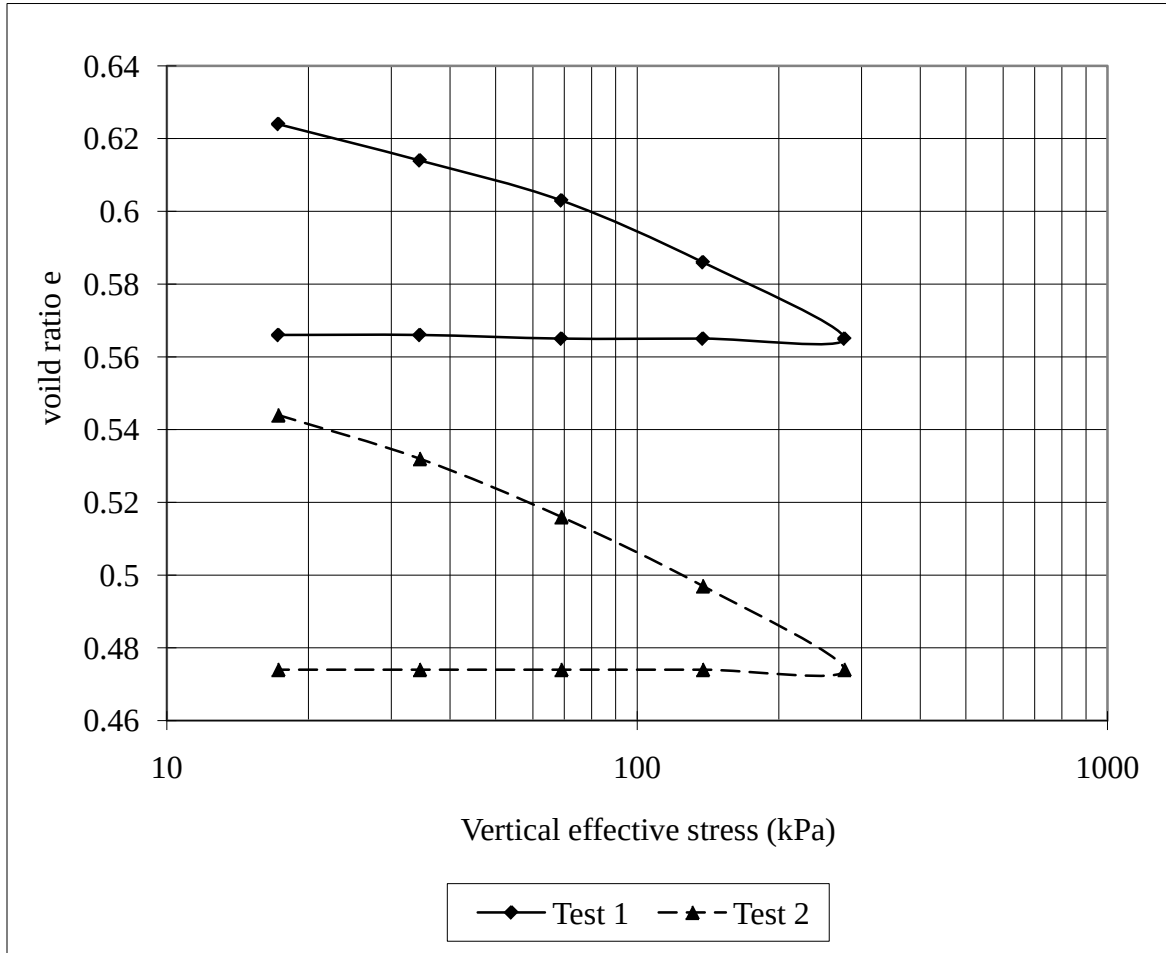


Figure 3.19 Plot of void ratio versus pressure for JSC-1A

3.3 CONCLUSIONS OF JSC-1A LUNAR MARE REGOLITH SIMULANT

A group of laboratory tests have been conducted in Case Western Reserve University (CWRU) to determine the geotechnical properties of a new lunar mare regolith simulant JSC-1A. Just as for benchmark soils like Nevada Sand, other groups (Arslan et al., 2007, Alshibli et al., 2009) have made independent measurements to establish benchmark properties of JSC-1A. The test results determined by different

groups are presented in Table 3.7. As shown from the Table 3.7, the test results are very close.

Table 3.7 Soil Properties of JSC-1A

Soil Properties \ Sources	CWRU	Alshibli et al.	Arslan et al.
D_{10} (mm)	0.017	0.016 [*]	0.020
D_{30} (mm)	0.042	0.043 [*]	0.054
D_{50} (mm)	0.086	0.090 [*]	0.100
D_{60} (mm)	0.110	0.120 [*]	0.137
Coefficient of Uniformity, C_U	6.47	7.50 [†]	6.85
Coefficient of Curvature, C_C	0.94	0.96 [†]	1.06
ρ_{max} (g/cm ³)	2.028	2.016	-
ρ_{min} (g/cm ³)	1.566	1.566	-
Specific Gravity, G_s	2.875	2.92	-
e_{max}	0.826	0.877	-
e_{min}	0.410	0.448	-
n_{max}	0.455	0.467	-
n_{min}	0.295	0.309	-
USCS Classification	SP - SM	-	-
Cohesion, c (kPa)	-	2 - 5	1.4 - 2.4
Friction Angle, ϕ (°)	41.9 - 51.6	40 - 59	43.9 - 48.8
Dilatancy Angle, (°)	-	3 - 26	8 - 36
Compression Index, C_c	0.068	-	-
Swelling Index, C_s	0.001	-	-

^{*} Estimated from the particle size distribution plot.

[†] Calculated based on the estimated values.

The measurements of JSC-1A form the basis to judge whether the simulant is effective in simulating the properties of lunar soil and are essential in the study of vehicle mobility and ISRU. Based on the results of this study, a summary comparing the properties of JSC-1A to the lunar soil and past lunar regolith simulants is presented in Table 3.8 and the following conclusions can be drawn:

1) The particle size distribution of JSC-1A simulant falls between +1 standard deviation and -1 standard deviation of typical lunar soils. In most particle size range, it is close to the average of lunar soils. The simulant is classified as a poorly-graded silty sand. There is no segregation of particles during transportation. Single compaction and shear events had little effect on the particle size distribution. As is normal, sizes below one micron are not considered here, even though sub-micron fines are more prevalent on the moon than on earth.

2) The average specific gravity was found to be 2.875, which is a little bit lower than recommended typical value of lunar soil. However, it is still considered within the range for the lunar soil as the minimum value has been approximated as 2.3.

3) The maximum void ratio of the simulant is 0.826 while the minimum void ratio is 0.410. The best way to achieve high compaction for the simulant is by vibration with a vertical surcharge. The range in mass density that can be achieved by JSC-1A is close to that estimated for lunar soils.

4) The peak angle of internal friction of JSC-1A is high and it increases with density. It is quite difficult to measure the cohesion of dry simulant accurately as the cohesion is relatively low.

5) The compressibility and swelling index of JSC-1A are considerably lower than recommended typical value of lunar soil. However, it is still considered within the range for the lunar soil.

In summary, the most geotechnical properties of JSC-1A are similar to that of lunar soils except the cohesion, which is difficult to measure. Developing a reliable way and understanding the physics behind the small amount of cohesion need further study.

Table 3.8 Comparison of JSC-1A with lunar regolith and lunar regolith simulants

Soil Properties	JSC-1A	Lunar Regolith	MLS-1	JSC-1
Median Particle Size (mm)	0.085	0.04 - 0.13	0.095	0.098 - 0.117
D_{10} (mm)	0.017	0.013	0.019	0.019
D_{30} (mm)	0.042	0.034	0.049	0.057
D_{60} (mm)	0.110	0.140	0.150	0.150
Coefficient of Uniformity, C_U	6.47	10.769	7.895	7.5
Coefficient of Curvature, C_C	0.94	0.635	0.842	1.12
ρ_{max} (g/cc)	2.03	1.93	2.20	1.80
ρ_{min} (g/cc)	1.57	0.87±0.03	1.56	1.33
Specific Gravity, G_s	2.875	2.3 - >3.2	3.2	2.9
e_{max}	0.826	2.37	1.05	1.18
e_{min}	0.410	0.670	0.454	0.61
n_{max}	0.455	0.970	-	-
n_{min}	0.295	0.416	-	-
USCS Classification	SP - SM	SW-SM to ML	SP - SM	SW - SM
Cohesion, c (kPa)	-	0.1 - 1.0*	0 - 0.9	0 - 14.4
Friction Angle, ϕ (°)	41.9 - 51.6	30 - 50*	37 - 58	44.4 - 53.6
Compression Index, C_c	0.068	0.3 - 0.05*	-	-
Swelling Index, C_s	0.001	0.003*	-	-

*Recommended typical value

3.4 PARTICLE SIZE DISTRIBUTION OF JSC-1AF DUST SIMULANT

As described in Chapter Two, the median particle size of lunar regolith is between 40 and 130 μm , with an average of 70 μm . Approximately half of the regolith is composed of particles that are very fine in size, much finer than terrestrial beach sand, for example. The Apollo missions showed that this lunar dust caused abrasion and contamination to the equipments and astronaut EVA suits and physiological irritation to the astronauts. Therefore, the 2005 Lunar Regolith Simulant Materials Workshop identified the need of standard lunar dust simulants for studies related to human toxicology, surface abrasion, and dust adhesion on system components. Dust SLRS materials are defined as the fraction of the material that is less than 50 μm in size.

JSC-1AF is a lunar dust simulant produced to support the NASA's future lunar exploration. It only composes of fine particles less than or equal to 50 μm in diameter. As described in the section 3.1, JSC-1AF ("fine fraction") is part of a suite three simulant materials labeled JSC-1AF, JSC-1A, and JSC-1AC that were created to match, as closely as possible, the composition of previous lunar regolith simulant JSC-1. JSC-1AF consists primarily of components of the plagioclase and basaltic glass. In addition, it contains components of the pyroxene and olivine, along with various trace minerals (Anonymous, 2006). Faierson et al. (2008) compared the bulk composition of JSC-1AF to that of the lunar samples from the Apollo and Luna missions as shown in Table 3.9. As shown from the table, the bulk composition of JSC-1AF is a close match.

Table 3.9 Bulk composition of lunar regolith and simulant JSC-1AF (Faierson et al., 2008)

Constituents	Maria		Highlands		Simulant
	Apollo 14	Luna 16	Luna 20	Apollo 16	JSC-1AF
SiO ₂	47.93	41.70	45.40	44.94	47.1
TiO ₂	1.74	3.38	.47	.58	1.87
Al ₂ O ₃	17.6	15.33	23.44	26.71	17.1
FeO	10.37	16.64	7.37	5.49	7.57
Fe ₂ O ₃	-	-	-	-	3.41
MgO	9.24	8.78	9.19	5.96	6.9
CaO	11.19	12.50	13.38	15.57	10.3

Note: values in weight %.

Both the development of dust mitigation technologies and toxicological experiments will involve the use of the JSC-1AF dust simulant. Therefore, it is very important to characterize the properties of this simulant. Obviously, the grain size is the most important property that must be matched. A small amount of JSC-1AF dust simulant was distributed to CWRU to perform particle size distribution analysis. In order to compute the particle size distribution, the specific gravity of the material has to be known first. Two specific gravity tests (ASTM D 854) were performed on JSC-1A. The average specific gravity of JSC-1AF was found to be 2.818 with a standard deviation of ± 0.006 . Two hydrometer tests for fine particles (ASTM D423) were performed to determine the particle size distribution of JSC-1AF as shown in Figure 3.20. As shown in the figure, the results of two samples are almost identical. D_{16} , D_{50} , and D_{84} for JSC-1AF were determined from the figure to be 7, 16, and 25 μm , respectively. Therefore, the average particle size of JSC-1AF can be calculated to be 16 μm , and the median size is 16 μm . It should be noted the hydrometer test is used to determine the particle size of material smaller than 75 μm while the JSC-1AF is less than or equal to 50 μm . Other

technique, for example, the laser fraction, may be a better choice to determine the particle size distribution of JSC-1AF.

In summary, the bulk composition of JSC-1AF is a close match to the lunar regolith. JSC-1AF can be used as a dust simulant to test systems. Currently, 1 metric ton JSC-1AF is available in Orbital Technologies Corporation for scientific study.

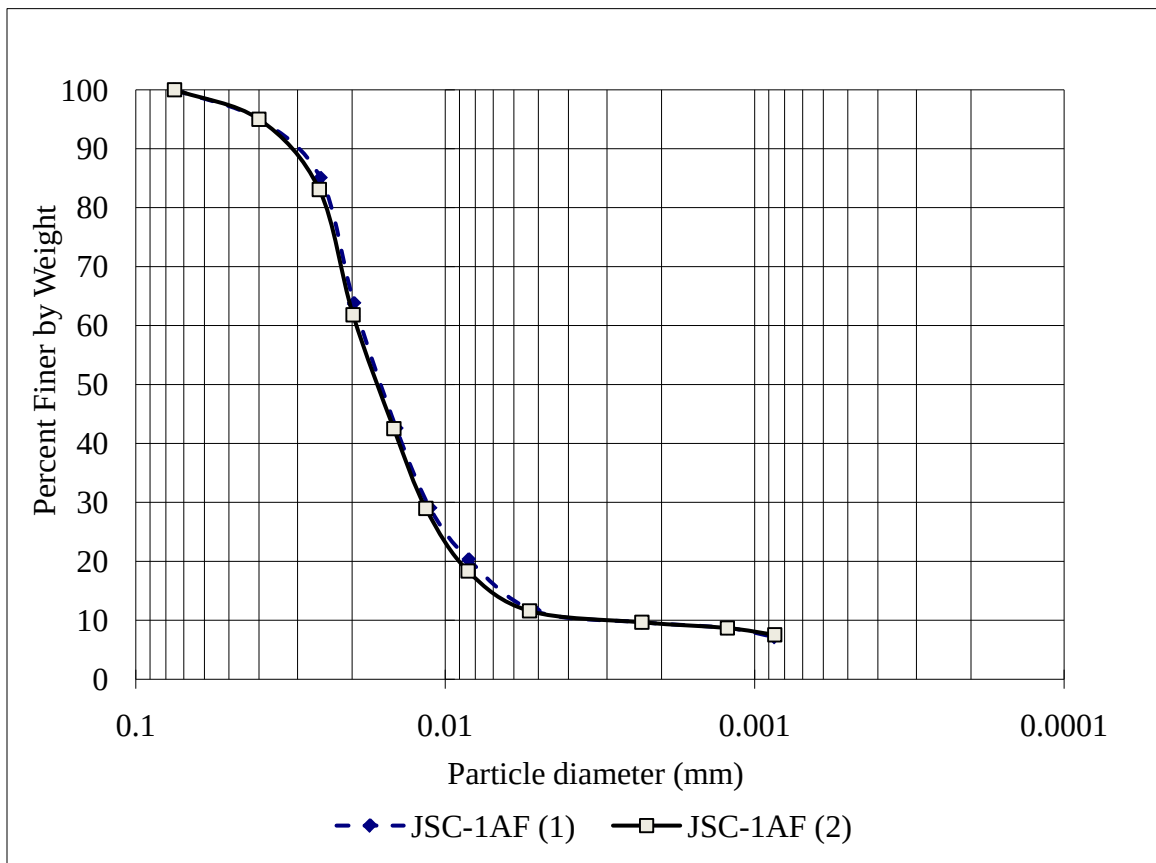


Figure 3.20 Particle size distribution of JSC-1AF

CHAPTER 4 GEOTECHNICAL PROPERTIES OF NU-LHT-2M

NASA's new mission to the moon is a part of the larger framework of a sustained and affordable space exploration architecture that will extend the human presence across the solar system. Several important tasks of these missions, such as In-Situ Resource Utilization (ISRU) and Vehicle Mobility, require a thorough understanding of the geotechnical properties of lunar soils and 'equivalent' soils (simulants) in which to test systems. Lunar samples returned from the Apollo missions represent diverse geological materials. As reviewed in the Chapter Two, these lunar samples were processed and have been studied in considerable detail using numerous characterization techniques. However, due to the limited quantity of lunar soils brought back to the earth and the limitations of in-situ testing devices during these missions, some important geotechnical properties such as strength, stiffness, compressibility, and compaction of the lunar soils were not fully understood. To satisfy the needs of the lunar research and development communities with large quantities of lunar regolith-like soils, new standard lunar simulants have been developed. This chapter describes both the development and geotechnical characterization of a lunar regolith simulant, NU-LHT-2M, which is intended to be used as a standard lunar highland regolith simulant for future lunar operations.

4.1 METHOD FOR CREATING NU-LHT-2M

The Lunar Regolith Simulant Materials Workshop was held in Huntsville, AL, on January 24-25, 2005 by the Marshall Space Flight Center (MSFC). “The purpose of the workshop was to identify the needs for widely-accepted, standard lunar regolith simulant (SLRS) materials to perform research and development of technologies required for lunar operations and to establish a common, traceable, and repeatable process regarding the standardization, characterization, and distribution of lunar simulants for use by the scientific and engineering communities”, stated by Sibille et al. (2005). SLRS materials must be able to support both near term and long term needs and be accurately characterized and evaluated. In this workshop, two main root simulants, a mare basaltic simulant and an anorthositic highland simulant, have been proposed. The development of the mare basalt root simulant, JSC-1A, has been described in detail in Chapter Three. The highland anorthosite root simulant should be a high-Ca terrestrial anorthosite in order to best match the high Ca and Al contents of lunar anorthosites. These simulants must be produced from terrestrial rock and mineral sources that match those of lunar materials in terms of chemistry and mineralogy, as well as physical and geotechnical properties (Sibille et al., 2005).

To fulfill the needs of lunar highland simulants, NASA’s Marshall Space Flight Center has established a cooperative agreement with U.S. Geological Survey (USGS) to research and prepare lunar regolith simulants. Four NU-LHT (NASA/USGS-Lunar Highlands Type) regolith simulants have been produced to date: NU-LHT-1M, -1D, -2M, and -2C. The “M” (medium) designation indicates a simulant with a grain size of smaller

than 1mm, “D” (dust) a simulant with a grain size of $<36\text{ }\mu\text{m}$, and “C” (coarse) a simulant with a 10 cm maximum particle size. The composition of these simulants is based on the average Apollo 16 regolith chemical composition. The mixing model and cation normative mineral calculation, which is based on crystalline lithic components, was used to match the overall mineralogy as closely as possible. Stoesser et al. (2008) stated that “the mixing model use to create these simulants is based on cationic normative mineral proportions derived from the target chemical composition to approximate lunar modal mineralogy rather than chemical composition per se”. All these simulants contains crystalline plagioclase, pyroxenes, olivine, trace minerals, synthetic agglutinate and a pure glass fraction. The 2C simulant also includes synthetic impact melt breccias clasts for the particles up to 10 cm. The particle type composition data can be found in Table 4.1. The bulk raw materials used to create these simulants include clinopyroxene-norite, anorthosite, orthopyroxene, hartzburgite and noritic mill waste from the Stillwater layer intrusion, southern Montana, courtesy of the Stillwater Mining Company (refer to Figure 4.1). Olivine was obtained from the Twin Sisters dunite, Washington State. Added trace minerals include beach sand ilmenite, chromite, synthetic β -tricalcium phosphate (whitlockite), gem grade fluor-apatite, and pyrite. The agglutinate, glasses, and synthetic breccias were designed and produced at the Zybek Advanced Products, Inc. plasma melting facility located in Boulder, Colorado, using Stillwater mill waste feedstock for the melt (refer to Figure 4.2). These simulants do not include nanophase- Fe^0 which is abundant in lunar dust. The M and C simulant particle size distribution (down to $0.4\text{ }\mu\text{m}$) approximates that of the Apollo 16 regolith and the regolith in general.

Table 4.1 Particle type modal data: regolith and simulants (Schrader et al., 2009)

	64001/ 64002	NU- LHT- 1M	NU- LHT -2M	OB-1	JSC-1	JSC- 1A	JSC- 1AF	FJS-1	MLS-1
Lithic Fragments	31.11	0.00	0.00	0.00	90.92	90.92	91.93	80.18	52.28
Glass	8.88	22.37	7.17	52.63	0.00	0.00	0.00	0.53	36.57
Agglutinates	32.51	29.02	23.49	0.00	0.00	0.00	0.00	0.00	0.00
Plagioclase	23.32	38.78	54.89	43.95	1.54	1.54	3.39	14.11	2.60
(<i>Plag. An%</i>)	95	80	80	75	68	70	70	50?	47
Olivine	0.00	2.88	9.51	0.04	5.63	5.63	4.13	1.13	0.01
Clinopyroxene	0.64	2.04	3.98	0.07	1.33	1.33	0.42	1.20	2.21
Orthopyroxene	3.24	4.37	0.20	0.00	0.01	0.01	0.01	0.04	0.03
Spinel minerals	0.03	0.05	0.01	0.19	0.00	0.04	0.02	0.05	0.03
Fe-sulfide	0.01	0.00	0.04	0.00		0.00	0.00	0.00	0.00
Ca-phosphates	0.12	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.00
Ilmenite	0.13	0.33	0.19	0.00	0.00	0.08	0.00	0.15	1.07
Native Iron	0.01	0.00	0.00	0.00		0.00	0.00	0.00	0.00
Other (sim. only)		0.16	0.07	3.12		0.46	0.09	2.62	5.21
Total	100	100	100	100	100	100	100	100	100

Note: these data report volume% of particles.

The chemistry or mineralogy may not have much effect on the critical properties required for engineering design; therefore this study is focused on the physical and mechanical properties of these simulants. The following section will discuss the geotechnical properties of one of these highland simulants: NU-LHT-2M.



Figure 4.1 Image of the Stillwater ultramafic layered intrusion and Stillwater platinum mine looking northwest showing location of source materials used in LHT-series highland simulants (credit Lowers et al., 2008)

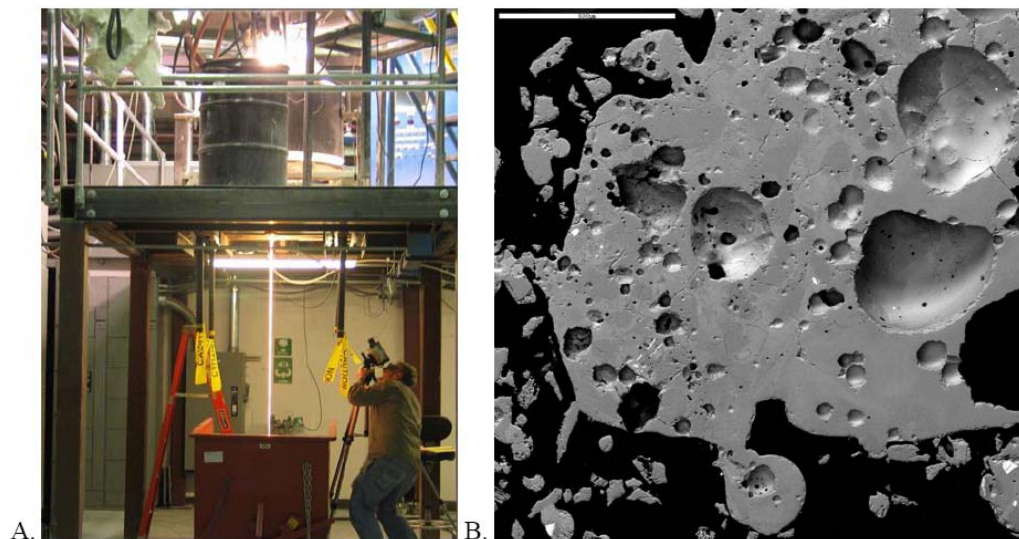


Figure 4.2 Melt stream to produce glass being collected at the Zybek Advanced Products, Inc. plasma melter facility, Boulder, Colorado (left). Backscattered electron image of pseudo-agglutinate glass produced from plasma melting of mill sand from the Stillwater complex (right, scale bar is 500 μm) (credit Lowers et al., 2008)

4.2 GEOTECHNICAL PROPERTIES OF NU-LHT-2M

According to Gustafson (2009), after the remaining three tons of JSC-1A are sold, ORBITEC has no plans to fund additional production of more JSC-1A, JSC-1AF, JSC-1AC, or JSC-1AVF in the future. NU-LHT simulant development may make JSC-1A family of simulants obsolete. As the second prototype lunar highland simulant, NU-LHT-2M will be used in many Earth-based studies such as testing of rovers, excavators, regolith transport devices, construction techniques, and radiation hardening technology. Therefore, it is very important to determine the geotechnical properties of this simulant. The laboratory tests conducted to measure the geotechnical properties of NU-LHT-2M followed strictly the standards specified by ASTM (1991), which are the standards commonly used by the geotechnical engineering community, so as to ensure the comparability of the results. These tests and corresponding ASTM standards are summarized in Table 3.1. Several tests were repeated multiple times in order to check the repeatability of the data. The test procedures have been described in detail in Chapter 3 and therefore are not included in this section. This section discusses the studies of particle size distribution, specific gravity, maximum and minimum densities, compaction characteristics, shear strength parameters and compressibility of NU-LHT-2M. The test results are compared with the information about lunar regolith provided in the Lunar Sourcebook.

4.2.1 Particle Size Distribution

The particle size distribution of a material controls the dominant physical nature of the material, such as shear strength and compressibility, as well as optical, thermal,

and seismic properties. Therefore, the particle size distribution of the material is the most important parameter in understanding its geotechnical properties. The 2005 Lunar Regolith Simulant Materials Workshop clearly stated that the particle size of the lunar regolith must to be matched. Based on the data from Apollo missions, the particle size distribution of lunar soils had a quite significant variation with depth and from location to location (Carrier et al. 1991, Carrier, 2003). In fact, the spatial variation in lunar soils is more significant than that commonly seen on the earth. Based on all the available data on particle size distribution of lunar regolith, a band of average particle size distribution with $\pm$ one standard deviation has been established. Therefore, the first step of the laboratory testing program is to investigate whether the particle size distribution of NU-LHT-2M matches that of lunar soils.

The tests to determine the particle size distribution of NU-LHT-2M include sample preparation (ASTM D421), sieve analysis for coarse particles (ASTM D422) and hydrometer tests for fine particles (ASTM D423). The testing procedures were presented in detail in section 3.2.1. The results of the measurements are shown in Figure 4.3, together with the average, +1 standard deviation, and -1 standard deviation of lunar soils that were tested in the past. As shown in the figure, the results from the two samples taken are almost identical, suggesting that there was no segregation of particles during the transportation process. In general, the particle size distribution of NU-LHT-2M falls between the +1 standard deviation and -1 standard deviation of lunar soils but not quite at the average range. There are also a small fraction of fine particles (smaller than two microns) that were not reported in the data on lunar regolith. At the same time, the LHT simulant has fewer particles larger than 1 mm in comparison with lunar regolith. A direct

consequence might be a lower shear strength for the simulant as coarse particles typically results in higher friction angle.

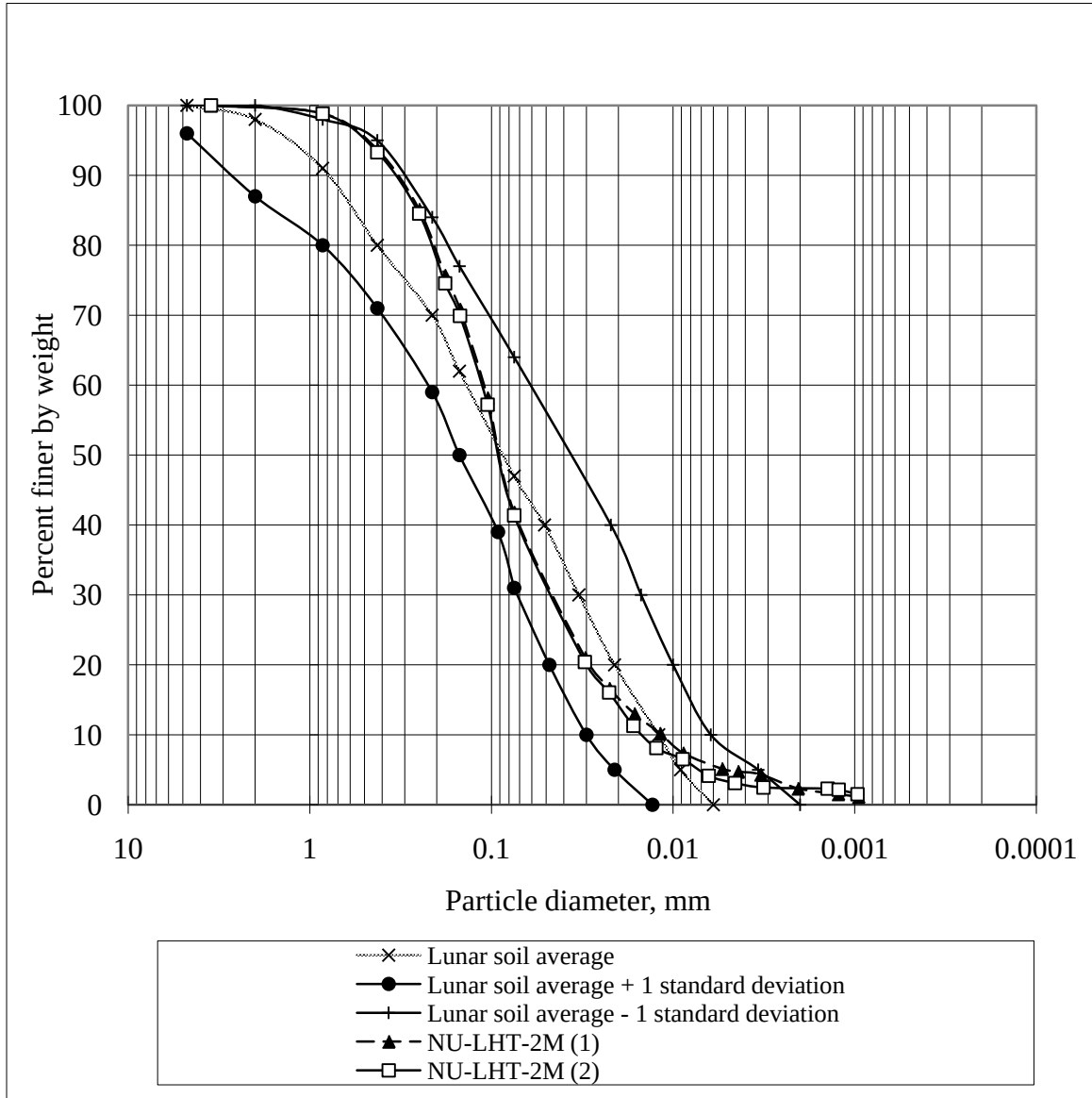


Figure 4.3 Particle size distribution of NU-LHT-2M

In addition to particle size distribution tests, Atterberg limit tests (ASTM D4318) were also carried out to determine the plastic and liquid limits of the fines. However, it was found that the soil has very little plasticity and the tests did not produce consistent

results. Based on the particle size distribution and the fact that the soil has little plasticity, the soil can be classified as a silty sand (SM) using the Unified Soil Classification System (ASTM D2481), the same as most lunar regolith (Carrier, 2003). The main characteristics of the soil can be summarized as the following:

- a) It contains 58% of sand and 42% of silt;
- b) It has $D_{10} = 0.013$ mm, $D_{30} = 0.047$ mm, and $D_{60} = 0.110$ mm, where D_{10} , D_{30} , and D_{60} are the diameters which are larger than 10%, 30%, or 60% of the particles (by weight), respectively.
- c) The coefficient of uniformity $C_u = D_{60}/D_{10} = 8.46$, and the coefficient of curvature $C_c = D_{30}^2/(D_{10} \times D_{60}) = 1.54$. Therefore, the soil is a well-graded silty sand.

Since the cost of making NU-LHT-2M is quite high, it is necessary to know whether the simulant can be reused after a test. After a soil sample went through the compaction test (using the standard Procter device), its particle size distribution was studied again to investigate the effects of mechanical compaction on the particle size distribution. In addition, the particle size distribution was measured again after a sample was tested in a triaxial testing device up to failure to study the possible influence of shear failure on particle size. The results of particle size distribution after soil samples were subjected to mechanical compaction and triaxial compression to failure are shown in Figure 4.4, together with the results on two samples that were original. It can be seen that these two processes after a single repetition had little impact on the particle size distribution of the NU-LHT-2M simulant. Thus the simulant can be used more than once

in most soil tests, as far as the size distribution is concerned. However, tracking changes in size distribution after prolonged repeated use is still merited.

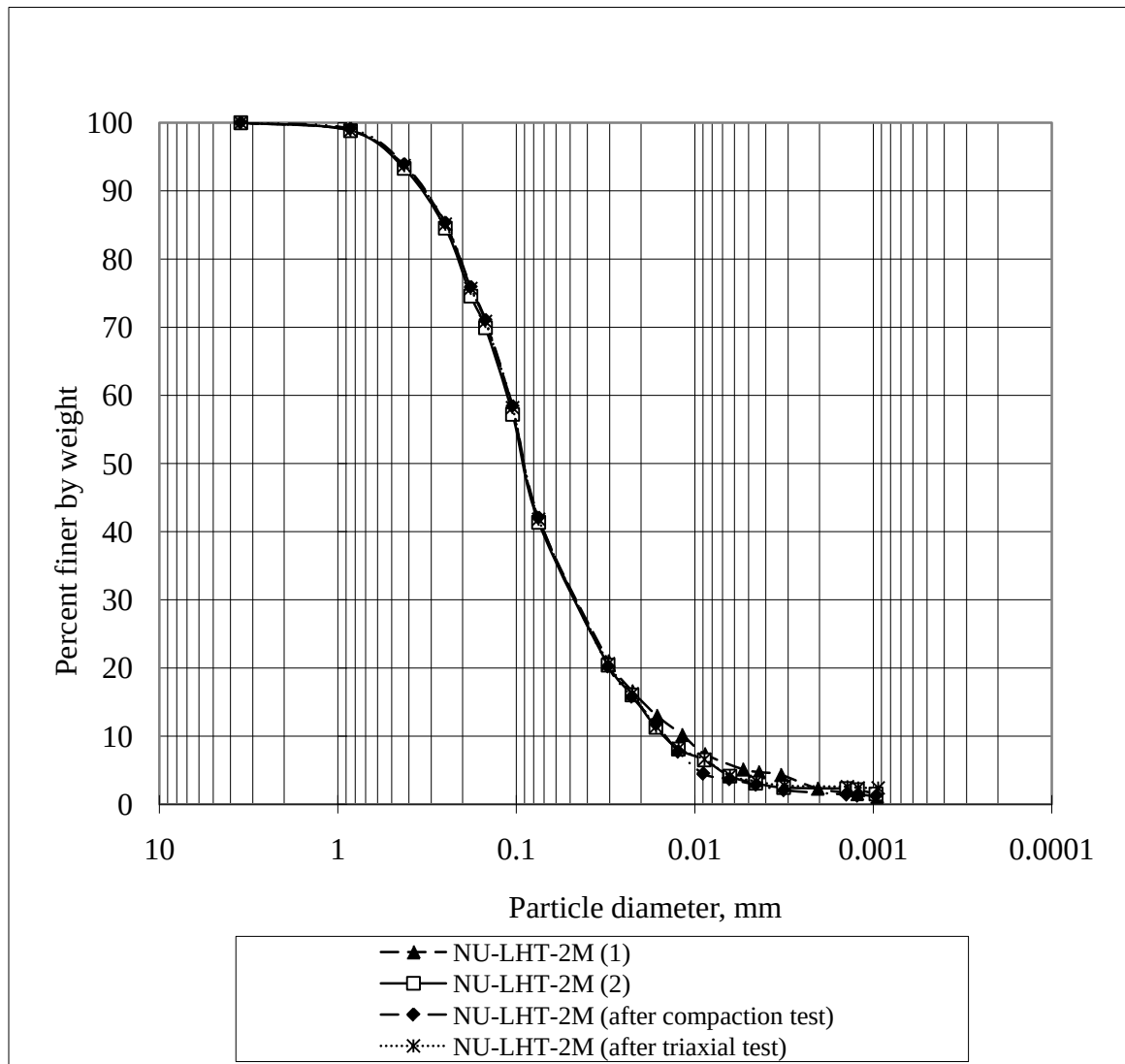


Figure 4.4 Particle size distribution of NU-LHT-2M after compaction and triaxial tests

4.2.2 Specific Gravity

The specific gravity of a soil is defined as the ratio of the mass density of solid particles to the mass density of pure water at 4°C. Values for lunar soils range from 2.3 to 3.2 and a value of 3.1 is recommended for general scientific and engineering analysis of lunar soils taking sub-granular porosity into account (Carrier et al., 1991). In this study, two samples of NU-LHT-2M were tested following ASTM standard D854. The testing procedures were discussed in detail in section 3.2.2. The results are summarized in Table 4.2. The average specific gravity of NU-LHT-2M was found to be 2.749, which is a little bit lower than that of typical lunar soils. In addition, there was the concern that the particles in different size range may have different specific gravities. Therefore, specific gravity tests were conducted on particles larger or smaller than 0.075m (or the opening of #200 sieve). The results are also listed in Table 4.2. The values show differences in their respective specific gravities. However, the measured differences between the three groups are within the experimental uncertainty of 2% for the test.

Table 4.2 Results of specific gravity tests of NU-LHT-2M

Specific Gravity	NU-LHT-2M	NU-LHT-2M (only particles passing #200 sieve)	NU-LHT-2M (only particle retained above #200 sieve)
Test 1	2.735	2.785	2.748
Test 2	2.743	2.790	2.749
Test 3	2.768	2.771	2.746
Average	2.749	2.782	2.748

4.2.3 Maximum and Minimum Densities

The state of density of a dry soil such as NU-LHT-2M is typically measured as a relative term with regards to the maximum and minimum densities possible. Therefore, it is important to determine the maximum and minimum densities of NU-LHT-2M. From the measured in-situ density of the soil, it is possible to calculate its relative density as

$$R_D = \frac{\rho_{max}}{\rho} \times \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}} \times 100\% \quad (4.1)$$

where, ρ_{max} is the maximum bulk density, ρ_{min} is the minimum bulk density, and ρ is the bulk density of the sample. The relative density generally refers to the degree of particle packing (which is particle size and shape distribution dependent) of a soil. It is probably the most important factor in determining the strength and stiffness of a soil. The relative density of the lunar soil is vital to vehicle mobility and ISRU operations as it directly affects the shear strength of the soil.

ASTM D4253 and ASTM D4254 standard testing procedures were followed to determine the maximum and minimum index densities, respectively. The detail of the testing procedures was presented in section 3.2.3. The results of the tests are summarized in Table 4.1. The maximum and minimum dry densities of NU-LHT-2M are 2057 kg/m³ and 1367 kg/m³, respectively. In comparison, the maximum and minimum densities of lunar regolith obtained from Apollo samples were 1930 kg/m³ and 870 kg/m³, respectively (Carrier et al., 1991).

Table 4.3 Results of maximum and minimum density tests of NU-LHT-2M

NU-LHT-2M	Maximum density (kg/m ³)	Minimum density (kg/m ³)
Test 1	2067	1376
Test 2	2053	1366
Test 3	2051	1359
Average	2057	1367

4.2.4 Porosity and Void Ratio

Based on the maximum and minimum densities and specific gravity of the soil, other engineering properties such as porosity and void ratio of the NU-LHT-2M can be estimated. The bulk density, specific gravity, and porosity of a soil are relates as:

$$n = 1 - \frac{\rho}{G_s \rho_w} \quad (4.2)$$

where ρ is the bulk density of the soil, G_s is the specific gravity of the soil, ρ_w is the density of water (1g/cc), and n is the porosity of the soil. This equation presents the ratio of the volume of the voids to the total volume of the soil sample. The void ratio of a soil in general is defined as a ratio of the volume of the voids to the volume of the soil solids. Mathematically it is related to the soil porosity by the following equation,

$$e = \frac{n}{1-n} = \frac{G_s \rho_w}{\rho} - 1 \quad (4.3)$$

Using equations (4.2) and (4.3) the porosity and void ratio of NU-LHT-2M has been determined and is related to bulk density and relative density as shown in Table 4.4. The average specific gravity of 2.749 for NU-LHT-2M was used to calculate the porosity and void ratio. It is important to note the porosity and void ratio as listed in Table 4.4

actually correspond to the densest and loosest conditions of NU-LHT-2M. Therefore, the maximum porosity of NU-LHT-2M is 0.503 while the minimum porosity is 0.252 and the maximum void ratio of NU-LHT-2M is 1.011 while the minimum void ratio is 0.336. In comparison, the maximum porosity of lunar soil is 0.970 while the minimum porosity is 0.416 and the maximum void ratio of lunar soil is 2.37 while the minimum void ratio is 0.670 (Carrier et al., 1991).

Table 4.4 Porosity and void ratio of JSC-1A

Condition	ρ (kg/m ³)	R_D (%)	n	e
Maximum	2057	100	0.503	1.011
Minimum	1367	0	0.252	0.336

4.2.5 Compaction Test

One of the objectives in this study is to find the best way to achieve compaction for NU-LHT-2M when preparing soil samples in a soil bin, in order to simulate extreme conditions that may be encountered on the moon. In geotechnical engineering, the Proctor compaction test is carried out by compacting the soil to be tested into a standard mold using a standardized compaction energy at several different levels of water content. The water content of the soil has a significant influence on the degree of compaction that can be achieved (Proctor, 1933). The water content that can achieve the best compaction or maximum dry density is called optimum moisture content. The tests reported here followed the standard described in ASTM D698. The detailed testing procedure was described in section 3.2.5. The results of the tests are summarized in Table 4.5. The optimum moisture content was found to be 13.1% and the maximum dry density achieved

by compaction is 1862 kg/m^3 . In comparison to the maximum dry density achieved by vibration, the maximum compacted density by adding water is much lower. Therefore, there is no need to use this method to achieve the maximum compaction. This is not surprising as the fines in the soil have little plasticity. Instead, the method of using vibration with vertical surcharge is much more effective, which can produce a density close to the maximum density.

Table 4.5 Results of compaction tests of NU-LHT-2M

Water Content	Compaction density (kg/m^3)	Dry density (kg/m^3)
9.3%	1942	1777
13.1%	2106	1862
15.2%	2094	1817
20.6%	2085	1728

4.2.6 Shear Strength

Shear strength parameters (cohesion and friction angle) are mechanical parameters of a soil that are critical in vehicle mobility, excavation, regolith moving and construction of roads. Therefore, laboratory tests were carried out to determine these parameters as a function of bulk density. The most common way to characterize the strength of a soil is the Mohr-Coulomb failure criterion, which can be expressed as:

$$\tau_f = c + \sigma \cdot \tan\varphi \quad (4.4)$$

where τ_f is the shear strength at failure on the failure plane, c is the cohesion of the soil, and φ is the friction angle. The triaxial test is the most common way to determine the shear strength of a soil for excavation and mobility.

A total of nine triaxial tests were conducted on NU-LHT-2M samples at three different dry densities following the standards described in ASTM D2850 and ASTM D4767. Due to the limitations of the sample preparation technique specified by ASTM D2850, it is not possible to prepare samples at the maximum or minimum densities. The detailed testing procedures were presented in section 4.2.6. The principal stresses at failure of three samples at different confining pressures are used to generate the Mohr's circle at failure, from which the failure envelopes can be drawn. Then the cohesion and friction angle of the soil can be determined. A typical result of triaxial tests is shown in Figure 4.5. NU-LHT-2M shows both peak and ultimate strength. Based on the peak strength recorded, the Mohr's circles at failure can be drawn and peak friction angle can be determined as shown in Figure 4.6. The results of triaxial tests are summarized in Table 4.6. There is a gradual increase in the friction angle of the soil as the density increases. The range of the friction angle is smaller than that reported for lunar soil (Carrier et al., 1991), especially for a sample at a medium density.

Table 4.6 Results of triaxial test of NU-LHT-2M

Average Bulk Density (kg/m^3)	Relative Density (%)	Friction Angle ($^\circ$)
1648	50.8	36.0
1750	65.2	38.5
1869	80.1	40.7

The measured cohesion was too low to make any meaningful conclusion and is considered to be zero here, as is consistent for typical silty sands. The reason is that the triaxial tests were conducted with a pretty high effective confining pressure while to measure cohesion accurately, one needs to use a very low effective confining pressure.

As pointed out by Das (1985), determination of cohesion from triaxial tests may be difficult as a straight line extrapolation of the failure enveloped back to the normal stress of zero is not accurate. In fact, the strength envelope is more likely to be curved near small confining pressure. However, due to the fact that there is neither an easy way to perform tensile test on a soil nor a reliable way to conduct triaxial test at a low effective stress (Mitchell, 1993), how to determine accurately the cohesion of a soil remains a challenge. There is also considerable uncertainty associated with the causes of the cohesion recorded by Willman *et al.* (1995).

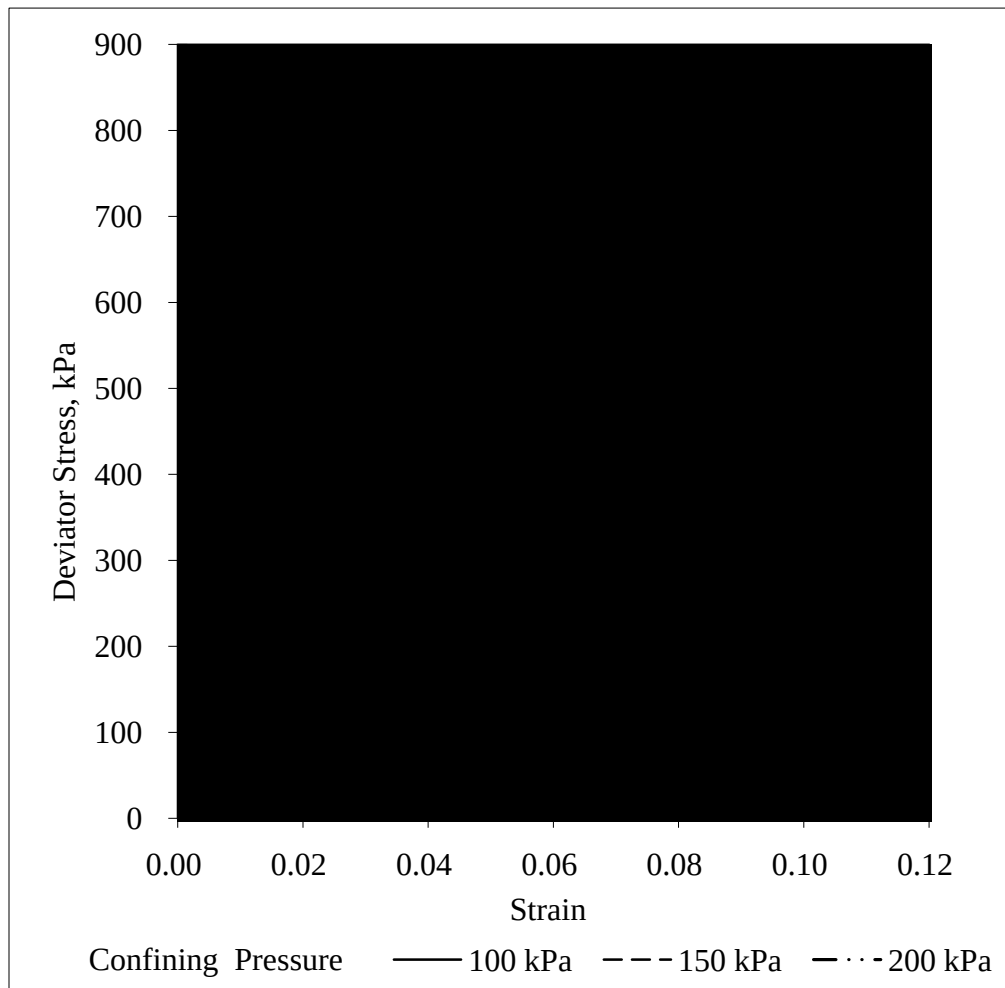


Figure 4.5 Deviator stress versus axial strain recorded in triaxial tests of NU-LHT-2M (density = 1869 kg/m³)

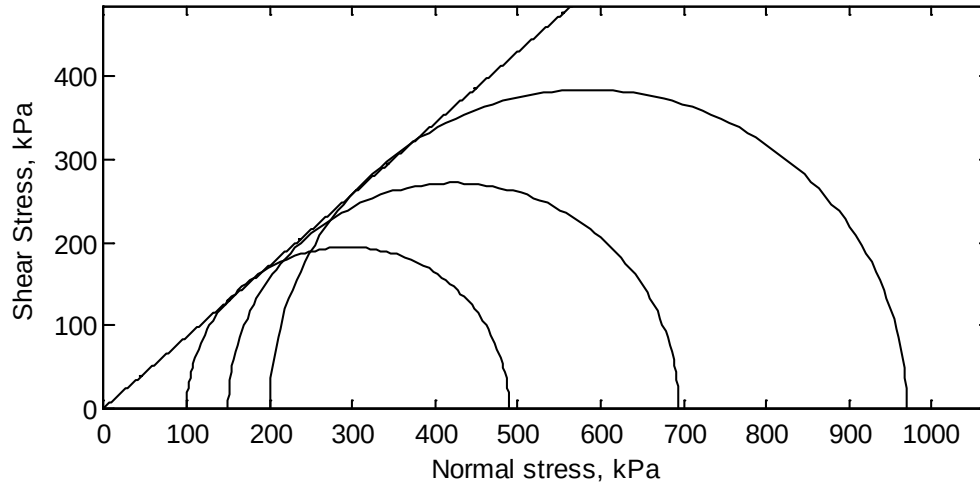


Figure 4.6 Mohr stress circles for NU-LHT-2M (density = 1869 kg/m³)

4.2.7 Compressibility

Compressibility is a measure of the relative volume change or densification of a soil as a response to a confining stress change to the soil. For the design of both a vehicle and excavation tools, it is necessary to know the compressibility of a soil. The soil compressibility parameters can be determined in a consolidation test conducted in the laboratory following the standard procedures described in ASTM D2435. The detailed testing procedure was described in section 3.2.7. In a consolidation test, a soil sample is subject to a series of one-dimensional loads with a load increment ratio $\Delta p/p = 1$ and the corresponding deformation is measured. Then the results are plotted as void ratio versus log effective stress. From the straight-line part of the relationship, the compression index, C_c is determined as

$$C_c = \frac{e_1 - e_2}{\log\left(\frac{p_2}{p_1}\right)} \quad (4.5)$$

in which e_1 and e_2 are the void ratios of the soil corresponding to effective vertical stress of p_1 and p_2 , respectively. Then, the vertical loading is gradually reduced with a load decrement ratio $\Delta p/p = 1$ and the resulting void ratio is measured. From the recorded data on the unloading line, the swelling index of the soil can be determined as

$$C_s = \frac{e_1 - e_2}{\log\left(\frac{p_2}{p_1}\right)} \quad (4.6)$$

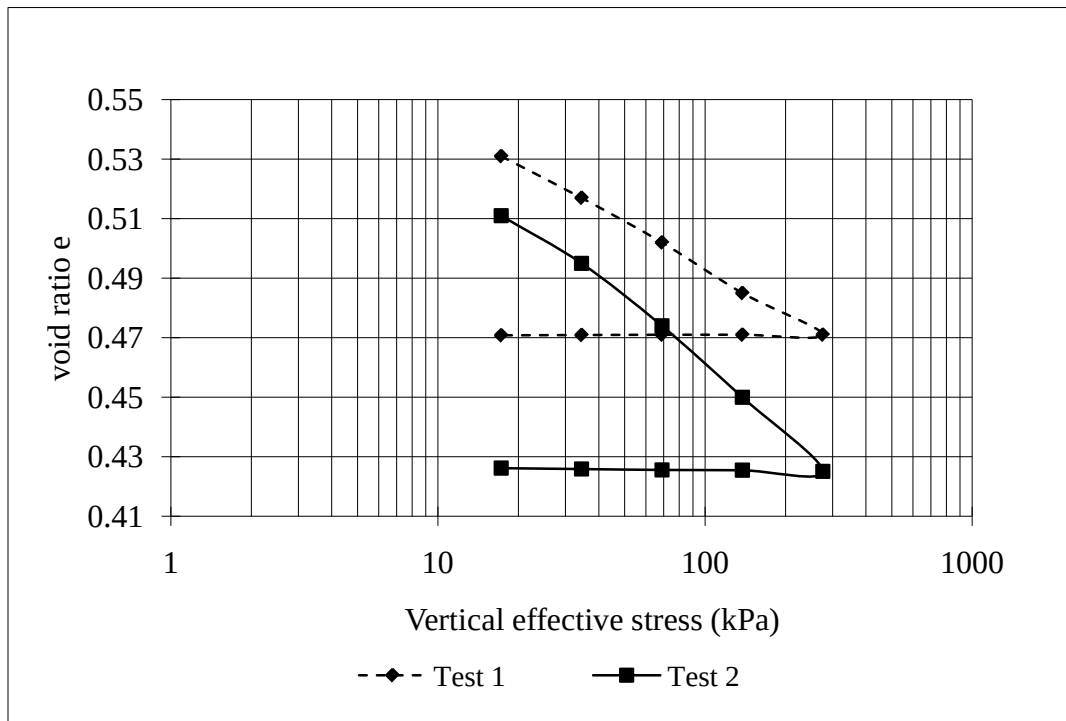


Figure 4.7 Plot of void ratio versus vertical effective stress for NU-LHT-2M

The results of consolidation tests on NU-LHT-2M are shown in Figure 4.7. From the data it is found that the compression index of NU-LHT-2M is 0.060 and the swelling index is 0.001. Both values are pretty low, indicating the soil is less compressible with lower swelling than most terrestrial soils. This agrees with the information about lunar regolith provided by Carrier et al. (1991).

4.3 CONCLUSIONS

A group of laboratory tests have been conducted to determine the geotechnical properties of a lunar regolith highland simulant NU-LHT-2M. These measurements form the basis to judge whether the simulant is effective in simulating the properties of lunar soil and are essential in the study of vehicle mobility and ISRU. Based on the results of this study, the following conclusions can be drawn:

1) The particle size distribution of NU-LHT-2M simulant falls between +1 standard deviation and -1 standard deviation of typical lunar soils. In most of the particle size range, it is close to the average of lunar soils. The simulant is classified as a poorly-graded silty sand. There is an observed deficit with respect to the lunar regolith average of larger particles near 1 mm. There was no segregation of particles during the transportation at this lab. Single compaction and triaxial compression and shear events had little effect on the particle size distribution. Effects on size after many repeated uses were not included here. Due to the limitation of the testing equipment used, particle sizes smaller than 1 μm are not considered here.

2) The average specific gravity was found to be 2.749, which is lower than that of typical regolith. However, it is still considered within the range for the lunar soil as the minimum value has been approximated as 2.3.

3) The maximum void ratio of NU-LHT-2M is 1.011 while the minimum void ratio is 0.336 and the maximum porosity of this simulant is 0.503 while the minimum porosity is 0.252. The best way to achieve high compaction for the simulant is by

vibration with a vertical surcharge. The range in mass density that can be achieved by NU-LHT-2M is close to that estimated for lunar soils.

4) The peak angle of internal friction of NU-LHT-2M is a little bit lower than that of typical lunar soils and it increases with density. It is quite difficult to measure the cohesion of dry simulant accurately as the cohesion is relatively low. The variation of cohesion and internal friction angle with bulk density of lunar regolith has never been studied.

5) The compression and swelling index of NU-LHT-2M are within the range for lunar soils provided by Lunar Sourcebook and a little bit lower than the recommended typical values of lunar soils.

In summary, most geotechnical properties of NU-LHT-2M are similar to that of lunar soils except the cohesion, which is difficult to measure. Developing a reliable way to measure and understanding the physics behind a small amount of cohesion need further study.

CHAPTER 5 GEOTECHNICAL PROPERTIES OF GRC-3

In order to develop equipment for ISRU operations on the moon, it is necessary to test prototypes under simulated conditions. It is a challenging task because sufficient lunar regolith is unavailable. Hence, soil simulants have been developed. Most simulants are made from exotic materials using complex procedures, which can be hazardous. So far they are not available or affordable in large quantities, e. g., JSC-1A and NU-LHT-2M costs about \$20,000 per metric ton. NASA Glenn Research Center requires at least 40 metric tons for building a test bin to design excavation tools and to develop criteria to interpret soil parameters from the cone penetrometer test. To satisfy this need, a lunar regolith simulant, which can be produced in large quantities at a reasonable and affordable price, has been developed. This chapter describes both the development and geotechnical characterization of a lunar regolith simulant, GRC-3, which is intended to be used as a standard soil bin lunar simulant at the NASA Glenn Research Center for which it is named after.

5.1 METHOD FOR CREATING GRC-3

As described in Chapter Two, a lunar regolith simulant, GRC-1, is developed to be used as a standard vehicle mobility lunar simulant at the NASA Glenn Research Center. However, due to the safety precaution, GRC-1 does not simulate the fine fraction of lunar regolith. The particle size distribution of a soil is an extremely important engineering property which influences the shear strength and compressibility of the soil. Therefore, a new lunar regolith simulant, GRC-3, has been proposed to better simulate

the particle size distribution of lunar regolith. Soil mechanical properties, to the precision we know them for lunar regolith, can be matched even if the mineral and chemical properties of a simulant are not equivalent to the lunar regolith, so the mineral and chemical composition of lunar regolith are not considered in the development of GRC-3.

“Grain size is the most important property that must be matched, although the upper size limit that characterize the lunar dust is somewhat a matter of choice depending on the type of testing to be perform”, stated by Sibille et al. (2005). The replication of the particle size distribution of the lunar regolith is the basis for creating GRC-3. Based on all the available data on particle size distribution of lunar regolith, Carter et al. (2004) established a band of particle size distribution with $\pm$ one standard deviation as shown in Figure 5.1. The first task of this project is to create a soil mixture that has a particle size distribution similar to that of the average of lunar regolith. To obtain a soil mixture that has a particle size distribution which closely simulates that of the lunar regolith, while at the same time can be easily produced in large quantities, four types of silica sands and Bonnie silt were chosen. The Bonnie silt is a natural loess excavated from a site in Burlington Colorado (refer to Figure 5.2 and Figure 5.3), and four types of silica sands are provided by the Best Sand (BS) Corporation. These sands are denoted by BS 110, BS 530, BS 565, and BS 1635 and their grain size distribution characteristics are listed in Figure 2.21 (Best Sand Corporation of Chardon, Ohio). This total soil mixture, named GRC-3, was produced by mixing 6% by weight of BS 620, 10% of BS 2040, 16% of BS 565, 16% of BS 110 and 52% of Bonnie silt. The GRC-3 soil mixture is a set of odorless powder/grand sand like material as shown in Figure 5.4. Backscattered electron image of GRC-3 soil mixture is shown in Figure 5.5. Since these soils are commercially available

at low cost, GRC-3 can be produced in large quantities for ISRU operation testing at a cost of about \$250 per metric ton.

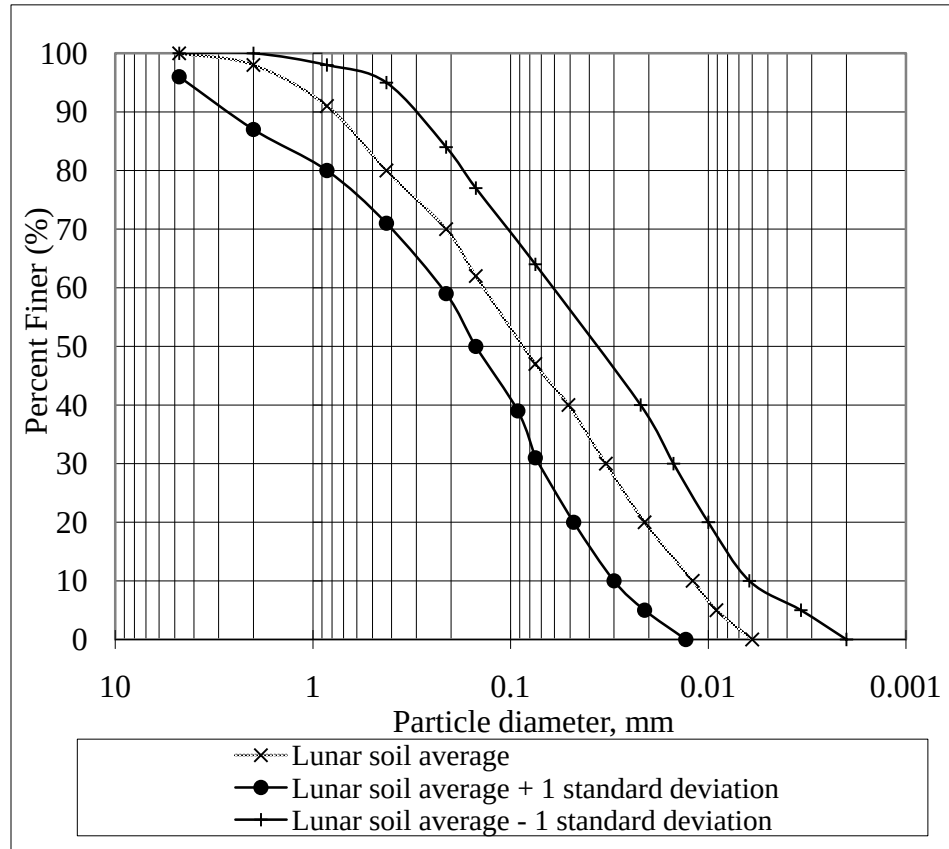


Figure 5.1 Particle size distribution of lunar regolith



Figure 5.2 Loess near Burlington Colorado (credit NASA)



Figure 5.3 Feedstock source for Bonnie silt (credit NASA)



Figure 5.4 GRC-3 sample

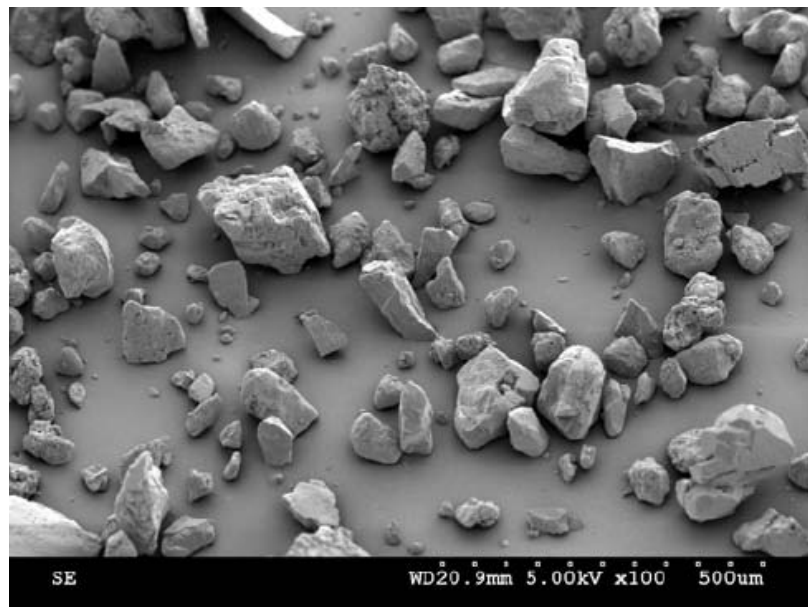


Figure 5.5 Backscattered electron image of GRC-3

5.2 GEOTECHNICAL PROPERTIES OF GRC-3

After the proper mixture of Best Sands and Bonnie silt for the creation of GRC-3 was obtained, the next step was to measure the index and geotechnical properties of the simulant and compare them with that of the lunar regolith. The laboratory tests conducted to measure the geotechnical properties of GRC-3 followed strictly the standards specified by ASTM (1991), which are the standards commonly used by the geotechnical engineering community, so as to ensure the comparability of the results. These tests and corresponding ASTM standards are summarized in Table 3.1. Several tests were repeated multiple times in order to check the repeatability of the data. The test procedures, except the Atterberg limits test, have been described in detail in Chapter 3 and therefore are not included in this section. This section discusses the initial characterization of GRC-3 as provided by particle size distribution, Atterberg limits, specific gravity, maximum and minimum densities, porosity and void ratio, shear strength, compressibility, stiffness and Poisson's ratio.

5.2.1 Particle Size Distribution

The first step of the laboratory testing program is to investigate whether the particle size distribution of GRC-3 matches that of lunar regolith. Based on the recipe of GRC-3 provided in the preceding section, the Bonnie silt and Best Sands were obtained as the designed weight percentage and mixed thoroughly by a Hobart A200 mixer. Then, the soil mixture was tested the particle size distribution via sieve testing for coarse particles (ASTM D422) and hydrometer test for fine particles (ASTM D423). The soil

separation test procedure using the standard sieves for the coarse particles and the hydrometer for fine particles are described in detail as in section 3.2.1.

Two particle size analyses were performed and the results of the measurements are shown in Figure 5.6, together with the average, +1 standard deviation, and -1 standard deviation of lunar soils that were tested in the past. As shown in the figure, the two particle size analyses are almost identical. In general, the particle size distribution of GRC-3 falls between the +1 standard deviation and -1 standard deviation of lunar regolith but not at the average range. In medium range of the particle size, slightly exceeds the -1 standard deviation of typical lunar soil. There are also a small fraction of fine particles (smaller than two microns) of GRC-3 that were not reported in the previous data on lunar regolith. The particle size distribution can be used to determine the following soil basic parameters:

a) It contains 70 % of sand and 30 % of silt;

b) It has $D_{10} = 0.021$ mm, $D_{30} = 0.075$ mm, and $D_{60} = 0.210$ mm (see Figure 5.3), where D_{10} , D_{30} , and D_{60} are the diameters which are larger than 10%, 30%, or 60% of the particles (by weight), respectively.

c) The coefficient of uniformity $C_u = D_{60}/D_{10} = 10.00$, and the coefficient of curvature $C_c = D_{30}^2 / (D_{10} \times D_{60}) = 1.29$.

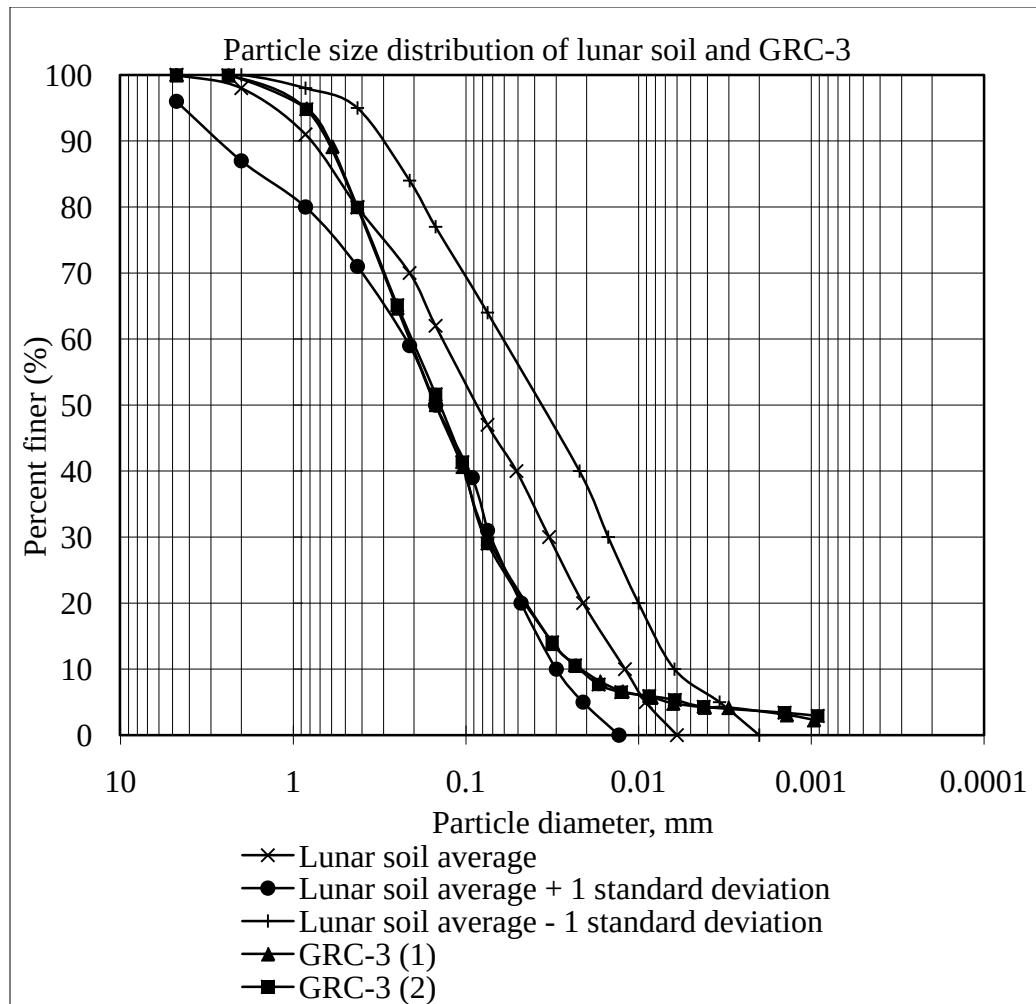


Figure 5.6 Particle size distribution of GRC-3

5.2.2 Atterberg Limits

The Atterberg limits are key parameters used for classifying a fine-grained soil. They can be used to distinguish between silt and clay, and it can be distinguish between different types of silts and clays. Depending on the water content of the soil, it may appear in four states: solid, semi-solid, plastic and liquid. As water content increases, a point called the plastic limit (PL) is reached where the material has a plastic (putty like) consistency. As water content continues to increase, a point called the liquid limit (LL) is reached when the material changes from plastic to liquid behavior.

Atterberg limits of GRC-3 were performed according to ASTM D4318 (ASTM 1991) for the particles smaller than 0.425 mm in diameter (smaller than No. 40 sieve). The general procedure can be summarized as:

(Preparation of test specimens)

1. Select sufficient soil to provide 200 g of material passing the No. 40 sieve after processing. Dry the sample at room temperature or in an oven at a temperature not exceed 60°C until the soil clods will pulverize readily. Pulverize the sample in a mortar with a rubber-tipped pestle or in some other way that does not cause breakdown of individual grains. Separate the sample on a No. 40 sieve, shaking the sieve by hand to assure thorough separation of the finer fraction. Place the material remaining on the No. 40 sieve in a dish and soak in a small amount of water. Stir the soil water mixture and pour over the No. 40 sieve, catching the water and any suspended fines in the washing pan. Pour this suspension into a

dish containing the dry soil previously sieved through the No. 40 sieve. Discard material retained on the No. 40 sieve.

2. Let the material passing the No. 40 sieve air-dry down to first test point (about 30 to 35 blows). Carefully mix the test sample on the glass plate using the spatula. Put the mixed soil in the storage soil, cover to prevent loss of moisture, and allow standing for at least 16 h. After the standing period and immediately before starting the test, thoroughly remix the soil.

(Liquid limit test)

3. Adjust the height of fall of the liquid-limit machine to exactly 10 mm, using the 10 mm block on the end of the grooving tool as shown in Figure 5.7.
4. Place a portion of the prepared soil in the cup of the liquid limit device at the point where the cup rests on the base, squeeze it down, and spread it into the cup to a depth of about 10 mm at its deepest point, tapering to form an approximately horizontal surface. Keep the unused soil in the storage dish. Cover the storage dish with a wet towel to retain the moisture in the sample.
5. Form a groove in the soil pat by drawing the tool, beveled edge forward, through the soil on a line joining the highest point to the lowest point on the rim of the cup. When cutting the groove, hold the grooving against the surface of the cup and draw in an arc, maintaining the tool perpendicular to the surface of the cup throughout its movement.



Figure 5.7 Atterberg limit test

6. Lift and drop the cup by turning the crank at a rate of 1.9 to 2.1 drops per speed until the two halves of the soil pat come in contact at the bottom of the groove along a distance of 13 mm. Record the number of drops, N , required to close the groove. Remove a slice of soil approximately the width of the spatula, extending from edge to edge of the soil cake at right angles to the groove and including that portion of the groove in which the soil flowed together, place in a weighed container, and put the lid on the can to avoid evaporation.
7. Return the soil remaining in the cup to the storage dish. Wash and dry the cup and grooving tool and reattach the cup to the carriage in preparation for the next trial.
8. Add additional distilled water in small amounts, using the squeeze bottle, to increase the water content of the soil and decrease the number of blows required

to close the groove, and mix thoroughly, usually about 5 minutes. Repeat Steps 4 through 7 for at least two additional trials producing successively lower numbers of blows to close the groove. One of the trials shall be for a closure requiring 25 to 35 blows, one for closure between 20 and 30 blows, and one trial for a closure requiring 15 to 25 blow.

9. Weigh all moisture containers and record their “container + wet soil” masses. Now remove the lids and place the containers in the oven (set at 110°C) to dry overnight. Return the lab on the following day, weigh all the oven-dried samples and record their “container + wet soil” masses, then compute the water contents.
10. Plot the relationship between the water content between the water content (%) and the corresponding number of drops, N , of the cup on a semilogarithmic graph with the water content as ordinates on the arithmetical scale, and number of the drops as abscissas on a logarithmic scale. Draw the flow curve as a best fit.
11. Take the water content corresponding to the intersection of the line with the 25-drop abscissa as the liquid limit LL of the soil.

(Plastic limit test)

12. Select a 20-g portion of soil from the material prepared for the liquid limit test, then mix continuously on the glass plate to reduce water content of the soil to a consistency at which it can be rolled without sticking to the hands.
13. Select a portion of 1.5 to 2.0 g from the 20-g mass. Form the test specimen between the palm or fingers and the ground-glass plate with just sufficient pressure to roll the mass into a thread of uniform diameter throughout its length.

The thread shall be further deformed on each stroke so that its diameter reaches 3.2 mm, taking no more than 2 min.

14. When the diameter of the thread becomes 3.2 mm, break the thread into several pieces. Squeeze the pieces together, knead between the thumb and first finger of each hand, reform into an ellipsoidal mass, and reroll. Continue this alternate rolling to a thread 3.2 mm in diameter, gathering together, kneading and rerolling, until the thread crumbles under the pressure required for rolling and the soil can no longer be rolled into a 3.2-mm diameter thread.

15. Gather the portions of the crumbled thread together and place in a weighed container. Immediately cover the container.

16. Select another 1.5 to 2.0-g portion of soil from the original 20-g specimen and repeat Steps 13 through 15 until container has at least 6 g of soil.

17. Repeat Steps 13 through 16 to make another container holding at least 6 g of soil. Place the containers in the oven to dry overnight. Determine the water content of the soil contained in the containers. The plastic limit PL is the average of the two water contents.

18. Calculate the plasticity index as follows:

$$PI = LL - PL \quad (5.1)$$

19. Conduct plastic limit test. Plastic limit is defined as the water content at which a soil thread just crumbles when it is rolled down to a diameter of 1/8 in.

The liquid and plastic limits of GRC-3 are found to be 20.2% and 18.2%, respectively. Hence the plasticity index of the GRC-3 material is determined to be 2% water. Based on the particle size distribution and the plasticity, the soil can be classified as a well graded silty sand (SM) using the Unified Soil Classification System (ASTM D2481), just like average lunar regolith.

5.2.3 Specific Gravity

The specific gravity of a soil is defined as the ratio of the mass density of solid particles to the mass density of pure water at 4°C. Specific gravity is one of the most important geotechnical parameters. The specific gravity is determined by measuring the volume of fluid which the weighted soil is immersed in to displace.

The specific gravity, G_s , of the GRC-3 was determined by following ASTM standard D854. The detailed test procedure is presented in section 3.2.2. The results are summarized in Table 5.1. The average specific gravity of GRC-3 was found to be 2.633, which is lower than that of typical lunar soils at 3.1. In addition, there was the concern that the particles in different size range may have different specific gravities. Therefore, specific gravity tests were conducted on particles larger or smaller than 0.075 mm (or the opening of #200 sieve). The results are also listed in Table 2. The values show differences in their respective specific gravities.

Table 5.1 Results of specific gravity tests of GRC-3

Specific Gravity	GRC-3	GRC-3 (only particles passing #200 sieve)	GRC-3 (only particle retained above #200 sieve)
Test 1	2.636	2.583	2.646
Test 2	2.631	2.599	2.645
Average	2.633	2.591	2.646

5.2.4 Maximum and Minimum Densities

The state of density of a dry soil such as GRC-3 is typically measured as a relative term with regard to its maximum and minimum densities. Therefore, it is important to determine the maximum and minimum densities of GRC-3. From the measured in-situ density of the soil, it is possible to calculate its relative density as

$$R_D = \frac{\rho_{max}}{\rho} \times \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}} \times 100\% \quad (5.2)$$

where, ρ_{max} is the maximum bulk density, ρ_{min} is the minimum bulk density, and ρ is the bulk density of a sample. The relative density generally refers to the degree of particle packing (which is particle size and shape distribution dependent) of a soil. It is probably the most important factor in determining the strength and stiffness of a soil.

A total of six tests were performed in the laboratory at CWRU in order to determine the maximum and minimum bulk density of GRC-3 (three repeat tests for maximum bulk density and three repeat tests for minimum bulk density). The tests followed ASTM D4253 and ASTM D4254 for maximum and minimum index densities, respectively. The test procedures were discussed in section 3.2.3.

The results of the maximum and minimum bulk density tests are summarized in Table 5.2. The average maximum and minimum dry densities of GRC-3 are 1939 kg/m³ and 1520 kg/m³, respectively. In comparison, the maximum and minimum densities of lunar regolith obtained from Apollo samples were 1930 kg/m³ and 870 kg/m³, respectively (Carrier et al., 1991). Compared to several hundred grams required for ASTM procedures, the maximum density of lunar regolith was determined by using 6.5-g Apollo 12 lunar regolith tested in a cup with 1.0 cm inside diameter and 1.1 cm depth (Jaffe, 1971a); the minimum density of lunar regolith was determined by using 1.26-g Apollo 14 lunar regolith tested in a core tube with 4.13 cm diameter (Carrier et al., 1991).

Table 5.2 Results of maximum and minimum density tests of GRC-3

GRC-3	Maximum density (kg/m ³)	Minimum density (kg/m ³)
Test 1	1933	1525
Test 2	1939	1515
Test 3	1946	1519
Average	1939	1520

5.2.5 Porosity and Void Ratio

Based on the maximum and minimum densities and specific gravity of the soil, other engineering properties such as porosity and void ratio of the GRC-3 can be estimated. The bulk density, specific gravity, and porosity of a soil are relates as:

$$n = 1 - \frac{\rho}{G_s \rho_w} \quad (5.3)$$

where ρ is the bulk density of the soil, G_s is the specific gravity of the soil, ρ_w is the density of water (1g/cc), and n is the porosity of the soil. This equation presents the ratio

of the volume of the voids to the total volume of the soil sample. The void ratio of a soil in general is defined as a ratio of the volume of the voids to the volume of the soil solids. Mathematically it is related to the soil porosity by the following equation,

$$e = \frac{n}{1-n} = \frac{G_s \rho_w}{\rho} - 1 \quad (5.4)$$

Therefore, the maximum porosity of GRC-3 is 0.264 while the minimum porosity is 0.423 and the maximum void ratio of GRC-3 is 0.732 while the minimum void ratio is 0.358. In comparison, the maximum and minimum void ratio of lunar regolith from Apollo samples were 2.37 and 0.67, respectively (*Carrier et al.*, 1991).

5.2.6 Compaction Test

One of the objectives in this study is to find the best way, dry or wet, to achieve compaction for GRC-3 when preparing soil samples in a soil bin, in order to simulate extreme conditions that may be encountered on the moon. In geotechnical engineering, the Proctor compaction test is carried out by compacting the soil to be tested into a standard mold using a standardized compaction energy at several different levels of water content. The water content of the soil has a significant influence on the degree of compaction that can be achieved (*Proctor*, 1933). The water content that can achieve the best compaction or maximum dry density is called optimum moisture content.

The tests reported here followed the standard described in ASTM D698. The results of the tests are summarized in Table 5.3. The optimum moisture content was found to be 10.11% at the maximum dry density achieved by compaction, 1877 kg/m³. In comparison to the maximum dry density achieved by vibration, the maximum compacted dry density by adding water is much lower. Therefore, there is no need to use this method

to achieve the maximum compaction. This is not surprising as the fines in the soil have low plasticity. Instead, the method of using vibration with vertical surcharge is more effective, and can produce a density closest to the maximum density.

Table 5.3 Results of compaction tests of GRC-3

Water Content (%)	Compaction density (kg/m ³)	Dry density (kg/m ³)
5.89	1940	1832
8.32	2023	1868
10.11	2067	1877
10.92	2071	1867
14.54	2032	1774
16.58	2030	1741

5.2.7 Shear Strength

Shear strength parameters (cohesion and friction angle) are mechanical parameters of a soil that have profound influence on vehicle mobility, and excavation. Therefore, laboratory triaxial tests were carried out to determine these parameters as a function of bulk density. The most common way to characterize the strength of a soil is the Mohr-Coulomb failure criterion, which can be expressed as:

$$\tau_f = c + \sigma \cdot \tan\varphi \quad (5.5)$$

where τ_f is the shear strength at failure on the failure plane, σ is the normal stress on the failure plane, c is the cohesion of the soil, and φ is the internal friction angle. Values of cohesion and internal friction angle for GRC-3 were determined via the most commonly used laboratory test to determine the shear strength and stress-strain relationship of soil: the triaxial test.

A total of nine triaxial tests were conducted on GRC-3 samples of three different dry densities each at 100, 150 and 200 kPa confining pressure following the standards described in ASTM D2850. The procedures were generally followed the standards to determine the shear strength of GRC-3 via triaxial tests under unconsolidated undrained (UU) conditions (drain-air conditions for dry sand) and were summarized in section 3.2.6.

The principal stresses at failure of three samples at different confining pressures for each density are used to generate the Mohr's circles at failure, from which the failure envelopes can be drawn. Then the cohesion and friction angle of the soil can be determined. A typical result of triaxial tests is shown in Figure 5.8. It is clear that GRC-3 shows both peak and ultimate strength. Based on the peak strength recorded, the Mohr's circles at failure can be drawn and the peak friction angle can be determined as shown in Figure 5.9. The results of triaxial tests are summarized in Table 5.4. As shown by the data, there is a gradual increase in the friction angle of the soil as the density increases. The friction angle is quite high, which is normal for angular soils such as GRC-3. The range of the friction angle is similar to that reported for lunar soil (*Carrier et al.*, 1991).

Table 5.4 Summary of triaxial test results of GRC-3

Average Bulk Density (kg/m ³)	Relative Density	Friction Angle (°)
1627	30.4%	37.8
1734	57.2%	42.0
1839	80.3%	47.8

However, the measured cohesion was too low, as is consistent for typical silty sands, to make a meaningful conclusion here. The reason is that the triaxial tests were conducted with a pretty high effective confining pressure while to measure cohesion

accurately, one needs to use a very low effective confining pressure. As pointed out by *Das (1985)*, determination of cohesion from triaxial tests may be difficult as a straight line extrapolation of the failure envelope back to the normal stress of zero is not very accurate. In fact, the strength envelope is more likely to be curved near small confining pressure. However, due to the fact that there is neither an easy way to perform tensile test on a soil nor a reliable way to conduct triaxial test at a low effective stress (*Mitchell, 1993*), how to determine accurately the cohesion of a soil remains a challenge. There is also considerable uncertainty associated with the causes of the cohesion recorded, as stated by *Willman et al. (1995)*.

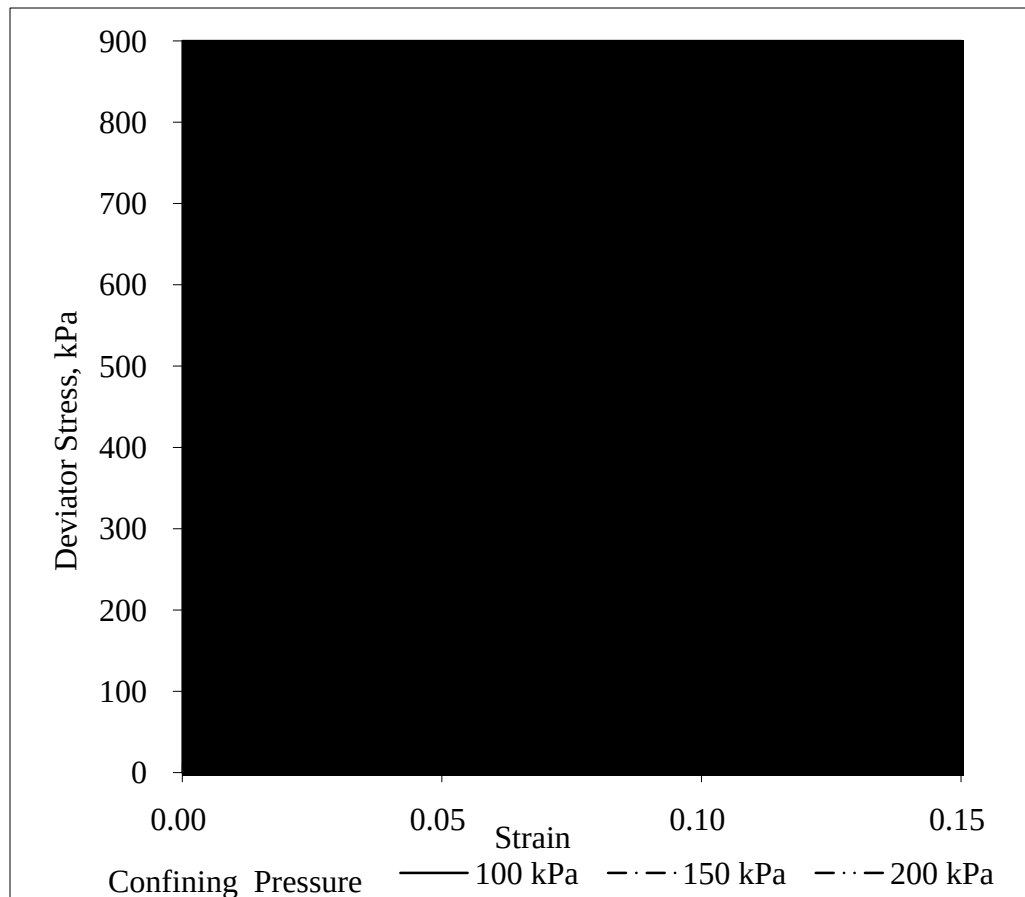


Figure 5.8 Deviator stress versus axial strain recorded in triaxial tests of GRC-3 (density = 1734 kg/m³)

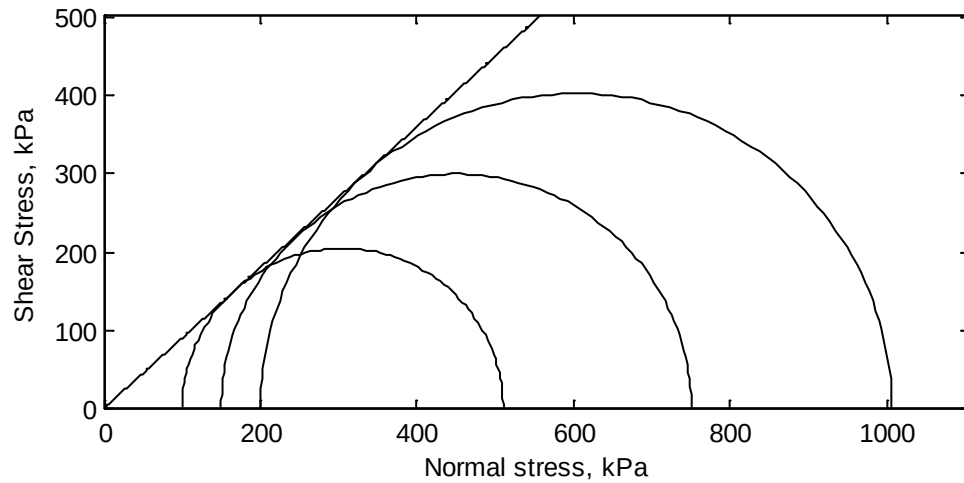


Figure 5.9 Mohr stress circles for GRC-3 (density = 1734 kg/m³)

5.2.8 Compressibility

Compressibility is used to quantify the ability of a soil to reduce in volume with applied pressure. It is an important concept in geotechnical engineering in the design of certain structural foundations whose settlement is concerned. If the load applied during trafficking and excavation is larger than the resistance the soil against the compressibility, compressibility of the soils occurs. Hence, it is also necessary to know the compressibility of a soil in the design of vehicle and excavation tools. The soil compressibility parameters can be determined in a consolidation test conducted in the laboratory following the standard procedures described in ASTM D2435. In a consolidation test, a soil sample is subject to a series of one-dimensional loads with a load increment ratio $\Delta p/p = 1$ and the corresponding deformation is measured. Then the results are plotted as void ratio versus logarithm of applied effective vertical stress. From the straight-line part of the relationship, the compression index, C_c is determined as

$$C_c = \frac{e_1 - e_2}{\log\left(\frac{p_2}{p_1}\right)} \quad (5.6)$$

in which e_1 and e_2 are the void ratios of the soil corresponding to effective vertical stress of p_1 and p_2 , respectively. Then, the vertical loading is gradually reduced with a load decrement ratio $\Delta p/p = 1$ and the resulting void ratios are measured. From the recorded data on the unloading line, the swelling index of the soil can be determined as

$$C_s = \frac{e_1 - e_2}{\log\left(\frac{p_2}{p_1}\right)} \quad (5.7)$$

The results of consolidation tests on GRC-3 are shown in Figure 5.10. From the data it is found that the compression index of GRC-3 is 0.075 and the swelling index is 0.001. Both values are pretty low, indicating the soil is less compressible with lower swelling than most terrestrial soils. This agrees with the information about lunar regolith provided by Carrier et al. (1991).

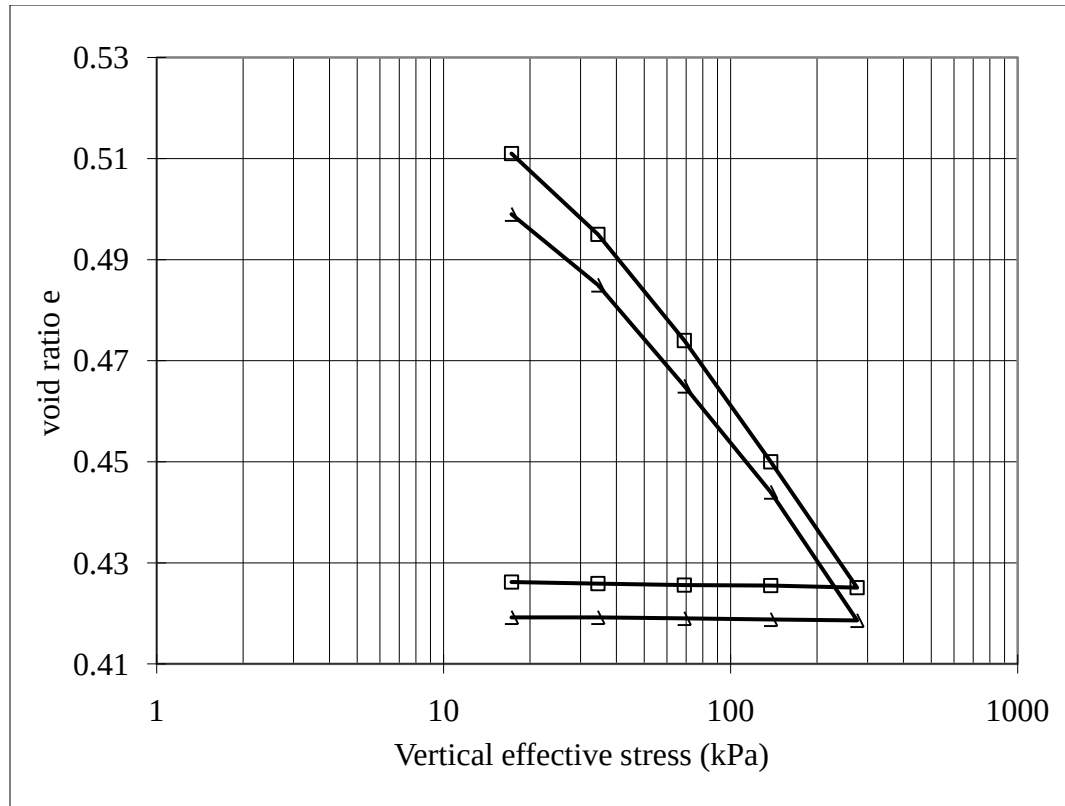


Figure 5.10 Void ratio versus vertical effective stress for GRC-3

5.2.9 Stiffness and Poisson's Ratio

The stiffness (elastic modulus and shear modulus) and Poisson's ratio of soils are important design parameters in many geotechnical problems. A laboratory method for testing the elastic and shear moduli is the use of Piezoelectric Sensors (Bender-Extender Elements). These sensors are made of piezoceramic materials. Bender elements are used to generate and receive shear (s) wave in a soil while the extender elements are used to generate and receive primary (p) wave in the soil. When an electrical excitation is applied to a transmitter element, it leads to mechanical vibrations, which generate shear (s) or primary (p) waves in a soil. Similarly for a wave receiver, a mechanical vibration of the element leads to an electrical output. Thus, the shear or primary wave velocity can be

determined by measuring the travel time and the distance between the wave transmitter and receiver. According to Dyvik and Madshus (1985), the maximum strain generated by a piezoelectric sensor in the surrounding soil is on the order of 10^{-3} %, so the stress-strain relationship is well within the elastic range of soils. This technique has been used by a number of researchers such as Dyvik and Madshus (1985), Thomann and Hryciw (1990), Jovicic (1996), Viggiani and Atkinson (1995), Hryciw and Thomann (1993), Jovicic and Coop (1998), Zeng and Ni (1998), Zeng et al. (2003) and Zeng et al. (2004) to measure stiffness of sand and clay in the laboratory in recent years.

Theory behind the testing

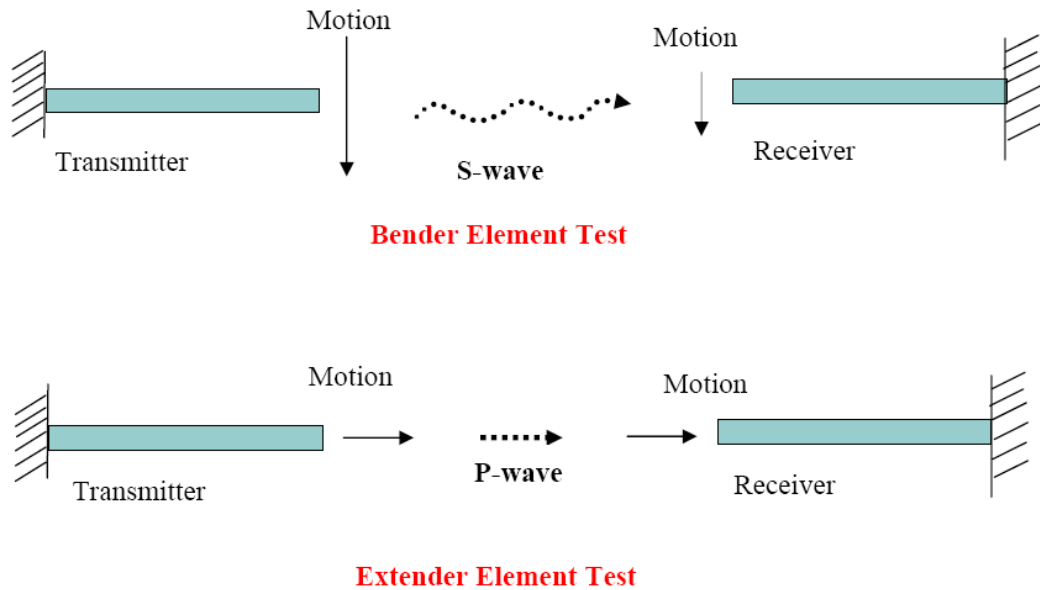


Figure 5.11 Experimental principal of bender-extender element test

Assuming that the distance between the bender element transmitter (BT) and the bender element receiver (BR) (see Figure 5.11) is L_s and the time for the wave to travel

this set distance is t_s , the average shear wave velocity and shear modulus can be determined by:

$$V_s = L_s/t_s \quad (5.8)$$

In a similar fashion, the primary wave velocity can be calculated from the travel time of the primary waves generated and received. In this case, the following equation is employed:

$$V_p = L_p/t_p \quad (5.9)$$

where L_p is the distance between the extender element transmitter and receiver, t_p is the travel time of P-wave.

The shear modulus, G_{max} , and the constrained modulus, M , of the soil can be calculated as:

$$G_{max} = \rho V_s^2 \quad (5.10)$$

$$M = \rho V_p^2 \quad (5.11)$$

where ρ is the bulk density of soil. Using the values of the shear modulus and the constrained modulus at the same density and axial pressure of the soil, Poisson's ratio can be calculated by:

$$\mu = (M/G_{max} - 2)/(2M/G_{max} - 2) \quad (5.12)$$

Finally, the elastic modulus (E) can be determined using the calculated values for shear modulus and Poisson's ratio:

$$E = 2G_{max} (1 + \mu) \quad (5.13)$$

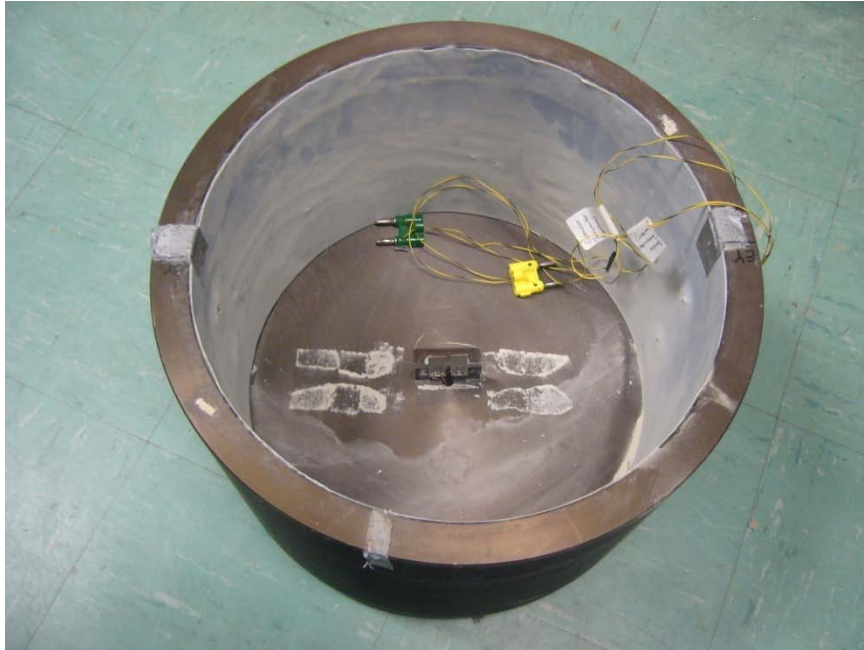
Experiment setup of oedometer with bender-extender element system structure

The oedometer with bender-extender element system is shown in Figure 5.12. The oedometer is an aluminum hollow cylindrical casting with an inside diameter of 30.48 cm, thickness of 2.54 cm, and a height of 23.5cm. A Teflon sheet is pasted on the inside surface to reduce friction. Additional frames have been attached to facilitate the fixing of sensors in vertical direction. A total of four piezoelectric sensors were installed in the oedometer. The sensors installed are two bender elements designated BT and BR, and two extender elements designated ET and ER. The types of the elements are listed in Table 5.5. The bender and extender transmitters were installed in an alternate fashion in vertical direction in line with their respective receivers. Because of this unique setup, the shear modulus, Young's modulus, and Poisson's ratio can be determined simultaneously.

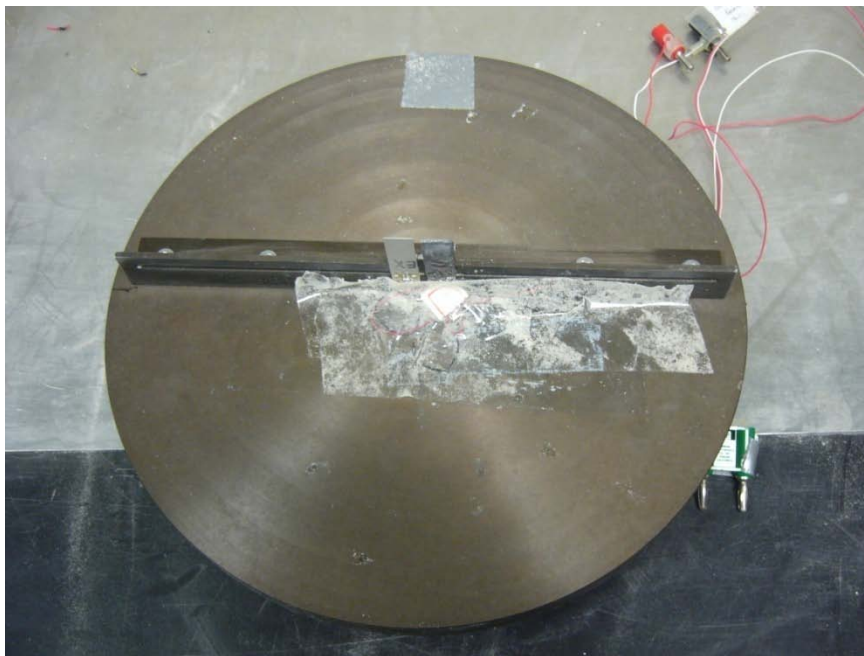
Table 5.5 Types of the elements

Sensor	Function	Type
BT	Transmitter	Bender element, Q220-A4-303Y
BR	Receiver	Bender element, Q220-A4-303X
ET	Transmitter	Extender element, Q220-A4-303YE
ER	Receiver	Extender element, Q220-A4-303XE

The experimental setup for laboratory test is shown in Figure 5.13. A wave generator (Agilent 54624A) is needed to produce source signals and the received signals are displayed and stored by an oscilloscope (Agilent 33120A). A linear variable differential transformer (LVDT) is mounted to record the settlement of sample.



a) Sample container



b) Loading cap

Figure 5.12 Oedometer with bender-extender elements attached: a) Sample container; b) Loading cap



Figure 5.13 Experimental setup

For GRC-3, one loose sample and one dense sample were tested in the bender-extender element test. During each test, the vertical load was applied in steps to a maximum load corresponding to a vertical stress of 60 kPa. At each load step, shear wave velocities and compression wave velocities in the vertical direction were measured. The settlement of the sample was measured continuously by the LVDT, and the distances between the wave transmitters and the receivers were updated for each step so as to calculate the shear wave velocity, compression wave velocity and bulk density accurately. Then the shear modulus, constrained modulus, Poisson ratio and Young's modulus in the vertical direction were determined based on the shear wave velocity, compression wave

velocity and the updated mass density of the soil. The general procedure used is as follows for obtaining the shear wave velocity of GRC-3:

1. Measure and record the inner diameter and height of the oedometer, the diameter and thickness of loading cap, and the protrusion lengths of bender-extender element system. Place the oedometer into the loading machine.
2. Measure and record the mass of bucket filled with the oven-dried soil (typically 20-25 kg is sufficient).
3. Use a funnel to pour the oven dried soil into the oedometer. Loose sample preparation: place the end of funnel close to the base of the oedometer and let the soil evenly deposit into the mold via lifting the bottom of the funnel throughout the process so that the bottom is always just above the soil surface. Continue this process until the soil fills into the oedometer about 2 cm to 3 cm below the top of the oedometer. Carefully level the soil surface.
4. Measure and record the mass of bucket filled with remaining oven-dried oil.
5. Place the loading cap into the oedometer with the transmitters and receivers of the bender and extender elements in alignment, respectively. Slowly apply air into the piston to raise the oedometer so that the load cell just in touch with the loading cap.
6. Attach LVDT to the machine and zero the LVDT. Connect the circuit of the transmitter of the extender element into the wave generator and the receiver of the extender element into the oscilloscope.
7. Using compressed air into the piston to raise the oedometer until the load cell reaches the first determined axial load to the soil. Wait approximately 5 min after

the application of axial load to allow the specimen to stabilize under the axial load.

Record current LVDT reading.

8. Using the wave generator apply the trigger signal into the transmitter. Read and record the traveling time between the transmitter and the receiver from the oscilloscope. Repeat this step 4 times to obtain the average traveling time.
9. Disconnect the circuit of the extender elements. Connect the circuit of the transmitter of the bender element into the wave generator and the receiver of the bender element into the oscilloscope. Repeat step 8.
10. Apply the next determined axial load into the sample. Repeat step 7 to 9. Continue change loads throughout the desired load range and taking readings.
11. Unload the oedometer and use scoop to place the sample back into the bucket.
12. Prepare a dense sample and repeat steps 2 through 11. Dense sample preparation: using a funnel, place the soil into the oedometer in 4 to 6 layers. For each layer, use a block to tamp the soil.

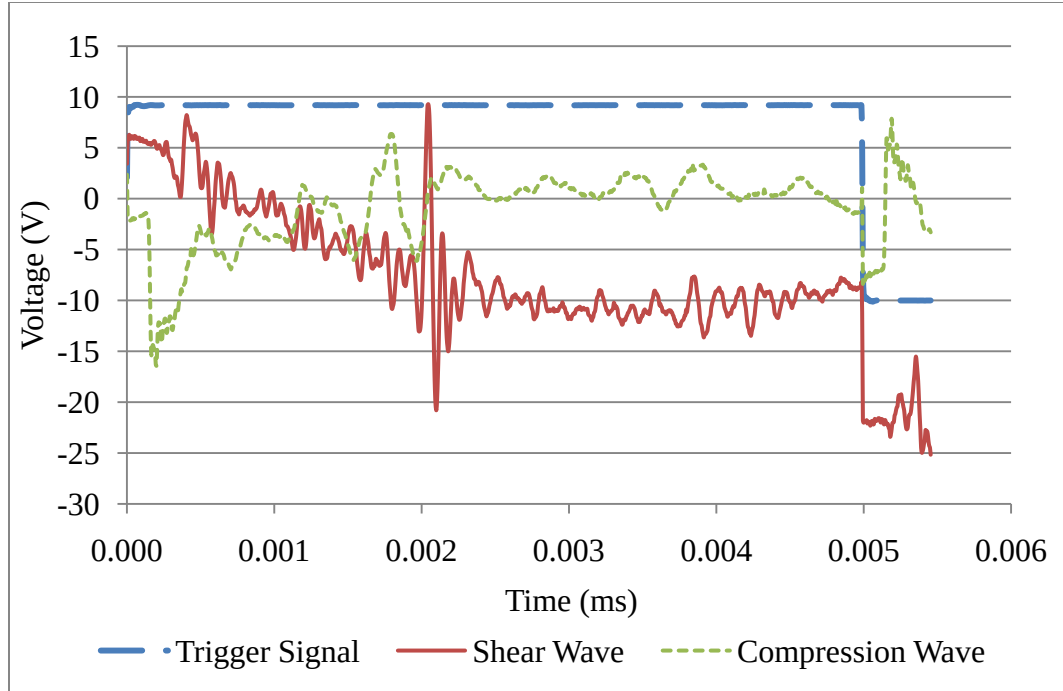


Figure 5.14 Identification of wave arrivals

The experimental results are primarily based on the arrival time of the S- and P-waves produced by the bender and extender elements, respectively. Typical outputs as recorded by oscilloscope are shown in Figure 5.14. Compared to the signal of the bender element receiver, the signal of the extender element has shorter traveling time. Element test results of loose and dense GRC-3 are summarized in Table 5.6 and Table 5.7 and plotted in Figure 5.15, Figure 5.16 and Figure 5.17. The results show that the shear modulus, constrained modulus and elastic modulus increase with the increase of the axial stress. It is obvious that the shear modulus, constrained modulus and elastic modulus of dense GRC-3 are larger than those of loose GRC-3. The shear modulus, constrained modulus and elastic modulus ratios between dense and loose GRC-3 are given in Table 5.8. In general, as the axial stress increases, the ratio decreases. From the shear and constrained moduli, Poisson's ratios were also calculated and shown in the Figure 5.18.

Obviously, the Poisson's ratios of dense GRC-3 are larger than those of loose GRC-3. For both the loose and dense GRC-3, the Poisson's ratios show little difference under different axial stress.

Table 5.6 Test results of loose GRC-3 (initial bulk density: 1590 kg/m³)

Axial Stress (kPa)	Shear Modulus G_L (MPa)	Constrained Modulus M_L (MPa)	Young's Modulus E_L (MPa)	Poisson's Ratio μ_L
5	21.1	52.4	49.1	0.16
10	26.1	65.4	60.9	0.17
20	38.5	97.8	90.5	0.17
40	53.5	135.7	125.6	0.17
60	71.3	180.9	167.5	0.17

Table 5.7 Test results of dense GRC-3 (initial bulk density: 1827 kg/m³)

Axial Stress (kPa)	Shear Modulus G_D (MPa)	Constrained Modulus M_D (MPa)	Young's Modulus E_D (MPa)	Poisson's Ratio μ_D
5	37.1	120.8	94.8	0.28
10	43.2	152.3	112.4	0.30
20	61.4	187.9	154.3	0.26
40	80.8	245.8	202.8	0.26
60	92.3	298.1	235.6	0.28

Table 5.8 Comparison test results between the loose and dense GRC-3

Axial Stress (kPa)	G_D/G_L	M_D/M_L	E_D/E_L	μ_D/μ_L
5	1.76	2.31	1.93	1.71
10	1.66	2.33	1.84	1.79
20	1.59	1.92	1.70	1.47
40	1.51	1.81	1.61	1.46
60	1.29	1.65	1.41	1.58

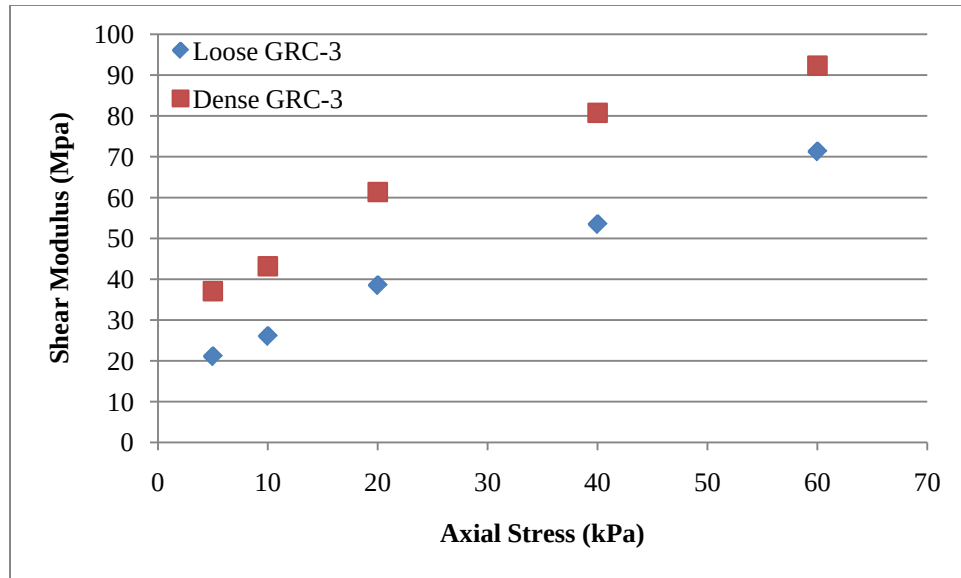


Figure 5.15 Shear modulus versus the axial stress for GRC-3

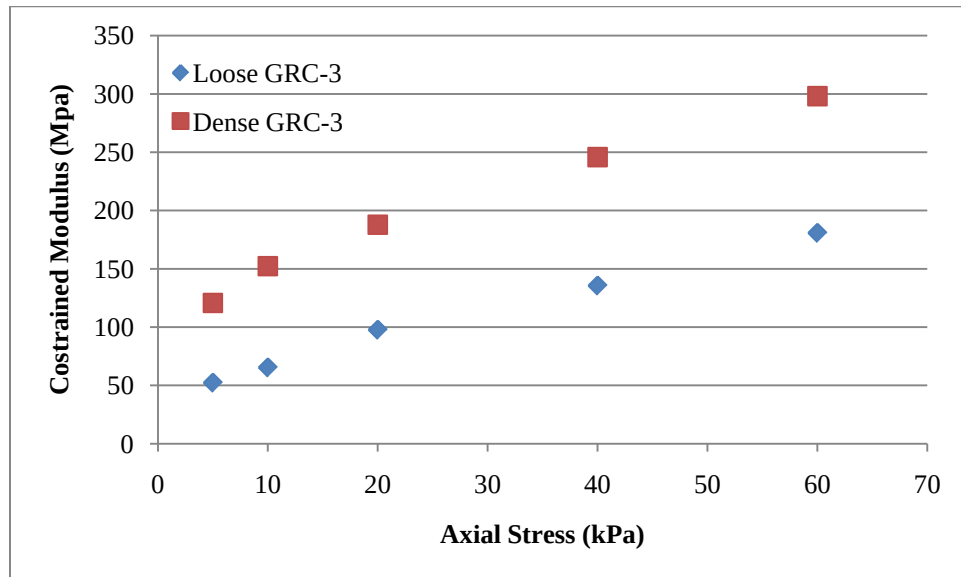


Figure 5.16 Constrained modulus versus the axial stress for GRC-3

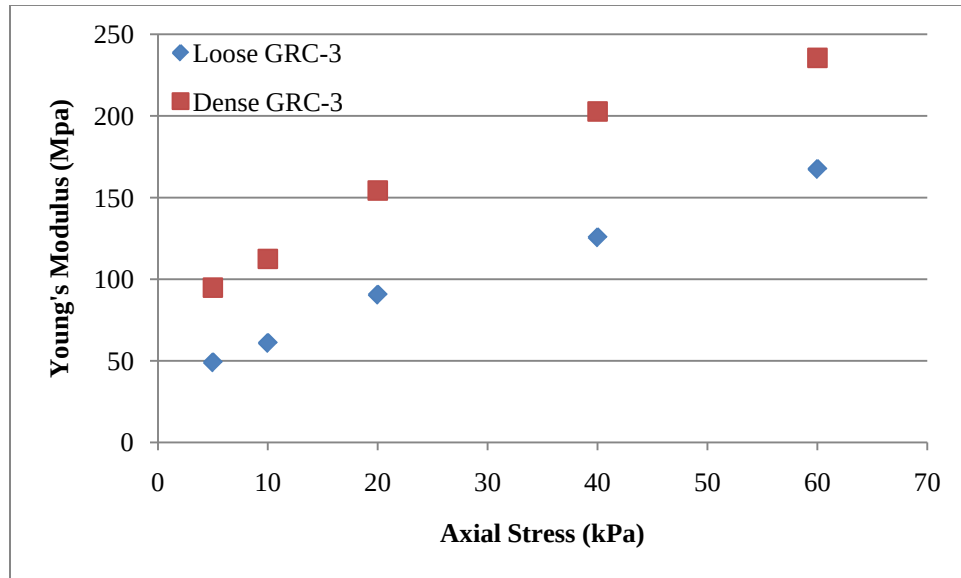


Figure 5.17 Elastic modulus versus the axial stress for GRC-3

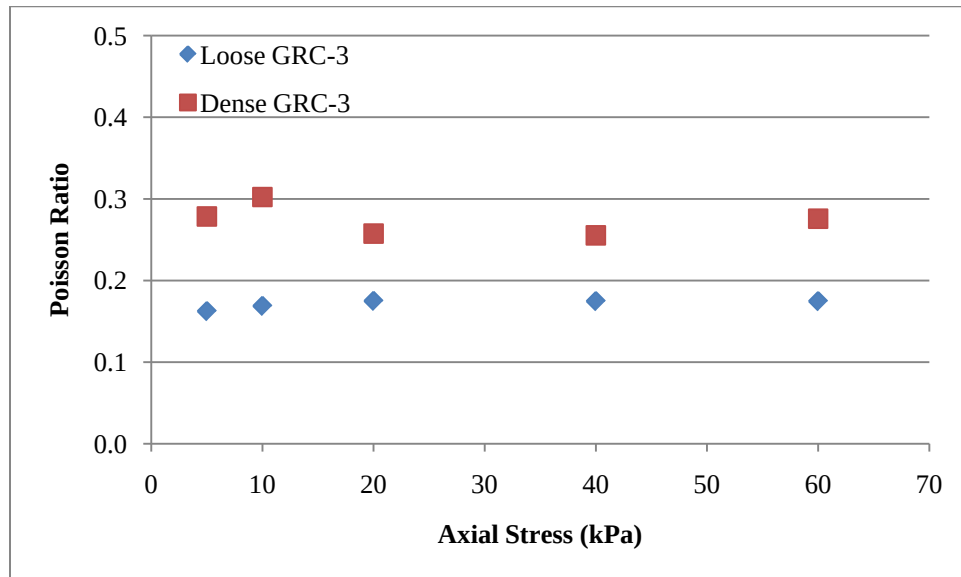


Figure 5.18 Poisson's ratio versus the axial stress for GRC-3

5.3 CONCLUSIONS

A group of laboratory tests have been conducted to determine the geotechnical properties of a geotechnical lunar-like soil mixture GRC-3. These measurements form the basis to judge whether the mixture is effective in simulating the properties of lunar regolith. Based on the results of this study, the following conclusions can be drawn:

1) The particle size distribution of GRC-3 simulant falls between +1 standard deviation and -1 standard deviation of typical lunar soils. In medium range of the particle size, slightly exceeds the -1 standard deviation of typical lunar soil. GRC-3 is classified as a silty sand like lunar regolith.

2) The average specific gravity was found to be 2.633, which is lower than that of typical lunar regolith. However, it is still considered within the range for the lunar soil as the minimum value has been approximated as 2.3.

3) The maximum porosity of GRC-3 is 0.264 while the minimum porosity is 0.423. The maximum void ratio of GRC-3 is 0.732 while the minimum void ratio is 0.358. The best way to achieve high compaction for the simulant is by vibration with a vertical surcharge. The range in mass density that can be achieved by GRC-3 is close to that estimated for lunar soils.

4) The peak angle of internal friction of GRC-3 is a little bit lower than that of typical lunar soils and it increases with density. The cohesion of GRC-3 is difficult to measure using a triaxial device. The variation of internal friction angle with bulk density of lunar regolith has never been studied.

5) The compression and swelling index of GRC-3 are within the range for lunar soils provided by Lunar Sourcebook and a little bit lower than the recommended typical values of lunar soils.

6) The shear, constrained, and elastic moduli of GRC-3 increase with confining pressure and density. Generally, the ratios of shear, constrained, and elastic moduli between dense and loose GRC-3 decreases as the increase of the confining pressure. The Poisson's ratio of GRC-3 shows little difference with the increase of the confining pressure, but increases with density.

In summary, most geotechnical properties of GRC-3 are similar to that of lunar soils. Since it can be produced in large quantity at a low cost, it is acceptable as a simulant for ISRU studies.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

New approaches and technologies will be developed to fulfill NASA's lunar exploration program, which is a part of the larger framework of a sustained and affordable space exploration architecture that will extend the human presence across the solar system. Two components of this program, In-Situ Resource Utilization (ISRU) and Vehicle Mobility, require a thorough understanding of the geotechnical properties of lunar regolith and large quantities of equivalent lunar simulant soils in which to test systems that will be used on the Moon. Therefore, the first object of this research is to develop a lunar regolith simulant that can be produced in large quantities at a reasonable cost and to characterize the geotechnical properties of this simulant. The second object of this research is to characterize the geotechnical properties of the lunar regolith simulants developed by other agencies in order to establish benchmark properties.

In this thesis, a comprehensive investigation was performed on the geotechnical properties of the lunar regolith and three lunar regolith simulants including JSC-1A, NU-LHT-2M, and GRC-3. A series of laboratory tests were used to measure the geotechnical properties of the simulants included particle size distribution, specific gravity, Atterberg limits, maximum and minimum densities, compaction, triaxial and consolidation tests. The test procedures followed strictly the standards specified by ASTM (1991), which are the standards commonly used by the geotechnical engineering community, so as to

ensure the comparability of the results. In addition, the oedometer equipped with piezoelectric sensors was used to measure the stiffness and Poisson's ratio of GRC-3 lunar regolith simulant. The following sections provide conclusions based on the results of the laboratory tests and recommendations for future work.

6.2 CONCLUSIONS

A comprehensive laboratory testing program was conducted in ambient conditions to determine the geotechnical properties of three lunar regolith simulants: JSC-1A, NU-LHT-2M, and GRC-3.

6.2.1 Geotechnical Properties of JSC-1A

Founded the results of the analyses performed throughout this investigation it can be concluded that JSC-1A is a useful lunar regolith mare simulant for many Earth-based studies of future lunar operations. Based on the results of this study, the following additional conclusions can be drawn:

- 1) The particle size distribution of JSC-1A simulant falls between +1 standard deviation and -1 standard deviation of typical lunar soils. In most particle size range, it is close to the average of lunar soils. The simulant is classified as a poorly-graded silty sand. There is no segregation of particles during transportation. Single compaction and shear events had little effect on the particle size distribution. As is normal, sizes below one micron are not considered here, even though sub-micron fines are more prevalent on the moon than on earth.

2) The average specific gravity was found to be 2.875, which is a little bit lower than recommended typical value of lunar soil. However, it is still considered within the range for the lunar soil as the minimum value has been approximated as 2.3.

3) The bulk density of JSC-1A ranges from 1.57 to 2.03 g/cm³ which correspond to a maximum void ratio of 0.826 and a minimum void ratio is 0.410. The best way to achieve high compaction for the simulant is by vibration with a vertical surcharge. The range in mass density that can be achieved by JSC-1A is close to that estimated for lunar soils.

4) The peak angle of internal friction of JSC-1A is high and it increases with density. It is quite difficult to measure the cohesion of dry simulant accurately as the cohesion is relatively low. However, it is reasonable to assume that JSC-1A has cohesion in the range of 1 kPa and lower which agrees with that of the lunar soil.

5) The compressibility and swelling index of JSC-1A are considerably lower than recommended typical value of lunar soil. However, it is still considered within the range for the lunar soil.

In summary, the most geotechnical properties of JSC-1A are similar to that of lunar soils except the cohesion, which is difficult to measure. Developing a reliable way and understanding the physics behind the small amount of cohesion need further study.

6.2.2 Particle Size Distribution of JSC-1AF

Based on the hydrometer test results, D_{16} , D_{50} , and D_{84} for JSC-1AF can be determined to be 7, 16, and 25 μm , respectively. The average particle size of JSC-1AF

can be calculated to be 16 μm , and the median size is 16 μm . In summary, JSC-1AF can be used as a dust simulant to test systems.

6.2.3 Geotechnical Properties of NU-LHT-2M

A group of laboratory tests have been conducted to determine the geotechnical properties of a lunar regolith highland simulant NU-LHT-2M. These measurements form the basis to judge whether the simulant is effective in simulating the properties of lunar soil and are essential in the study of vehicle mobility and ISRU. It can be concluded that NU-LHT-2M is a useful simulant for general purpose in the lunar exploration studies. Based on the results of this study, the following conclusions can be drawn:

1) The particle size distribution of NU-LHT-2M simulant falls between +1 standard deviation and -1 standard deviation of typical lunar soils. In most of the particle size range, it is close to the average of lunar soils. The simulant is classified as a poorly-graded silty sand. There is an observed deficit with respect to the lunar regolith average of larger particles near 1 mm. There was no segregation of particles during the transportation at this lab. Single compaction and triaxial compression and shear events had little effect on the particle size distribution. Effects on size after many repeated uses were not included here. Due to the limitation of the testing equipment used, particle sizes smaller than 1 μm are not considered here.

2) The average specific gravity was found to be 2.749, which is lower than that of typical regolith. However, it is still within the recommended lunar range of 2.3 to 3.2.

3) The bulk density of NU-LHT-2M ranges from 1.37 to 2.06 g/cm³ which correspond to a maximum void ratio of 1.011 and a minimum void ratio is 0.336. The best way to achieve high compaction for the simulant is by vibration with a vertical surcharge. The range in mass density that can be achieved by NU-LHT-2M is close to that estimated for lunar soils.

4) The peak angle of internal friction of NU-LHT-2M is a little bit lower than that of typical lunar soils and it increases with density. It is quite difficult to measure the cohesion of dry simulant accurately as the cohesion is relatively low. The variation of cohesion and internal friction angle with bulk density of lunar regolith has never been studied.

5) The compression and swelling index of NU-LHT-2M are within the range for lunar soils and a little bit lower than the recommended typical values of lunar soils.

In summary, most geotechnical properties of NU-LHT-2M are similar to that of lunar soils except the cohesion, which is difficult to measure. Developing a reliable way to measure and understanding the physics behind a small amount of cohesion need further study.

6.2.4 Geotechnical Properties of GRC-3

Founded the results of the analyses performed throughout this investigation it can be concluded that GRC-3 is a useful lunar regolith simulant for design excavation tools and interpret soil parameters from the cone penetrometer test. As GRC-3 is created from industrially produced silica sand from the Best Sand Corporation in Chardon, Ohio and

Bonnie silt excavated from a site in Burlington, Colorado; it can be easily reproduced in large quantities for large scale laboratory testing at a relatively low cost. Based on the results of this study, the following additional conclusions can be drawn:

1) The particle size distribution of GRC-3 simulant falls between +1 standard deviation and -1 standard deviation of typical lunar soils. In medium range of the particle size, slightly exceeds the -1 standard deviation of typical lunar soil. GRC-3 is classified as a silty sand like lunar regolith.

2) The average specific gravity was found to be 2.633, which is lower than that of typical lunar regolith.

3) The maximum porosity of GRC-3 is 0.264 while the minimum porosity is 0.423. The maximum void ratio of GRC-3 is 0.732 while the minimum void ratio is 0.358. The best way to achieve high compaction for the simulant is by vibration with a vertical surcharge. The range in mass density that can be achieved by GRC-3 is close to that estimated for lunar soils.

4) The peak angle of internal friction of GRC-3 is a little bit lower than that of typical lunar soils and it increases with density. The cohesion of GRC-3 is difficult to measure using a triaxial device. The variation of internal friction angle with bulk density of lunar regolith has never been studied.

5) The compression and swelling index of GRC-3 are within the range for lunar soils provided by Lunar Sourcebook and a little bit lower than the recommended typical values of lunar soils.

6) The shear, constrained, and elastic moduli of GRC-3 increase with confining pressure and density. Generally, the ratios of shear, constrained, and elastic moduli between dense and loose GRC-3 decreases as the increase of the confining pressure. The Poisson's ratio of GRC-3 shows little difference with the increase of the confining pressure, but increases with density.

In summary, most geotechnical properties of GRC-3 are similar to that of lunar soils. Since it can be produced in large quantity at a low cost, it is acceptable as a simulant for ISRU studies.

6.3 SUGGESTIONS FOR FUTURE STUDY

Recommendations for future work in this area of study shall include but not limited to:

- Since most of the testing procedures used to determine the geotechnical properties of lunar soils are different to those used to determine the geotechnical properties of lunar simulants because of the limited quantities of lunar samples, it is necessary to study how much the different techniques will affect the test results.
- It may be more useful to perform the UU triaxial tests using an internal vacuum as the confining pressure on the lunar simulants instead of the typical external air confining pressure. The confining pressure applied by the vacuum is better to mimic the environment on the Moon which is lacking of air. Additionally, the low confining pressures applied by the vacuum should also provide more reliable values of cohesion for these simulants.

- The cohesions of these lunar regolith simulants were too small to be measured using the conventional triaxial test under high confining pressure. It is necessary to develop a reliable technique to effectively measure the small values of cohesion for these simulants.
- Volume change characteristics are key to understanding and predicting the mechanical behavior of the regolith simulant. This is a challenge as the volume change of the material under the applied normal load cannot physically be measured by the conventional triaxial equipment at CWRU due to limitations of the equipment.
- Further study should be conducted on the affect of the lunar dust as well as the electrostatic charges and magnetism of the particles on the excavators and vehicle systems since the dust causes material and contamination issues and astronaut toxicological issues.
- The gravity has a profound influence on the mechanical properties of soils while the gravity on the Moon is only $1/6^{\text{th}}$ that on the Earth, so it is necessary to develop relevant simulation rules and scaling laws to properly relate the results of studies conducted on the Earth to those expected on the Moon.
- An investigation should be conducted on the minimum depth to which soil can be prepared in a testing bin without being influenced by bottom boundary conditions.
- A study should be conducted on how to properly store and process large quantities of lunar regolith simulants and how to mitigate the dust produced in the process of the simulants.

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