Development and Geotechnical Engineering Properties of KLS-1 Lunar Simulant

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Abstract: Lunar exploration, which slowed in the 21st century after the Apollo program, has seen more activity recently with the participation of Asian countries such as Japan, China, and India. Because lunar modules and rovers cannot be tested directly on lunar soil, these countries have developed lunar simulants. Simulating lunar soil is difficult and expensive because its formation mechanism and geotechnical behavior are comprehensively different from those of the terrestrial soil. Johnson Space Center Number One (JSC-1) and Johnson Space Center Number One A (JSC-1A), developed by the National Aeronautics and Space Administration, are the most widely used simulants. Korea has yet to succeed in developing a lunar simulant that meets international standards. The authors perform basic research on lunar simulant development based on basalt samples having similar chemical and mechanical properties to those of lunar soil, with reference to lunar soil data reported under the Apollo program. The resulting prototype is named Korea Lunar Stimulant—Type 1 (KLS-1). Compared with other lunar simulants [JSC-1 and Fuji Japanese Simulant 1 (FJS-1)], KLS-1 shows promise in terms of affordability and similarity to real lunar soil. As such, it is expected to find a wide variety of applications not only in space development projects but also in international research. **DOI: 10.1061/(ASCE)AS.1943-5525.0000798.**

Introduction

With the growing importance of space development and the reported shortage of water and He-3, advanced countries such as the United States and Russia as well as emerging economies such as those of Europe, China, India, and Japan have actively engaged in space and lunar exploration missions. The Moon is the nearest celestial body to the Earth and has the same geologic time scale (Weill et al. 1971). Lunar soil once had a similar chemical composition to that of the Earth, but the thin atmosphere and shortage of water on the Moon have led to significant changes in the last billion years (Taylor 1975).

Lunar soil, formed through repeated pulverization, condensation, and mixing with exposure to cosmic collisions and solar wind for long periods, continues to change even today due to collisions with meteorites and high-energy solar/space charged particles (Taylor 1982). Because the lunar surface is lacking in atmosphere, moisture, and organic materials, it is composed only of single-phase solids (Slyuta 2014). Lunar soil tends to be thicker in areas that have existed for longer geological periods, and these areas are called lunar highlands (Pieters 1986; Taylor et al. 2001). The darker surfaces, known as lunar maria, formed from volcanic eruptions caused by iron-rich magma and have a higher iron content and a low degree of oxidation (Tindle and Kelley 2012).

Research on lunar soil grew active in the 1960s when the Apollo program succeeded in carrying samples of lunar soil back to Earth. Recently, the demand for research on the lunar surface and lunar soil has increased with advanced image-analysis techniques revealing the mineralogy, chemical composition, and insufficient resources (water, He-3, and so on) on the Moon. However, only 380 kg of lunar soil exists on Earth (Schnetzler and Nava 1971), and accordingly most advanced countries have developed their own lunar simulants for use in Moon-related and space-related research (performance assessment of lunar exploration equipment and payloads under actual lunar conditions) (Morris 1980).

Real lunar regolith, which originates from basalt and anorthosite, is subject to continuous pulverization, dissolution, and crystallization. It consists of various minerals, vitreous crystals, and vapor-deposited reduced iron (Fe) (Sasaki et al. 2001). Table 1 shows basic geotechnical engineering properties of real lunar regolith (lunar soil 14163 sampled by the Apollo 14 mission) (Carrier 1973; Carrier et al. 1973). Lunar regolith shows relatively high specific gravity ($G_s = 2.7$–3.1) and density ranges while having distinctively low particle composition conditions ($e_{\max}$), resulting in a high compression index (C_c) on the Moon's surface. Meanwhile, the friction angle shows extremely high values, whereas cohesion is close to zero even though it consists of fine particles.

However, the amount of real lunar soil samples is too limited to allow use on a macroscale or in destructive research. A well-defined and reliable simulant is thus required for various scientific and engineering studies related to lunar exploration programs (Sibille et al. 2006). The first stage of lunar simulant development is to acquire a terrestrial material that has a similar chemical composition and contains similar minerals to actual lunar soil. Finding a naturally occurring soil with a similar chemical composition and physical properties to those of lunar soil is extremely challenging. Advanced countries in space technology have developed lunar regolith simulants based on basalt, anorthosite, minerals, vitreous material, dust (including volcanic ash), and nano-Fe. The few

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Note. This manuscript was submitted on October 12, 2016; approved on June 26, 2017; published online on October 25, 2017. Discussion period open until March 25, 2018; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Aerospace Engineering***, © ASCE, ISSN 0893-1321.

Table 1. Basic Geotechnical Engineering Properties of Lunar Soil 14163 (Data from Carrier et al. 1973; Carrier 1973)

Mission	Sample number	Density		Specific gravity (G_s)	Void ratio		Shear strength properties	
		ρ_{min} (g/cm^3)	ρ_{max} (g/cm^3)		e_{max}	e_{min}	Cohesion, c (kpa)	Friction angle, ϕ (degrees)
Apollo 14	14163,148	0.89 ± 0.03	1.55 ± 0.03	2.90 ± 0.05	2.26	0.87	<0.03–0.1	35–45
	14259,3	0.87 ± 0.03	1.51 ± 0.03	2.93 ± 0.05	2.37	0.94		

Table 2. Chemical Compositions of Typical Lunar Regolith Simulants (Data from McKay et al. 1994; Weiblen et al. 1990; Kanamori et al. 1998; Zheng et al. 2009; Spray 2010)

Simulant	Country	Institution	Raw material	Chemical element													
				SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	LOI
JSC-1	United	NASA	Volcanic ash	47.71	1.59	15.02	0.04	7.35	3.44	0.18	9.01	10.42	2.70	0.82	0.66	—	0.71
JSC-1A	States			46.67	1.71	15.79	—	8.17	12.50	0.19	9.39	9.90	2.83	0.78	0.71	—	0.01
MLS-1		University of Minnesota	Basalt	47.3	1.6	17.8	—	10.5	—	0.1	9.6	11.4	0.7	0.6	—	—	—
MKS-1	Japan	Shimizu	Basaltic	52.69	1.01	15.91	—	12.28	—	0.22	5.41	9.36	1.90	0.58	0.14	—	0.50
FJS-1		Corporation	lavas	49.14	1.91	16.23	—	8.30	4.77	0.19	3.84	9.13	2.75	1.01	0.44	0.43	—
NAO-1	China	Chinese Academy	Gabbro	43.83	0.77	25.79	—	3.52	2.62	0.09	4.93	15.12	1.41	0.47	0.08	—	1.10
CAS-1		of Science		49.24	1.91	15.80	—	11.47	—	0.14	8.72	7.25	3.08	1.03	0.51	—	0.52
OB-1	Canada	NORCAT	Anorthosite	46.60	0.12	21.55	—	5.08	1.24	0.09	9.50	12.6	0.97	0.12	0.07	—	2.74

Note: LOI = limit oxygen index.

countries in addition to Korea engaged in the development of lunar simulants are the United States, Japan, Canada, and China (Table 2) (Kanamori et al. 1998; McKay et al. 1994; Spray 2010; Weiblen et al. 1990; Zheng et al. 2009).

The lunar simulant that is considered to have the most similar characteristics to those of lunar soil is Johnson Space Center Number One (JSC-1), developed by the National Aeronautics and Space Administration (NASA) Johnson Space Center (McKay et al. 1994). JSC-1 is classified as silty sand (MS) by the Unified Soil Classification System (USCS) due to its particle-size distribution and consistency indexes and shows an average G_s of 2.91 (Willman et al. 1995). Its interparticle friction angle (ϕ) and cohesion (c) values vary in ranges of 44.4–53.6° (45° at 1.65 g/cm^3) and 3.9–14.4 kPa, respectively, depending on the bulk density of the specimens (Klosky et al. 2000).

However, because most lunar simulants consist largely of crushed basalt and volcanic ash, and chemical synthesis has been employed to increase their iron (Fe) content [e.g., JSC-1 = US$19/kg; Japan's Fuji Japanese Simulant 1 (FJS-1) = US$4/kg], they are expensive and thus less versatile. In Korea, some attempts were made to develop lunar simulants in 2010 (Hanyang University) and 2014 (Korea Aerospace University) (Kim et al. 2014; Yoo et al. 2014), but their geotechnical behaviors were insufficient to satisfy international standards.

Another major consideration that is just as important as chemical composition is the geotechnical engineering behavior of lunar simulants. Recently, advanced countries in space technology have focused on unmanned rovers to explore and acquire resources on the Moon. Because lunar missions are restricted by the size and weight of launchers and landers, it is essential for the unmanned rovers to exhibit stable driving performance on the lunar surface. Although the lunar surface is a key factor in research on the ability of rovers to pass or avoid obstacles as well as for self-driving algorithms, the geotechnical engineering parameters of lunar soil have a significant influence on driving performance from a terramechanics perspective (Oravec et al. 2010; Sreenivasulu and Jayalekshmi 2014).

In geotechnical engineering aspects, the rover weight acts as a normal stress (σ_v) on the ground and determines the maximum shear strength ($\tau_{max} = \tau_f$) between rover wheels and the lunar surface, along with the friction angle ϕ and cohesion c of lunar regolith. When the torque for a unit area becomes larger than the maximum shear strength moment at the interface due to rover operation, soil failure arises from the driving of the wheels, resulting in a wheel slip that is difficult to predict. Unexpected wheel slip is the main cause of poor driving stability and a loss of driving energy. As such, an accurate evaluation of τ_{max} is necessary to ensure safe and efficient driving on the heterogeneous lunar surface (Wong 2010).

This study was conducted to develop an economical Korean lunar simulant with high geotechnical engineering similarity to actual lunar soil, to be adopted in concurrent lunar exploration projects in Korea and various international cooperative space-related studies. Based on an understanding of the Moon's formation and geological characteristics, raw materials were selected with consideration of various factors, including the chemical composition of basalts in Korea, economic feasibility, and commercialization potential. Basic research for the development of a reliable Korean lunar simulant (KLS-1) was carried out through a series of experimental verifications with Apollo samples and common lunar simulants (JSC-1 and FJS-1) via chemical composition, particle-size distribution, specific gravity, and shear properties (friction angle and cohesion) analyses and comparisons.

Development of Korea Lunar Simulant

Sites of Interest

Because of the absence of atmosphere on the Moon, iron oxide in lunar soil mostly exists as FeO, which has a very high composition ratio averaging 10.5%. On the other hand, the Earth's soil is more easily oxidized because of the abundance of oxygen, and thus contains more Fe_2O_3 than Fe (Taylor et al. 2001). In past studies conducted outside of Korea, lunar simulants were developed using basaltic lava or volcanic ash containing a relatively high amount of FeO from the rapid cooling of high-temperature magma (Lucey et al. 2006). In the case of Korea, on-site surveys were first performed in areas with basaltic rocks given the country's poor soil conditions for volcanic ash.

In terms of chemical composition, this study focused on matching the total iron (Fe) content ($FeO + Fe_2O_3$) of the developed Korean lunar simulant with that of actual lunar soil. Lunar soil 14163 was chosen as the reference soil for KLS-1 development in this study because of the abundant and reliable information on its chemical and mechanical properties, which were replicated in the development of other lunar simulants (Carrier 1973; McKay et al. 1972; Mitchell et al. 1972b; Schnetzler and Nava 1971; Slyuta 2014).

Because of gases emitted from lava, basalt has a well-developed vesicular structure with many slag-shaped cavities. Basalt can be broadly classified into intrusive basalt and extrusive basalt. Intrusive basalt, a dolerite with quartz and feldspar as its main constituents, forms when magma crystallizes below the Earth's surface and cools rapidly to produce dense crystals. For extrusive basalt, the rapid cooling on the surface leads to the formation of vitreous rocks instead of crystals. Crystal growth occurs in basaltic magma before the crystals are extruded as lava. The porphyritic structure of extrusive basalt refers to a texture in which large crystals are embedded in a fine-grained, vitreous groundmass (Kim et al. 2013).

Target sites for basalt deposits in Korea include the following: Jeju (one site: Suwon-ri, 33° 25′ 345.34″ N, 126° 15′ 44.34″ E), which saw volcanic activity in the late tertiary period; Pohang (three sites: Guryong-ri, 35° 59′ 36.99″ N, 129° 34′ 00.39″ E; Mopo-ri, 35° 55′ 57.60″ N, 129° 31′ 00.26″ E; and Daljeon-ri, 36° 02′ 01.94″ N, 129° 17′ 19.37″ E) in North Gyeongsang Province, formed in the tertiary period; Yeoncheon County (one site with both intrusive and effusive basalts: Jeongok-ri, 38° 00′ 55.57″ N, 127° 03′ 59.10″ E) in Gyeonggi Province; and Cheorwon County (one site with both intrusive and effusive basalts: Jangheung-ri, 38° 11′ 41.67″ N, 127° 15′ 53.18″ E) in Gangwon Province, where both basalt layers were formed in the Quaternary Period (Fig. 1). To identify the most appropriate basalt material, on-site surveys were performed as well as direct core sampling from the sites. Rock samples were collected using a hydraulic rotary wash-type drill with an NX core (hole diameter of 76 mm, core diameter of 54.7 mm). Three holes were drilled in each site to acquire highly reliable basalt parent rocks.

Chemical Analyses for Raw Material Selection

To analyze the chemical composition of basalt, a rock cutter was used to obtain rock fragments of approximately 1 cm^3. The inner areas of large samples were used to minimize the influence of weathering and alteration over time. After reducing the samples to powder in a nickel mortar and sifting through a sieve, an inorganic chemical compositional analysis was conducted with an X-ray fluorescence (XRF) spectrometer (XRF-1800, Shimadzu, Kyoto, Japan) (Table 3).

The analysis showed that basalt in Pohang contained SiO_2 at 46.7–61.2%, which is higher than the content of lunar soil 14163 (47.3%), and small traces of FeO at 0.75–3.67%. The high concentration of salt, attributed to the proximity of the site to the sea, made it unsuitable as a parent rock for the lunar simulant. Basalt retrieved from Jeju had a similar chemical composition to lunar soil, with SiO_2 and FeO accounting for 47.5 and 8.47%, respectively. Although CaO at 9.20% was similar to that of actual lunar soil (11.4%), the high amounts of CaO are likely to absorb water and carbon dioxide in the air and decompose into calcium hydroxide $[Ca(OH)_2]$ and calcium carbonate ($CaCO_3$). Furthermore, recent legal regulations restrict the commercial usage of natural Jeju basalts. Thus Jeju basalt also is inappropriate for use in lunar simulant development.

Basalt samples obtained from Yeoncheon and Cheorwon Counties showed relatively high amounts of Fe. Compared with extrusive basalt, intrusive basalt tends to be richer in MgO, which is unrelated to the crystallization of olivine, clinopyroxene, and anorthosite. Intrusive basalt found in Yeoncheon contained a

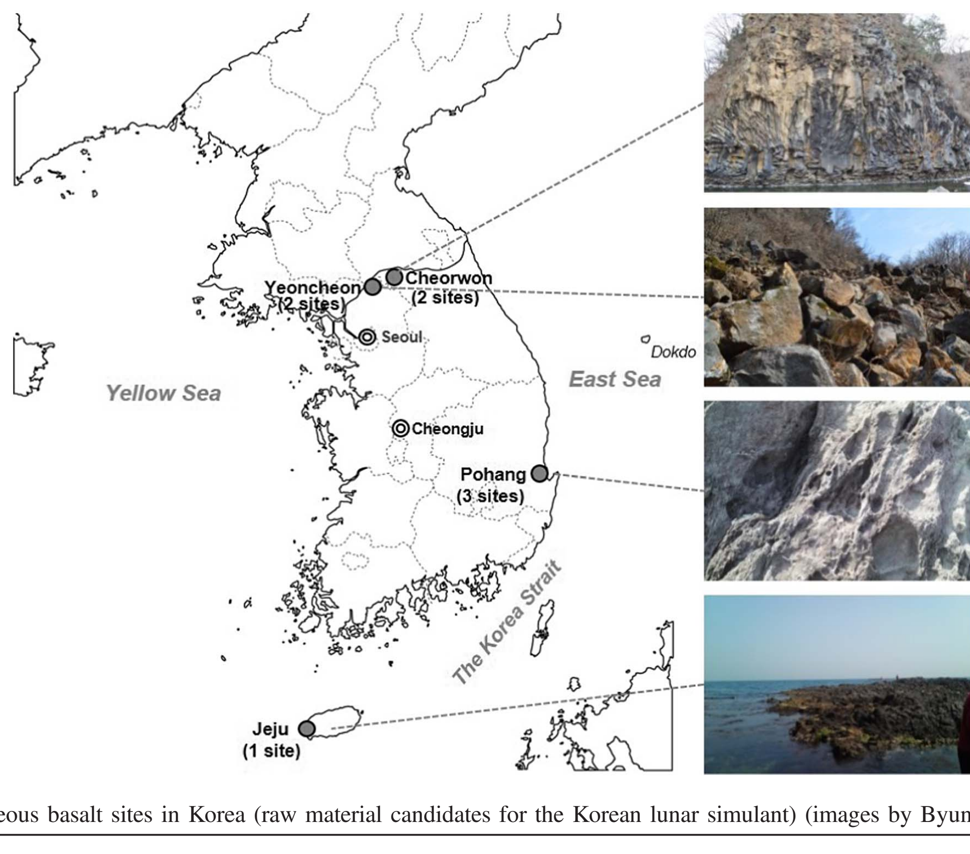

Fig. 1. Igneous basalt sites in Korea (raw material candidates for the Korean lunar simulant) (images by Byung-Hyun Ryu)

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Table 3. Chemical Compositions of Igneous Rock Sites in Korea

Element	Yeoncheon (Jeongok-ri) Intrusive rock	Yeoncheon (Jeongok-ri) Effusive rock	Cheorwon Intrusive rock[a]	Cheorwon Effusive rock	Pohang Guryongpo	Pohang Daljeon-ri	Pohang Mopo-ri	Jeju (Suwon-ri)	Lunar soil 14163
SiO_2	47.6	48.1	48.0	48.1	57.7	46.7	61.2	47.5	47.30
TiO_2	1.76	1.75	1.67	1.78	0.89	1.86	0.72	2.56	1.60
Al_2O_3	15.3	15.3	15.3	15.8	16.6	17.8	17.9	14.1	17.80
FeO	8.83	7.89	6.64	6.13	1.21	3.67	0.75	8.47	10.50
Fe_2O_3	2.22	3.17	4.75	3.78	6.15	3.91	4.95	3.29	—
MnO	0.18	0.18	0.17	0.16	0.20	0.13	0.14	0.16	0.14
MgO	9.79	9.65	9.64	7.53	2.15	5.88	1.63	8.67	9.60
CaO	8.26	8.45	8.38	8.40	5.31	4.88	5.12	9.20	11.40
Na_2O	2.80	2.94	3.42	2.95	3.59	6.18	4.60	3.02	0.70
K_2O	1.53	1.54	1.52	1.56	2.62	2.67	2.03	1.53	0.55
P_2O_5	0.37	0.34	0.33	0.36	0.20	1.63	0.26	0.48	—
Specific gravity (Gs)	2.77	2.78	2.94	2.92	2.62	2.55	2.68	3.02	3.1

[a]Becomes the main (mother) material of Korea Lunar Simulant (KLS)—1.

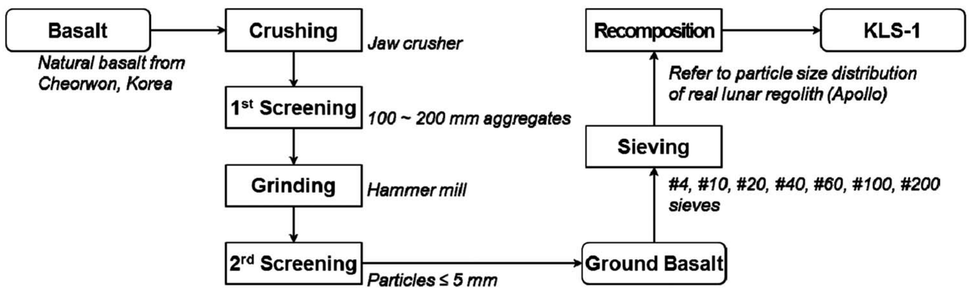

Fig. 2. Proposed manufacture system for KLS-1 lunar simulant development using natural igneous basalts

significantly higher amount of FeO (8.83%). The iron content and chemical composition were the most similar to actual lunar soil, but large-scale retrieval of basalt for lunar simulant development is difficult because the basalt deposit in Yeoncheon is in a military-controlled area near the Demilitarized Zone (DMZ) in Korea. As for intrusive basalt from Cheorwon, the amount of FeO (6.64%) was lower than that of samples from Yeoncheon. The total iron content ($FeO + Fe_2O_3$) exceeded 11%, and the samples were easier to obtain compared with other candidate sites. Therefore basalt from Cheorwon was selected as the mother material from which to develop a Korean lunar simulant.

Preliminary Production of KLS-1

To reconstitute a particle-size distribution similar to that of actual lunar soil, the intrusive basalt sample from Cheorwon was powderized, sieved, and separated before recomposition (Fig. 2). After crushing the samples into sizes of 10–20 cm, sand and other impurities were removed. A second round of crushing was then performed. Crushed basalt samples were sifted through standard #4 (4.75 mm), #10 (2.00 mm), #20 (0.85 mm), #40 (0.425 mm), #60 (0.25 mm), #100 (0.15 mm), #200 (0.075 mm), and finer (<0.075 mm) sieves using a gyratory shaker (capacity of single series of sieving: 10 kg). Based on the particle-size distribution data of real lunar soil 14163 (McKay et al. 1972), crushed basalt samples were recomposed to derive a prototype for the Korean lunar simulant. Particles remaining on the #4 sieve were separated, and only particles finer than 4.75 mm were used. KLS-1 is composed of 2.75% #10 remaining, 2.80% #20 remaining, 6.00% #40 remaining, 10.80% #60 remaining, 10.45% #100 remaining, 11.80% #200 remaining, and 55.40% #200 passing basalt, by mass ratios.

Chemical and Physical Properties of Korea Lunar Simulant

KLS-1 has a particle-size distribution closer to that of lunar soil 14163 than do other lunar simulants (JSC-1, FJS-1) (Fig. 3). In particular, the amount of fine-grained (<0.075 mm) particles (48.92%) and the particle-size distribution of actual lunar soil were highly similar to that of KLS-1 (fine-grained particles amounting to 48.2%). Similar to other lunar simulants, KLS-1 is categorized as silty sand (SM) under the USCS.

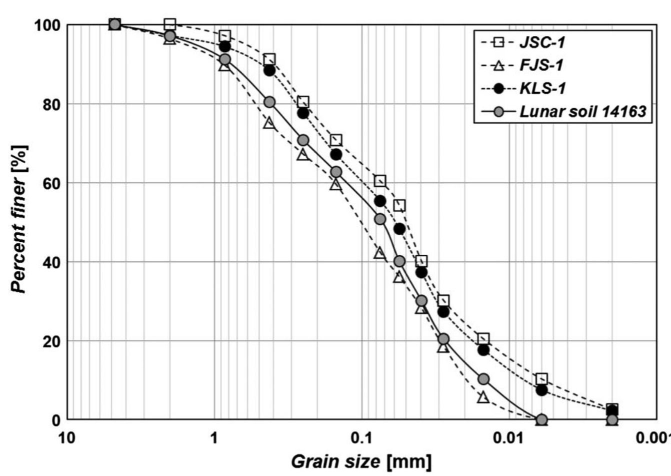

Fig. 3. Particle-size distribution of real lunar regolith and lunar simulants JSC-1, FJS-1, and KLS-1

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Table 4. Chemical Compositions of KLS-1 and Real Lunar Regolith (Lunar Soil 14163)

Material	Chemical element											
	SiO_2	TiO_2	Al_2O_3	FeO	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	S
KLS-1	48.00	1.67	15.30	6.64	4.75	0.17	9.64	8.38	3.42	1.52	0.33	0.01
Lunar soil 14164	47.30	1.60	17.80	10.50	—	0.14	9.60	11.40	0.70	0.55	—	—
Difference	+0.70	+0.07	−2.50	−3.86	+4.75	+0.03	+0.04	−3.02	+2.72	+0.97	+0.33	+0.01

Table 5. Mechanical Properties of JSC-1, FJS-1, and KLS-1 Lunar Simulants

Lunar simulant	c	φ	G_s	Cost	Remarks
JSC-1	≤1.00	45.0	2.90	US$19/kg[a]	Willman et al. (1995)
	1.65	45.0	2.92	—	From this study
FJS-1	3–8	32.5–39.4	2.94	US$4/kg[b]	Kanamori et al. (1998)
	8.13	39.4	2.90	—	From this study
KLS-1	1.85	44.9	2.94	US$2/kg (approximately)	From this study

[a]Price provided by ORBITEC (2014).
[b]Price provided by Shimizu Corporation (2014).

Table 4 compares the chemical compositions of KLS-1 and lunar soil 14163. KLS-1 consists of 48.0% silicon dioxide (SiO_2), 15.3% dialuminum dioxide (Al_2O_2), 8.38% calcium oxide (CaO), 4.75% ferric oxide (Fe_2O_3), 6.64% iron oxide (FeO), and 9.64% magnesium oxide (MgO). KLS-1 has lower amounts of Al_2O_3, FeO, and CaO; higher amounts of SiO_2, Fe_2O_3, and Na_2O; and similar amounts of TiO_2, MnO, and MgO compared with lunar soil 14163. With the exception of iron oxide, KLS-1 is more similar to lunar soil than are other lunar simulants in terms of chemical composition. The amount of FeO in KLS-1 is lower than that of other simulants because the prototype was not mixed with volcanic ash or plasma processed to increase iron content. Moreover, the amount of Fe_2O_3 in KLS-1 is relatively higher than that in real lunar soil due to the oxidation on Earth (Taylor and McLennan 2009; Wade and Wood 2016).

Actual lunar soil is known to have a specific gravity higher than 2.9 (Colwell et al. 2007). The G_s of lunar soil 14163, brought back to Earth under the Apollo program, is 3.1 (Carrier 2003). Along with particle-size distribution and chemical composition, G_s must be taken into account in the development of lunar simulants (Sibille et al. 2006). The G_s values of JSC-1, FJS-1, and KLS-1 obtained in this study in accordance with ASTM D854-14 (ASTM 2014) were 2.9, 2.94, and 2.94, respectively (Table 5). The obtained G_s value of JSC-1 is consistent with the known value, $G_s = 2.91$ (Willman et al. 1995). In other words, KLS-1 had a G_s value lower than that of lunar soil 14163 but similar to that of existing lunar simulants. A G_s of 2.94 was obtained from crushed basalt alone without artificial additives or chemical processing because intrusive basalt in Cheorwon, Korea is known to have G_s values between 2.7 and 3.0 (Min and Chin 1999; Nam et al. 2008; Park et al. 2014; Yeon et al. 1999).

Geotechnical Engineering Behavior of KLS-1

Geotechnical Engineering Considerations of Lunar Simulant Development

For unmanned rovers to perform specific missions such as exploration and transport, they must be equipped with humanlike visual and cognitive functions, and the ability to move effectively according to circumstances. Rovers must maintain stability while driving on uneven surfaces that are far more challenging than standard roads. They must have high traversability, which determines the maximum power or speed depending on the materials constituting the terrain (Karafiath and Nowatzki 1978).

The traversability of rovers varies with interactions between the wheels and the ground, and it is significantly affected by friction-slip characteristics. One method of terrain modeling, with consideration of friction-slip characteristics in extreme environments, is the semiempirical terrain model (Wong 2010). The main parameters used in this model are cohesion and internal friction angle, where the maximum shear stress (τ_f) is calculated based on the cohesion and internal friction angle ($\tau_f = c + \sigma_v \cdot \tan\phi$). The maximum shear stress can be described as the maximum friction, acting between the wheels and the ground, needed to stop the rover.

In geotechnical engineering aspects, geotechnical properties of lunar soils show less variation than do those of soils on Earth due to the absence of chemical weathering, water, and wind on the Moon (Heiken et al. 1991). Geotechnical characterization of lunar soils usually has been presented in terms of shear strength, shear modulus, density, and void ratio in previous studies (Carrier 2003; Carrier et al. 1973; Slyuta 2014). Shear strength and shear stress-displacement relationships obtained via shear tests (direct shear or triaxial tests) are essential to evaluate the maximum rover traction and traction-slip characteristics.

Direct Shear Behavior of KLS-1

To evaluate the shear behavior of the lunar simulant, direct shear tests were performed with a shear testing machine (Humboldt HM-2560A, Elgin, Illinois). The samples were created using free-fall and dry-compaction methods. Lunar regolith simulants were dried in an oven at 110°C for 48 h before testing to provide fully dried soils (the Moon's surface is also completely dry). Dried lunar simulants were poured uniformly into the shear box via the raining method (standard) from a 100-mm height. Simulants were poured in five steps, and compaction was performed after each raining with a laboratory tamper. Finally, a disk-shaped lunar simulant specimen with 60-mm diameter and 20-mm height and relative density (D_r) of 60% (i.e., initial void ratio $e_o = 0.67$, $e_{min} = 0.46$, $e_{max} = 0.98$) was prepared. Direct shear tests were performed with five different vertical confinement levels ($\sigma_n = 10$, 20, 50, 100, and 200 kPa). To eliminate the influence of shear rate on shear strength, all tests were performed at a constant shear rate of 1 mm/min until a shear displacement of 10 mm was reached (ASTM 2011a).

Fig. 4 shows representative results of direct shear tests on diverse lunar simulants. The direct shear strength increased with vertical confinement increment, and the horizontal shear displacement (δ) at τ_f gradually increased with higher σ_v. In contrast with JSC-1 [Fig. 4(a)], FJS-1 [Fig. 4(c)] and KLS-1 [Fig. 4(e)] showed residual τ–δ behaviors ($\tau_{peak} = \tau_{residual}$) that were similar to those of ordinary loose sand, regardless of σ_v levels. The peak direct shear strength (τ_f) had similar values due to identical σ_v levels, regardless of the simulant type. However, the vertical strain–horizontal shear displacement (ε_v–δ) behavior of JSC-1 simulant implies typical shear behavior of dense sands (obvious dilation), whereas FJS-1 and KLS-1 simulants are close to the typical shear behavior

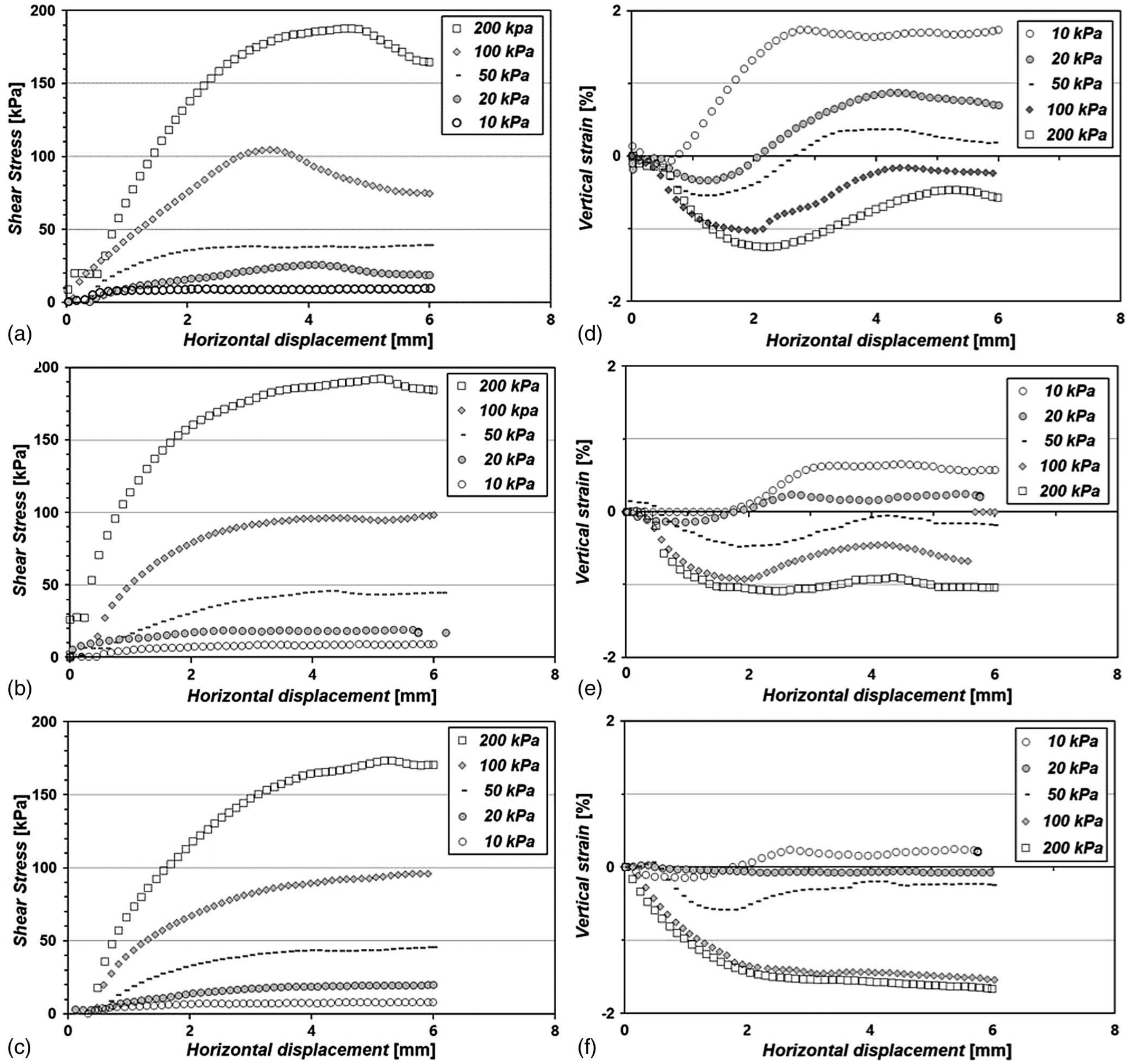

Fig. 4. Direct shear stress–horizontal shear displacement results of (a) JSC-1; (b) FJS-1; (c) KLS-1 lunar stimulants; and vertical strain–horizontal shear displacement relationships of (d) JSC-1; (e) FJS-1; (f) KLS-1 lunar simulants

of loose sands. In particular, FJS-1 [Fig. 4(d)] and KLS-1 [Fig. 4(f)] showed slight dilation at low σ_v and became contractive at $\sigma_v >$ 50 kPa conditions, whereas JSC-1 mostly showed dilative behaviors [Fig. 4(b)] regardless of σ_v levels.

All direct shear tests were performed with completely dried simulants with similar particle-size distributions (Fig. 3) and similar initial structural composition ($D_r = 60\%$) for shearing. Thus the different vertical strain behavior along horizontal shear displacement appears to be affected by specific characteristics of individual particles (e.g., shape, angularity, surface roughness) (Mitchell and Soga 2005).

Shear Strength Properties of KLS-1

Fig. 5 shows vertical confinement (σ_v) and accompanying peak shear strength (τ_f) relationships of JSC-1, FJS-1, and KLS-1 with real Apollo data. The friction angle and cohesion values of each simulant were obtained via Mohr–Coulomb linear approximation. Shear strength properties of real lunar soil are known to be $c =$ 0.3–2.1 kPa and $\phi = 35$–$47°$ based on Apollo 11, Apollo 12, and Apollo 14 data (Mitchell et al. 1972a).

Interparticle friction angle and cohesion of KLS-1 were 1.85 kPa and 44.91°, respectively, which successfully represent the shear strength properties of real lunar soil. The ϕ and c values of JSC-1 ($\phi = 45.0°$ and $c = 1.65$ kPa) and FJS-1 ($\phi = 39.4$ and $c = 8.13$ kPa) obtained from this study were in accordance with existing findings on both simulants: $\phi = 45.0°$ and $c = \leq 1$ kPa for JSC-1 (Willman et al. 1995); and $\phi = 32.5$–$39.4°$ and $c = 3$–8 kPa for FJS-1 (Kanamori et al. 1998) (Table 5). However, the interparticle cohesion value of FJS-1 simulant ($c = 3$–8.4 kPa) was higher than the typical range ($c = 0.3$–2.1 kPa) of real lunar soils, whereas KLS-1 and JSC-1 showed high similarity in both interparticle

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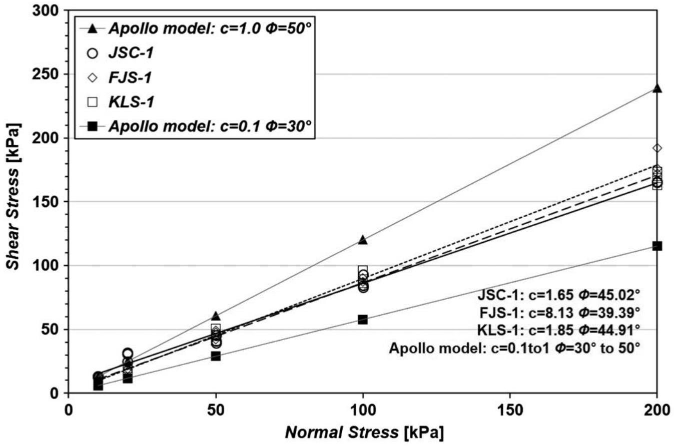

Fig. 5. Direct shear strength–vertical confinement (τ_f–σ_v) relationships of lunar soil and lunar simulants

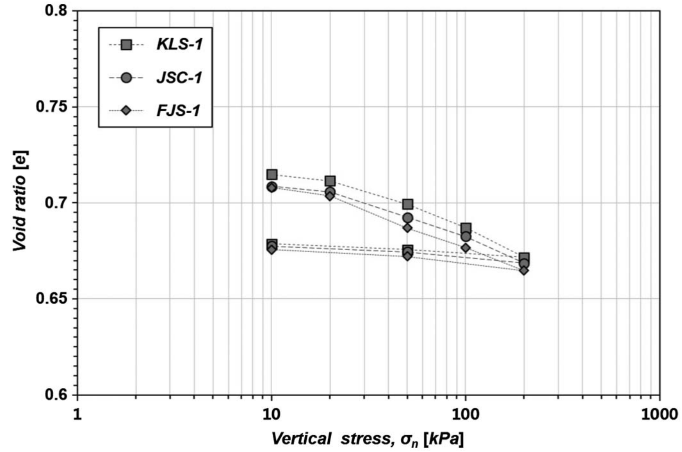

Fig. 6. Stress-strain variations of lunar simulants from oedometer apparatus loading and unloading

friction and cohesion values to real lunar soils. Thus the newly developed KLS-1 from this study holds promise as a lunar simulant for various geotechnical engineering and terramechanic purposes based on its high reliability in terms of representing shear strength properties.

Stress-Strain (Compressibility) Characteristics

Compressibility parameters (compression index, C_c; swelling or recompression index, C_s or C_r) of lunar simulants are also important considerations for lunar vehicle and surface construction designs. The typical C_c value of loose lunar soil is recommended to be 0.05–0.3 depending on the density conditions (Suescun-Florez et al. 2015). In this study, a typical one-dimensional oedometer test (ASTM 2011b) was performed to evaluate compressibility parameters of JSC-1, FJS-1, and KLS-1 lunar simulants.

Dried simulants were placed in a standard oedometer cell (50 mm in diameter and 20 mm in height) with $D_r = 50\%$. Pressure of 10 kPa was applied vertically for 24 h to obtain the initial void ratio at 10 kPa vertical confinement (0.714 for KLS-1, 0.709 for JSC-1, and 0.708 for FJS-1). Incremental loadings of 10, 30, 50, and 100 kPa were then applied to represent 20, 50, 100, and 200 kPa confinement conditions. Each load increment was applied for 24 h, at which point no further settlement was monitored. After 200 kPa confinement, specimens were unloaded to 50 kPa and 10 kPa confinement conditions for swelling (or recompression) simulation. Fig. 6 presents void ratio values with confinement variations of each lunar simulant.

The compression index ($C_c = \Delta e/\Delta \log_{10}\sigma_n$ for loading) values of KLS-1, JSC-1, and FJS-1 were 0.29, 0.26, and 0.28, respectively. The C_c value of KLS-1 (0.29) was similar to the suggested C_c of 0.3 for loose lunar soil (Heiken et al. 1991). The recompression index (C_r) values were 0.0043 (KLS-1), 0.0045 (JSC-1), and 0.0050 (FJS-1), which are consistent with the known C_r value (0.0042) of initially compressed (dense) lunar simulants (Suescun-Florez et al. 2015).

Scanning Electron Microscope Analysis of Particle Characteristics

The biggest difference between KLS-1 and other lunar simulants is the raw material used for production. JSC-1 uses volcanic ash, whereas FSJ-1 was developed from rapidly cooled lava. Because KLS-1 was made from intrusive basalt samples formed during the Quaternary Period, a scanning electron microscope (SEM) analysis was performed to examine possible differences in particle characteristics (shape, roughness, and so on).

The lunar simulant in powder form was thinly scattered on a carbon adhesive sheet and coated with osmium (Os) for 1 min in a vacuum state before observation with an SEM (Magellan XHR 400L, Hillsboro, Oregon). The signals were acquired in the secondary electron mode, and the laser voltage was kept at 5.0 kV.

Fig. 7 shows photographic images and 500X-magnified SEM images of JSC-1, FJS-1, and KLS-1. Although the three lunar simulants had similar particle shapes, angularity, and particle-size distributions (Fig. 3), the color of the lunar simulants became darker in order KLS-1 [Fig. 7(e)] → FJS-1 [Fig. 7(c)] → JSC-1 [Fig. 7(a)]. This distinction can be traced to the crushing method, the presence of volcanic ash, and plasma processing. To develop a more precise and reliable Korean lunar simulant, further research to develop an advanced Korean lunar simulant with enhanced FeO content via plasma treatment or other methods is recommended.

Discussion: Economic Feasibility and Future Prospects of KLS-1

JSC-1 was developed by NASA Johnson Space Center with the establishment of the Space Exploration Initiative in 1989. This lunar simulant, which exhibits vitreous characteristics, was developed from volcanic ash found near Flagstaff, Arizona. It consists of anorthosite, pyroxene, and olivine, and has weak metallic properties. It has a specific gravity of 2.9, a cohesion of 1.0, and a friction angle of 45° (Willman et al. 1995). However, JSC-1 or Johnson Space Center Number One A (JSC-1A) simulants are insufficient for large-scale simulation programs due to their scarce quantities. New lunar regolith simulants with large procurement, such as NASA/USGS-Lunar Highlands Type-2 Medium regolith simulant (NU-LHT-2M) (Stoeser et al. 2010; Zeng et al. 2010), are thus currently being actively used in large-scale lunar programs (e.g., ESA PROSPECT).

FJS-1 was developed using samples obtained from the basaltic lava of Mount Fuji in Japan. Although FJS-1 was designed to match the bulk mechanical properties and chemical composition of soils in the lunar maria (Kanamori et al. 1998), the abundance of SiO_2 and lower MgO content show that FJS-1 is more quartz normative than are lunar soils. Moreover, even though physical properties such as $G_s = 2.94$ and $\phi = 32.5$–$39.4°$ (Kanamori et al. 1998) are similar to those of lunar soil, the interparticle cohesion of FJS-1 is higher than that of KLS-1, JSC-1, and real lunar soils.

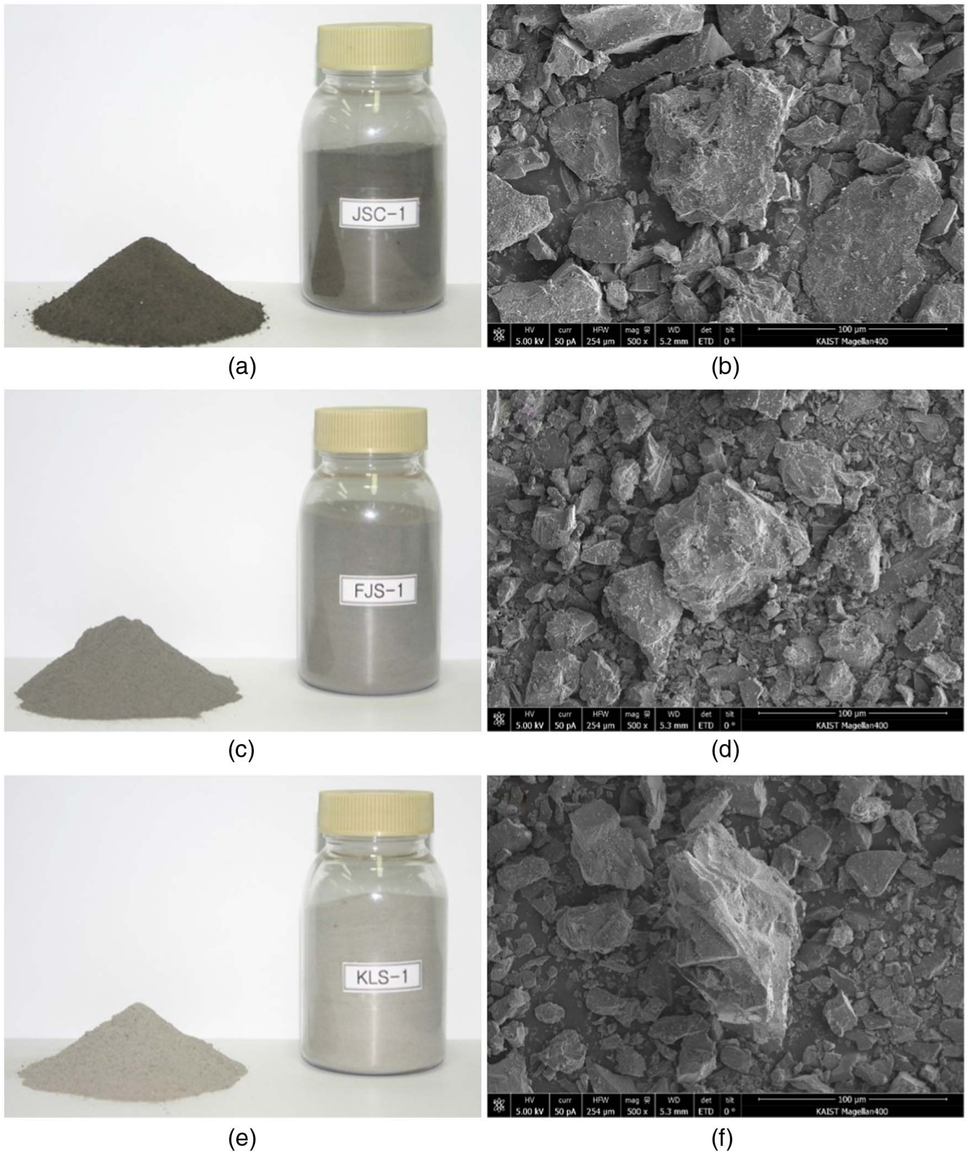

Fig. 7. Photographs and SEM images of (a and b) JSC-1; (c and d) FJS-1; and (e and f) KLS-1 lunar simulants (images by Ilhan Chang)

This study developed KLS-1 by recomposing sieved crushed basalt from Cheorwon, Korea. The developed simulant KLS-1 has a specific gravity of 2.9, which is the typical range (2.9 to 3.2) of lunar soils (Carrier 2003; Carrier et al. 1973). Moreover, the chemical composition and physical shear strength properties (c, ϕ) of KLS-1 also successfully represent characteristics of real lunar soils.

Generally, a lunar regolith simulant is recommended to be a material manufactured from natural or synthetic terrestrial or meteoritic components to simulate one or more physical (e.g., particle-size distribution, specific gravity, relative density, interparticle friction angle and cohesion, and compressibility) and/or chemical properties of a lunar soil (Sibille et al. 2006). A series of experimental verifications provided technical evidence that the newly developed KLS-1 is a promising reliable lunar regolith simulant for use in the fields of aerospace and geotechnical engineering.

For macroscale utilization, the economic feasibility of lunar regolith simulants is an important criterion. Because the costs of 1 kg of JSC-1 and FJS-1 lunar simulants are reported to be US$19 and US$4, respectively, the expected material costs to simulate a 1 m^2 lunar surface area with 34 cm thickness (approximately 1 t in mass) are estimated to be US$30,000 and US$4,000, respectively. Meanwhile, the material, transportation, and production (labor for sieving and recomposing) costs are estimated to be US$2,000 for 1 t of KLS-1 production in this study. Fig. 8 represents the large-scale KLS-1 production system (Baek et al. 2015) which is currently being installed at the Korea Institute of Civil Engineering and Building Technology (KICT). With the in situ supply of crushed basalts, the system has a capacity to treat (drying, sieving, and separating) 1.5 t of raw material in a single cycle. The entire system is perfectly sealed and pneumatically controlled to minimize dust. Crushed basalts are immediately heated and dispersed to be completely dried and separated into single particles. Dried particles are then transported via air flow into layers of sieves (#4–#200, and finer). All remaining particles on each sieve are moved by air and collected in their primary containers. Separated particles can be used separately, and an automatic vacuum and mass control system can recompose KLS-1 based on the detailed mass composition presented in the Preliminary Production of KLS-1 section. The system is estimated to produce 1 t of KLS-1 per 8 h (1 day) of operation. Moreover, the cost of KLS-1 is expected to be less than US$1,000/t, representing the most economically feasible lunar

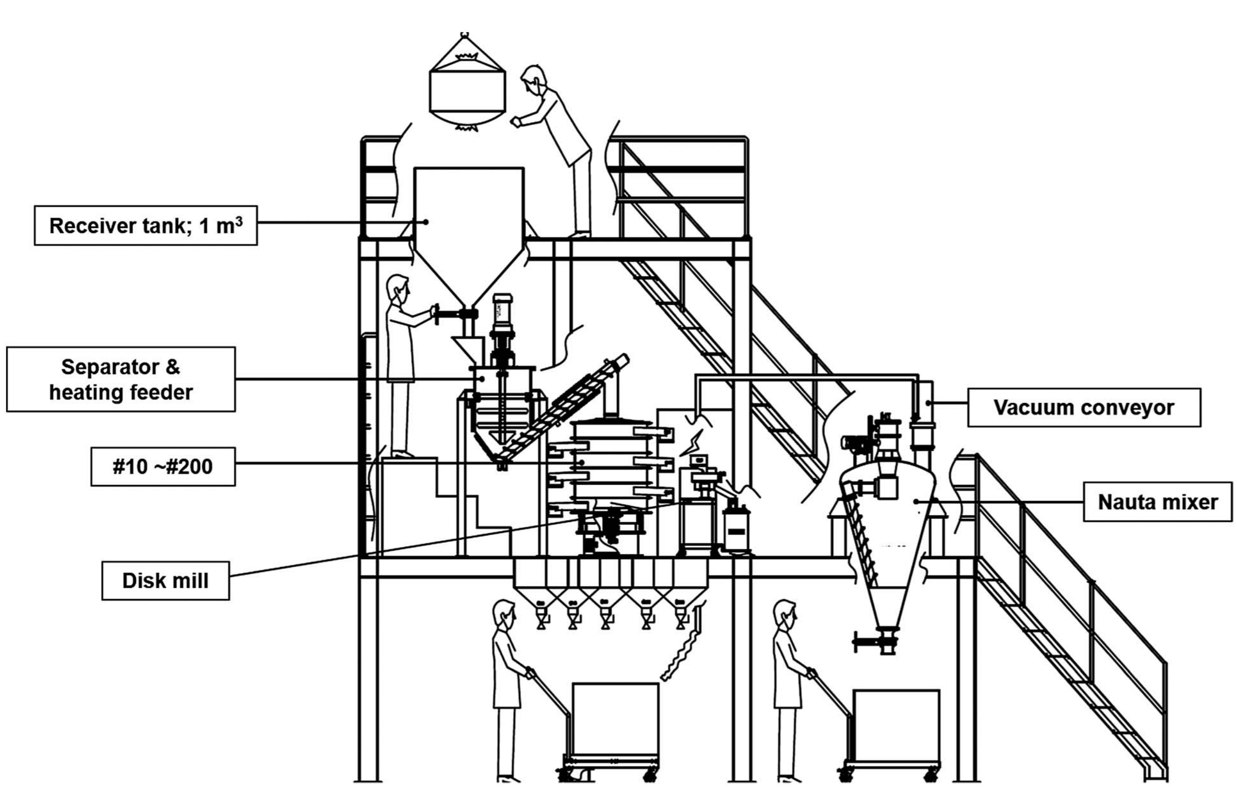

Fig. 8. Schematic diagram of massive commercialized production system (1 t/day) of KLS-1

regolith simulant. Therefore, due to its high similarity to real lunar soil and potential for tonnage quantities, KLS-1 is a promising root lunar regolith simulant (Sibille et al. 2006) for application in various research programs, including macroscale drilling and excavation.

Conclusions

Lunar regolith is an essential component for understanding and simulating the surface environment of the Moon for concurrent and future lunar missions. However, real lunar regolith samples returned to the Earth are priceless and in quantities that are far too small to be used for macroscale research programs. Thus various lunar soil simulants have been developed by different countries and organizations using terrestrial materials to represent the physical and chemical properties of real lunar soils. However, most lunar simulants have been made with exotic materials and complicated processes, and many are in short supply.

This study developed a new lunar regolith stimulant—KLS-1—using natural basalt from Korea with a simple manufacturing procedure. The chemical and physical (geotechnical engineering) properties of KLS-1 were verified to represent the real characteristics of lunar soil 14163.

To find the most appropriate mother material for KLS-1, natural basalts in Korea were examined and classified in terms of chemical composition and total iron content ($FeO + Fe_2O_3$). Among eight candidate samples, Quaternary intrusive basalt from Cheorwon, Korea shows the highest appropriateness to become the mother material for KLS-1 production. After powderization and precision sieving, separated basalt grains were recomposed according to the particle-size distribution of lunar soil 14163. The resulting mixture is Korea Lunar Simulant—Type 1, with a particle-size distribution (SM: silty sand; $G_s = 2.94$) and a chemical composition having high similarity to those of real lunar soil.

Geotechnical shear strength properties of KLS-1 were evaluated via a series of laboratory direct shear tests within the context of Mohr–Coulomb failure criteria. The peak internal friction angle of KLS-1 is high and increases with density, with negligible cohesion. The measured peak friction angle was 44.91° on average, and interparticle cohesion was $c = 1.85$ kPa. Standard laboratory oedometer apparatus testing yielded a compression index of $C_c = 0.029$ and a recompression index of $C_r = 0.0043$ for KLS-1 simulant. All mechanical properties (G_s, ϕ, c, C_c, and C_r) of KLS-1 were consistent with real lunar soil and other major simulants, demonstrating the high reliability of using KLS-1 in the area of aerospace engineering.

This study focused on basic research (particle-size distribution and chemical composition) for the development of KLS-1. In addition to chemical and physical reliability, economic feasibility is another important advantage of KLS-1. Based on the sufficient supply of raw materials and a concurrently developed automatic producing system, KLS-1 is expected to be the most inexpensive root lunar simulant to be deployed in various macroscale lunar research programs. Meanwhile, further research is required to evaluate other geotechnical engineering components such as compressibility. Moreover, additional processes such as plasma treatment or glass fragment bonding are expected to provide a strong representation of irregular agglutinates and dust particles to further improve the similarity of KLS-1.

Acknowledgments

The research described in this paper was financially supported by grants from the Strategic Research Projects—(1) Geotechnical Engineering Preparations for Lunar Exploration: Soil Mechanics with Lunar Soil and Laboratory Demonstration of Lunar Environments; and (2) Development of environmental simulator and advanced construction technologies over TRL6 in extreme conditions—funded by the Korea Institute of Civil Engineering and Building Technology. The authors also acknowledge Dr. Moonkyung Chung, Dr. Kiseok Kwak, and Dr. Jin-Tae Han at KICT for their sincere support and advice on this research.

Notation

The following symbols are used in this paper:

C_c = compression index;
C_r = recompression index;
C_s = swelling index;
c = interparticle cohesion (kPa);
D_r = relative density;
e = void ratio;
$e_{\max}$ = maximum void ratio;
$e_{\min}$ = minimum void ratio;
e_o = initial void ratio;
G_s = specific gravity;
γ = horizontal strain (%);
δ = shear displacement (mm);
ε_v = vertical stain;
σ_n = normal (vertical) stress;
σ_v = vertical confinement for direct shear testing;
τ = shear stress during horizontal shearing;
τ_f = shear stress at failure;
$\tau_{\max}$ = (maximum) shear stress; shear strength;
τ_{peak} = peak shear stress for direct shear testing;
τ_{residual} = residual shear stress for direct shear testing; and
ϕ = interparticle friction angle (degrees).

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