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CAS-1 lunar soil simulant

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Abstract

Lunar soil simulant is a geochemical reproduction of lunar regolith, and is needed for lunar science and engineering researches. This paper describes a new lunar soil simulant, CAS-1, prepared by the Chinese Academy of Sciences, to support lunar orbiter, soft-landing mission and sample return missions of China's Lunar Exploration Program, which is scheduled for 2004–2020. Such simulants should match the samples returned from the Moon, all collected from the lunar regolith rather than outcrops. The average mineral and chemical composition of lunar soil sample returned from the Apollo 14 mission, which landed on the Fra Mauro Formation, is chosen as the model for the CAS-1 simulant. Source material for this simulant was a low-Ti basaltic scoria dated at 1600 years from the late Quaternary volcanic area in the Changbai Mountains of northeast China. The main minerals of this rock are pyroxene, olivine, and minor plagioclase, and about 20–40% modal glass. The scoria was analyzed by XRF and found to be chemically similar to Apollo 14 lunar sample 14163. It was crushed in an impact mill with a resulting median particle size 85.9 μm, similar to Apollo soils. Bulk density, shear resistance, complex permittivity, and reflectance spectra were also similar to Apollo 14 soil. We conclude that CAS-1 is an ideal lunar soil simulant for science and engineering research of future lunar exploration program.

Keywords: CAS-1; Lunar soil simulant; China's Lunar Exploration Program

1. Introduction

Lunar soil simulant is a kind of geological material, which has similar mineral and chemical composition, similar physical and mechanical properties with lunar surface material. It is a geochemical reproduction of lunar regolith.

In the 1980s and 90s, there was a need for a lunar simulant that had the correct mechanical and geotechnical properties for use by the engineering community. In 1990s, a group of US scientists produced and distributed a new standardized lunar regolith simulant termed JSC-1 (Johnson Space Center) (Carrier et al., 1991; Willman et al., 1995). JSC-1 was developed from volcanic ashes, and readily available. Like as lunar soil, it contains ~50% glass. When crushed and properly sized, JSC-1 had the approximate geotechnical soil properties of lunar soil (Carrier et al., 1991). Till now about 25 tons JSC-1were created and distributed to the lunar scientific and engineering community; which is not available any more.

Weiblen et al. (Weiblen and Gordon, 1988; Weiblen et al., 1990) had developed a lunar regolith simulant MLS-1 at the University of Minnesota, in which they used an in-flight sustained shockwave plasma (ISSP) reactor to produce synthetic agglutinates. However, previously prepared simulants, have been used up, new lunar simulant needed to be developed in US science and engineer community.

Recently, two simulants FJS-1 and MKS-1 were developed in Japan by the Japan Aerospace Exploration Agency (JAXA) (Kanamori et al., 1998). But these two simulants

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were only appropriate for engineering purpose for their difference with lunar regolith.

The first Chinese lunar orbiter, Chang'E-1 lunar probe, was launched by a Long March 3A carrier rocket from Xichang Satellite Launch Center in 24th October, 2007. The success of Chang'E-1 is the first step into its ambitious three-stage Moon mission. This will be followed by robotic landing missions between 2009 and 2013, and sample return missions between 2015 and 2017 (Ouyang, 2005). To plan such missions and subsequent ones, realistic lunar soil simulants will be necessary, since actual lunar samples are too valuable to use for engineering purposes. Therefore, a new lunar simulant, CAS-1, was developed in China. The basic physical, chemical and geological properties of simulant were present in the paper.

2. Geologic setting of source material

Although not widely known, there are several recently active volcanic areas in northeast China (Fig. 1). Over 100 volcanos with explosive activity and many maars with phreatovolcanic activity are found in a 2000 km^2 area of the Longgang Volcano Group of the Changbai Mountains of Jilin Province. We sampled and analyzed scoria and ash of Haikou Volcano in Hainan Province, the Tengchong Volcano Group in Yunnan Province, the Wudalianchi and Jingbohu Volcanos in Heilongjiang Province, and the Longgang Volcano Group in Jilin Province. We chose scoria from the Sihai pyroclastics erupted by Jinlongdingzi Volcano as our source material.

The Jinlongdingzi Volcano, a 999.4 m high scoria cone, is in the center of the Longgang Volcanic Group, and is surrounded by the airborne Sihai tephra sheet. Liu and Xiang (1997) have made a ^{14}C age determination of carbonized wood at the base of the Sihai sheet, and found it to be 1587–1690 BP (Liu and Xiang, 1997). Another ^{14}C age, from charred but uncarbonized trees in the same layer, is 1500 BP (Liu and Xiang, 1997). Finally, humus under the scoria layer was dated at 1750 BP (Liu et al., 1999). Collectively, these data point to a sub-Plinean eruption of this volcano about 1600 years ago, making it the youngest volcano in the Longgang Group. The Sihai pyroclastic sheet, almost all distributed in the east of the scoria cone, is up to 16 km from the cone to south and north. The material for the CAS-1 simulant was collected from a scoria layer 2 m thick on the north side of Diaoshuihu Road, 3 km east of the cone.

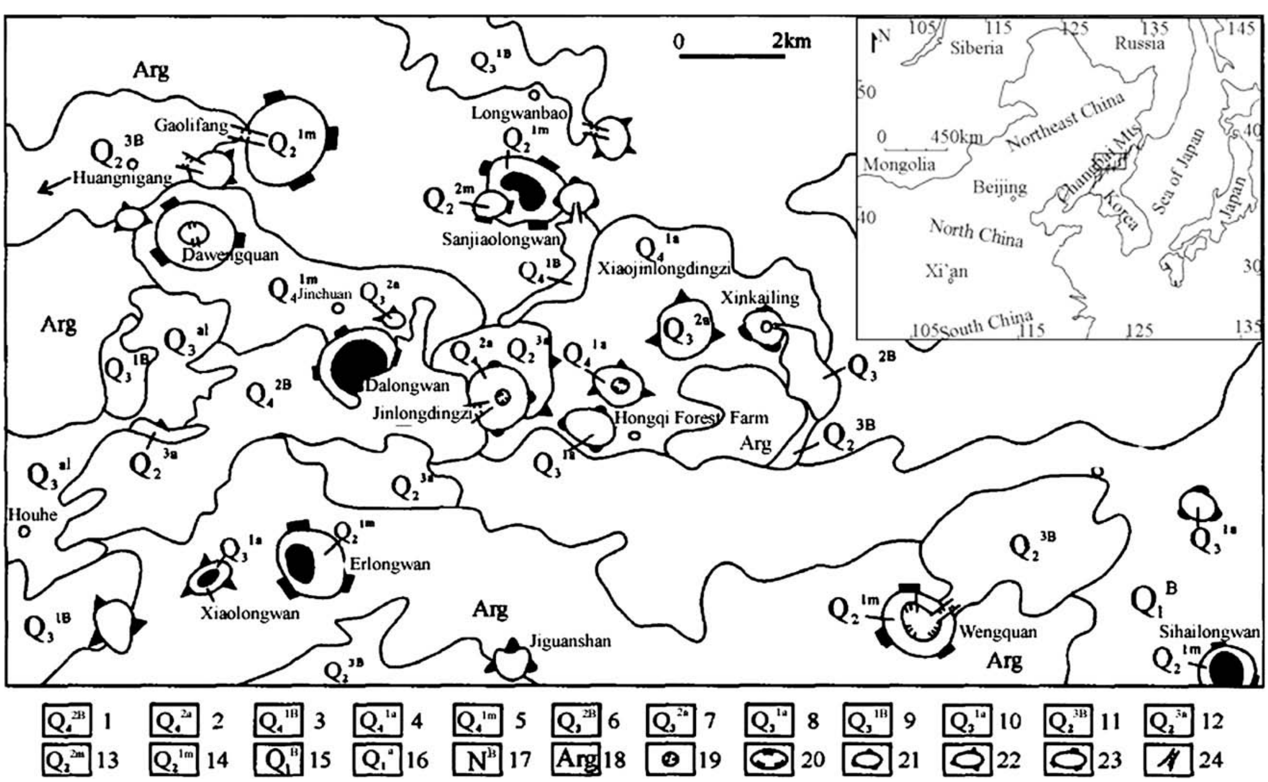

Fig. 1. Volcanic geological background of Longgang volcanic cluster. (l) Late Jinlongdingzi period basalt; (2) late Jinlongdingzi period scoria; (3) Hongqi Forest Farm period basalt; (4) Hongqi Forest Farm period scoria; (5) Dawengquan period volcanic deposit; (6) East Jinchuan period basalt; (7) East Jinchuan period scoria; (8) late early Pleistocene scoria; (9) late early Pleistocene basalt; (10) late Pleistocene alluvia; (11) early Jinlongdingzi period basalt; (12) early Jinlongdingzi period scoria; (13) Hanlongwan period volcanic deposit; (14) Sanjiaolongwan period; (15) early Pleistocene basalt; (16) early Pleistocene scoria; (17) Neogene basalt; (18) Archean Gneiss; (19) crater; (20) maar crater; (21) spatter cone; (22) scoria cone; (23) maar cone; (24) lava gate.

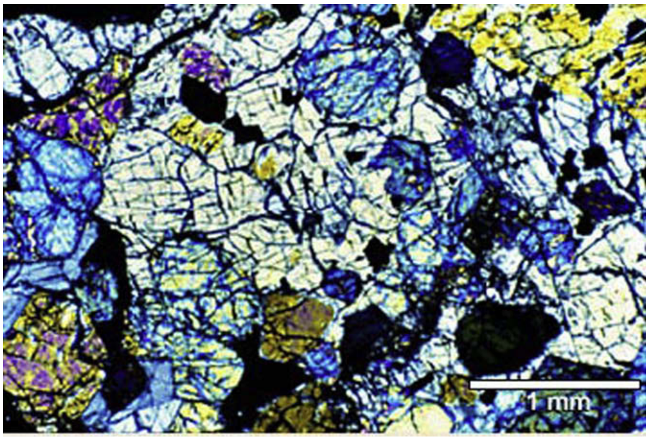

Fig. 2. Photomicrograph in cross polarized light of the mare basalt fragment in lunar impact breccia 14305. 14305 was sampled at Fra Mauro Formation of Apollo 14 landing site. The view is dominated by pyroxene, olivine, and chromium and titanium oxides.

3. Lunar analogues

The 2005 Lunar Regolith Simulant Materials Workshop recommended production of two types of simulant corresponding to a low-Ti mare basalt and one to a high-Ca highland anorthosite (Sibille and Carpenter, 2005). These were assumed to be compositional end members of mare and highland rocks. Most of the lunar regolith is of the highland type for the whole Moon. However, for the nearside of the Moon, especially in the middle-low latitude area, mare is distributed more extensively. Furthermore, for future landing plan or the construction of the lunar base, smooth mare is more preferred than rugged highland. For in-situ resource utilization (ISRU), mare regolith contains high content of ilmenite, np-Fe^0 iron metal, uranium and helium-3 (Zheng et al., 2008). Mare regolith simulant is principal for ISRU.

There are three soil types on the Moon, mare soil, highland soil, mixture of mare soil and highland soil. Apollo 14 landing site was located in the boundary of mare and highland. The sample is mixture of mare soil and highland soil, mainly composed by mare crater ejecta. We chose source material whose lunar analogue was an Apollo 14 soil sample 14163. Although this is not a simple rock, its bulk chemical composition is similar to the simulant JSC-1 as we will show. The nature of the lunar samples from Fra Mauro Formation at Apollo 14 landing site, agglutinate and lunar impact breccia, such as 14305, is shown in Fig. 2, from Taylor et al. (1983).

In order to satisfy the different science and engineering research, two root simulant, typical mare simulant and typical highland simulant, are also need. We are planning to develop another highland simulant.

4. Analytical methods

The scoria chosen was air-dried for 3 months before analysis, then ground to pass an 80 mesh (177 μm) sieve. Oxides, loss on ignition, and Fe_2O_3/FeO ratios ere determined by the methods of Boyd and Mertzman (1987). Loss on ignition was determined by heating samples in argon for

Table 1
Major element composition of CAS-1 and compared with JSC-1, FJS-1, MKS-1 lunar soil simulant, and Apollo 14 lunar regolith

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Apollo 14	48.1	1.7	17.4	10.4	0.14	9.4	10.7	0.7	0.55	0.51	–	99.6
CAS-1	49.24	1.91	15.80	11.47	0.14	8.72	7.25	3.08	1.03	0.3	0.52	99.46
JSC-1	47.71	1.59	15.02	10.79	0.18	9.01	10.42	2.7	0.82	0.66	0.11	99.01
FJS-1	49.14	1.91	16.23	13.07	0.19	3.84	9.13	2.75	1.01	0.44	0.43	98.14
MKS-1	52.69	1.01	15.91	12.28	0.22	5.41	9.36	1.9	0.58	0.14	0.5	100
14163	47.3	1.6	17.8	10.5	0.1	9.6	11.4	0.7	0.6	–	–	99.6

Apollo 14, average chemical composition of lunar regolith sampled by astronauts at Apollo 14 landing sites. Data of Apollo 14 and 14163 were cited from Heiken et al. (1991), data of JSC-1 was cited from McKay et al. (1993, 1994).

Table 2
Trace element abundances of CAS-1 lunar soil simulant

Li	Sc	TiO_2	Cr	MnO	Co	Ni	Cu	Zn	Ga	Ge	As	Rb
5.61	19.72	1.88	367.7	0.147	49.82	301.2	63.51	186.7	17.77	1.637	13.9	30.97
Sr	Y	Zr	Nb	Mo	Cd	In	Sn	Sb	La	Ce	Pr	Nd
459.5	20.96	139.3	30.53	2.036	0.257	0.055	1.894	6.055	24.79	48.12	5.439	24.04
Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	W	Tl	Pb
4.485	1.73	5.013	0.697	3.948	0.755	2.208	0.283	1.707	0.281	0.733	0.059	4.631
Bi	∑REE	La/Yb	La/Sm	Th/Sc	La/Sc							
5.73	363.4	14.52	5.53	0.177	1.26							

Trace element concentration of CAS-1 was analyzed by ICP-MS in the Institute of Geochemistry, Chinese Academy of Sciences. Except for concentration of oxides TiO_2, MnO is wt.%, the remaining elements is in the unit of μg/g.

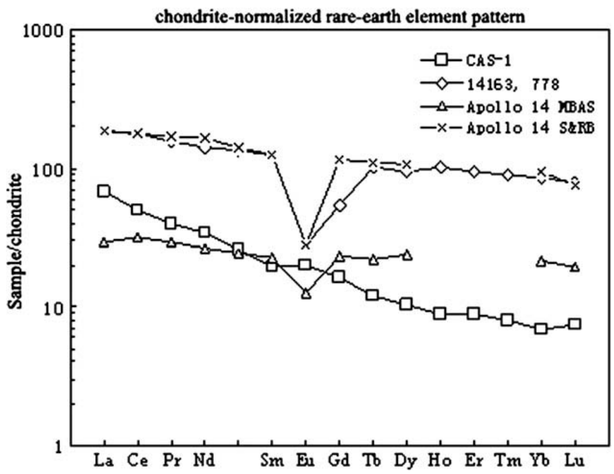

Fig. 3. Chondrite-normalized REE distribution pattern of CAS-1 lunar soil simulant and compared with lunar regolith sampled at Apollo 14 landing site. 14163,778 is a selected soil sample from Apollo 14 site. MBAS, mare basalts; S&RB, soils and regolith breccias. Data of lunar soil is cited from Brunfelt and Steinnes (1971) and Papike and Simon (1982), and REE content of chondrite is cited from Taylor and Mclennan (1985).

1 h at 900 °C, which drove off volatiles in general, not only water but also sulfur and chlorine compounds. To evaluate the degree of weathering of the scoria, we used standard soil analysis methods to determine the concentration of organic materials. The concentrations of C, N, H, S are 0.155, 0.022, 0.134, 0.034 wt.%, respectively. The low organic element contents suggest that the scoria material had not experienced obvious weathering.

Major element composition is shown in Table 1, comparing it with that of JSC-1, FJS-1, and MKS-1. CAS-1 is similar to JSC-1 and to the Apollo 14 agglutinate sample 14163.

Trace element composition of CAS-1 was analyzed by ICP-MS (Table 2), and found to resemble trachybasalt. Rare earth element (REE) concentrations are shown in Fig. 3, displaying light REE enrichment though no Ce or Eu anomalies. CAS-1 has high ratios of incompatible elements and is enriched in large ion lithophiles. This implies that the Sihai pyroclastic sheet was mantle-derived, without differentiation of the magma chamber during emplacement.

5. Mineralogy and petrography

The scoria has a porosity of 50–60%, with pores round, elliptical, and irregular in shape, and an average particle size of about 15 mm. Major minerals of CAS-1 lunar regolith simulant are pyroxene, olivine, and a small amount of plagioclase (Table 3 and Fig. 4), with a glass content of 20–40 modal percent. Scanning electron microscope (SEM) images show its similarity to lunar basaltic regolith (Fig. 5). No alteration products, such as quartz, illite, or other clay minerals were found, and pyroxene and olivine showed no alteration. It suggests that the source materials of CAS-1 are fresh scoria, and did not experience obvious weathering process after eruption. CIPW normative compositions (vol.%) of CAS-1 are shown in Table 4.

6. Physical characteristics

The lunar regolith is formed by long periods of meteoritic bombardment, producing surfaces saturated with impact craters. This produces a soil that is unique to airless planets, very different from terrestrial ones. Consequently, lunar simulants should come as close to possible to the structure of the regolith in size and shape of the grains.

After comminution, drying, and mixing, the simulant was studied with a scanning electron microscope at 1100×. The photographs show broken glass and mineral fragments as large as several hundred micrometers (Fig. 6). Glass fragments show broken vesicles with sharp edges. Mineral fragments are angular to sub-rounded, and many show scars from the milling process.

Table 3
Mineralogical composition of CAS-1 lunar soil simulant

Rock type	Texture	Porphyriticcrystals (including pores)	Matrix
Basalt	Aphanitic and vesicular (contains abundant large gas cavities)	Pyroxene Straight, parallel, and perfect Size: 1 × 2 mm Olivine Fracture developed Size: 2.5 × 1.5 mm Feldspar Cleavage: perfect, intergranular texture Size: 0.5 × 0.7 mm Pores Shape: circular or near-circular Content: about 50–60% Porphyriticcrystals Content: about 5–10%	Pyroxene and olivine Appeared in small crystals Size: less than 0.06 mm Content: about 15% Glass Content: about 20–40%

Major minerals of CAS-1 lunar soil simulant are pyroxene, olivine, and a small amount of plagioclase, with a glass content of 20–40 modal percent.

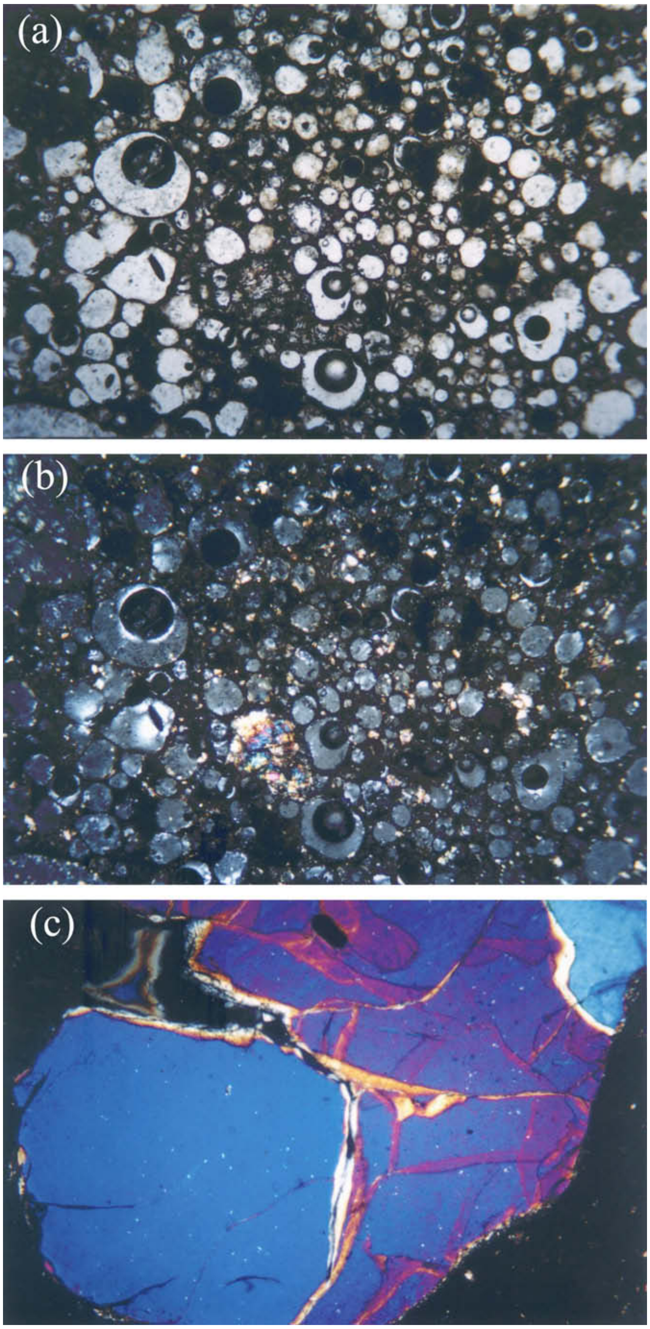

Fig. 4. Photomicrograph of CAS-1 lunar soil simulant through the microscope. (a) Vesicular structure, photomicrograph in plane polarized light at 40 magnification. (b) Photomicrograph in cross polarized light at 40 magnification. (c) Olivine phenocryst in cross polarized light at 63 magnification. Major minerals of CAS-1 lunar soil simulant are pyroxene, olivine, and a small amount of plagioclase, with a glass content of 20–40 modal percent.

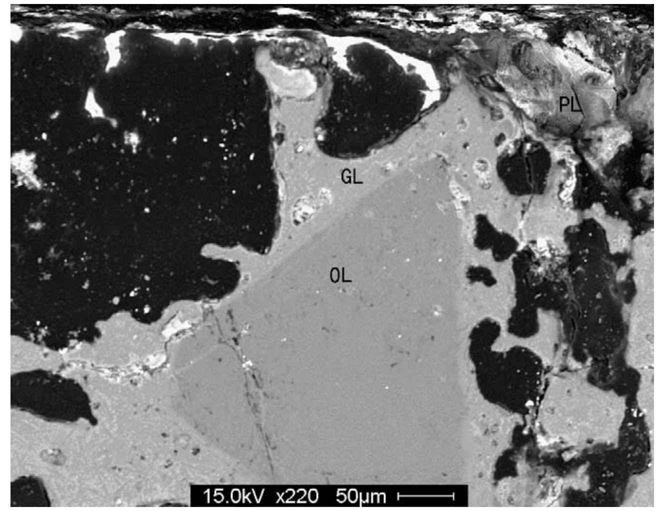

Fig. 5. Scanning electron microscope images of CAS-1 lunar soil simulant. GL, glass; PL, plagioclase; OL, olivine. Back-scattering image of CAS-1 were taken with a JSM6460LV/EDAX scanning electron microscope (SEM) in the Institute of Geochemistry, Chinese Academy of Sciences.

The median particle size for CAS-1 was 85.9 μm. The sample was found to be homogeneous with three measurements (Table 5 and Fig. 7). Its particle size is located in the low-end range of Apollo 14 soil sample, and is typical size for those at the Apollo 14 and 15 sites, as shown in Table 6 (McKay et al., 1991).

Shear resistance is expressed by the angle of internal friction and cohesion. For lunar soils, the angle of internal fraction ranges from 25 to 50 deg, and cohesion values from 0.26 to 1.8 kPa (Carrier et al., 1991). CAS-1 has values of 33.3 deg and 1.0 kPa for the corresponding values, similar to the lunar values. Cohesions of terrestrial soils are several times higher than those of lunar soils because they are composed by clay mineral with high cohesiveness. However, there was no clay mineral found in CAS-1. Dried red soils from Huaxi and Pingba Counties, Guizhou Province, had values of 37.2 and 35.5 deg, and cohesions of 10 and 12 kPa, respectively.

Complex permittivity expresses the ability of a material to propagate electromagnetic radiation, and is important in understanding radar backscatter data and microwave radiation (Zheng et al., 2005a,b). In the frequency domain, the complex permittivity (ε) can be expressed as $\varepsilon = \varepsilon'$(dielectric constant) $- i\varepsilon''$(loss), where i is the imaginary part. The permittivity of the basaltic bedrock of the Jinlongdingzi volcano and CAS-1 in the 1–20 GHz range was measured,

Table 4
CIPW normative compositions (vol.%) of CAS-1 lunar soil simulant

Mineral type	Olivine	Anorthite	Orthoclase	Diopside	Hypersthene	Ilmenite	Magnetite	Apatite	Total
CAS-1	8.13	56.28	7.24	7.74	14.6	2.33	3.03	0.65	100

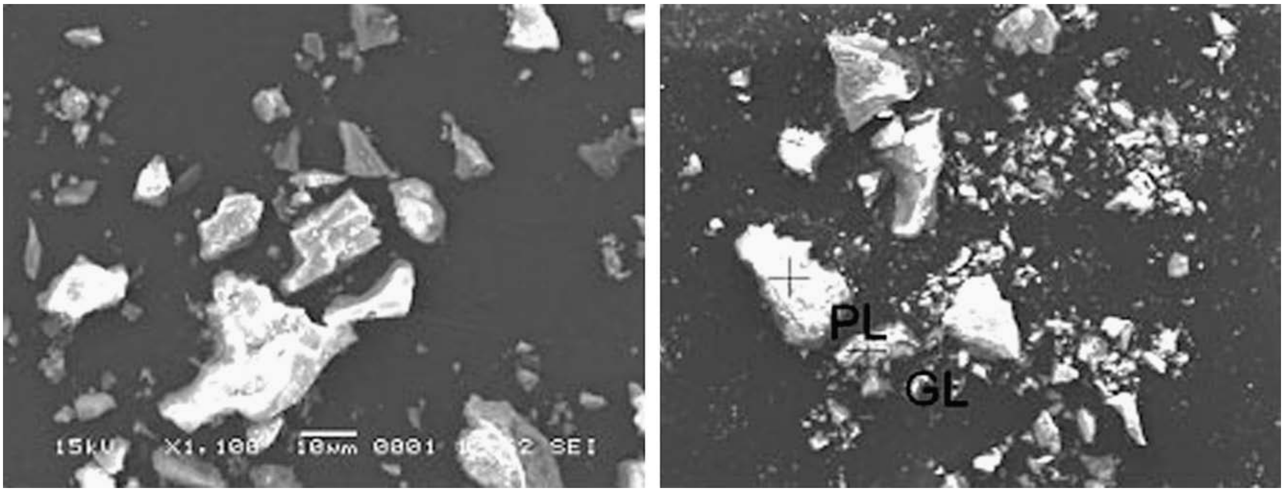

Fig. 6. Particle shape of CAS-1 lunar soil simulant (secondary electron images by SEM). After comminution, drying, and mixing, CAS-1 lunar soil simulant was studied with a scanning electron microscope at 1100×. The photographs show broken glass and mineral fragments as large as several hundred micrometers. Glass fragments show broken vesicles with sharp edges. Mineral fragments are angular to sub-rounded, and many show scars from the milling process.

Table 5
Particle size distribution of CAS-1 lunar soil simulant

Sample	*d* (0.1)	*d* (0.2)	*d* (0.5)	*d* (0.8)	*d* (0.9)
No. 1	13.5	27.5	85.3	172.3	227.5
No. 2	12.7	26.6	84.4	172.2	227.9
No. 3	13.0	27.5	88.0	175.6	230.0
CAS-1 average	13.1	27.2	85.9	173.3	228.5

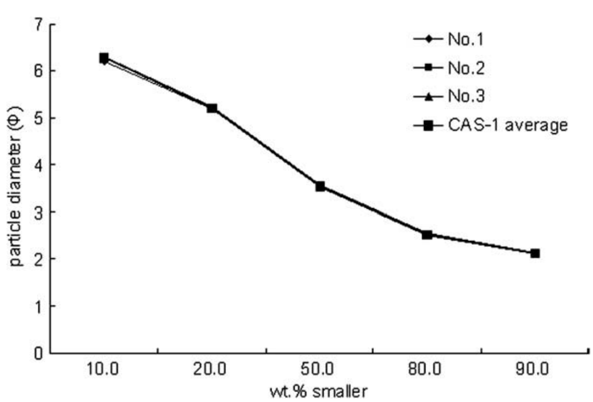

Fig. 7. Particle size of CAS-1 lunar soil simulant. The median particle size for CAS-1 was 85.9 μm. The sample was found to be homogeneous with three measurements. Particle diameters in phi units ($\Phi(\mathrm{phi}) = -(\ln d)/(\ln 2)$, d = diameter in mm).

Table 6
Mean and median values of particle sizes of lunar regolith at Apollo 11–17 landing sites (McKay et al., 1991)

Sample	Particle size (μm)
Apollo 11 (median grain size)	48–105
Apollo 12 (median grain size)	42–94
Apollo 14 (median grain size)	75–802
Apollo 15 (median grain size)	51–108
Apollo 16 (mean particle size)	101–268
Apollo 17 (mean particle size)	42–166

Median, half of the particles are coarser than the median and half are finer; correspondings to the 50% mark on a cumulative curve. Mean, the graphic mean is based on three points on a cumulative curve (see Folk, 1968).

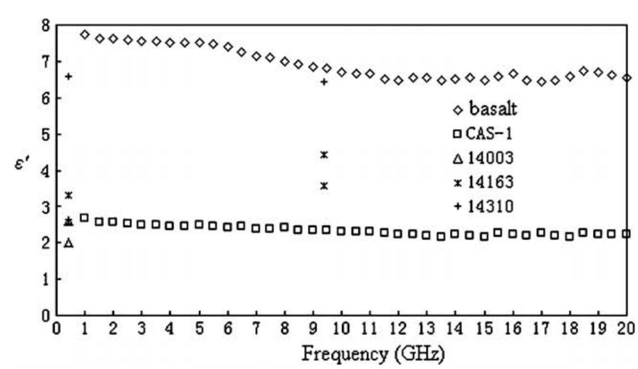

Fig. 8. Dielectric constant ε' of CAS-1 lunar soil simulant. ε' values for Apollo 14 samples 14003, 14163, and 14310 are shown for comparison, and are close to the value for the CAS-1 simulant.

with results shown in Fig. 8. Values for Apollo 14 samples 14003, 14163, and 14310 are shown for comparison, and are close to the value for the CAS-1 simulant.

Reflectance spectra of the lunar regolith varies greatly from place to place, and is an essential factor for interpretation of remote sensing spectral data, both Earth-based and from lunar orbit. Reflectance spectra of CAS-1 was measured in the Anhui Institute of Optical and Fine Mechanics of Chinese Academy of Sciences. Reflectance spectra of CAS-1 lunar simulant, Apollo 11 soil 10084, Apollo 14 soil 14141, 14163, 14259, 14260, have been dotted and compared in Fig. 9. It suggests that reflectance spectra of CAS-1 is similar with Apollo 11 and 14 lunar soil sample.

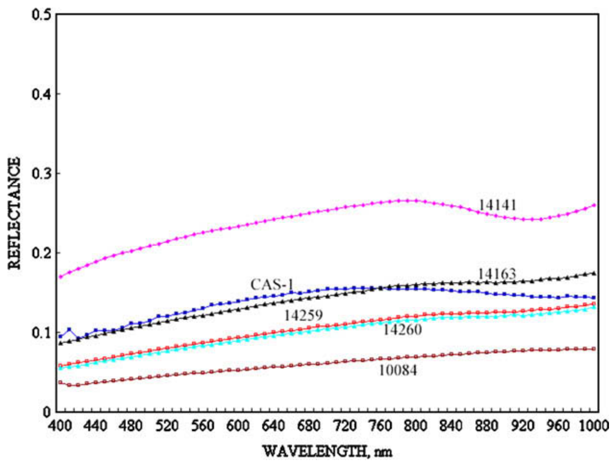

Fig. 9. Reflectance spectra of CAS-1 lunar simulant and compared with Apollo 11 soil 10084, Apollo 14 soil 14141, 14163, 14259, 14260 in the range of wavelength 400–1000 nm.

7. Summary

We have found readily available volcanic scoria from China that can be used to make a realistic lunar simulant, CAS-1. These scoria and the simulant have been analyzed for a wide range of chemical, physical, and geological properties, and compared with Apollo lunar soils and previously prepared lunar simulants. CAS-1 displays properties essentially similar to these, and is therefore proposed as a tool for planning and preparing for future lunar landing missions of China's Lunar Exploration Program.

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