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Development and characterization of the PolyU-1 lunar regolith simulant based on Chang'e-5 returned samples

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A B S T R A C T

Leading national space exploration agencies and private enterprises are actively engaged in lunar exploration initiatives to accomplish manned lunar landings and establish permanent lunar bases in the forthcoming years. With limited access to lunar surface materials on Earth, lunar regolith simulants are crucial for lunar exploration research. The Chang'e-5 (CE-5) samples have been characterized by state-of-the-art laboratory equipment, providing a unique opportunity to develop a high-quality lunar regolith simulant. We have prepared a high-fidelity PolyU-1 simulant by pulverizing, desiccating, sieving, and blending natural mineral materials on Earth based on key physical, mineral, and chemical characteristics of CE-5 samples. The results showed that the simulant has a high degree of consistency with the CE-5 samples in terms of the particle morphology, mineral and chemical composition. Direct shear tests were conducted on the simulant, and the measured internal friction angle and cohesion values can serve as references for determining the mechanical properties of CE-5 lunar regolith. The PolyU-1 simulant can contribute to experimental studies involving lunar regolith, including the assessment of interaction between rovers and lunar regolith, as well as the development of in-situ resource utilization (ISRU) technologies.

1. Introduction

The quest to understand the origin and evolution of the Moon has been a persistent endeavor since the 1960s, marked by continuous exploration projects aimed at not only unraveling the mysteries of the Moon but also facilitating the expansion of human presence beyond Earth [1]. In recent years, large-scale lunar exploration initiatives have been undertaken worldwide, with notable projects including NASA's Artemis program, China Lunar Exploration Program (CLEP) [2], and India's Chandrayaan program [3]. These programs aim to accomplish manned landings and establish permanent bases on the lunar surface in the forthcoming years.

A layer of unconsolidated granular material, named as lunar regolith or soil [4], covers the surface of the Moon, with a thickness of several meters [5]. The study on the physio-mechanical properties of lunar regolith plays a crucial role in the performance and reliability of equipment operating in lunar surface environments, such as rovers and landers. The utilization of lunar regolith simulants has always played a significant role in lunar regolith-related experiments on Earth, such as in-situ resource utilization (ISRU) techniques and wheel-soil interaction tests [6–8]. On December 17, 2020, the Chang'e-5 (CE-5) mission successfully returned approximately 1731 g of regolith samples from the near side of the Moon [9]. The sampling site, the northeast region of Oceanus Procellarum, was far away from the previous sampling locations of the Apollo and Luna missions [10]. In May 2021, the Research Centre for Deep Space Explorations (RCDSE) was established at the Hong Kong Polytechnic University (PolyU). Among the institute's research endeavors, a prominent focus was placed on investigating the particle characteristics and geotechnical mechanics of lunar regolith, as well as developing regolith-based material for planetary base construction. The CE-5 samples provide us with a unique opportunity to study the physio-mechanical properties of lunar regolith and prepare a high-quality simulant.

Petrological and geochemical analysis of the CE-5 basalt clasts revealed the 2-billion-year-old basalts represented the youngest lunar samples ever reported [11]. The CE-5 samples exhibited a higher Fe and lower Mg content than previous Apollo samples, indi-

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cating the potential existence of a new class of lunar basalt [12]. The median particle size of CE-5 samples was roughly 55 μm, falling within the lower range of the range of Apollo samples [13]. However, the existing research on the physical properties of CE-5 lunar regolith is insufficient, and additional studies employing alternative methods are required to further define the physical parameters of this lunar material. The residual friction angle of CE-5 lunar regolith under low confining pressure was estimated to be 53°–56°, based on the geometric characteristics of particles [14]. Few studies have been conducted on the mechanical properties of CE-5 lunar regolith, as the limited lunar samples are insufficient to support the demand for geotechnical tests on Earth.

Lunar regolith was categorized into three types: highland, as well as high-Ti (≥5 wt%) and low-Ti mare, based on the terrain and Ti contents [15]. Over the past several decades, many simulants have been developed based on the key properties of different types of lunar regolith. In 1988, a high-Ti mare simulant MLS-1 was made from the basalt to match the mare soil 10084 returned by the Apollo 11 mission [16]. A few years later, Johnson Space Center created a low-Ti mare simulant JSC-1 using a basaltic pyroclastic sheet deposit, based on the Apollo 14 samples [17]. Later, Fuji volcano ash was used to manufacture a low-Ti mare simulant FJS-1 to simulate the samples returned by the Apollo 14 mission [18]. These simulants greatly promoted the research progress of lunar regolith, whereas most of them are currently unavailable due to the suspension of production. In recent years, the large demand for lunar regolith-related experiments led to the development of more simulants. A low-Ti mare simulant TJ-1 was created from red volcanic ash deposits collected in northern China to match the physical and mechanical properties of Apollo 14 samples [19]. A highland simulant KLS-1 was made from basalt to approximate the sample 14163 returned by the Apollo 14 mission [20]. The European Astronaut Centre used basanite to produce a low-Ti mare simulant EAC-1A [21]. More simulants were created, such as GRC-3 [22], BP-1 [23], DNA-1A [24], LSS-ISAC-1 [25], JLU-H [26], and CUMT-1 [27]. All these simulants were developed based on the properties of Apollo samples. In the development of most simulants, researchers focused on the match of the chemical composition, while paying insufficient attention to mineral constituent and particle morphology.

In this study, a high-fidelity lunar regolith simulant PolyU-1 was developed based on key characteristics of the CE-5 returned samples, which distinguished it from previous simulants. A series of laboratory experimental results indicated that this simulant matches closely with the CE-5 lunar regolith in terms of the mineral and chemical compositions, as well as the physical and mechanical properties. The friction angle and cohesion values were obtained using direct shear tests, which can serve as a reliable reference for the mechanical properties of the CE-5 lunar regolith. The PolyU-1 simulant can be used as a substitute for basaltic lunar regolith for scientific experiments on Earth such as mechanical testing and ISRU applications.

2. Materials and methods

2.1. Micro-CT imaging of lunar regolith

The CE-5 sampling site (Fig. 1a) is located in a mid-latitude area (43.058 °N), distinct from the low-latitude regions explored during previous Apollo and Luna missions [12]. The robotic arm developed by PolyU researchers significantly contributed to the successful sample collection (Fig. 1b). The majority of CE-5 samples consisted of basaltic regolith, exhibiting the youngest crystallization age observed in lunar basalts to date [28]. To study the particle morphology of CE-5 lunar regolith, the regolith sample CE5C0100YJFM00103 was scanned using the high-resolution micro-CT imaging equipment (Fig. 1c). X-rays undergo stronger attenuation in high-density materials compared to low-density materials in the sample [29], and the intensity of the attenuated X-ray is recorded as the raw image data, which is reconstructed

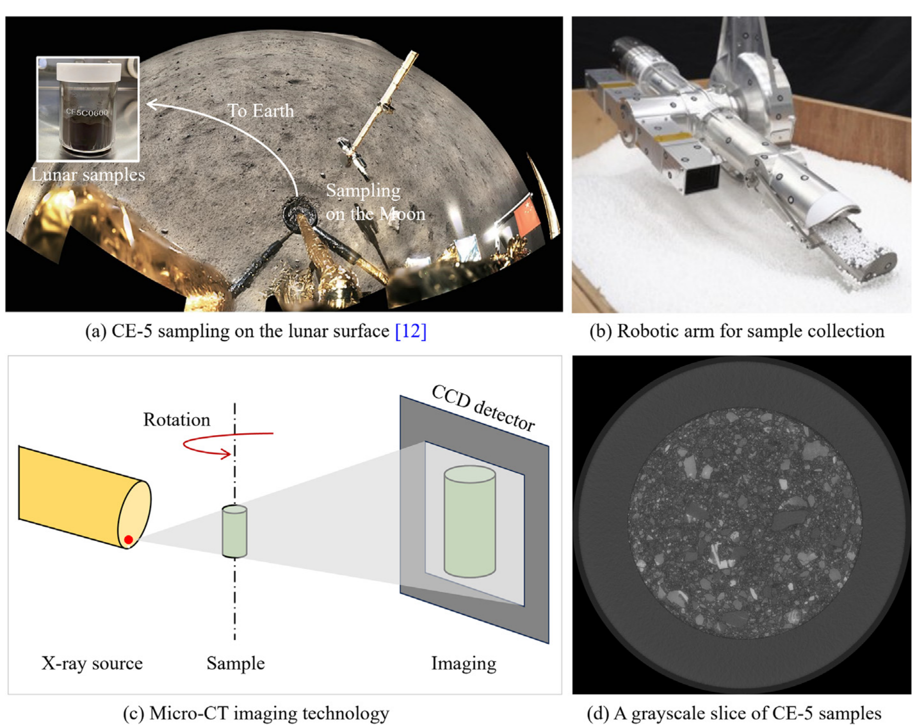


Fig. 1. Lunar regolith samples returned by the CE-5 mission was studied by micro-CT imaging technology.

into a stack of grayscale images (Fig. 1d) representing the three-dimensional geometrical characteristics of the sample. As a first approximation, the grayscale values of the images are linearly correlated to material densities [30]. By employing segmentation techniques on grayscale images, the size and morphology of sample particles can be determined. In this study, image segmentation was conducted using the pixel classification workflow of the ilastik tool [31]. This workflow involved assigning labels to pixels based on their intensities, shape attributes, and manual annotations provided by users. We examined the grain morphology of the PolyU-1 simulant using micro-CT imaging and compared it with that of the CE-5 lunar regolith samples.

2.2. Mineral composition

The foremost step for preparing the PolyU-1 simulant is to obtain the average mineral and chemical composition of CE-5 lunar samples. Previous studies indicated that the primary minerals of the CE-5 lunar regolith were pyroxene, plagioclase, olivine, ilmenite, and amorphous phase glass, with minor amounts of apatite, K-feldspar, and quartz [12]. This study focused on the primary constituent minerals that accounted for more than 5% of the total mass of the CE-5 lunar samples, and this simplifies the development process and reduces costs. The mean values of nineteen data sets of main minerals collected from existing studies were determined as the target mineral ratio for developing the simulant (Table 1) [11–13]. The two minerals with the highest content are pyroxene and plagioclase, accounting for over 75% of the total mass. The proportion of olivine is roughly 10%. The content of olivine and glass is equivalent, accounting for a total of approximately 12%. The chemical composition of CE-5 samples was also obtained (Table 2), and a distinguished feature of the CE-5 lunar regolith samples is that it contains high Fe and Ti content [11,12,32].

In this study, the PolyU-1 simulant was prepared using natural terrestrial minerals, as listed in Table 3. Necessary compromises in minerals were made due to the rarity of some minerals found in CE-5 samples on Earth, although the optimal scenario for preparing a simulant was to fully replicate the mineral composition of lunar regolith. The natural basalts, which serve as the primary raw material, were excavated from a quarry located in Shijiazhuang City, Hebei Province in the north of China. The rocks comprise anorthite, augite, olivine, and a small amount of quartz and magnetite. To match the mineral and chemical compositions, four additional unweathered minerals and a glass phase were incorporated. It was noticed that the olivine in lunar regolith was mainly comprised of fayalite, and the pyroxene mainly consisted of augite [12]. When preparing the PolyU-1 simulant, fayalite was replaced by forsterite as the former was hardly accessible in the natural Earth environment. This substitution resulted in a lower Fe content in the simulant than in CE-5 samples. Hedenbergite, instead of augite, was added to balance the Fe content in the simulant. Similarly, the anorthite in the simulant replaced the abundant bytownite found in CE-5 samples. Furthermore, ilmenite and China tektite were added to simulate the ilmenite and glass in lunar regolith.

2.3. Simulant preparation

Achieving a match in mineral and chemical composition between the actual materials and the simulant can be accomplished by carefully preparing appropriate ratios using suitable raw materials. Another significant point is to seek a match for particle size distribution (PSD) and particle morphology, which is the basis for maintaining consistency between both materials in terms of physical and mechanical properties. Key physio-mechanical parameters were collected as target values for the PolyU-1 simulant. Fig. 2 illustrates the procedure involved in the preparation of the simulant, as detailed below:

Table 1
The average contents (%) of major minerals and phases in CE-5 lunar samples [11–13] and Apollo samples [27].

Source	Pyroxene	Plagioclase	Olivine	Ilmenite	Glass	Total
CE-5	40.45	36.11	9.61	6.35	6.14	98.66
Apollo 14	3.22–41.65	2.80–47.01	0.28–6.68	0.18–11.06	8.40–17.20	
Apollo 15	4.43–54.4	0.93–38.01	0.61–19.29	0.11–9.70	5.50–19.00	

Table 2
The average contents (%) of major elements in CE-5 lunar samples [11,12,32] and Apollo samples [27].

Source	SiO_2	FeO	CaO	Al_2O_3	MgO	TiO_2	Na_2O	K_2O	P_2O_5	MnO
CE-5	41.34	23.16	10.77	11.14	5.06	6.59	0.53	0.08	0.26	0.29
Apollo 14	48.10	10.40	10.70	17.40	9.40	1.70	0.70	0.55	0.51	0.14
Apollo 15	46.90	14.30	10.80	14.60	11.50	1.40	0.39	0.21	0.18	0.19

Table 3
The comparison of phase characteristics between CE-5 lunar samples [12] and the PolyU-1 simulant.

Phases	Main phase types in CE-5 samples	Materials in the PolyU-1 simulant	Notes
		Basalt	Basalts primarily consist of anorthite, augite, and olivine.
Pyroxene group	Augite	Hedenbergite	Iron rich end member of the pyroxene group.
Plagioclase group	Bytownite	Anorthite	Bytownite is not easily accessible, and anorthite accounts for 70%–90% in bytownite.
Olivine group	Fayalite	Forsterite	Fayalite is not easily obtainable. Forsterite is another type of olivine.
Ilmenite	Ilmenite	Ilmenite	
Glass	Glass	China tektite	China tektite is a glassy phase formed from molten rock sputtering.

(1) Each phase material was initially broken into fragments, each less than 1 cm, using a hammer. Subsequently, these fragments were further pulverized into powders finer than 500 μm using a pulverizer. Because 95% (by weight) of particles of CE-5 samples ranged from 4.84 and 432.27 μm, with a median particle size of 52.54 μm [12]. To mitigate contamination issues, it is essential to clean the materials prior to pulverization and to perform the main procedures in a controlled laboratory environment free from dust.
(2) The fine granular materials were completely desiccated. The lunar regolith in most areas of the Moon contains no liquid water [33], except for the possibility of water ice in permanent shaded areas at both poles.
(3) Each material was sieved to obtain various grades, enabling their subsequent mixing to achieve a desired PSD.
(4) Materials were mixed based on the PSD and mineral composition of CE-5 samples and blended into a uniform mixture.

Following this, a series of characteristic parameters of the mixed simulant, including the PSD, mineral, and chemical compositions, as well as physical and mechanical properties, were measured. The phase ratio and particle grading were adjusted iteratively until all these characteristic parameters of the simulant matched well with CE-5 samples.

2.4. Characterization of the lunar regolith simulant

After preparation, a comprehensive set of physical and chemical tests was performed to characterize the PolyU-1 simulant (Table 4). Scanning electron microscope (SEM) and X-ray micro-computed tomography (micro-CT) imaging techniques were used to examine particle morphology. The volume-based PSD of the simulant was determined by the wet method of a particle size analyzer. For mineral content and chemical composition analysis, X-ray diffraction (XRD) and X-ray fluorescence (XRF) were utilized, respectively. Glass was not added to the sample during the XRD test, as it was an amorphous material. The final content of all mineral phases was calculated based on the XRD results and adjusted according to the amount of added glass. It is worth noting that the XRF analysis cannot distinguish between different valence states of the Fe in minerals. The physical properties of the simulant, including specific gravity, bulk density, and porosity, were determined through laboratory measurements. With regard to the mechanical properties, the internal friction angle and cohesion of the simulant were constrained through laboratory direct shear tests.

3. Results

3.1. Appearance and particle morphology

The CE-5 lunar regolith is a dark gray, remarkably fine granular material (Fig. 3a) [16]. The two-dimensional slice of the micro-CT images revealed that the particles characterized by distinct edges and corners exhibited significant roughness (Fig. 3b). This can also be reflected in the reconstructed particles, as shown in Fig. 3c. A reasonable explanation lies in the fact that lunar regolith is primarily shaped by meteorite impacts and the influence of solar wind, devoid of terrestrial processes such as weathering, erosion, and sedimentation [34]. The analysis of a two-dimensional micro-CT slice revealed that the average aspect ratio of 3535 particles was determined to be 0.68. Moreover, the measured average circularity was found to be 0.81, which closely aligned with a previously obtained result of 0.875 [13].

The PolyU-1 lunar regolith simulant is also a dark gray fine granular material with a rough texture on its surface (Fig. 4a), similar to the CE-5 lunar regolith (Figs. 3a and 4b). The morphology of simulant particles was characterized by SEM (Fig. 4c) and micro-CT (Fig. 4d). Simulant particles were reconstructed based on grayscale images (Fig. 4e). Sharp edges and corners of the particles can be observed, as these fine particles were created by pulverizing natural mineral materials. The analysis of a two-dimensional micro-CT slice of the simulant indicated that the average aspect ratio and circularity of 1963 particles were determined to be 0.65 and 0.82, respectively, which were close to those of CE-5 lunar regolith. In summary, the simulant exhibits consistency with CE-5 lunar regolith in terms of appearance and particle morphology.

3.2. Mineral and chemical composition

The exact mineral composition of the PolyU-1 simulant (Fig. 5a) was determined based on the XRD pattern (Fig. 5b). Among the minerals, pyroxene has the highest weight-based proportion of

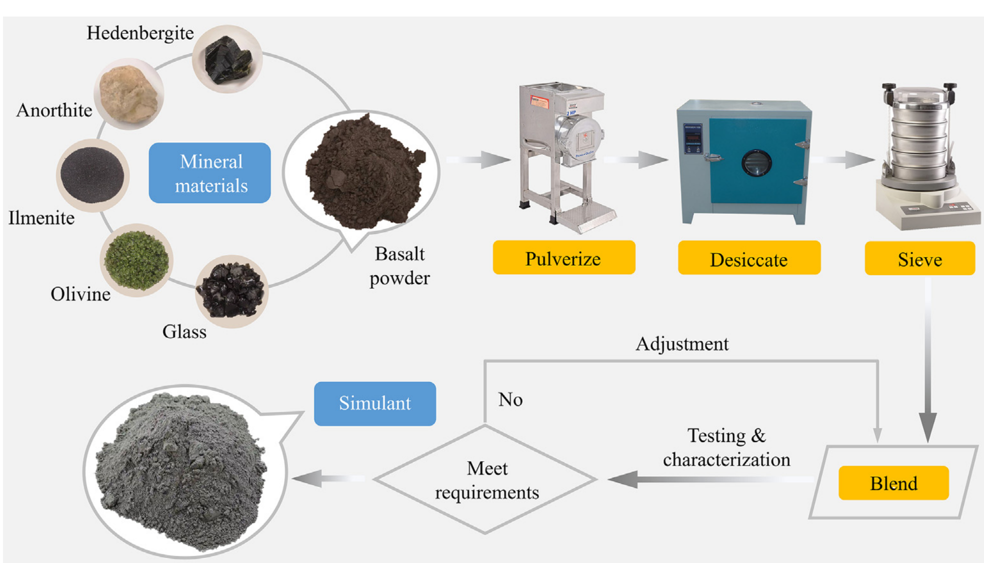
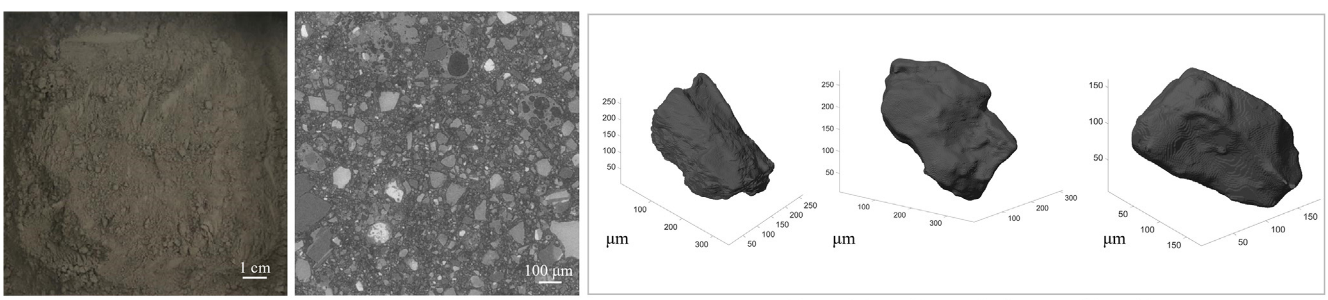


Fig. 2. Preparation procedures of the PolyU-1 simulant.

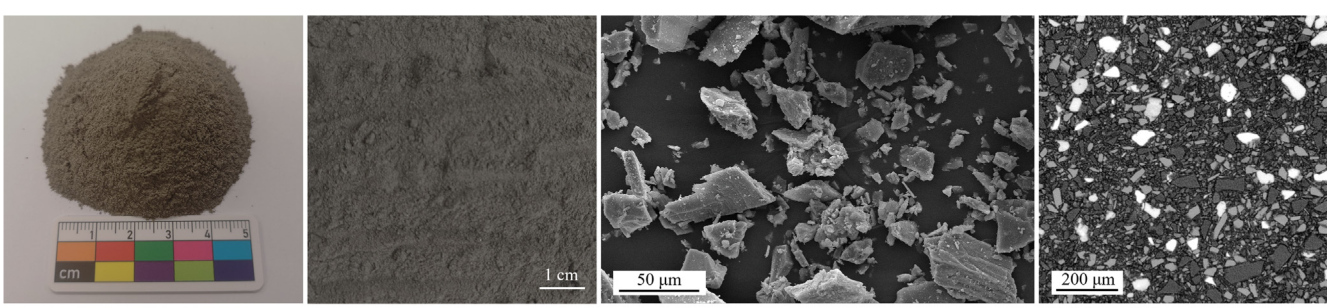
Table 4
Characterizations of the PolyU-1 simulant.

Properties	Methods/Parameters	Equipment	Notes
Particle morphology	Micro-CT	NanoVoxel-3000	Voxel size: 2.01 μm
	SEM	Thermo Fisher Scientific Quattro ESEM	Working distance: 9.5 mm Magnitude: 2000×
PSD	In volume	Malvern Mastersizer 3000 particle size analyzer	Wet testing Solvent: water Range: 0.1–3500 μm
Mineral content	XRD	Rigaku SmartLab X-ray diffractometer	Cu target, 40 kV, 100 mA Continuous, 3°–70°(2θ) Scan speed: 8°/min
Chemical content	XRF	X-ray fluorescence spectrometer ZSX Primus III	50 kV, 60 mA
Physical properties	Specific gravity	Pycnometer	50 mL pycnometer Heating in water bath
	Bulk density	Lab measurement	
	Porosity		Calculated by specific gravity and bulk density
Mechanical properties	Friction angle & cohesion	Direct shear test apparatus	Shear area: 6 cm × 6 cm Shear speed: 0.8 mm/min

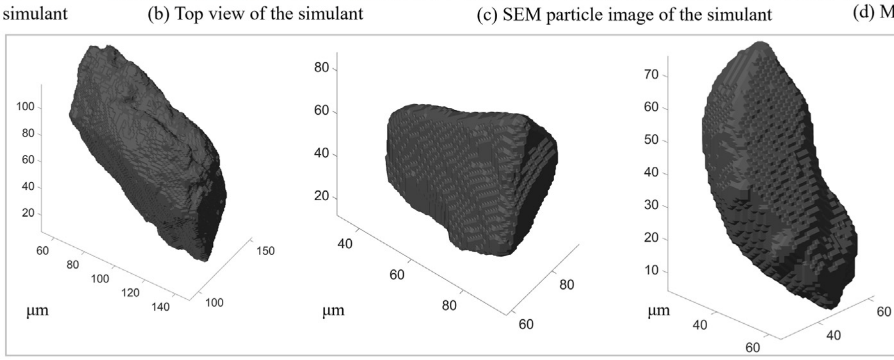


(a) Appearance of lunar regolith [16] (b) Micro-CT grayscale image of lunar regolith [35] (c) Morphology of three typical lunar regolith particles

Fig. 3. Appearance and particle morphology of CE-5 lunar regolith.

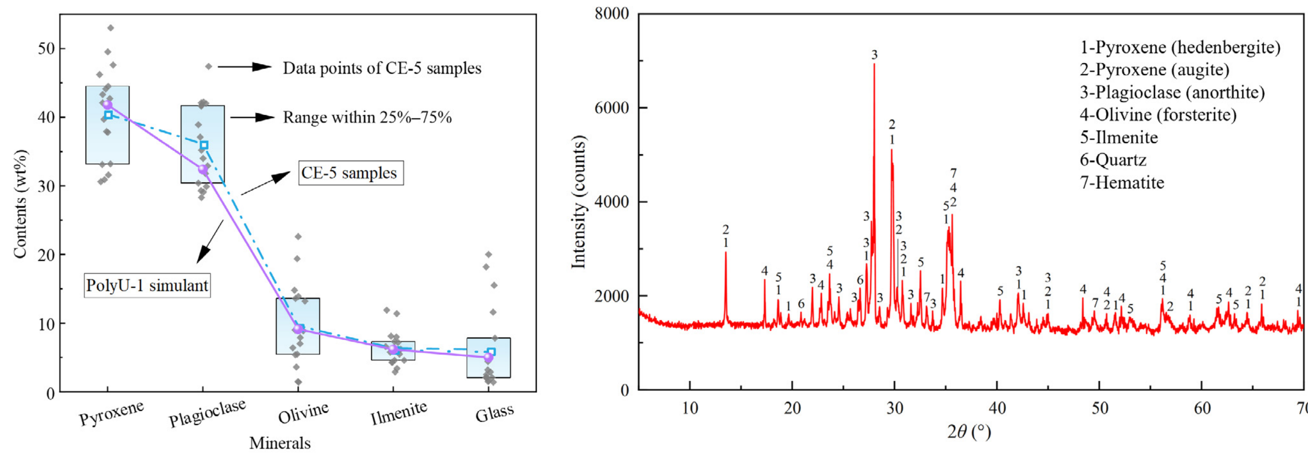


(a) Appearance of the simulant (b) Top view of the simulant (c) SEM particle image of the simulant (d) Micro-CT image of the simulant



(e) Morphology of three simulant particles reconstructed by grayscale images

Fig. 4. Appearance and particle morphology of the PolyU-1 simulant.



(a) Comparison of mineral composition (b) XRD pattern of the PolyU-1 simulant without glass

Fig. 5. Mineral compositions of the PolyU-1 simulant. Note: the rectangular boxes represent the distribution range from 25% to 75% (i.e., interquartile range) for each mineral.

41.7%, with hedenbergite and augite constituting 27.6% and 14.1%, respectively. The plagioclase predominantly exists in the form of anorthite, accounting for 32.4% of the total. Olivine, primarily composed of forsterite, contributes 9.1% to the overall content. Ilmenite and glass represent 6.2% and 5.0% of the material, respectively. Additionally, the simulant contains small amounts of impurities, namely quartz (2.1%) and hematite (3.4%).

Seventeen data sets on major mineral contents of CE-5 samples are presented in Fig. 5a [11–13]. Mineral contents from the literature exhibit a certain degree of dispersion, thus the average value of each mineral content is obtained to be the target value for preparing the PolyU-1 simulant (dotted line). The absolute differences in mineral content between the simulant and CE-5 lunar samples are calculated. The maximum difference is found in the plagioclase (3.7%), and the differences in other minerals are less than 2%.

The PolyU-1 simulant resembles the chemical composition of CE-5 samples as shown in Fig. 6 [11,12,32]. The differences in the content of Fe and Ti between the simulant and real lunar regolith are 2.24% and 1.65%, respectively. Although the contents of Na and K in the simulant do not fall within the interquartile range, their absolute differences to CE-5 samples are only 1.15% and 1.02%, respectively. The differences in other elements are less than 1.11%. Overall, the chemical composition differences of all elements between the simulant and CE-5 lunar samples are not larger than 2.24%. Therefore, the chemical composition of the PolyU-1 simulant has a satisfactory consistency with that of CE-5 lunar regolith, in terms of both mineral and chemical compositions.

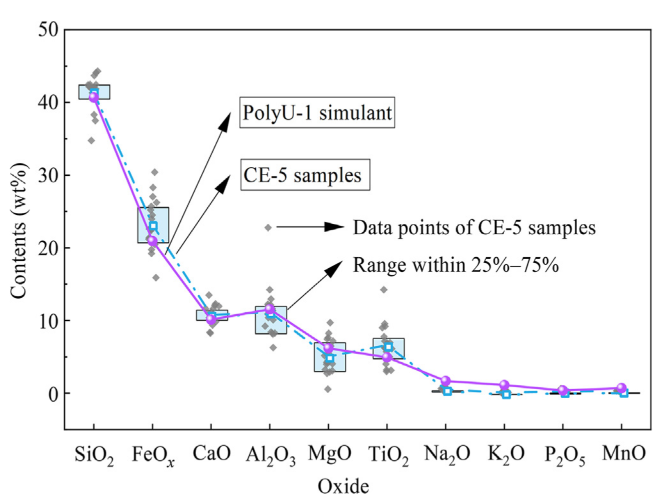


Fig. 6. Comparison of chemical composition between the PolyU-1 simulant and CE-5 lunar samples [11,12,32].

3.3. Physical and mechanical properties

The PSD of granular materials is the cumulative percentage in mass or volume of different particle sizes. In geotechnical engineering, the median particle size (D_{50}) is often used to evaluate the overall fineness of the material, and the coefficient of uniformity (C_u) and coefficient of curvature (C_c) are used to evaluate its uniformity and continuity. Table 5 lists the results of previous studies on the PSD of CE-5 lunar regolith. The mass-based PSD of this material indicated that the D_{50} was approximately 52.54 μm [12]. The D_{50} values varied with depth, and the values at the surface, 10 and 60 cm of depth were estimated to be roughly 30.2, 45.0, and 96.4 μm, respectively [26]. The three volume-based PSD results were obtained by laser diffraction, Raman-based particle analysis, micro-CT analysis (Fig. 7a) [13,35,36]. The PSD results exhibited certain deviations from different samples and testing methods. It was observed that the particle size of the vast majority of particles ranged between 10 and 100 μm and the D_{50} varied from 28.39 to 55.24 μm. The D_{50} of the PolyU-1 simulant was measured at roughly 40.40 μm, and the C_u and C_c were calculated to be 9.9 and 1.7, respectively (Table 5). Fig. 7b shows the comparison of PSD between the average of three sources of CE-5 lunar regolith and the PolyU-1 simulant. The general trend of the two curves is similar, despite a minor deviation observed in the lower portion of the curves.

In a recent micro-CT image-based study, the specific gravity (G_s), bulk density (ρ), and porosity (n) of CE-5 lunar regolith are determined to be approximately 3.17, 1.58 g/cm^3, and 62.0%, respectively (Table 6) [35]. The result is consistent with the result obtained by the previous study based on density analyzers, except for slight differences in bulk density [12]. The results obtained from Apollo samples indicate that the G_s of the lunar regolith is roughly 3.1, and the ρ value ranges from 1.45 to 1.79 g/cm^3 [37]. The G_s of the PolyU-1 simulant was measured to be around 3.17. The ρ of the material in the most loose and dense state was determined at roughly 1.22 and 1.83 g/cm^3, respectively. The minimum bulk density is close to that of CE-5 lunar regolith samples, namely 1.24 g/cm^3. It could be estimated that the value was measured in a relatively loose state. Compared with TJ-1, BP-1, KLS-1, and CUMT-1 simulants [19,20,23,27], the PolyU-1 simulant's G_s is slightly lar-

Table 5
Geotechnical parameters of the PSD of CE-5 lunar regolith and the PolyU-1 simulant.

Sources	Notes	D_{50} (μm)	C_u	C_c
Li et al. [12]	In mass, 155 mg	52.54		
	Optical microscope & image analysis			
Zhao et al. [39]	Surface (in volume)	30.2		
	Depth: 10 cm	45.0		
	Depth: 65 cm	96.4		
Zhang et al. [13]	In volume	55.24	15.1	1.7
	Laser diffraction.			
Cao et al. [36]	In volume, 30 μg × 2	28.39	3.4	1.3
	Raman particle analysis system			
Wu et al. [35]	In volume, micro-CT imaging	33.22	2.7	1.3
Mean PSD of CE-5 lunar samples	In volume, the average of results from Zhang et al., Cao et al., and Wu et al. above	38.39	4.9	1.2
PolyU-1 simulant	In volume, laser particle size analyzer	40.40	9.9	1.7

Note: D_{50} represents the median particle size; coefficient of uniformity (C_u) is expressed by D_{60}/D_{10}; coefficient of curvature (C_c) is expressed by $(D_{30})^2/(D_{60}\times D_{10})$; D_{10} represents the effective particle size; $D_{30}$the middle grain size; and D_{60} the constrained particle size.

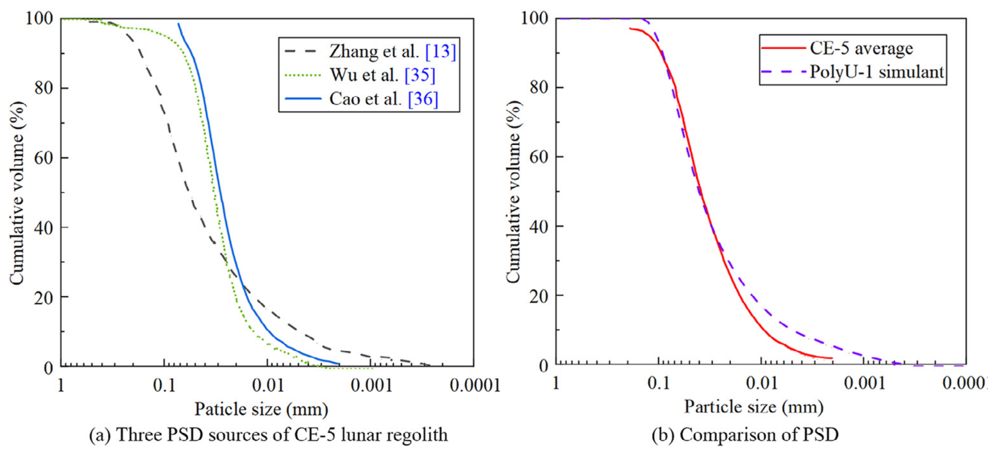


Fig. 7. Volume-based PSD results of CE-5 lunar regolith and the PolyU-1 simulant.

ger except for CUMT-1 simulant, but close to the CE-5 lunar regolith samples. The porosity of the PolyU-1 simulant also displays similarity to preceding simulants.

Through multiple sets of direct shear tests, the upper and lower bounds of the friction angle (φ) and cohesion (c) of the PolyU-1 simulant were estimated to be 35.7°–40.3° and 0–13.5 kPa, respectively (Fig. 8). Herein, the shear strength was determined by considering the shear stress corresponding to a shear displacement of 6 mm, following the guidelines set forth by Chinese standard for geotechnical testing method (GB/T 50123-2019) [38]. When the simulant was accumulated in a natural state, the angle of repose was measured to be approximately 38.9°. Until now, there were few results directly studying the mechanical properties of CE-5 lunar regolith, as the small volume of samples was not sufficient to support the needs of conventional geotechnical testing. The residual friction angle of CE-5 lunar regolith under low confining pressure was predicted to be 53°–56° based on the geometric characteristics of small number of particles [14], higher than the PolyU-1 simulant. However, the mechanical parameters of the PolyU-1 simulant may serve as reliable reference data for CE-5 lunar regolith, as they display high similarity in terms of particle morphology, mineral composition, chemical composition, as well as physical properties such as particle size distribution. The recommended values of the φ and c in the Apollo Model are 30–50° and 0.1–1.0 kPa [37], similar to the PolyU-1 simulant. In addition, the values maintain a certain consistency with the previous simulants [19,20,23,27] (Table 7), although they were developed based on the characteristics of Apollo samples.

4. Discussions

ISRU technologies involving lunar regolith are currently being studied, driven by worldwide lunar exploration projects. Experimental research was conducted to extract useful resources such as oxygen, metals, and minerals from lunar regolith [40]. Laser, microwave, and plasma sintering tests were studied to make contributions to the manufacturing of components used in the construction of permanent lunar bases [41]. Therefore, matching the mineral and chemical composition with the real lunar regolith is the primary requirement for preparing a simulant for ISRU research. In the process of preparing previous simulants, less attention was paid to the matching of mineral composition. The PolyU-1 simulant matches well both the chemical and mineral compositions of CE-5 samples. Although there were certain differences between the simulant and target values, all differences were less than 3.7%. The excellent agreement enables the PolyU-1 simulant to be used in experiments of lunar regolith-related ISRU technologies.

Another major use of simulants is to conduct mechanical experiments on lunar regolith, including studies on drilling on the lunar surface, bearing capacity performance of lunar regolith under landers, rovers, and potential building structures [42,43]. These aspects require an accurate representation of the physical and mechanical properties of the lunar regolith. The PSD is one of the

Table 6
True density, bulk density, and porosity of CE-5 and Apollo lunar regolith, as well as PolyU-1 and previous simulants.

Types	Specific gravity (G_s)	Relative density D_r (%)	Bulk density ρ (g/cm^3)	Porosity n (%)
Wu et al., CE-5 [35]	3.17		1.58	62.0
Li et al., CE-5 [12]	3.20		1.24	61.3
Apollo samples [37]	3.10	(Depth: 0–60 cm)	1.45–1.79	44–52
PolyU-1 simulant	3.17	0	1.22	61.6
		100	1.83	42.2
TJ-1 simulant [19]	2.72	0	1.08	60.3
		100	1.78	34.6
BP-1 simulant [23]	2.81	0	1.41	49.0
		100	1.86	32.4
KLS-1 simulant [20]	2.94	0	1.48	49.5
		100	1.99	32.4
CUMT-1 simulant [27]	3.45	0	1.47	57.4
		100	2.44	29.1

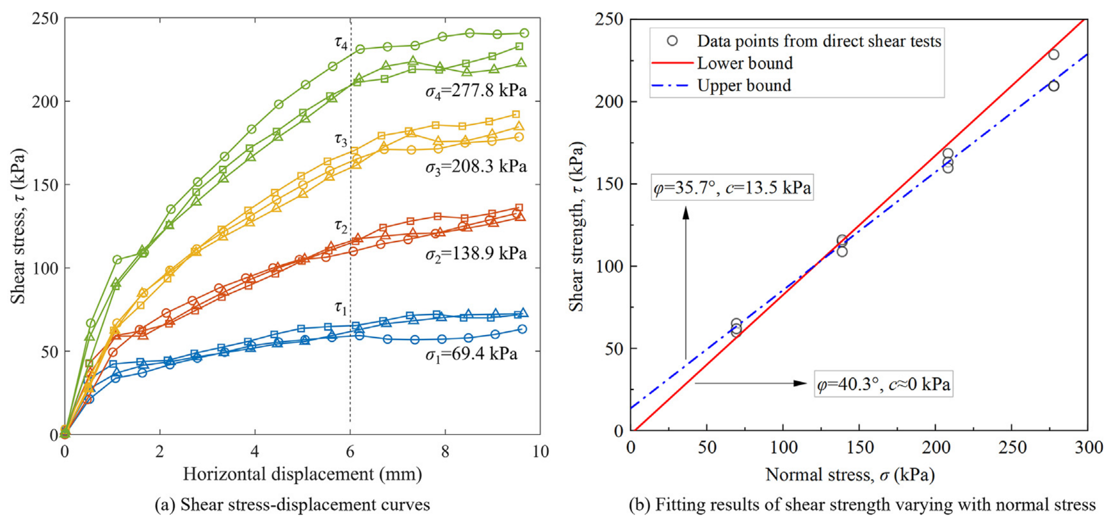


Fig. 8. Results of direct shear tests conducted on the PolyU-1 simulant.

Table 7
Internal friction angle and cohesion of the CE-5 and Apollo lunar regolith and their simulants.

Types	Friction angle φ (°)	Cohesion c (kPa)	Notes
CE-5 samples [14]	53–56		Numerical estimation, small number of grains with simplified morphology
Apollo Model [37]	30–50	0.1–1.0	Estimated based on data of Apollo samples
PolyU-1 simulant	35.7–40.3	0–13.5	D_r=75%, ρ=1.63 g/cm^3 Measured by direct shear tests
TJ-1 simulant [19]	47.6	0.86	
BP-1 simulant [23]	39.0	0–2.0	D_r=50%
KLS-1 simulant [20]	44.9	1.85	
CUMT-1 simulant [27]	51.40	16.93	Normal stress: 106–197 kPa D_r=80%

most important features for the shear strength of granular materials [44], and the PolyU-1 simulant has a PSD analogous to that of the CE-5 samples. Particle morphology of the simulant, significantly affecting the mechanical behaviors of granular materials [45], also has a high degree of similarity to CE-5 samples based on the SEM and micro-CT image analysis. In addition, the simulant is consistent with the CE-5 samples in terms of true density and bulk density. The similarity between the PolyU-1 simulant and CE-5 samples makes it a suitable substitute for lunar regolith in mechanical tests. The mechanical properties, most importantly, internal friction angle and cohesion we measured can provide a reference for future missions to the lunar surface such as landing and building bases. For the practical application of shear strength parameters in lunar regolith engineering, rigorous additional research is imperative to obtain more reliable parameters.

There are several areas for improvement and optimization in the PolyU-1 simulant. Regarding mineral materials, forsterite was used to serve as the olivine in the simulant, as fayalite mainly presented in lunar samples is not easily found in the Earth's environment. The simulant contains approximately 4.5% impurities such as quartz and hematite, which come from the natural basalt powders. In terms of element composition, the use of natural materials resulted in obviously higher Na and K contents than the target values, which may have adverse effects on high-precision chemical experiments. The Fe element generally exists in minerals in a bivalent state in lunar regolith, whereas the trivalent state in terrestrial minerals [14]. However, the PolyU-1 simulant we prepared is as close as possible based on the equipment currently available to us with raw materials at reasonable prices. The whole process can be improved in the future. To solve the above-mentioned limitations and achieve accurate replication of mineral and chemical composition of lunar regolith, adding artificial synthesis of minerals to the simulant is a feasible method. However, the high production costs brought by artificial synthesis make this method only suitable for studies requiring precise mineral and chemical compositions, rather than mechanical or geotechnical tests needing a large volume of simulants to achieve representative results.

In summary, the PolyU-1 simulant can be used as a replica for basaltic lunar regolith in mid-latitude regions on the near side of the Moon, especially near the sampling site of the CE-5 mission. With the simulant as the foundation, one study could be conducted to develop plasma sintering technology to produce high-strength structural components based on the lunar surface material. Numerical simulations can be conducted to study the mechanical properties of lunar regolith based on the particle characteristics of CE-5 samples. Numerical methods have advantages in the low gravity and vacuum environment conditions of the lunar surface, especially when a large amount of lunar regolith is unavailable on Earth. The experimental data of the simulant can provide reliable calibration targets for key parameters in numerical models.

5. Conclusions

The CE-5 lunar regolith samples provide us with the opportunity to study the physical properties of lunar regolith from a different region than previous missions. The PolyU-1 simulant was prepared using natural mineral materials on Earth, based on a variety of key characteristics of CE-5 lunar samples. A series of key parameters on the particle morphology, mineral and chemical composition, and physical and mechanical properties of the simulant were assessed by laboratory tests and compared with the corresponding parameters exhibited by CE-5 samples. Test results indicate that the PolyU-1 simulant is a high-fidelity replica of lunar regolith. The similarity in physical and mechanical properties between the simulant and lunar regolith made it suitable for testing the performance and reliability of equipment operating in lunar surface environments, such as soft landing, drilling, and rover movement. The simulant could also be used in the laboratory investigation of landslides on the Moon surface and the stability of craters. Due to the match in its mineral and chemical composition, this simulant can be utilized in experiments on ISRU technologies, such as microwave and laser sintering, to explore potential construction methods for lunar outposts. Furthermore, the obtained friction angle and cohesion from simulant tests can serve as reliable references for the mechanical properties of CE-5 lunar regolith.

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