

文章编号:1007-9629(2025)01-0072-10

面向原位建造技术的月壤模拟与制备

孙晓燕, 郑肖威, 王海龙*, 王冠楠

(浙江大学建筑工程学院, 浙江 杭州 310058)

摘要:原位开发月壤建材是实现中国探月和登月计划的基础和前提. 针对模拟精度要求最高的碱激发混凝土技术,厘清模拟月壤的关键控制组分及敏感参数,区分胶凝材料和骨料 2 种粒径范围,建立了高等代模拟月壤制备流程. 模拟月壤胶凝材料依据无定形物含量及其化学组成来保障化学性质高等代性,模拟月壤骨料通过颗粒形态精确模拟以实现湿拌工作性能高等代性. 结果表明:模拟月壤胶凝材料的激发活性主要取决于无定形物含量和硅、铝、钙组成,模拟高地月壤胶凝材料玻璃体含量最高可达 35.9%, Al_2O_3 与 CaO 质量比为 1.65, SiO_2 含量为 45.4%, 相比月海月壤更适宜作为碱激发月壤混凝土的前体材料;月壤颗粒形态与粒径范围不相关,模拟月壤骨料的关键是粒径级配,以原始月壤作为建筑材料时仍需要进行级配优化.

关键词:月壤模拟;材料活性;无定形物;颗粒形态;级配优化

中图分类号:TU43

文献标志码:A

doi:10.3969/j.issn.1007-9629.2025.01.010

Lunar Regolith Simulants and Preparation Aimed at In-Situ Construction Technology

SUN Xiaoyan, ZHENG Xiaowei, WANG Hailong*, WANG Guannan

(College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China)

Abstract: The in-situ development of building materials from lunar regolith is fundamental for the realization of Chinese lunar base and moon landing missions. The high-precision simulants requirements for alkali-activated concrete technology is addressed, the key control components and sensitive parameters for simulation is clarified, and a high-equivalent simulation process for lunar regolith production by distinguishing between cementitious and aggregate materials based on particle size ranges is established. The simulants of cementitious lunar regolith ensures high-equivalent chemical properties through the content and chemical composition of amorphous materials; aggregate lunar regolith achieves high-equivalent workability of wet mix through precise particle morphology simulation. The investigation reveals that the activation potential of cementitious lunar regolith largely depends on the content of amorphous material and the compositions of silicon, aluminum, and calcium, with the highest vitreous content in highland cementitious simulated lunar regolith reaching up to 35.9%, Al_2O_3 to CaO mass ratio of 1.65 and SiO_2 content of 45.4%, could be used as suitable building material for alkali-activated lunar regolith concrete. The morphology of lunar regolith particles shows insensitivity to size changes, making particle size gradation crucial for simulating aggregate lunar regolith, which can be optimized by gradation before in-situ construction.

Key words: lunar regolith simulant; material activity; amorphous matter; particle morphology; gradation optimization

为了完成月球资源的研究、开发和利用等任务, 建立安全适用的月球基地成为人类探月的首要目

收稿日期:2024-01-14; 修订日期:2024-07-09

基金项目:国家自然科学基金资助项目(52478284,52279141);中国建筑材料行业重大科技攻关揭榜挂帅项目(2023JBGS0401)

第一作者:孙晓燕(1976—),女,河北故城人,浙江大学副教授,博士生导师,博士.E-mail: selina@zju.edu.cn

通讯作者:王海龙(1974—),男,江苏徐州人,浙江大学教授,博士生导师,博士.E-mail: hlwang@zju.edu.cn

标.受地月交通限制,利用月壤资源进行原位增材建造是必不可少的技术手段.现阶段亟待在地外科学研究基础上,聚焦建筑材料、人工智能、先进制造和工程结构等学科对月壤原位建材开发开展深入系统的科研攻关.现有月壤样本多取自月球正面^[1],不同源区月壤中均含有较多类地质聚合物.此外,大粒径的月球岩石蕴含丰富的含铁玄武岩,保障了粗骨料和刚性增强材料的来源^[2];月球冰储备量达到0.1~3.0亿t^[3],可供原位建造用水.在月表干燥真空环境下原位开发的月壤混凝土作为建筑材料应具备耐久性能卓越、抗压强度大、刚度高、保温隔热良好、耐冻、耐高温以及耐屏蔽辐射等突出技术优势^[4-6].

探月基地需要综合考虑能耗、工艺和结构安全来原位开发月壤进行建造.尽管现有研究表明月壤可作为骨料与胶凝材料通过水化反应制作高强度混凝土^[7],但是水泥/熟石灰/石膏等需要经过高温煅烧才具有胶结活性.因此,针对月壤进行低能耗、高原位资源利用率建材开发,合成适用于原位月表建造且服役性能良好的混凝土是当前研究目标.为了控制物资运输成本并降低制作能耗,采用少量碱溶液在常温环境下激发月球表层风化物成型混凝土取得了良好的效果^[6,8].

如何针对原位利用月表风化物开发建材进行月壤精准模拟是首要技术问题.只有实现化学组成、矿物组成等物相信息的匹配,同时考虑颗粒形态、粒径分布等物理特征的影响,利用地表材料进行月壤模拟并进行建材开发试验,才能对月表原位建造起到可靠的指导和参考作用.本文针对月壤模拟精度要求最高的碱激发混凝土技术,厘清影响月壤激发效率的关键参数,通过搜集真实月壤样本的化学组成和物相特征

数据提取出关键成分及其含量,区分胶凝材料和骨料,建立了参数分析和控制方法,实现了同矿物组成、同化学组成、同颗粒形态、同粒径分布特征的高精度月壤模拟,为原位建造月球基地的建筑材料研发提供原材料和模拟精度控制指标.

1 月壤成因与材料分析

1.1 月壤成因

月壤的化学组成、矿物组成非常复杂,与月球形成及演化过程有关^[9].在不存在大气层的情况下陨石可直接作用于月表,冲击压力达到50 GPa以上后产生的热量可将温度提高到1 000 °C以上,在冲击产生短暂的极高温环境中部分原有风化物物相转变形成了月表玻璃体凝集物^[10].

常温状态下地质聚合物碱激发效率取决于前体材料中活性无定形物含量及其化学组成^[11].月壤中无定形物含量¹⁾在15%~36%之间浮动,不同地形的月壤样本中无定形物含量存在较大差异^[12-13].由于细小颗粒冷却速率极快,大颗粒冷却速率较慢,粒径分布在10~20 μm的月壤中的无定形物含量要比50~70 μm中高约15%^[14-16].因此对于原位建材开发而言,仅依据基本化学组成和矿物组成进行月壤模拟会导致化学性质模拟精度的不足.

1.2 面向原位建材开发的月壤物化性能分析

1.2.1 月壤物理性质

月壤的颗粒形态、粒径分布以及密实程度会影响物理性质,对月壤物理性质的模拟可对建材开发过程中贯入、拌和、加工效率和制作精度提供指导意见^[17],月壤物理参数^[12, 18-19]统计见表1.

表1 月壤物理参数

Table 1 Physical parameters of lunar regolith^[12, 18-19]

Sample	Average specific surface area/(m ² ·kg ⁻¹)	Density/(g·m ⁻³)	Porosity ratio/%	Cohesion/kPa	Internal friction angle/(°)
CE5 ^[12]	560	1.24~3.19			
Apollo11 ^[18]		1.26~1.99	0.64~1.59	0.8~2.1	37~45
Apollo12 ^[18]		1.55~2.00		0.6~0.8	38~44
Apollo14 ^[18]		0.87~1.60	0.87~2.37	0.1~2.0	35~45
Apollo15 ^[18]	500	1.10~1.93	0.71~1.94	1.0	48~52
Apollo16 ^[19]		1.38~2.07	0.31~0.54	0.3~2.1	47~50
Apollo17 ^[19]		1.57~2.29		1.1~1.8	30~50

当利用碱激发地质聚合物工艺制作月壤混凝土时,作为胶凝材料的细颗粒月壤粒径是关键控制参数.在控制比表面积与月壤样本接近的基础上,参考现有建筑材料中普遍采用的粒径分级控制,更具有

作为建筑材料加工制作的操作可行性.GB/T 175—2023《通用硅酸盐水泥》规定,水泥胶凝材料比表面积应大于300 m²/kg,其细度应满足80 μm方孔的筛余量不大于10%.碱激发混凝土依赖胶凝材料在碱

1)文中涉及的含量、组成及比值等除特别说明外均为质量分数或质量比.

性环境中发生化学反应形成凝胶产物^[20-21],较小粒径的胶凝材料比表面积更高,可有效促进地质聚合物的形成,从而获得更高的力学性能.考虑到月表环境下低温、真空及建造扰动等不利因素^[7,9],出于安全考

虑取粒径 $d < 75 \mu\text{m}$ 的月壤作为胶凝材料.参考GB/T 14684—2022《建设用砂标准》和现有增材制造工艺参数^[22],将 $0.15 \text{ mm} \leq d < 2.36 \text{ mm}$ 的月壤作为骨料.各系列月壤样本粒径分布^[23-24]如图1所示.

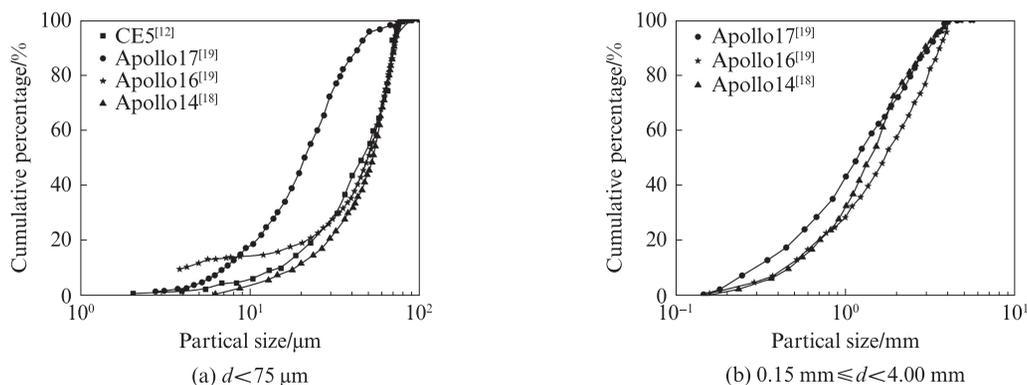


图1 月壤粒径分布

Fig. 1 Particle size distribution of lunar regolith^[23-24]

1.2.2 月壤化学性质

月壤化学性质由其中无定形物含量及其化学组成决定.无定形物中的硅、铝、钙元素的组成直接决定了碱激发地质聚合物的反应过程和反应物类型^[25-26],从而影响其硬化后的力学性能和耐久性能,是开发模拟月壤的关键控制参数.当硅钙比 $n(\text{Si})/n(\text{Ca}) < 0.3$,硅铝比 $n(\text{Si})/n(\text{Al}) = 2.0$ 时,产物以水化硅铝酸钠(N-A-S-H)为主;当硅钙比

$n(\text{Si})/n(\text{Ca})$ 接近1.0,硅铝比 $n(\text{Si})/n(\text{Al})$ 在3.0左右时,产物为水化硅铝酸钙(C-A-S-H),这种产物具有更高的刚度和耐久性能^[27].

通过取样地点将月壤分为月海、高地和月海-高地3种样本,样本编号及其钙、铝氧化物含量^[13]见图2.由图2可见,高地月壤中钙、铝氧化物含量最高,分别为17%、28%, Al_2O_3 与CaO质量比为1.65,具有更高的化学反应活性.

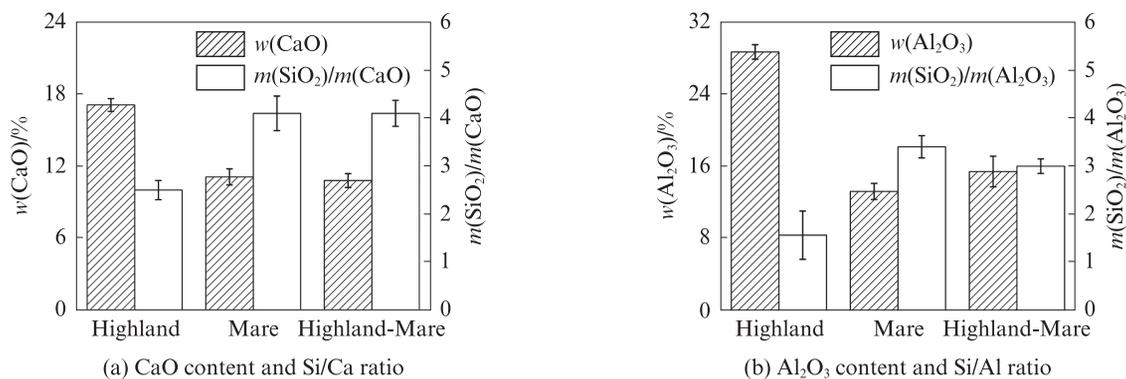


图2 月壤样本中钙、铝氧化物含量

Fig. 2 Content of calcium oxide and aluminum oxide in lunar regolith samples^[13]

2 基于物理化学特征的月壤模拟

2.1 现有模拟月壤

模拟月壤与真实月壤^[19,23,28-30]的物理性质、化学组成以及矿物组成对比如图3所示.由图3可见,现有模拟月壤在物理性质、化学组成方面模拟精度较高,但在矿物组成方面有所偏差,细粒径月壤的无定形物含量集中在15%~36%之间,粗颗粒月壤的无定形物含量在10%以内^[31].现有模拟月壤多采用火

山灰作为原材料,其中无定形物含量显著高于真实月壤.采用无定形物含量较高的模拟月壤如OPRL2N^[19]、JSC-1A^[30-31]、JSC-2A^[30]、BH-1^[8]制作碱激发月壤聚合物时,其力学性能发展规律不尽相同,其中采用JSC-2A制备的地质聚合物力学强度最高可达40 MPa以上,这可能与碱激发真实月壤的力学性能存在差别.

面向原位建造技术来模拟月壤,需要精准控制具有化学活性的无定形物含量及其化学组成.此外,

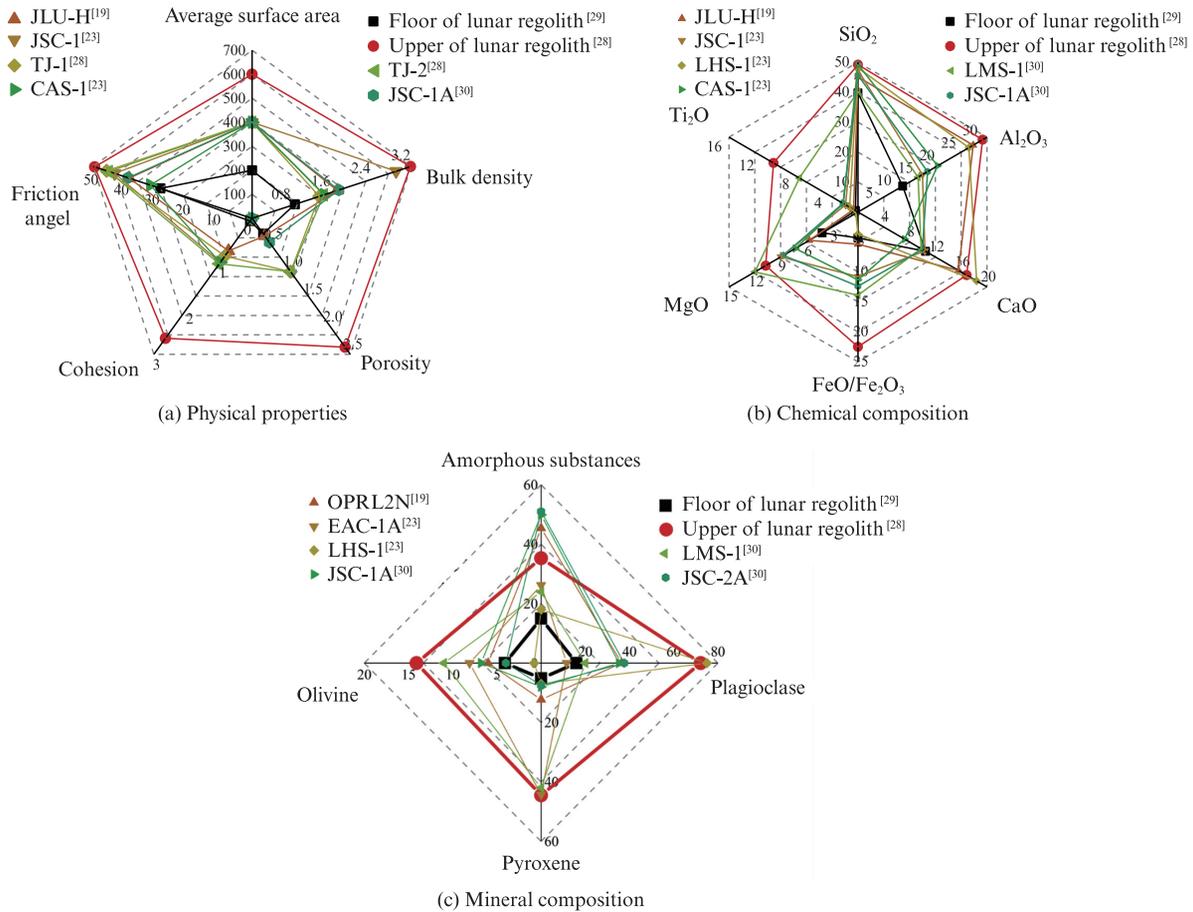


图3 模拟月壤与真实月壤样本各项性质对比

Fig. 3 Comparison of properties of simulated lunar regolith and real lunar regolith samples

月壤颗粒形态和粒径分布对建材的堆积密度和压实效果具有显著影响,是原位建材开发的关键控制参数.只有通过实现物理、化学性质的高等代进行准确模拟才能保证所制作月壤与真实月壤样本的相似性.

2.2 模拟材料

选用矿物组成及化学组成与真实月壤样本相近的玄武岩作为原材料,控制粉磨和筛分工艺使其物理特征与月壤相似的加工流程已用于制作模拟月壤^[30,32].但地表玄武岩主要由非活性晶体组成,无定形物含量与月壤差距较大,需从外部引入纯度较高、成因相近的人工无定形物.硅灰是在高温熔炼工业硅(1 410~1 414 °C)及硅铁(1 500~2 200 °C)的过程中对逸出烟尘捕集处理而成,具有无定形物特征的微米级材料. ρ 相氧化铝由三水铝石粉末经900 °C闪速焙烧后瞬时生成.矿粉由长石、橄榄石、辉石等矿物经1 000~1 200 °C高温处理的炉渣粉磨得到.这3种材料的形成过程均具有瞬时高温特征,其粒径分布与月壤无定形物相似.尽管单一材料在化学组成上仍有差别,但是由于碱激发反应会将无定形物的网络

结构溶解为单体从而进一步反应^[27],因此以月壤样本的玻璃体含量、玻璃体化学组成为目标,调配3种材料掺量,可实现模拟月壤化学性质的目标.选择玄武岩、硅灰、S95矿粉、 ρ 相氧化铝进行月壤模拟,其宏观状态见图4,X射线衍射(XRD)得到的物相特征见图5,化学组成见表2,物理性能见表3.

不同区域取样月壤的无定形物中SiO₂含量在42.7%~48.2%之间,Al₂O₃与CaO质量比在1.2~1.8之间.控制玄武岩和无定形物的质量比为0.65:0.35,无定形物中硅灰、矿粉和氧化铝的质量比为0.32:0.45:0.23,配置细颗粒的模拟月壤.此时模拟月壤中无定形物含量为35.9%,无定形物中SiO₂含量为45.4%,Al₂O₃与CaO质量比为1.66,接近高地月壤样本化学组成.

2.3 模拟制备流程

模拟月壤制备流程如图6所示:将玄武岩研磨形成原始材料,以粒径为75 μm为界限筛分得到粗细2类颗粒;将粒径 $d < 75 \mu\text{m}$ 的玄武岩粉末与硅灰、S95矿粉和 ρ 相氧化铝依据高地月壤化学组成进行混合得到模拟月壤胶凝材料.将 $d \geq 75 \mu\text{m}$ 的玄武

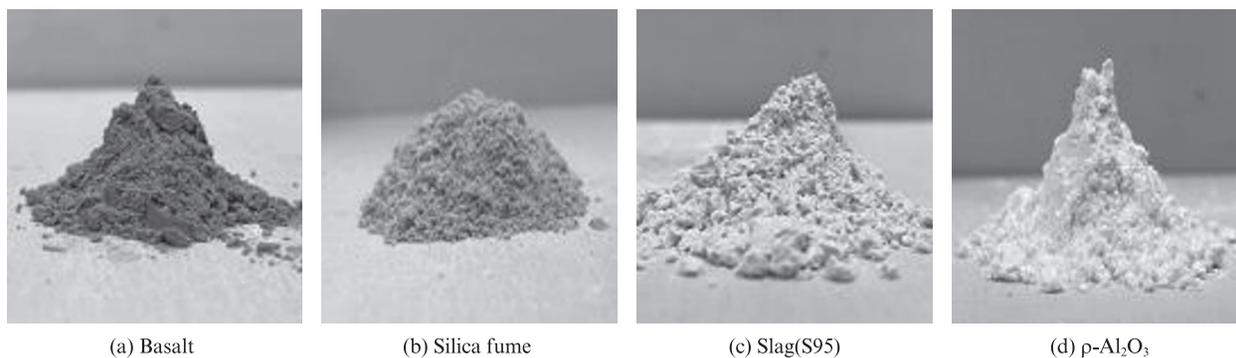


图4 原材料宏观状态

Fig. 4 Macro state of raw materials

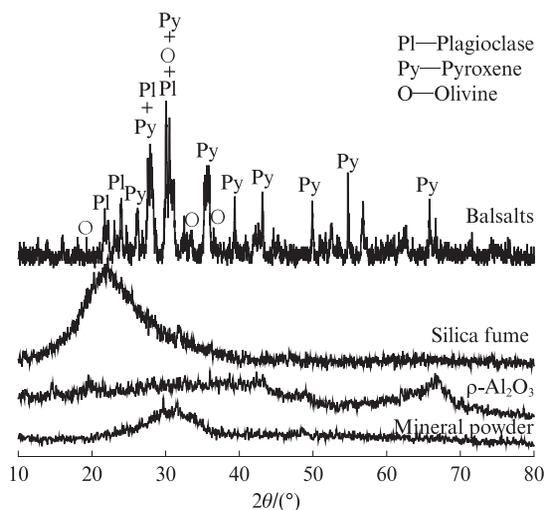


图5 原材料物相特征

Fig. 5 Mineral composition properties of raw materials

表2 原材料化学组成

Table 2 Chemical compositions (by mass) of raw materials

Component	SiO ₂	Al ₂ O ₃	CaO	MgO	Fe ₂ O ₃	FeO	TiO ₂	K ₂ O	Na ₂ O
Basalt	47.54	14.01	7.14	9.77	3.38	6.90	1.74	2.30	4.57
Silica fume	97.51	0.33	0.41	0.30	0.50	0	0.00	0.62	0.02
Slag(S95)	31.53	16.42	37.70	9.28	0.29	0	1.08	0.35	0.64
ρ-Al ₂ O ₃	0.21	91.69	0.40	0.23	0.03	0	0.06	0.32	0.45

表3 原材料物理性能

Table 3 Physical properties of raw materials

Component	Particle size/mm	Specific surface area/(m ² ·kg ⁻¹)	w(amorphous)/%
Basalt	0.003~0.075	449	5
Silica fume	0.001~0.003	21 000	99
Slag(S95)	0.008~0.040	412	99
ρ-Al ₂ O ₃	0.005~0.012	276 000	93

岩颗粒筛分为细砂(0.15~0.60 mm)、中砂(0.60~1.18 mm)和粗砂(1.18~2.36 mm)这3种粒径范围,按照月壤样本颗粒信息制备模拟月壤骨料.将配置好的模拟月壤在烘箱中于60℃下干燥12 h后密封保存,编号ZJM-01.

3 月壤模拟精度分析

3.1 化学组成与无定形物含量

采用XRD对ZJM-01模拟月壤进行矿物组成分析,如图7所示.由图7可见,ZJM-01模拟月壤混合

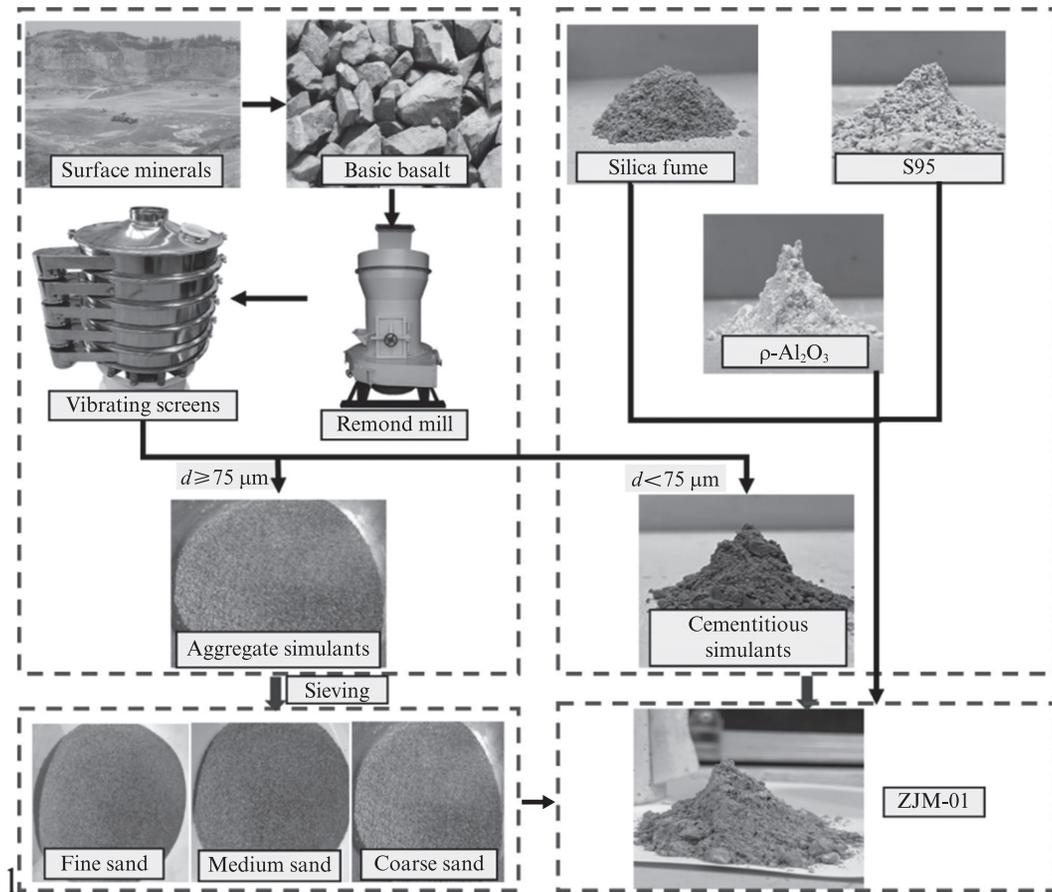


图6 模拟月壤制备流程

Fig. 6 Preparation process of simulating lunar regolith

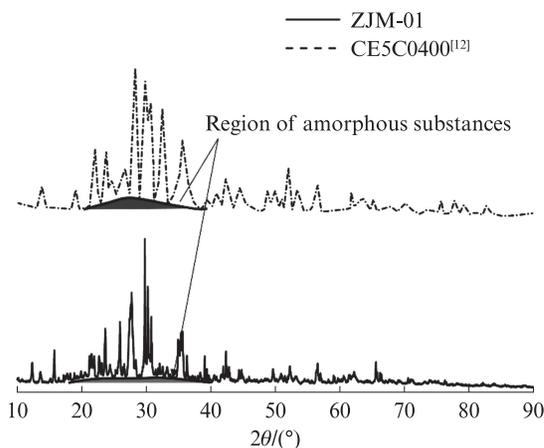


图7 ZJM-01和CE5C0400的XRD图谱

Fig. 7 XRD patterns of ZJM-01 and CE5C0400^[12]

了玄武岩和无定形物,在20°~40°位置与嫦娥5号的月壤样本CE5C0400^[12]出现了相似的物相特征,该区域由无定形物的宽峰与晶体的尖锐峰组成.同时ZJM-01模拟月壤矿物组成与高地月壤样本Apollo16^[14]极其相似,如图8所示,说明其达到了面向原位建造的建材开发对月壤模拟精度的要求.

3.2 力学性能

将ZJM-01模拟月壤作为胶凝材料,采用

Na_2SiO_3 、 NaOH 作为复合激发剂,设定碱当量 N (以 Na_2O 质量分数计)为8%,模数 M_s ($m(\text{SiO}_2)/m(\text{Na}_2\text{O})$)为1.5,添加纯水至水胶比(m_w/m_b)为0.35.现有研究及本文所采用的配合比见表4.参考GB/T 17671—2021《水泥胶砂强度检验方法(ISO法)》制作边长为40 mm的立方体净浆试件,在40℃下固化1 d后脱模取出,标准养护至3、7、14、28 d,进行抗压强度测试,然后与现有其他模拟月壤进行碱激发效果对比.

各龄期试件抗压强度如表5所示.由表5可见:碱激发ZJM-01模拟月壤试件早期强度低于JSC-1A和OPRL2N,高于BH-1和EAC-1A,与OPRH2N接近;其28 d抗压强度与JSC-1A接近,均为24 MPa左右.

3.3 颗粒形态

通过扫描电镜对ZJM-01中粒径小于75 μm的模拟月壤胶凝材料颗粒形态进行观测,如图9所示.由图9可见,模拟月壤胶凝材料颗粒表面粗糙,形态不规则,主要为棱角状、椭球状和锯齿状,与CE5C0400^[12]、JLU-H^[23]、JSC-1A^[33]、CAS-1^[34]等模拟月壤细颗粒微观形态相似.

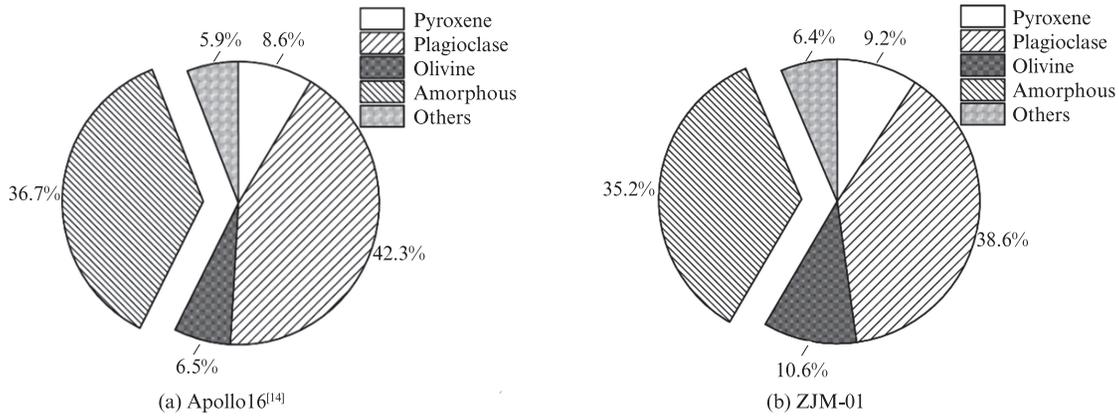


图8 ZJM-01与月壤样本Apollo16物相对比

Fig. 8 Mineral composition comparison of ZJM-01 to Apollo16^[14] lunar regolith samples

表4 碱激发模拟月壤配合比

Table 4 Mix proportions of alkali activated lunar regolith simulants

Reference	Lunar regolith simulant	Activator	m_w/m_b	Sample size
Ref. [32]	JSC-1A	$\text{Na}_2\text{SiO}_3 + \text{NaOH}$ $M_s = 2.0$ $N = 4\%$	0.21	Cylinder $\phi 19.3 \times 40.6 \text{ mm}$
	JSC-2A			
	OPRL2N			
	OPRH2N			
	EAC-1A			
Ref. [8]	BH-1	$\text{Na}_2\text{SiO}_3 + \text{NaOH}$ $M_s = 1.6$ $N = 7\%$	0.28	Cube $40 \text{ mm} \times 40 \text{ mm} \times 40 \text{ mm}$
This paper	ZJM-01	$\text{Na}_2\text{SiO}_3 + \text{NaOH}$ $M_s = 1.5$ $N = 8\%$	0.35	Cube $40 \text{ mm} \times 40 \text{ mm} \times 40 \text{ mm}$

表5 各龄期试件抗压强度

Table 5 Compressive strength for specimens at different ages

Reference	Lunar regolith simulant	Compressive strength/MPa		
		3 d	7 d	28 d
Ref. [32]	JSC-1A	22.5	24.1	24.2
	JSC-2A	41.2	53.1	53.9
	OPRL2N	22.3	23.8	20.2
	OPRH2N	7.8	18.4	20.2
	EAC-1A	4.3	6.2	19.4
Ref. [8]	BH-1		15.2	18.0
This paper	ZJM-01	13.4	20.7	23.9

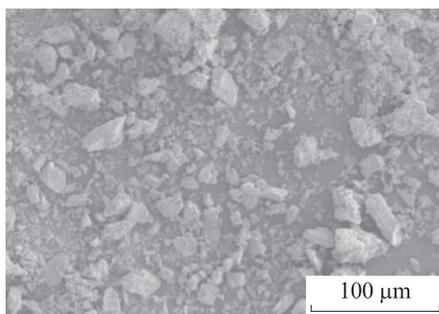


图9 模拟月壤胶凝材料的颗粒形态

Fig. 9 Particles morphology of cementitious lunar regolith simulants

采用工业相机获取模拟月壤骨料颗粒图像,与文献[35]中月壤颗粒形态参数进行对比,将颗粒图像进行二值化处理并增强对比度。

根据ISO 9276-6:2008《粒度分析结果的表示》选择长宽比(A_r)、圆度(C_r)和凸度(C_o)作为颗粒形态参数。

基于OpenCV包编写Python视觉分析程序,用以识别颗粒轮廓、凸包轮廓.该程序基于机器视觉实现颗粒的特征计算,计算流程如图10所示,颗粒形态参数计算结果见表6.由表6可见,3种粒径范围的模拟月壤骨料的颗粒形态参数与粒径大小无显著相关性,整体颗粒形态参数与月壤样本统计数据接近,满足颗粒形态的模拟精度要求。

3.4 粒径分布特征

针对模拟月壤颗粒粒径信息开展级配分析,以曲率系数 C_c 和均匀系数 C_u 为特征值描述级配优劣.当 $C_u > 6$ 且 C_c 在1~3之间时认为级配良好^[18]. C_c 和 C_u 的计算方法如式(1)、(2)所示,计算结果见表7.由表7可见,现有真实月壤样本和本文ZJM-01模拟月壤的曲率系数和均匀系数均不满足级配良好的标准。

$$C_u = \frac{D_{60}}{D_{30}} \quad (1)$$

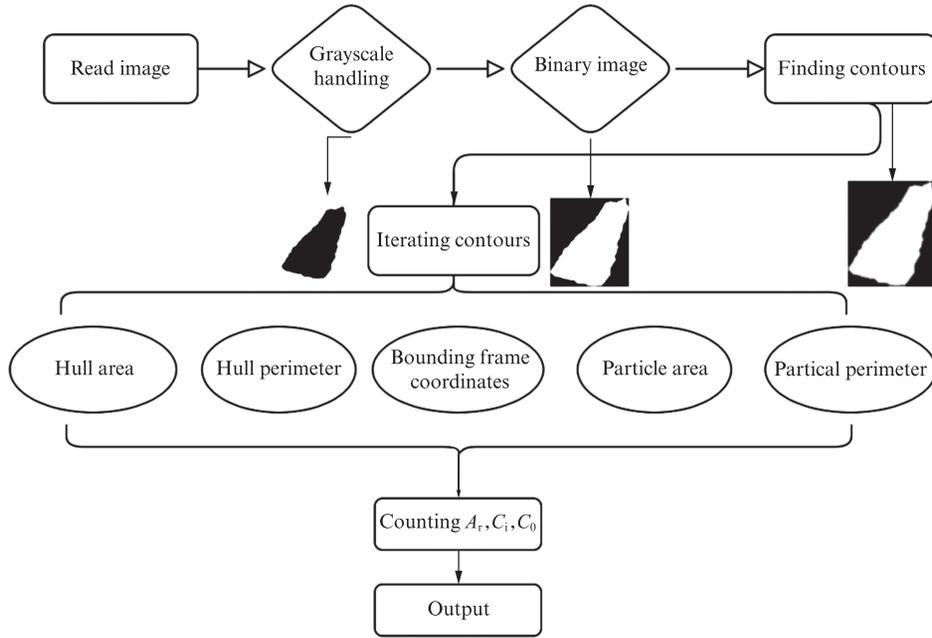


图10 颗粒形态参数计算流程

Fig. 10 Flowchart of particle morphology parameter calculation

表6 颗粒形态参数计算结果

Table 6 Calculated results of particle morphology parameters

Sample	A_r	C_i	C_0
Lunar regolith ^[35]	0.80	0.81	0.91
ZJM-01(overall)	0.81	0.74	0.92
ZJM-01(0.15-0.6 mm)	0.79	0.73	0.88
ZJM-01(0.6-1.18 mm)	0.83	0.71	0.94
ZJM-01(1.18-2.36 mm)	0.77	0.77	0.90

表7 月壤及模拟月壤粒径分布特征对比

Table 7 Comparison of particle size distribution characteristics of lunar regolith and simulants

Sample	$D_{10}/\mu\text{m}$	$D_{30}/\mu\text{m}$	$D_{60}/\mu\text{m}$	C_u	C_c
ZJM-01	5.12	11.00	22.74	4.46	1.04
Apollo17 ^[19]	7.05	14.52	25.05	3.55	1.19
Apollo16 ^[19]	3.23	34.17	55.58	17.18	6.51
CE5 ^[12]	16.30	32.93	54.35	3.33	1.23

$$C_c = \frac{D_{30}^2}{D_{10} \times D_{60}} \quad (2)$$

式中: D_{60} 、 D_{30} 、 D_{10} 分别为通过率为60%、30%、10%时对应的粒径.

ZJM-01模拟月壤和真实月壤样本^[12,14,36]的骨料粒径分布如图11所示.由图11可见:ZJM-01模拟月壤的粒径分布特征与除Apollo17以外的月壤样本有较大差别;由于选用的无定形物添加物粒径较细,导致ZJM-01具有更高的细度,粒径分布更接近通过Anderson连续级配理论优化得到的级配曲线;而真实月壤样本的粒径分布与级配优化曲线相差较大,这会影响激发效率和反应产物黏结强度.在实际建造时可对原位月壤样本进行筛分优化以获得更好的建造效果.

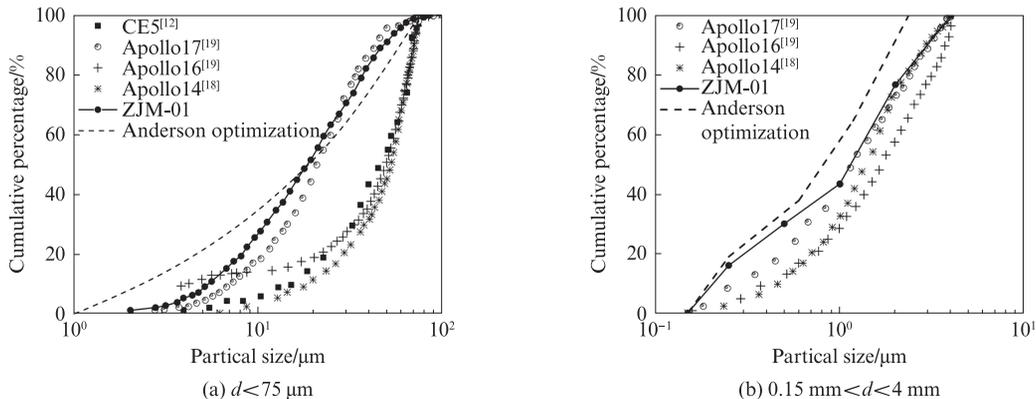


图11 ZJM-01模拟月壤和真实月壤样本的骨料粒径分布

Fig. 11 Aggregates of ZJM-01 and actual lunar soil samples^[12,18-19]

4 结论

(1)月壤样本根据粒径 d 区分为 $d < 75 \mu\text{m}$ 的月壤胶凝材料和 $0.15 \text{ mm} \leq d < 2.36 \text{ mm}$ 的月壤骨料.参考具备更高化学活性的高地月壤确定了模拟月壤胶凝材料中无定形物含量为35.9%, SiO_2 含量为45.4%, Al_2O_3 与CaO质量比为1.65,研制了ZJM-01模拟月壤.

(2)碱激发模拟月壤与JSC-1A、BH-1、OPR系列模拟月壤的28 d抗压强度接近,为24 MPa.由化学性质模拟精度提升所引起的混凝土性能差异体现在早期强度上.

(3)针对月壤骨料,区分不同粒径范围,编写了视觉分析程序用于颗粒形态特征分析.计算表明颗粒形态参数对粒径范围并不敏感.ZJM-01的粒径分布与Apollo17样本接近.原始月壤可通过Anderson连续级配理论进一步优化其粒径分布,以提高月壤混凝土材料性能.

参考文献:

- [1] LI C L, HU H, YANG M F, et al. Characteristics of the lunar samples returned by the Chang'e-5 mission[J]. National Science Review, 2021,9(2):1-13.
- [2] CHE X C, NEMCHIN A, LIU D Y, et al. Age and composition of young basalts on the Moon, measured from samples returned by Chang'e-5[J]. Science, 2021,374(6569):887-890.
- [3] XU Y C, TIAN H C, ZHANG C, et al. High abundance of solar wind-derived water in lunar soils from the middle latitude[J]. Proceedings of the National Academy of Sciences of the United States of America, 2022,119(51):e 2214395119.
- [4] LÜ Y J, QIN Y M, WANG J L, et al. Effect of incorporating hematite on the properties of ultra-high performance concrete including nuclear radiation resistance [J]. Construction and Building Materials, 2022,327:126950.
- [5] MIAO Y J, YE T H, XIAO J Z, et al. Investigation on alkali-activated insulation mortar containing high-volume recycled concrete powder for energy-efficient buildings[J]. Energy and Buildings, 2024,303:113825.
- [6] WANG K T, LEMOUGNA P N, TANG Q, et al. Lunar regolith can allow the synthesis of cement materials with near-zero water consumption[J]. Gondwana Research, 2017,44:1-6.
- [7] TOUTANJI H, FISKE M R, BODIFORD M P, et al. Development and application of lunar "concrete" for habitats[C]// Earth and Space 2006-Proceedings of the 10th Biennial International Conference on Engineering, Construction, and Operations in Challenging Environment. Houston, Texas: American Society of Civil Engineers, 2006:69.
- [8] ZHOU S Q, LU C H, ZHU X Y, et al. Preparation and characterization of high-strength geopolymer based on BH-1 lunar soil simulant with low alkali content[J]. Engineering, 2021,7(11):1631-1645.
- [9] SCHMITT H H, HEIKEN G, VANIMAN D, et al. Lunar surface processes[M]//Lunar Sourcebook:A User's Guide to the Moon. Cambridge:Cambridge University Press, 2005:62-120.
- [10] STÖFFLER D. Progressive metamorphism and classification of shocked and brecciated crystalline rocks at impact craters[J]. Journal of Geophysical Research, 1971,76(23):5541-5551.
- [11] OH J E, MONTEIRO P J M, JUN S S, et al. The evolution of strength and crystalline phases for alkali-activated ground blast furnace slag and fly ash-based geopolymers [J]. Cement and Concrete Research, 2010,40(2):189-196.
- [12] ZHANG H, ZHANG X, ZHANG G, et al. Size, morphology, and composition of lunar samples returned by Chang'e-5 mission [J]. SCIENCE CHINA Physics, Mechanics & Astronomy, 2022,65(2):229511.
- [13] LABOTKA T C, KEMPA M J, WHITE C, et al. The lunar regolith-Comparative petrology of the Apollo sites[C]// Lunar and Planetary Science Conference Proceeding. Houston, Texas: Pergamon Press, 1980:1285-1305.
- [14] ROSE JR H J, CUTTITTA F, BERMAN S, et al. Compositional data for twenty-two Apollo 16 samples [C]// Lunar and Planetary Science Conference Proceedings. [S.l.: s. n.], 1972:1149.
- [15] NEAL C R, TAYLOR L A. Petrogenesis of mare basalts: A record of lunar volcanism[J]. Geochimica et Cosmochimica Acta, 1992,56(6):2177-2211.
- [16] BOREMAN J A, CHAO E C T, JACKSON E D, et al. Petrology of unshocked crystalline rocks and evidence of impact metamorphism in Apollo 11 returned lunar sample [C]// Proceedings of the Apollo 11 Lunar Science Conference. [S.l.]: Pergamon Press Inc., 1970, 1:287-314.
- [17] CHEN T, ZHAO Z, WANG Q, et al. Modeling and experimental investigation of drilling into lunar soils[J]. Applied Mathematics and Mechanics (English Edition), 2019,40(1):153-166.
- [18] CARRIER W D. Particle size distribution of lunar soil [J]. Journal of Geotechnical and Geoenvironmental Engineering, 2003,10(129):956-959.
- [19] SLYUTA E N. Physical and mechanical properties of the lunar soil (a review)[J]. Solar System Research, 2014,48(5):330-353.
- [20] PALOMO A, GRUTZECK M W, BLANCO M T. Alkali-activated fly ashes: A cement for the future[J]. Cement and Concrete Research, 1999,29(8):1323-1329.
- [21] RUIZ-SANTAQUITERIA C, SKIBSTED J, FERNÁNDEZ-JIMÉNEZ A, et al. Alkaline solution/binder ratio as a determining factor in the alkaline activation of aluminosilicates[J]. Cement and Concrete Research, 2012,42(9):1242-1251.
- [22] XIAO J Z, JI G C, ZHANG Y M, et al. Large-scale 3D printing concrete technology: Current status and future opportunities[J]. Cement and Concrete Composites, 2021,122:104115.
- [23] SUN X M, ZHANG R, LI X J, et al. JLU-H: A novel lunar

- highland regolith simulant for use in large-scale engineering experiments[J]. *Planetary and Space Science*, 2022, 221:105562.
- [24] HILL E, MELLIN M J, DEANE B. Apollo sample 70051 and high- and low-Ti lunar soil simulants MLS-1A and JSC-1A: Implications for future lunar exploration [J]. *Journal of Geophysical Research: Planets*, 2007, 112(E2):E02006.
- [25] REES C A, PROVIS J L, LUKEY G C, et al. In situ ATR-FTIR study of the early stages of fly ash geopolymer gel formation[J]. *Langmuir*, 2007, 23(17):9076-9082.
- [26] PUERTAS F, PALACIOS M, MANZANO H, et al. A model for the C-A-S-H gel formed in alkali-activated slag cements[J]. *Journal of the European Ceramic Society*, 2011, 31(12):2043-2056.
- [27] SHI C J, JIMÉNEZ A F, PALOMO A. New cements for the 21st century: The pursuit of an alternative to Portland cement[J]. *Cement and Concrete Research*, 2011, 41(7):750-763.
- [28] 蒋明镜, 李立青. TJ-1 模拟月壤的研制[J]. *岩土工程学报*, 2011, 33(2):209-214.
- JIANG Mingjing, LI Liqing. Development of TJ-1 lunar soil simulant[J]. *Chinese Journal of Geotechnical Engineering*, 2011, 33(2):209-214. (in Chinese)
- [29] MCKAY D S, CARTER J L, BOLES W W, et al. JSC-1: A new lunar soil simulant[C]// *Proceedings of the 4th International Conference on Engineering, Construction and Operations in Space*. [S.l.:s.n.], 1994:857-866.
- [30] TOKLU Y C, AKPINAR P. Lunar soils, simulants and lunar construction materials: An overview [J]. *Advances in Space Research*, 2022, 70(3):762-779.
- [31] STURE S. A review of geotechnical properties of lunar regolith simulants[C]// *Earth and Space 2006 - Proceedings of the 10th Biennial International Conference on Engineering, Construction, and Operations in Challenging Environment*. Houston, Texas: American Society of Civil Engineers, 2006:90.
- [32] COLLINS P J, EDMUNSON J, FISKE M, et al. Materials characterization of various lunar regolith simulants for use in geopolymer lunar concrete [J]. *Advances in Space Research*, 2022, 69(11):3941-3951.
- [33] ZENG X W, HE C M, ORAVEC H, et al. Geotechnical properties of JSC-1A lunar soil simulant[J]. *Journal of Aerospace Engineering*, 2010, 23(2):111-116.
- [34] 郑永春, 王世杰, 冯俊明, 等. CAS-1 模拟月壤[J]. *矿物学报*, 2007, 27(3/4):571-578.
- ZHENG Yongchun, WANG Shijie, FENG Junming, et al. CAS-1 lunar soil simulant[J]. *Acta Mineralogica Sinica*, 2007, 27(3/4):571-578. (in Chinese)
- [35] LPI. Lunar sample atlas[EB/OL]. (2010-07-30)[2024-01-14]. <https://www.lpi.usra.edu/lunar/samples/atlas/>.
- [36] FRONDEL C, KLEIN C J, ITO J. Mineralogical and chemical data on Apollo 12 lunar fines[C]// *Proceedings of the Lunar Science Conference*. [S.l.:s.n.], 1971:719.