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RESEARCH

Micro-Raman and FTIR spectroscopic characterization of the first Turkish lunar regolith simulant

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Abstract
In this work, Infrared and Raman spectroscopic investigations on a new Turkish lunar regolith simulant (TBG-1), Chinese (own product), and Japanese simulants are presented for the first time. Our Raman spectroscopic investigation on TBG-1 simulant implies that it is mainly forsteritic olivine. Moreover, the Chinese sample produced by our group in Türkiye showed carbonate peaks at 712 cm^{-1} and 878 cm^{-1} in the IR spectra, which were attributed as calcium or sodium carbonates which could be a result of terrestrial weathering. Here, we propose that TBG-1 is close to the composition of lunar highland impact glass in terms of its (Mg, Ca)/Al_2O_3 ratios. Our effort suggested that our recently produced Turkish simulant is similar to the Apollo 11 lunar soil sample in terms of its Al_2O_3 and TiO_2 composition. Some of the samples we collected to simulate lunar regolith also show similarities to the Apollo 14 samples and JSC-1A simulant produced by NASA.

Keywords Turkish lunar regolith simulant · FTIR · Raman · ISRU

1 Introduction

Lunar exploration has long been a focal point of scientific and technological interest, particularly in the context of future missions aimed at establishing a sustainable human presence on the Moon. One of the key challenges in preparing for lunar surface operations is the urgent need to comprehend and mitigate the effects of the Moon's unique surface material, lunar regolith. Lunar regolith is a complex, fine-grained, and highly abrasive material that covers the Moon's surface, formed through micrometeoroid impacts, solar wind exposure, and other space weathering processes which are still not crystal clear, yet. Due to the fact that both access to actual lunar samples and the mission budgets are very limited, lunar regolith simulants have been developed to replicate the physical, chemical, and mechanical properties of the real lunar regolith. These simulants are indispensable in research, providing a terrestrial substitute for several activities such as testing construction techniques, life support systems, robotic mobility, and human activities in simulated lunar environments. They also play a key role in studies related to in-situ resource utilization (ISRU), which involves leveraging local resources like lunar regolith to produce oxygen, water, and building materials essential for long-term lunar habitation (Toklu et al. 2017; Toklu and Akpinar 2019, 2022).

Lunar regolith simulants are artificial materials designed to replicate the physical and chemical properties of lunar regolith, which is a critical component for various scientific and engineering applications related to lunar exploration and habitation. As space agencies and private entities intensify their efforts to return humans to the Moon, understanding the characteristics of lunar regolith becomes paramount for mission planning, resource utilization, and habitat construction. These simulants serve multiple purposes, includ-

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ing testing equipment, conducting experiments, and developing technologies that will be essential for ISRU on the lunar surface (Zhang et al. 2024).

To determine physical, chemical and geological properties, NASA brought 2200 samples with a weight of around 382 kg to the Earth with the Apollo missions between 1969 and 1972 (Stansbery 2023). 300 g sample was collected by the Soviets during the Luna missions between 1970 and 1976, particularly from Luna 16 (a sample of 101 g), Luna 20 (55 g of soil from the Apollonius highlands region) and Luna 24 (material blown off the descent stage) missions (Harvey 1996; Johnson 1979; Vinogradov 1973). More recently, 1.7 kg of samples were brought from the dark side of the Moon in 2020 with the Chinese mission Chang'e 5 spacecraft and analyzed (Mao 2024). A detailed list of past, current and future missions, including Chinese, Japanese, and Indian, to the Moon can be accessed at NASA website (Williams 2024).

The first lunar simulant produced was MLS-1, whose chemical composition was similar to Apollo 11 soil (Weiblen et al. 1990). Research on lunar soil simulants has started in many countries for various purposes and has begun with the start of the era of producing lunar soil simulants. In 1993 JSC-1 (McKay et al. 1993) was produced in the USA specifically for large- and medium-scale engineering studies in support of future human activities on the Moon. The first lunar soil simulants were produced by NASA to simulate drillings of the lunar surface during the Apollo missions. FJS-1/2/3 simulant, which imitates the chemical composition and physical properties of real lunar soil, was produced by the Japanese in 1998 (Kanamori et al. 1998). However, these simulants were not similar to real lunar regolith in terms of lunar mineralogy, composition, and particle size distribution. Studies have shown that the production of lunar regolith simulant is not that easy and that a single simulant is not sufficient for all purposes (Taylor et al. 2016). Later, various simulants have been created, including JSC-1A, a widely used lunar simulant developed by NASA, and other materials produced by different organizations worldwide (Taylor et al. 2016). New simulants have been produced for other specific purposes such as general use or geotechnical and chemical compositions similar to soils in the high-Ti mare, low-Ti mare, and highlands regions of the Moon (Taylor et al. 2016). Recently, the production and research of Moon soil analogues increased thanks to the studies performed by Türkiye (LEAG-CAPTEM SWG 2010; Toklu and Akpinar 2022).

These materials are primarily characterized by their mechanical, thermal, and dielectric properties, which are crucial for the development of infrastructures on the Moon (Colwell et al. 2007; DiGiuseppe et al. 2009; Grun et al. 2011; Lim et al. 2017; Ruess et al. 2010). For example, lunar regolith simulants such as BP-1 and KLS-1, demonstrate compressive strengths ranging from 18 to 30 MPa, influenced by factors like particle size and binder type (Kulkarni et al. 2024; X. Zheng et al. 2024). The mechanical performance of lunar regolith simulants is significantly affected by environmental conditions, with reductions in strength observed under vacuum and temperature cycling (X. Zheng et al. 2024). The dielectric properties of lunar simulants, particularly ilmenite, show high permittivity and dielectric loss, indicating their potential for microwave processing, which could facilitate construction techniques on the Moon (Kim et al. 2024). Besides, the composition of lunar simulants, including the ratios of Si/Al and Si/Ca, plays a critical role for specific compositions yielding optimal mechanical properties (Egnaczyk et al. 2024).

Regarding characterization of regolith simulants, there is a need for a focus on vibrational spectroscopic (Raman and Infrared) techniques on such samples among the various optical (petrography, electron microscopy etc.) mechanical, and geological characterization techniques. Most studies dealt with FTIR spectra just on emissivity and reflectance on such samples, rather than absorbance or transmittance. Thus, our study by vibrational spectroscopy can be regarded as a contributing work to the current gap in this area. A recent research by Hanke and coworkers (Hanke et al. 2024) applied Raman spectroscopy on various biological and mineral samples relevant to astrobiology and they highlighted the importance of optimizing laser photon energy to achieve high-quality Raman spectra for various samples, demonstrating a method to enhance the scientific return from Raman spectroscopy (Hanke et al. 2024). Another research team analyzed lunar surface materials and analogues by Raman spectroscopy and developed correlations for detection and identification of lunar surface minerals (E. Cloutis et al. 2023). A very detailed rover concept that has a Raman spectrometer onboard for lunar missions was also proposed to analyze in-situ analysis of lunar regolith. This is a compact, sub-3 kg Raman spectrometer which would be capable of detecting and discriminating a wide variety of lunar regolith materials (E. A. Cloutis et al. 2022).

This paper focuses on the vibrational spectroscopic characterization of the first Turkish lunar regolith simulants, together with Chinese (own) and Japanese simulants by determining their mineralogic compositions essentially based on the Toklu and coworkers' previous production effort (Toklu 2005a; Toklu et al. 2017, 2022, 2023; Toklu and Akpinar 2022). By analyzing these simulants, it would be possible to prepare for the technical challenges posed by lunar missions, while also advancing the development of technologies aimed at creating a sustainable presence on the Moon. We identified the main endmembers as plagioclase feldspars, pyroxenes, and olivine. We used early published correlations to separate pyroxenes from each other (orthopyroxene or clinopyroxene). The findings revealed the utility of Raman and FTIR spectroscopy for determining the mineralogy of the lunar regolith simulants.

2 Materials and methods

2.1 Materials

The first Turkish lunar regolith simulant (TBG-1) was produced by adding ilmenite, olivine, ashes, and two different types of basalts at the determined optimum ratios to the samples collected from nine different volcanic regions of Türkiye. The simulant produced is similar to the chemical mixture of 18 samples from real lunar soils brought from the Apollo missions. In order to achieve this, an optimization process was performed in this study using the Jaya algorithm (Bekdaş et al. 2018; Venkata Rao 2016). In this way, unlike the classical lunar soil simulants suitable for a region of the Moon (Low-Ti mare or High-Ti mare or Highlands), TBG-1 contains a chemical composition similar to the Moon in general. Bulk chemistry data on the TBG-1 and the samples collected from Türkiye in comparison with previous worldwide samples were presented in Table 1. (The locations and their codes were also presented in Table 1). Turkish lunar regolith production process were described extensively by Toklu and coworkers (Toklu 2005b; Toklu et al. 2017, 2022, 2023; Toklu and Akpinar 2022). All figures and data were plotted by a licensed OriginPro 2024 (64 bit) SR1 v.10.1..0.170 (learning edition) software (OriginPro 2024). Raman data of all three simulants used here was normalized to 1 to compare each other properly. All spectra were baseline corrected, normalized and smoothed by Spectragryph 1.12.16.1 version (Menges 2024). Production details of the simulants and mixing procedures were introduced in Toklu et al. 2023. They stated that *"To prepare lunar soil simulants 5 more raw materials were added into volcanic rocks. These are ilmenite and olivine minerals taken from the mines, fly ash and two different types of basalt, one from the Ankara region and the other from the Kayseri region, were added to these samples and the number of samples available was 14"* (page 569, Table 2 in their work).

2.2 Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy

All powdered samples were placed on the diamond crystal of the ATR unit of the IR spectrometer. A Perkin Elmer Spectrum Two infrared spectrometer, equipped with a deuterium triglycide sulfide (DTGS) detector was used for IR experiments. Polystyrene reference card supplied by Perkin Elmer was used for calibration purpose. All spectra were recorded between 4000 cm^{-1} and 400 cm^{-1} at ambient temperature. In order to get better signal to noise ratio and minimize background fluctuations, 64 scans (approximately 9 minutes) each at 2 cm^{-1} spectral resolution with data interval of 0.5 cm^{-1} were accumulated. Due to the manufacturer's manual (Perkin Elmer), UATR is a single bounce ATR unit and single bounce was selected for the bounce parameter with 45° angle of incidence. IR spectroscopy experiment details were also explained previously (Unsalan and Altunayar-Unsalan 2020) as performed here. Briefly, the simulants were ground in an agate mortar and the FTIR experiments were performed. All FTIR spectra were smoothed by Spectragryph 1.12.16.1 version (Menges 2024).

2.3 Raman spectroscopy

Raman spectra of all samples were recorded between 2100 cm^{-1} ~ 220 cm^{-1} by Renishaw İnVia Raman spectrometer equipped with a diode-pumped solid state (DPSS) 532 nm laser excitation line. Reference silicon wafer (520.7 cm^{-1} ± 0.5 cm^{-1}) was used for the calibration of the Raman spectrometer. The spectrometer was attached to a Research Grade Leica DM2700 microscope with better than 2 μm depth resolution. Spectral and spatial resolutions were better than 1 cm^{-1} and 1 μm, respectively. Detector was cooled to −70 °C thermoelectrically by Peltier module. Integrated detector was Renishaw Centrus 2945K7 (1040 × 256 pixels). Approximately 5% (~1 mW corresponding to a laser power density of ~0.625 $mW/\mu m^2$) power of laser was applied on the sample. Laser exposure time was 10 s and fixed laser spot size was 2 μm. 2400 lines/mm of grating was used in the compartment of the spectrometer. Raman spectral images were collected by Renishaw confocal İnVia Raman Microscope with 50× magnification. During the analysis of the obtained spectra, Renishaw Wire 4.4 software of the spectrometer was used. Micro-Raman spectroscopy experiment details were also explained previously (Unsalan and Altunayar-Unsalan 2020) as performed here.

3 Results and discussion

Samples investigated here were listed in Table 1 with their compared bulk chemistry data to previous Apollo samples and lunar regolith simulants. Besides, our Ü1 sample was found to resemble JSC-1A sample produced by NASA. On the other hand, in line with the previous bulk chemistry data results on Apollo 17 landing site lunar regolith samples (Hill et al. 2007; Rhodes et al. 1974) and in terms of Al_2O_3 and TiO_2 comparison data, our A1 sample shows similarity to the Apollo 11 lunar soil sample whereas E1 has bulk chemistry similarity to N massif (Hill et al. 2007; Rhodes et al. 1974). We found K1, AB, and KB samples studied here as

Table 1 Bulk chemistry data of the samples compared with Turkish regolith simulant in this study*

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3
Kohyama	44.39	0.70	18.05	9.04	0.24	2.97	15.25	4.13	1.52	0.13	0.01
ALRS-1	42.36	2.73	13.48	12.55	0.18	10.23	8.61	3.29	1.49	0.53	0.02
ALS	49.00	2.40	14.75	9.75	2.25	5.20	9.30	2.85	1.00	n.d.**	n.d.
BHLD20	50.17	1.18	17.21	8.81	0.12	3.34	9.41	5.59	1.67	n.d.	n.d.
BP-1	47.20	2.30	16.70	5.90	0.21	6.50	9.20	3.50	1.10	0.52	n.d.
CAS-1	49.24	1.91	15.80	12.75	0.14	8.72	7.25	3.08	1.03	0.30	n.d.
OB-1	48.40	0.08	31.60	1.33	0.00	0.35	15.40	2.47	0.08	0.00	n.d.
CLDS-i	49.99	1.22	14.09	12.81	0.11	8.16	7.17	2.78	1.23	n.d.	n.d.
CSM-CL-S	47.90	1.58	17.20	11.70	0.24	6.44	8.93	3.95	2.42	0.98	n.d.
CSM-LHT-1	48.00	2.94	22.90	6.33	n.d.	1.89	15.90	2.56	n.d.	n.d.	n.d.
CSM-LMT-1	46.90	5.12	15.10	15.56	n.d.	4.11	12.20	2.70	n.d.	n.d.	n.d.
CUG-1A	48.32	2.38	16.01	13.89	0.15	6.95	7.39	0.19	2.12	0.54	n.d.
CUMT-1	42.68	1.31	15.20	29.74	0.11	3.44	5.62	3.23	0.00	0.13	0.04
DNA-1	41.90	1.31	16.02	14.60	0.21	6.34	12.90	2.66	2.53	0.34	n.d.
EAC-1	43.70	2.40	12.60	12.00	0.20	11.90	10.80	2.90	1.30	0.60	n.d.
FJS-1	49.10	1.90	16.20	4.80	0.19	3.80	9.10	2.80	1.00	0.44	n.d.
FJS-2	49.70	1.70	14.80	4.70	0.19	8.10	8.40	2.60	0.92	0.40	n.d.
FJS-3	46.00	6.70	13.70	5.90	0.28	7.30	7.80	2.60	0.87	0.39	n.d.
JLU-H	65.15	0.04	19.28	1.31	0.01	0.06	6.45	4.95	2.74	0.01	n.d.
JSC-1A	47.40	1.56	16.10	11.40	0.18	7.72	10.50	2.94	0.80	0.59	n.d.
JSC-1	47.71	1.59	15.02	3.44	0.18	9.01	10.42	2.70	0.82	0.66	n.d.
MLS-1	43.90	6.30	13.70	2.60	0.20	6.70	10.10	2.10	0.20	n.d.	n.d.
KLS-1	48.00	1.67	15.30	4.75	0.33	9.64	8.38	3.42	1.52	0.33	0.03
KOHLS-1	54.56	0.70	16.73	n.d.	0.18	2.32	5.44	2.28	3.38	0.21	n.d.
LCATS-1	33.47	3.00	8.34	13.93	0.17	n.d.	12.66	n.d.	1.32	1.17	n.d.
MKS-1	52.69	1.01	15.91	13.65	0.22	5.41	9.36	1.90	0.58	0.14	n.d.
MLS 1/1P	42.80	6.77	12.10	18.12	0.22	6.19	11.10	2.22	0.20	0.04	n.d.
MLS-2	48.30	0.03	32.40	0.50	n.d.	0.15	16.00	2.42	0.06	n.d.	n.d.
NAO-1	43.83	0.77	25.79	2.62	0.09	4.93	15.12	1.41	0.47	0.08	n.d.
NEU-1	44.92	2.87	17.23	14.55	0.34	4.37	9.44	3.97	3.01	0.54	n.d.
NU-LHT-1M	47.60	n.d.	24.40	4.78	n.d.	8.50	13.10	1.40	n.d.	n.d.	n.d.
OB-1	48.40	0.08	31.60	1.33	0.00	0.35	15.40	2.47	0.08	0.00	n.d.
TJ-1/2	47.70	2.00	16.20	10.75	0.15	5.04	8.21	4.92	2.29	0.58	n.d.
TLS-01	n.d.	n.d.	13.60	n.d.	n.d.	7.80	11.90	0.47	0.16	0.05	n.d.
TUBS-M	48.61	2.29	13.28	11.27	0.18	8.73	8.31	3.67	1.71	0.51	n.d.
TUBS-T	48.71	0.12	30.33	1.17	0.02	0.57	14.57	3.05	0.22	n.d.	n.d.
UoM-W	68.24	0.06	1.40	0.13	0.01	5.21	9.06	13.40	1.07	0.33	n.d.
*A1***	47.68	0.91	15.39	12.08	0.04	2.96	7.28	1.08	4.63	0.14	0.22
P1	66.22	0.57	16.09	7.45	0.12	0.62	2.42	5.12	3.94	0.15	0.02
E1	51.93	0.66	14.86	13.30	0.24	8.36	10.14	3.85	0.15	0.07	0.00
G1	7.98	0.03	2.29	1.86	0.09	17.75	27.88	0.25	0.80	0.05	0.05
K1	47.34	1.78	18.14	13.17	0.15	4.61	8.35	5.23	3.49	0.81	0.10
S1	59.73	0.54	17.97	8.52	0.12	1.91	6.15	4.64	3.08	0.35	0.02
T1	1.98	0.00	1.00	0.61	0.00	0.43	54.21	0.12	0.05	0.03	0.02
U1	2.26	0.00	1.02	0.52	0.02	0.39	53.35	0.06	0.14	0.03	0.05
Ü1	68.23	0.24	15.45	4.47	0.09	0.63	3.26	3.13	3.46	0.09	0.05
AB	59.81	0.98	16.65	9.20	0.12	2.99	5.94	4.57	1.88	0.34	0.00

Table 1 (*Continued*)

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3
KB	51.77	1.27	18.00	15.56	0.18	5.25	9.79	3.72	0.73	0.20	0.00
OL	42.12	0.00	0.85	14.99	0.15	46.35	0.58	0.00	0.03	0.01	0.00
UK	59.72	0.86	19.98	14.13	0.07	2.24	2.39	1.50	2.29	0.16	0.12
İL	1.83	57.40	0.82	70.61	0.65	0.58	0.13	0.00	0.00	0.12	0.05
UoM-B	30.99	0.22	3.30	51.73	0.43	2.07	3.14	0.83	0.62	0.17	n.d.
TBG-1	49.73	2.04	16.04	9.8354	0.183	8.874	9.124	3.296	0.65	0.18	n.d.

*n.d.: not determined. ** Italic acronyms for the locations where the samples collected correspond to: A1: Avanos, P1: Palandöken, E1: Erciyes Mountain, G1: Göreme, K1: Kula, S1: Sivrihisar, T1: Taurus Mountains, U1: Uludağ, Ü1: Ürgüp, OL: olivine (provided), UK: Fly Ash (provided), KB: Kayseri basalt (provided), İL: ilmenite (provided)

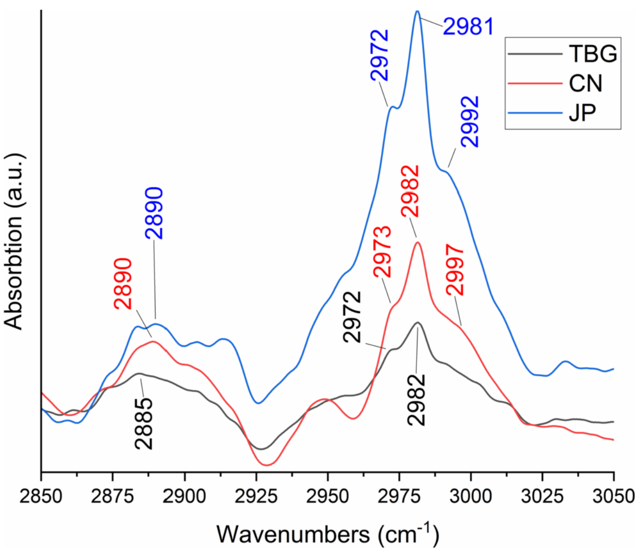

Fig. 1 Compared wavenumbers for CH stretching vibrations of the simulants studied

Table 2 Characteristic IR wavenumbers (cm^{-1}) of the simulants

Wavenumbers*	Assignment
2981-2972	symmetric and asymmetric CH stretching
950-1250 (s)	asymmetric stretching (Si-O-Si) and Al-O-Si)
1165 (sh)	asymmetric stretching (Si-O-Si)
1115-1140 (sh)	asymmetric stretching (Si-O-Si) and Al-O-Si)
1077 (s)	asymmetric stretching (Si-O-Si) and Al-O-Si)
950-980 (sh)	Si-O stretching (Si-O-R+)
882 (s)	Si-O stretching and OH bending (Si-OH)
798 (m)	symmetric stretching (Si-O-Si)
727 (sh)	symmetric stretching (Si-O-Si)
620 (sh)	symmetric stretching (Si-O-Si) and Al-O-Si)
561 (s)	symmetric stretching (Al-O-Si)
466 (s)	bending (Si-O-Si and O-Si-O)

*s: strong, sh: shoulder, m: medium, R = Na and K

similar as Apollo 14 lunar soil sample in terms of their bulk chemistry compositions.

In our FTIR spectroscopic work, Si-O stretching vibrations for TBG-1 were observed at 989 cm^{-1} together with 1001 cm^{-1} and 998 cm^{-1} for Chinese and Japanese samples. Previous studies showed that this type of broad and strong peaks are stretching vibration peaks of Si-O-Si and Al-O-Si asymmetric stretching vibration (Lee and van Deventer 2003) and there is a shift towards lower wavenumbers after polymerization due to the rearrangement of Si-O (Zhou et al. 2021). The peaks observed at 2885 cm^{-1} and 2982 cm^{-1} for Turkish simulant (Fig. 1) were attributed to symmetric and antisymmetric CH stretching peaks, respectively, and these similar peaks were also observed for Japanese and Chinese simulants (Fig. 1). Moreover, we have observed no indication of strong C=O bonds around 1722 cm^{-1} (Chen et al. 2022) and broad OH bonds around 3500 cm^{-1} (Chen et al. 2022) that were observed in FTIR spectra of three samples in our study. In our study on the Chinese sample we observed 712 cm^{-1} and 878 cm^{-1} peaks and we attributed these peaks to calcium or sodium carbonates that were generally assigned to C=O bonds in carbonates as previously reported at 873 and 712 cm^{-1} by Ahmad and coworkers (Ahmad et al. 2011). Here, we should point out that, even it exists very rare amounts, carbonates could exist (Gibson and Moore 1973) on the Lunar regolith as previously reported by Luna 20 soil and Apollo 16 soil 66081. (List of the lunar simulants ((Battler and Spray 2009; Bonanno and Bernold 2015; Byung-Hyun et al. 2018; Cesaretti et al. 2014; Desai 2013; Dreyer and van Susante 2010; Engelschiøn et al. 2020; Gaier et al. 2011; C. He et al. 2013; X. X. He et al. 2010; Hill et al. 2007; Hooper et al. 2020; Jiang et al. 2012; Just et al. 2020; Kanamori et al. 2012; Linke et al. 2020; Liu et al. 2017; Long-Fox and Britt 2023; McKay et al. 1993; Mingjing et al. 2012; Oravec et al. 2010; Off Planet Research 2024; Rickman et al. 2007, 2013; Sandeep et al. 2019; Sreenivasulu 2014; Suescun-Florez et al. 2015; Sueyoshi et al. 2012; H. Sun et al. 2017; X. Sun et al. 2022; Takashi et al. 2009; Tang

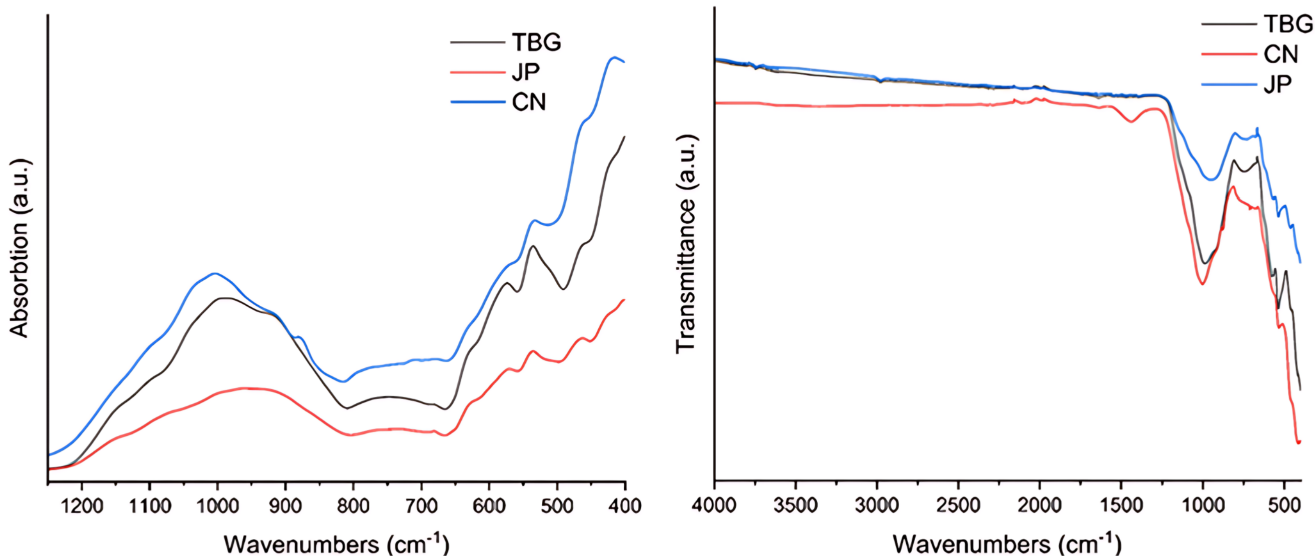

Fig. 2 Comparative FTIR spectra of the lunar regolith simulants in this work

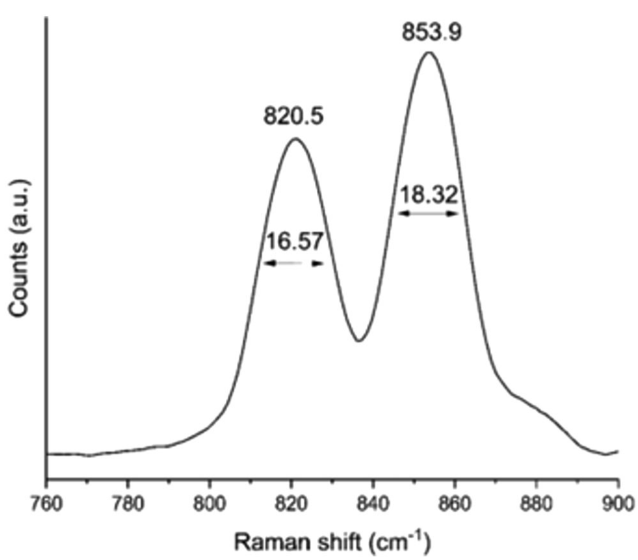

Fig. 3 Micro-Raman spectrum of TBG-1 (forsteritic olivine)

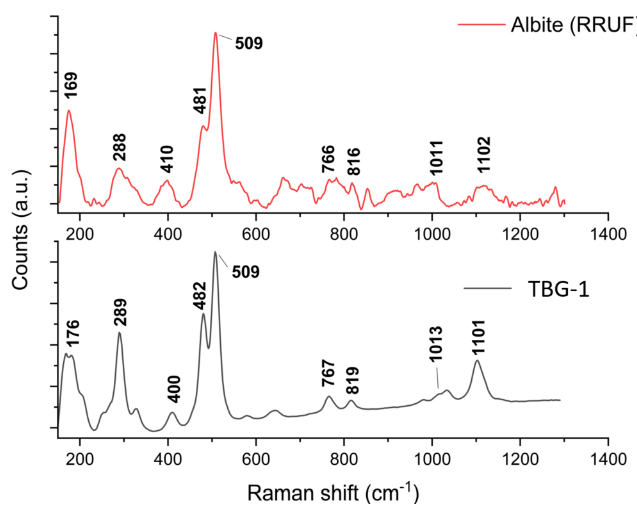

Fig. 4 Micro-Raman spectrum of TBG-1 and reference spectrum of albite

et al. 2017; Taylor et al. 2016; Toklu and Akpinar 2019; Venugopal et al. 2020; Wasin et al. 2023; Weiblen and Gordon 1988; Yongquan et al. 2009; Yoo et al. 2014; Zeng et al. 2010; Zheng et al. 2009; Zou et al. 2024)) that were produced to date was given in Table S1.) Characteristic IR wavenumbers (cm^{-1}) of the simulants were given in Table 2 for the comparison of TBG vibrational characteristic vibrational bands. Comparative FTIR spectra of the lunar regolith simulants in this work was shown in Fig. 2.

Raman spectra (Fig. 4) of TBG-1 powder sample indicated that we created olivine abundant Turkish Lunar regolith simulant based on the characteristic olivine doublets observed at 820.5 cm^{-1} (Full Width at Half Maximum: FWHM: 16.57 cm^{-1}) and 853.9 cm^{-1} (FWHM: 18.32 cm^{-1}, Lorentz fitting procedure applied). Micro-Raman spectrum of TBG-1 as forsteritic olivine was presented in Fig. 3. According to previously published data by Kuebler et. al (Kuebler et al. 2006) we obtained 82.42% forsteritic (Fo) olivine for TBG-1. Our findings are in consistency with previously published Raman spectrum for olivine for the lunar samples where Estep and co-workers reported olivine bands at 851 cm^{-1} and 819 cm^{-1} for derived Fa_{20} (=Fo_{80}) content (Estep et al. 1972). We were also able to determine that TBG-1 sample also contains albite ($NaAlSi_3O_8$) as shown in Fig. 4. As shown in Fig. 4, we also successfully determined the plagioclase and pyroxene mixtures from the peaks at 410 cm^{-1}, 509 cm^{-1}, ~670 cm^{-1},

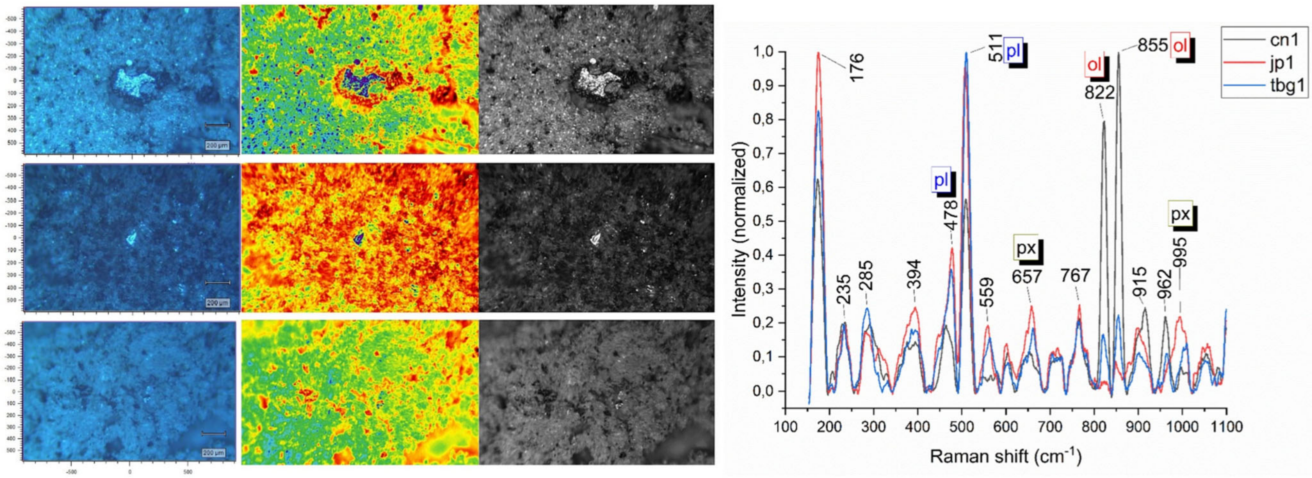

Fig. 5 Comparative Micro-Raman spectral maps of the selected regions of interest of the simulants in this work

and 1011 cm^{-1} as suggested by Haskin et al. in their earlier work (at 329 cm^{-1}, 400 cm^{-1}, 507 cm^{-1}, 671 cm^{-1}, and 1000 cm^{-1}) (Haskin et al. 1997).

A very recent work on lunar regolith samples well showed the presence of these minerals (Tucker et al. 2024). Our Raman spectrum for JP sample showed plagioclase peaks at 482.7 and 506.8 as a doublet. We observed a 23 cm^{-1} separation between 478 and 511 cm^{-1} pyroxene peaks and this corresponds to $Ab_{32}An_{67.3}Or_{0.7}$ composition of plagioclase as previously measured for plagioclases (E. Cloutis et al. 2023). Characteristic olivine Raman spectral doublets were only observed for CN-1 sample at 822 and 855 cm^{-1}. 657 cm^{-1} JP lunar regolith sample is also shown in Fig. 5. shows optical Raman images of the mapped regions of CN, JP, and TBG simulants together with the average Raman spectra of the mapped regions.

4 Conclusions

Here we have presented analytical techniques including IR and Raman spectroscopy and bulk chemistry analysis that we applied on the first Turkish, Chinese (own production by our group) and Japanese lunar regolith simulants. The evidence from our work suggests that we produced a lunar regolith simulant similar to Apollo 11 lunar soil sample in terms of Al_2O_3 and TiO_2 composition and our A1 sample shows similarity to the Apollo 11 lunar soil sample .We also found K1, AB, and KB samples studied here to be as similar as Apollo 14 lunar soil sample. Besides, our Ü1 sample was found to resemble JSC-1A sample produced by NASA. Based on the Raman spectroscopic investigation on TBG-1 sample, we obtained mainly forsteritic olivine lunar simulant. The Chinese sample produced by our group shows carbonate peaks at 712 cm^{-1} and 878 cm^{-1}, which could be attributed as calcium or sodium carbonates. We can safely suggest that TBG-1 (low-Ti composition of %2.04) is very close to the JSC simulant (low-Ti-mare %1.59 TiO_2) based on MgO-vs-Na_2O and MgO-vs-Al_2O_3 compositions which were reported earlier by Taylor et al., in 2016 (Taylor et al. 2016). Taken together, these findings highlight a role for producing more simulants for better understanding the lunar surface properties particularly for constructing new materials from the real lunar regolith samples. We believe that our spectroscopic and analytical findings might be useful for further production of lunar regolith simulants. We are currently in the process of producing bulk amounts of lunar simulants and investigating them by multi-analytical techniques. However, we are aware that our results are promising and should be validated by larger sample sizes.

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Declarations

Competing interests The authors declare no competing interests.

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