Rock and Soil Mechanics

Volume 43 | Issue 5 Article 1

7-4-2022

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Custom Citation
TANG Xu-hai, XU Jing-jing, ZHANG Yi-heng, HE Qi, WANG Zheng-zhi, ZHANG Guo-ping, LIU Quan-sheng, . Determining the mechanical parameters of asteroid rocks using NWA13618 meteorites and microscale rock mechanics experiment[J]. Rock and Soil Mechanics, 2022, 43(5): 1157-1163.

Rock and Soil Mechanics 2022 43(5): 1157−1163 ISSN 1000−7598
https: //doi.org/10.16285/j.rsm.2021.6342 rocksoilmech.researchcommons.org/journal

Determining the mechanical parameters of asteroid rocks using NWA13618 meteorites and microscale rock mechanics experiment

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Abstract: In the future, the extraterrestrial human activities, such as resources exploitation and base construction beyond the Earth need the aid of geotechnical engineering technology. Currently, there are only two approaches for humans to obtain the rock samples beyond the Earth: sample-return activities by spacecraft and meteorite investigation. Meteorites are rare, expensive, small and arbitrary in shape, so it is difficult to process them into standard rock samples required by MTS and other traditional macroscale rock mechanical tests. In this paper, a novel technique for measuring mechanical property of small-size meteorites was developed based on microscale rock mechanics experiments (micro-RME) and statistical probability models. Firstly, the composition, content and distribution of rock-forming minerals in NWA13618 meteorites were obtained by TIMA. Then, Gaussian mixture model was used to calculate the mechanical parameters of four main minerals in meteorite NWA13618. The elastic moduli of olivine, pyroxene, Fe-Ni and feldspar are 116.73, 101.77, 87.24 and 70.74 GPa, respectively. Lastly, the homogenization method Mori-Tanaka model isapplied to calculate the macroscale centimeter elastic modulus of NWA13618 meteorite is 90.48 GPa according to the achieved mineral content and mechanical properties. The microscale rock mechanical experiment and scale upgrading method proposed in this paper provide theoretical basis and technical means for predicting the mechanical properties of L4 parent asteroid.

Keywords: space mining; extraterrestrial rock mechanics; nanoindentation; asteroid rock; meteorite; cross-scale

1 Introduction

Since the Soviet cosmonaut Yuri Gagarin visited space for the first time in 1961, human beings have continuously launched new journeys to space. The American "Apollo" spacecraft successfully landed on the Moon six times, and brought back about 382 kg of lunar rocks and lunar soil samples between 1969 and 1972[1]. In 2020, China "Chang'e 5 lunar probe successfully collected lunar soil and returned to the Earth. On May 15, 2021, China's Tianwen-1 probe successfully landed on the Utopia Plain of Mars. The American "Perseverance" rover successfully landed on Mars on February 18, 2021, becoming the fifth rover of the National Aeronautics and Space Administration (NASA), which will collect Mars samples for finding the evidence of life. On May 22, 2021, China "Zhurong" Mars rover also landed safely on Mars, as well as began to patrol and explore. Japan Hayabusa 2 successfully collected sample from asteroid Ryugu, and has successfully returned to the Earth on December 6, 2020, which provides direct samples for understanding the early evolution of solar system[2].

Human will carry out extraterrestrial exploration, resource development, base construction and other activities beyond the Earth, which all need the development of geotechnical engineering technology. In the future extraterrestrial exploration, human beings are not satisfied with the surface of extraterrestrial objects. NASA proposed that the harsh Martian surface environment is not suitable for biological survival, and it is necessary to develop drilling technology and equipment suitable for the Martian environment to further explore signs of underground life[3]. Additionally, for space mining, near-Earth asteroids are rich in resources and easy to mine, which are the best choice for the first mining beyond the Earth. There are more than 2,300 near-Earth asteroids, ranging in size from rock blocks to celestial objects several kilometers in diameter, and some of them are rich in precious metals, such as platinum, cobalt, rhodium, iridium, and osmium[4]. A number of companies, including SpaceX, are developing cargo missions to the International Space Station using the reusable Falcon 9 Dragon rocket[5].

Predicting the rock mechanical parameters of extraterrestrial objects, such as the Mars, the Moon, and asteroids, is of great significance for the future exploitation of space resources. However, human still know little about the mechanical properties of extraterrestrial rocks and their engineering response [6]. Currently, there are only two approaches for humans to obtain extraterrestrial rock samples: sample-return missions via spacecraft [7–8]

Received: 14 August 2021 Revised: 20 December 2021
This work was supported by the National Natural Science Foundation of China (12172264).
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and meteorites collected on the Earth. The United States, China, and Russia have used space vehicles to obtain extraterrestrial rocks and soil samples, but the cost is huge and the sampling volume is too small. About 500 meteorites fall to the Earth each year, therefore meteorites provide an available way to obtain the samples of extraterrestrial rocks. Due to the scarcity, high price, small size and arbitrary shape of meteorites, it is difficult to process them into standard rock samples required by traditional macroscale rock mechanics experiments (macro-RME), such as MTS[9]. Therefore, new technique is need to be developed for meteorite mechanics measurement[10−11].

With microscale rock mechanics experiment (micro-RME), there is no requirement on the size and shape of the rock samples, which solves the problem of sampling during traditional macro-RME. Meanwhile, the micro-RME is able to understand the mechanical behavior of rocks at microscale. Over the past decades, nanoindentation, with the advantages of non-destructiveness, high resolution and easy operation, has been widely used to measure the mechanical properties of multiphase materials. Bobko et al.[12] measured the elastic characteristics of porous clay in shale using nanoindentation technology, which confirmed that the elastic modulus of shale obtained by nanoindentation is in good agreement with the data measured by ultrasonic pulse velocity. Zhang et al.[13] conducted nanoindentation tests on the main minerals of granites, and quantitatively analyzed the evolution law of elastic modulus and hardness of various minerals after heat treatment with different temperatures. Akono et al.[14] studied the changes of mineral mechanical properties in sandstone after fluid–rock reaction using nanoindentation technology. Slim et al.[15] measured the creep properties of shale using nanoindentation technology. Liu et al.[16] studied the anisotropy of shale using nanoindentation technology. Zeng[17], Lu[18], Luo[19] et al. investigated the fracture toughness and water softening properties of shale by nanoindentation technology, and developed a methodology for measuring the crossscale mechanical properties of shale based on continuous stiffness measurement and big data analysis. Based on nanoindentation experiments and numerical simulations, Xu et al.[11] developed an approach to investigate the softening of weak interlayers, which might trigger landslides. Zhang et al.[20] measured the mineral composition and microstructure of slate using atomic force microscopy, and proposed a cross-scale characterization method of Young's modulus.

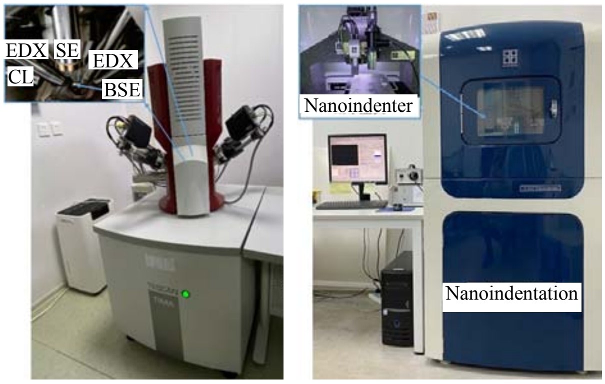
In this paper, the mineral composition and distribution of NWA13618 (L4) meteorites were obtained by the TESCAN Integrated Mineral Analyzer (TIMA). Then, the elastic moduli of NWA13618 meteorites at microscale were obtained by nanoindentation testing. Lastly, the Gaussian mixture model and Mori-Tanaka homogenization model were used to calculate the elastic moduli of minerals and the elastic moduli of NWA13618 meteorites at macroscale, respectively.

2 Microscale rock mechanics experiment

2.1 Equipment of micro-RME

The system of micro-RME includes the rock microstructure testing equipment TIMA and the rock micromechanical property testing equipment nanoindentation. In this paper, TIMA (Fig. 1(a)), an automated quantitative analysis system for rocks and minerals based on scanning electron microscopy (SEM) in back-scattered electron (BSE) imaging modes and energy-dispersive spectroscopy (EDS), is adopted to obtain the mineral classification, abundance, and distribution of rock samples quickly and accurately.

Nanoindentation is a technique that presses the material of interest with a diamond tip whose geometry and mechanical properties are known. In this work, Hysitron TI950 TriboIndenter system (Fig. 1(b)) is applied to measure the microscale mechanical properties of rock samples.



(a) The TIMA3 X GMH system (b) Hysitron TI950 TriboIndenter System

Fig. 1 Microscale rock mechanics experiment system(micro-RME)

2.2 Microscale elastic modulus testing

As shown in Fig. 2(a), the nanoindentation technique presses a diamond indenter with known geometry (such as triangular pyramid, sphere, etc.) and mechanical parameters (such as elastic modulus and hardness) into a material with unknown mechanical properties to obtain the load–displacement (*P*–*h*) curve of the loading–unloading process (Fig. 2(b)) and calculate the elastic modulus *E* and hardness *H* of the sample. During the pressing of the indenter into the surface of the sample, the load force *P* is continuously increased to the peak load P_{max} of the test; then, the peak load force P_{max} is held constant for several seconds, finally, the load force is linearly decreased to zero. The initial unloading slope of the applied load force *P* and indentation depth *h* is defined as the contact stiffness *S*[21]:

$$S = \frac{dP}{dh}\Big|_{h_{max}} \quad (1)$$

where $h_{\max}$ is the maximum indentation depth. The reduced modulus E_{r} is calculated as[22]

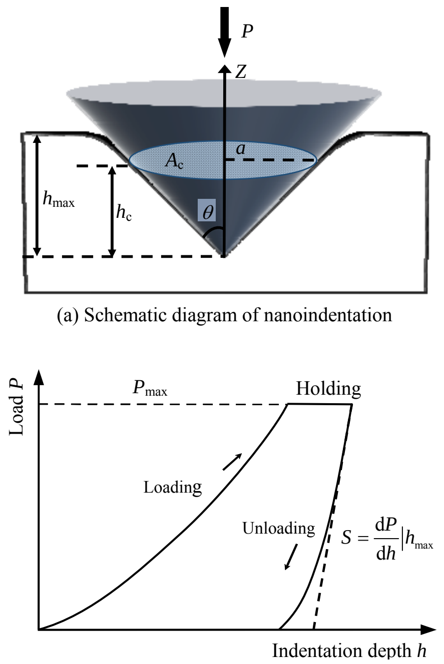
$$E_{\mathrm{r}}=\frac{\sqrt{\pi}}{2\beta\sqrt{A_{\mathrm{c}}}}S \qquad (2)$$

where β is a dimensionless correction factor associated with the indenter tip shape, for Berkovich indenter, $\beta=1.05$; A_{c} is the projected contact area of the indenter on sample surfaces, which is typically determined by a function of maximum contact depth h_{c}, and $h_{\mathrm{c}}=h_{\max}-\varepsilon\dfrac{P}{S}$ (ε is a constant that depends on the indenter tip. For Berkovich indenter, $\varepsilon=0.75$).

Elastic modulus of the sample obtained by nanoindentation is calculated by following equation:

$$E=\left(1-v^{2}\right)\left[\frac{1}{E_{\mathrm{r}}}-\frac{1-v_{\mathrm{i}}^{2}}{E_{\mathrm{i}}}\right]^{-1} \qquad (3)$$

where E_{i} is the elastic modulus values of the indenter, which is 1140 GPa; v and v_{i} are the Poisson's ratios of the sample and indenter, respectively. The Poisson's ratio of the sample has little effect on the calculation result of the elastic modulus. Therefore, it can be reasonably assumed that the Poisson's ratio of the sample is 0.2 in this paper. For diamond indenter, the value of v_{i} is 0.07.



(a) Schematic diagram of nanoindentation

(b) Typical load–displacement curve

Fig. 2 Principle of nanoindentation test

3 Upscaling analysis with statistic models

A set of elastic modulus parameters of the indentation lattice have been obtained above. In this section, the microscale elastic modulus and volume fraction of four main minerals: olivine, pyroxene, Fe-Ni metal, and feldspar, are firstly obtained by Gaussian mixture model. The equivalent elastic modulus of rock samples is upscaled from the mineral crystal scale to the macroscale by Mori-Tanaka homogenization model.

3.1 Mineral elastic modulus and volume fraction calculated by Gaussian mixture model

In the context of Gaussian mixture models, the data is assumed to obey the Gaussian mixture distribution, which means that the data can be generated from *K* Gaussian distributions. The probability distribution of the Gaussian mixture model is

$$P_{\mathrm{f}}(x|\theta)=\sum_{k=1}^{K}\alpha_{k}\phi\left(x|\theta_{k}\right) \qquad (4)$$

where α_k is the probability that the data belongs to the *k*-th component, which satisfies $\alpha_k\geqslant 0$, $\sum_{k=1}^{K}\alpha_k=1$; $\phi\left(x|\theta_k\right)$ is the Gaussian distribution density function of the *k*-th component and θ is calculated by max log-likelihood. For the Gaussian mixture model, the Log-likelihood function is

$$\lg L(\theta)=\sum_{j=1}^{N}\lg\left[\sum_{k=1}^{K}\alpha_{k}\cdot\phi\left(x|\theta_{k}\right)\right] \qquad (5)$$

Since the above equation cannot take derivative directly, the expectation-maximization algorithm (Dempster et al., 1977)[23] is applied for iterative solution.

3.2 Upscaling analysis with Mori-Tanaka homogenization model

As a method for homogenization of multiphase elastic composites, Mori-Tanaka model approximately describe the interactions between the different phases by assuming that every inclusion is embedded[13]. The homogenization macro elastic modulus E_{hom} can be calculated by the following equation:

$$E_{\mathrm{hom}}=\frac{9K_{\mathrm{M}}G_{\mathrm{M}}}{3K_{\mathrm{M}}+G_{\mathrm{M}}} \qquad (6)$$

where K_{M}, G_{M} are the equivalent volume modulus and shear modulus of each phase. They are calculated by the following equations[24]:

$$K_{\mathrm{M}}=\frac{\sum f_r\dfrac{k_r}{3k_r+4\mu_{\mathrm{low}}}}{\sum\dfrac{f_r}{3k_r+4\mu_{\mathrm{low}}}}\quad (r=0,\ 1,\ 2,3) \qquad (7)$$

$$G_{\mathrm{M}}=\frac{\sum\dfrac{f_r\mu_r}{\mu_{\mathrm{low}}(9k_{\mathrm{low}}+8\mu_{\mathrm{low}})+6\mu_r(k_{\mathrm{low}}+2\mu_{\mathrm{low}})}}{\sum\dfrac{f_r}{\mu_{\mathrm{low}}(9k_{\mathrm{low}}+8\mu_{\mathrm{low}})+6\mu_r(k_{\mathrm{low}}+2\mu_{\mathrm{low}})}} \qquad (8)$$

$$k_r=\frac{E_r}{3(1-2v_r)} \qquad (9)$$

$$\mu_r=\frac{E_r}{2(1+2v_r)} \qquad (10)$$

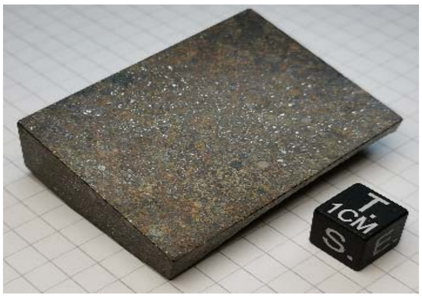
where k_r, μ_r and f_r are the volume modulus, shear modulus and volume fraction of different phases; k_{low} and μ_{low} are the equivalent volume modulus and equivalent shear modulus of low-strength minerals, which is related to the porosity ϕ; v_r is the Poisson's ratio of different phases; E_r is the elastic modulus of different phases, $r = 0, 1, 2, 3$.

4 Measuring the mechanical parameters of asteroid rocks based on NWA13618 meteorites

4.1 NWA13618 meteorite sampling

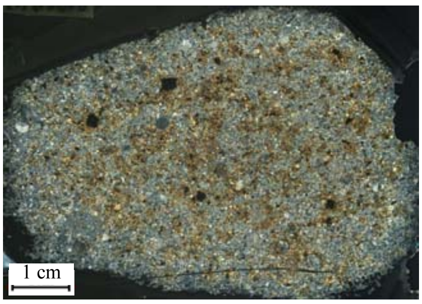
Meteorites can be divided into three categories: stony meteorites, stony-iron meteorites, and iron meteorites, which provide important clues for understanding the evolution of the universe[25]. In this work, the typical NWA13618 meteorite with a large number of samples is selected (Fig.3(a)). NWA13618 meteorites are L4 ordinary chondrite with typical visible chondrules (Fig.3(b)). It is generally believed that the parent body of NWA13618 meteorites is an S-asteroid[9].

The smooth of sample surface ensures the accuracy of nanoindentation testing and TIMA mineral testing. Firstly, the sample was cut to cubic specimen with a dimension of 50mm×30 mm×5 mm, and one surface was polished in a polisher with silicon carbide (SiC) papers of different grain fineness levels, including P800, P1200, P2500 and P5000. Then, the rough ground side was bonded to the glass sheet with epoxy, and the other side was thinned after curing. Then, the sample was further polished using an extra fine alumina suspension to reduce surface roughness as much as possible. Lastly, the meteorite sample was prepared as a thin section with a dimension of 50 mm×30 mm×30 μm (Fig. 3(c)).



(a) NWA13618 meteorite samples cut into pieces

(b) Typical chondrule in NWA13618 meteorites



(c) Thin section of NWA13618 meteorites

Fig. 3 Meteorite NWA13618 and sample preparation

4.2 Mineral composition, content and distribution of NWA13618 meteorites

In this work, the TESCAN Integrated Mineral Analyzer (TIMA) was used to obtain the mineral composition and distribution of the NWA13618 meteorites. The mineral composition analysis process of each test point mainly includes: (i) obtain the energy spectrum of the test point; (ii) automatically analyze the characteristic value of the energy spectrum of the test point to identify the elements; (iii) automatically calculate the content of the elements at each test point; and (iv) determine the mineral type and name of the test point according to the energy spectrum line and the element content of the test point (The software with a mineral database that covers the basic information of nearly 5 000 minerals in rock on earth and beyond earth)[26]. In the present work, TIMA collects the BSE signals with the pixel spacing of 3 μm and collects the EDS signals (X-ray spectrum) (>1000 counts) with the pixel spacing of 9 μm. Finally, the rock-forming minerals composition and distribution of meteorites were identified (Fig.4), and the volume fraction and mass fraction of various minerals were obtained (Table 1). The results show that the main minerals in the NWA13618 meteorites are olivine, pyroxene, Fe-Ni metal and feldspar. Olivine has the most content, with the volume fraction of 48.53%, and its distribution is relatively uniform; the volume fraction of pyroxene is 30.83%, which is mostly found in chondrules; the volume fractions of Fe-Ni metal and

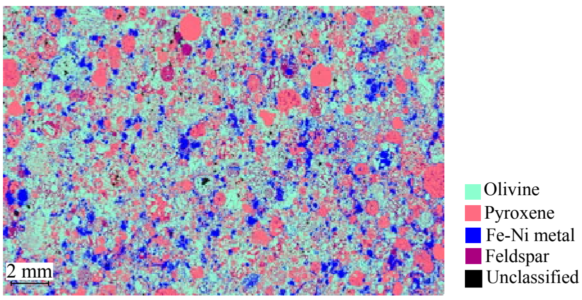


Fig. 4 Mineral distribution of NWA13618 meteorite

Table 1 Mineral proportion of NWA13618 meteorite

Minerals	Volume fraction /%	Mass fraction /%
Olivine	48.53	50.88
Pyroxene	30.83	27.47
Fe-Ni metal	11.33	14.75
Feldspar	8.72	6.39
Unclassified	0.59	0.51

feldspar are 11.33% and 8.72%, respectively; the content of other minerals is very small.

4.3 Elastic modulus and volume fraction of minerals in NWA13618 meteorites

The grid nanoindentation experiment was carried out using a Hysitron TI950 TriboIndenter system with a Berkovich indenter. The matrice of indents contains 900 indentations with a 30×30 square grid. The space between two adjacent indentations is 30 μm in order to avoid negative interference (Fig. 5)[27]. The indentation depth h should be shallow enough to ensure that the relationship with the length of the individual material phases, D, satisfies $h/D < 0.1$[28]. The load force is increased linearly to the maximum load of 4 mN at the constant loading rate of 0.8 mN/s, then it is held for 2 seconds and finally decreased to zero at the rate of 0.8 mN/s.

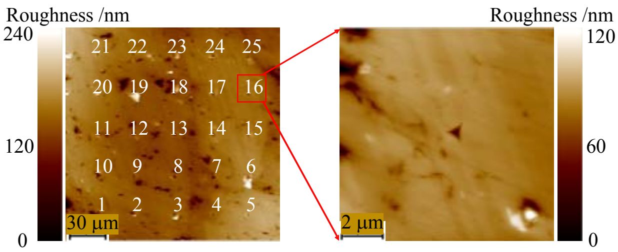


Fig. 5 Grid nanoindentation

To exclude the abnormal data caused by several factors, such as porosity, surface roughness or material failure, part of load–displacement curves were eliminated (Fig.6). Based on the Gaussian mixture model and the meteorite mineral composition measured by TIMA, the experimental frequency plot of elastic modulus was fitted by the probability density functions (PDF, calculated by Eqs. (4) and (5)) (Fig.7), meanwhile the elastic modulus and volume fraction of minerals were calculated (Table 2).

4.4 Macroscale elastic modulus of NWA13618 meteorite

After obtaining the elastic moduli and volume fractions of the above-mentioned mineral phases, the macroscale elastic modulus of NWA13618 meteorite are calculated by Mori-Tanaka homogenization model.

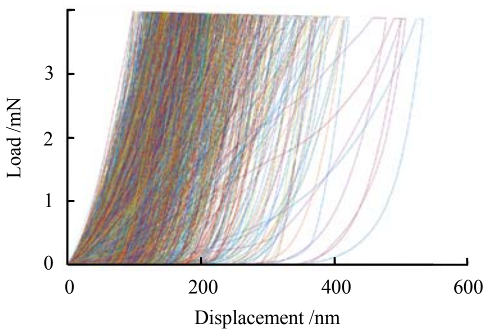


Fig. 6 Load−displacement curves

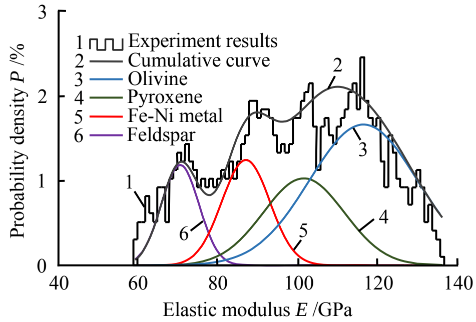


Fig. 7 Curves of probability density function

Table 2 Elastic modulus and volume fraction of mineral obtained by Gaussian fitting

Minerals	E /GPa	Volume fraction /%		Deviation /%
		Fitted	TIMA	
Olivine	116.73	49.77	48.57	1.20
Pyroxene	101.77	21.17	30.86	9.69
Fe-Ni metal	87.24	16.60	11.34	5.26
Feldspar	70.74	12.46	8.73	3.73

According to the mineral content and distribution of NWA13618 meteorites, olivine is selected as the matrix solid phase; the porosity is 0.0109 (TIMA); and the homogenized macroscale elastic modulus of the sample is $E_{hom} = 90.48$ GPa .

The results of previous shale studies show that there is relationship between macro and micro mechanical properties. For the shale in northwestern Hubei, the macroscale elastic modulus of standard cylindrical rock sample obtained by the present method with micro-RME is about 1.4 times as big as that obtained using MTS testing[11]. Because, the micro-RME ignores the influence of micro-cracks and cleavage, so the elastic modulus obtained by the present method is often larger than that obtained by macro-RME. In fact, the elastic modulus with MTS testing is not absolutely accurate, which is different from that of large rocks with fractures.

5 Conclusions

(1) A method was developed based on macro-RME and upscaling analysis, which provided the theoretical basis for predicting rock mechanical properties of the L4 meteorites parent asteroids.

(2) The elastic modulus of four rock-forming minerals in NWA13618 meteorites was achieved using grid nanoindentation technology and Gaussian mixture model. The elastic moduli of olivine, pyroxene, Fe-Ni metal and feldspar are 116.73, 101.77, 87.24 and 70.74 GPa, respectively. Meanwhile, the volume fractions of four rock-forming minerals were achieved.

(3) The macroscale elastic modulus of the NWA13618 meteorites is $E_{hom} = 90.48$ GPa , which was obtained using Mori-Tanaka model. The previous studies shown that although the elastic moduli obtained by micro-RME are often larger than those obtained by traditional macro-RME, the two have a strong correlation.

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