A New Method for Estimating Elastic Parameters of Clay Rock Host Rock in Geological Disposal of High-Level Radioactive Waste in China

GENG WEI RAO1,2,a*, XIAO DONG LIU1,2,3,b, HAI AN LIANG1,2 & PING HUI LIU1,2

1School of Geosciences, East China University of Technology Nanchang 330013, China
2State Key Laboratory of Nuclear resources and environment East China University of technology, Nanchang 330013, China
3Jiujiang University, Jiujiang,332000,China

Abstract. Taking the clay rock from the Tamusu pre-selected area of China's high-level radioactive waste geological repository as the research background. Using the methods of triaxial compression testing, X-ray diffraction and microscopic analysis, the main mineral composition, structure and mechanical properties of clay rock under different confining pressures were systematically obtained. Combined with the classical elastic parameter estimation methods at home and abroad, the elastic modulus of the clay rock in the Tamusu pre-selected area is estimated. It finds that the classical elastic parameter estimation method has a large error with the actual test value when calculating the elastic modulus of Tamusu clay rock. The maximum error can reach 788%, and the error decreases with the increase of confining pressure, however, the minimum error is still also 46%. In order to establish the deformation evaluation index suitable for the clay rock in the Tamusu pre-selected area of high-level radioactive waste, considering the influence of the mineral properties and structure of the clay rock on the macro-mechanics properties, a new method for estimating the elastic parameters of the clay rock was established. Compared with the classic elastic parameter estimation method, the maximum error is reduced to 33% and the minimum error is only 2%. Therefore, we suggest that the new elastic parameter estimation method proposed here may be used to evaluate and predict the elastic modulus parameters of the clay rock in the Tamusu pre-selected area for geological disposal of high-level radioactive waste in China.

1 Introduction

The deep geological disposal of high-level radioactive waste (HLW) is a systematic and complex project. At present, the most in-depth research on the host rocks of the HLW geological repository in Finland, Sweden, China and other nuclear countries is granite and clay rocks (Pan et al., 2009; Laurence, 1997; Ma et al., 2020). The research on granite as the host rock of the HLW geological repository is much earlier than that of clay rock. On May 6, 2019, State Administration of Science. Technology and Industry for National Defense, China, approved the "Clay Rock Project" and made the Tamusu area of the Bayin Gobi Basin in Inner Mongolia as the pre-selected area for the HLW geological repository, the research mainly focuses on the site selection and suitability evaluation of the pre-selected area (Yuan et al., 2018; Xiang et al., 2018; Wang et al., 2018; Gong, 2017). But the research on the mechanics of the clay rock in the area is relatively basic (Wan, 2018; Hu, 2014; Hu et al., 2014; Hu et al., 2020; Xue et al., 2016; Rao, 2018).

At present, the research on the correlation between the clay rock mineral composition and the elastic modulus in the Tamusu pre-selected area are based on the classic elastic parameter estimation method of Voigt (1910) and Reuss (1929) et al. (see Table 1 for specific methods) (Wan et al., 2017; Wang et al., 2018). However, the above-mentioned elastic parameters of clay rock estimated on the basis of volume average of mineral properties have large errors when compared with actual
test values, which makes it impossible to correctly evaluate the deformation characteristics of clay rock in the Tamusu pre-selected area for geological disposal of HLW.

Rock is a complex aggregate of various minerals, and its mineral composition and structure simultaneously affect the mechanical properties of the rock. Voigt and Reuss et al.’s classical elastic parameter estimation method test samples are both hard rocks such as igneous rocks, while clay rock in the Tamusu pre-selected area is a kind of sedimentary rock, which is structurally different from hard rocks.

In this paper, TAW-2000 microcomputer-controlled rock servo triaxial compression testing machine, X-ray diffraction and microscopic analysis are used to study the main mineral components and mechanical properties of clay rock in the Tamusu pre-selected area and their mechanical properties under different confining pressures. On the basis of comparing clay rock as the structural difference between sedimentary rock and igneous rock, considering the volume average of mineral properties in clay rock and the influence of interstitial materials on the mechanical properties under different confining pressures. It is of positive significance to the research and development process of the actual related engineering of the clay rock host rock of the HLW geological repository.

2 Materials and Methods

2.1 Classic elastic parameter estimation methods at home and abroad

Different scholars have different understandings on the estimation of rock elastic modulus. The classical estimation methods are based on the estimation of rock elastic parameters, and then calculate the elastic modulus of rock according to the elastic modulus conversion formula (Formula 1). In the formula, \( K \) is the bulk modulus of the rock, \( G \) is the shear modulus of the rock, and \( E \) is the elastic modulus of the rock. The specific estimation method is shown in Table 1.

\[
E = \frac{9KG}{3K+G}
\]  

| Elastic parameter estimation method | Meaning and explanation of formula |
|-----------------------------------|----------------------------------|
| Estimation method of elastic parameters proposed by Voigt in 1910 | \( K_v = \sum_{i=1}^{N} K_i \cdot V_i, \mu_v = \sum_{i=1}^{N} \mu_i \cdot V_i, \) \( N \) is the kind of mineral in the rock, the percentage of the ith mineral in the rock volume is \( V_i (i=1,...,N) \). Rock bulk modulus \( K_v \), shear modulus \( \mu_v \). |
| Estimation method of elastic parameters proposed by Reuss in 1929 | \( K_r = \sum_{i=1}^{N} K_i \cdot V_i, \mu_r = \sum_{i=1}^{N} \mu_i \cdot V_i, \) \( N \) is the kind of mineral in the rock, the percentage of the ith mineral in the rock volume is \( V_i (i=1,...,N) \). Rock bulk modulus \( K_r \), shear modulus \( \mu_r \). |
| Estimation method of elastic parameters proposed by Hill in 1952 | Bulk modulus parameters obtained by Voigt and Reuss estimation methods respectively, \( \mu_v \) and \( \mu_r \) are shear modulus parameters obtained by Voigt and Reuss estimation methods respectively. \( K_{vHI} \) and \( \mu_{vHI} \) are bulk modulus and shear modulus respectively. |
| Estimation method of elastic parameters proposed by Kumazawa in 1969 | \( K_{vom} = (K_v \times K_r)^{\alpha}, \mu_{vom} = (\mu_v \times \mu_r)^{\alpha} \), \( K_v \) and \( K_r \) are bulk modulus parameters obtained by Voigt and Reuss estimation methods respectively, \( \mu_v \) and \( \mu_r \) are shear modulus parameters obtained by Voigt and Reuss estimation methods respectively. \( K_{vom} \) and \( \mu_{vom} \) are bulk modulus and shear modulus respectively. |
| Estimation method of elastic parameters proposed by Jianping ZUO in 2015 | \( K_{Zuo} = aK_r + \beta K_r, \mu_{Zuo} = a\mu_v + \beta\mu_r, \alpha, \beta \) is the percentage of hard minerals and soft minerals in the whole rock. \( K_v \) and \( K_r \) are bulk modulus parameters obtained by Voigt and Reuss estimation methods respectively, \( \mu_v \) and \( \mu_r \) are shear modulus parameters obtained by Voigt and Reuss estimation methods respectively. \( K_{Zuo} \) and \( \mu_{Zuo} \) are bulk modulus and shear modulus respectively. |
2.2. Geological background and sample collection

The Tamusu pre-selected area is located at the southern end of the Bayin Gobi Basin in Inner Mongolia, China. The basement in the area is composed of Archean, Proterozoic and Paleozoic metamorphic rock series, with simple structure and stable sedimentation (Zhang et al., 2015; Guan et al., 2014). The upper member of the Cretaceous Bayin Gobi formation (K1b2) is the key target formation in the Tamusu pre-selected area for geological disposal of HLW, mainly composed of gray white dark gray clay rock. The 15 clay rock samples studied in this paper are all collected from the designed borehole (TZK-2) of "Clay Rock Project" in Tamusu pre-selected area. The borehole location is shown in Fig 1. The collected samples were vacuum packaged on site to ensure their freshness and integrity.

2.3. Rock sample preparation and test scheme

The rock mechanics test were completed in the State Key Laboratory of Nuclear resources and environment (East China University of technology). The drilled core retrieved on site was processed into a standard sample of φ50×100 mm. Using TAW-2000 microcomputer control rock servo triaxial compression testing machine. According to the Chinese GB/T 50266-99 and SL 264-2001 test standards, the rock sample is loaded with a radial deformation of 0.005 mm/min, and the indoor conventional uniaxial and triaxial compression test at 5 MPa and 10 MPa on triaxial.

The analysis of rock mineral composition were completed in the State Key Laboratory of Nuclear resources and environment. Selecting broken samples from mechanical testing and grind them to below 200 mesh. Using German Brewer D8 ADVANCE polycrystalline ray diffractometer for X-ray powder crystal diffraction (XRD) method analysis, the accuracy of the goniometer is 0.0001°, the accuracy is ≤0.02°, the test peak record 2θ angle is 5-70° and the Bruker-Diffrac EVA software was used for semi-quantitative mineral composition estimation.

The observation experiment of the rock under the microscope were completed in the State Key Laboratory of Nuclear resources and environment. Selecting broken samples from mechanical testing and send them to Langfang Shangyi Rock and Mine Testing Technology Service Co Ltd to preparation of microscopic thin sections of rock. The rock and mineral analysis of the sample were carried out under single polarized light and orthogonal polarized light by Leitz polarized light microscope. The microscopic morphology of the rock was carried out under a scanning electron microscope. The experimental instrument was a JSM-35CF scanning electron microscope, the instrument model was Nova Nano SEM 450. The natural section of the broken sample was selected from mechanical testing, sprayed with platinum, and glued to the sample holder with conductive glue, scanning electron microscopy (SEM) observation was performed at an acceleration voltage of 10 kV.

3 Results

3.1. Analysis of mechanical characteristics

The photos of the clay rock standard samples in the Tamusu pre-selected area and their damaged state are
shown in Fig 2. The results of indoor conventional uniaxial, triaxial 5 MPa and triaxial 10 MPa compression tests are shown in Table 2. The stress-strain curves of some rock samples are shown in Fig 3.

The fracture characteristics and joint fractures of clay rock determine the strength of the clay rock mass in the entire Tamusu pre-selected area (Guo et al., 2019). Combining the damaged state of the sample (Fig. 2b) and its stress-strain curve (Fig. 3), it can be seen that under the conventional uniaxial compression test conditions, the deformation of the rock sample is mainly elastic deformation. After the axial stress reaches the elastic limit state. The rock sample begins to produce small local damage, and the stress-strain curve fluctuates. The axial stress reaches the peak stress. The rock sample is compacted under the axial stress, and the bearing capacity continues to rise until brittle failure.

Under the experimental conditions of 5 MPa at room temperature, the deformation of the rock stress-strain curve is mainly plastic deformation. When the peak strength is reached, the stress-strain curve of the rock sample drops sharply. The end face of the rock sample is crushed under pressure, and there are potential structural planes inside the rock sample, which will break along the structural plane when stressed. The rock sample increases with the confining pressure, but the brittle failure characteristics are not significant. The bearing capacity decreases slowly after reaching the peak, and gradually develops towards ductile deformation failure.

Under the experimental conditions of 10 MPa at room temperature, the deformation of the rock stress-strain curve is mainly elastic. The rock is brittle failure, reaching the peak stress, and the rock sample is broken. Under the action of confining pressure, and the damaged rock sample still maintains a high bearing capacity. The rock sample has an overall penetrating tensile fracture. The end face of the rock sample is seriously damaged, and a large number of joint cracks appear.

According to the mechanical test data of the rock samples in Table 2, the compressive strength and elastic modulus of the pre-selected clay rock have no significant correlation with depth changes. The compressive strength under various confining pressure conditions is relatively good, with the increasing trend of confining pressure. But the elastic modulus is relatively small, it shows that the macro-mechanics properties of rock are mainly affected by rock structure and mineral composition.

| Sample number | Depth (m) | Compressive strength (MPa) | Poisson's ratio (µ) | Elastic modulus (GPa) | Experimental conditions |
|---------------|-----------|-----------------------------|--------------------|-----------------------|-------------------------|
| 1             | 160.3     | 30.41                       | 0.13               | 6.98                  | Uniaxial                |

![Fig2](image1.png)

![Fig3](image2.png)

Table2 Results of uniaxial (triaxial) compression test of clay rock samples in the Tamusu pre-selected area
3.2. Correlation analysis of mineral composition and mechanics

The XRD test results of the rock samples are shown in Table 3. According to the analysis of mineral composition, the main minerals of rock samples are dolomite, analcime, clay minerals, albite, quartz and so on. Clay rock at different depths have basically the same mineral composition, but there are differences in mineral content. The elastic modulus of the rock sample does not increase with the increase of the depth, and is less affected by the depth of burial and compaction, but it is different due to the different mineral components. The compressive strength of the rock sample is significantly affected by the depth of burial and compaction, and it has an upward trend as the confining pressure and depth of burial increase.

| Sample number | Quartz | Analcime | Montmorillonite | Kaolinite | Chlorite | Illite | Calcite | Albite | Dolomite |
|---------------|--------|----------|----------------|-----------|----------|-------|---------|--------|----------|
| 1             | 0.4    | 2        | —              | 1.8       | 9.7      | 15    | 0.8     | 8.7    | 61.6     |
| 2             | 4.3    | 8.3      | —              | 3.6       | 2.9      | 10.6  | 49.1    | 9.3    | 11.9     |
| 3             | 2.6    | 24.1     | —              | 0.7       | 2.9      | 5.1   | —       | 7.6    | 57       |
| 4             | 14.1   | 28.4     | 0.3            | 2.6       | 5.2      | 9.7   | 2.7     | 11.2   | 25.8     |
| 5             | 4.5    | 37.5     | —              | 0.9       | 2.3      | 5.5   | 1.8     | 8.1    | 39.4     |
| 6             | 3.4    | 59.5     | —              | 0.8       | 1.8      | 5.6   | 1       | 8.3    | 19.6     |
| 7             | 8      | 20.3     | 0.5            | 1.9       | 6.6      | 6.9   | 3.4     | 6.9    | 46.1     |
| 8             | 6.9    | 20.6     | 0.6            | 1.7       | 4.9      | 6.3   | —       | 10.1   | 48.9     |
| 9             | 4.1    | 42.8     | —              | 1.2       | 2.9      | 5.7   | 1.8     | 8.8    | 32.7     |
| 10            | 2.7    | 48.1     | —              | 1.3       | 2.3      | 5.6   | 1.9     | 8.7    | 29.4     |
| 11            | 2.8    | 52.2     | 1.3            | 2.3       | 2.3      | 5.1   | 1.7     | 7.6    | 27       |
| 12            | 3.6    | 56.2     | 1.7            | 2.1       | 2.1      | 8.4   | 1.6     | 7.3    | 19.1     |
| 13            | 2.9    | 53.2     | 1.6            | 2.2       | 2.2      | 5.3   | 1.7     | 7.5    | 25.6     |
| 14            | 2      | 39.5     | 0.9            | 2.7       | 2.7      | 4.8   | —       | 9.4    | 40.7     |
| 15            | 1.8    | 30.4     | 1.4            | 2.8       | 2.8      | 4.2   | —       | 12.1   | 47.3     |

Comparing the changes of various minerals and mechanical parameters, it is found that the changes in the content of quartz, calcite, albite and other minerals in the clay rock in the Tamusu pre-selected area have little effect on the macro-mechanics characteristics. It can be seen, it will have a greater impact on the overall mechanical properties of the rock, when the mineral content reaches a certain value. Therefore, for dolomite, analcime and clay minerals that have significant effects on mechanics in rock samples, the correlation between mineral components and mechanics is explored under the conditions of conventional uniaxial, triaxial 5 MPa and triaxial 10 MPa (Fig. 4).

The analysis shows that the overall mechanical parameters of each mineral increase with the increase of confining pressure. The elastic modulus of rock samples increases first and then decreases with the increase of dolomite content. When the dolomite content exceeds 40%, it begins to make a negative contribution to the elastic modulus. The relationship between rock compressive strength and dolomite content also shows the same trend. The analcime content of the rock sample is positively correlated with the elastic modulus as a whole, but when the confining pressure increases, the elastic modulus of the rock sample decreases with the increase of the analcime content. The compressive strength varies slightly with the content of analcime, but increases significantly with the increase of confining pressure. The content of clay minerals in rock samples has a significant influence on mechanical parameters. When the clay mineral content is less than 15%, there is no obvious linear relationship with the elastic modulus and compressive strength, and the range of change will fluctuate greatly due to the different types of clay minerals. However, when the content of clay minerals is greater than 15%, the compressive strength and elastic modulus of rocks have a significant downward trend, indicating that clay minerals have a negative contribution to the elastic modulus and compressive strength of rocks. The clay minerals in the rock sample the increase will
weaken the mechanical properties of the rock mass.

As the argillaceous cement in the clay rock cannot be clearly distinguished under the polarized light microscope, the microscopic morphological characteristics of the rock sample are observed by SEM. It can be seen that the argillaceous cement is mainly clay minerals, and the surface is clean and the self-shape is good, it is an authigenic clay mineral (Fig. 5b).

3.3. Characteristics and structure analysis of rock under microscope

The macro photos of the clay rock in the Tamusu pre-selected area and the photos under the indoor microscope can be seen in Fig 5. The macroscopic characteristics of the rock in the field are mainly shown as continuous and uniform gray-white clay rock, with horizontal bedding structures (Fig. 5a). The analysis of rock minerals on the clay rock in the Tamusu pre-selected area by Leitz polarized light microscope shows that the sample has a higher mud content, and the whole is relatively clean and uniformly distributed under the microscope. The cement is mainly composed of carbonate minerals such as dolomite and calciteand argillaceous minerals. The rock structure mainly includes laminar structure, embedded crystal structure, comb-like structure and secondary large edge structure (Fig. 5c-f).

4 Discussion

4.1. Establishment of estimation method of clay rock elastic parameters

As a kind of sedimentary rock, clay rock is different from hard rock such as igneous rock in structure. The texture and structure of igneous rocks are mainly affected by the degree of crystallinity, crystal grain size and aggregate morphology of minerals in the rock. The texture of sedimentary rock is affected by the nature, size, shape and relationship of particles, while structure is the spatial distribution and arrangement of various components in sedimentary rock (Shu, 2010). Therefore, in order to establish a method for estimating the elastic parameters of the clay rock in the Tamusu pre-selected area for geological disposal of HLW, based on the volume average analysis of the mineral properties of the sedimentary rock, the influence of sedimentation on the
rock structure should also be considered.

Sedimentary rocks are mainly affected by compaction and cementation during consolidation and diagenesis. The compaction reduces the number of pores in the sediments, and the pores are reduced, causing the water to be squeezed out, which makes the thickness smaller and the sediments harder. This effect is especially obvious in muddy sediments. Cementation is the main factor that fills the interstitial materials between the particles, cement and solidifies the deposits and makes them hard. Different from the matrix in igneous rocks (small mineral particles in the rock) (as shown in Fig. 6), the fine clastic interstitial material filled in the grain voids of the sediments are the matrix (heterobase), while the cemented and consolidated sediments the chemical interstitial material is cement. Therefore, distinguishing the main forms of cementation interstitial materials is the key to exploring the structure of clay rock.

![Igneous rock and Clay rock](image)

**Fig6** Difference between igneous rock and clay rock in cement and matrix

Observed by Leitz polarized light microscope, it can be seen that the interstitial materials of the rock sample are mainly composed of embedded crystal structure, comb-like structure and secondary large-edge structure, which are the structural forms of cement. The argillaceous minerals under SEM are mainly authigenic clay minerals, combining with the paleo-sedimentary environment and sedimentary facies analysis of the clay rock in the Tamusu pre-selected area (Gong, 2017; Rao, 2018; Huang, 2018; Li, 2010; Li, 2018). The interstitial materials in the clay rock in the Tamusu pre-selected area are mainly cement, and the cement is mainly argillaceous cement (authigenic clay minerals) and carbonate cement (calcite, dolomite, etc.) of the syngenetic and diagenetic period.

![Graph of rock elastic parameters](image)

**Fig7** Estimation model of rock elastic parameters

According to the classic elastic parameter estimation method of Voigt and Reuss et al. (Fig. 7a, b), a new elastic parameter estimation method was established for the clay rock in the Tamusu pre-selected area for geological disposal of HLW. Based on the volume average analysis of rock mineral properties, the main minerals are divided into soft and hard minerals based on physical and mechanical properties, and it is assumed that the macroscopic mechanical parameters of the rock sample will be affected by the cement in the clay rock. Therefore, it is assumed that the stress and strain of the soft and hard minerals in the clay rock have almost equivalent effects on the macro-mechanics parameters of the rock, and the elastic parameters in the clay rock are mainly affected by the cementation during the sedimentation and diagenesis process (Fig. 7c). The new method of elastic parameter correction estimation is shown in formula 2, in the formula, $K_N$ and $\mu_N$ are the bulk modulus and shear modulus estimated by the clay rock evaluation method, $\alpha$ and $\beta$ are the percentages of hard minerals and soft minerals in the entire rock, and $\gamma$ is the proportion of cement. Table 4 shows the proportion of soft and hard minerals and the percentage of cement in each rock sample.

$$
\begin{align*}
K_N &= \frac{(\alpha + \beta)\cdot (K_V + K_R)}{2} \cdot \gamma \\
\mu_N &= \frac{(\alpha + \beta)\cdot (\mu_V + \mu_R)}{2} \cdot \gamma
\end{align*}
$$

**Table 4** The proportion of cement and the division ratio of soft and hard minerals in clay rock samples(%)

| Sample number | Hard mineral content | Soft mineral content | Proportion of cement | Experimental conditions |
|---------------|----------------------|----------------------|----------------------|------------------------|
| 1             | 74                   | 27                   | 27                   | Uniaxial               |
| 2             | 83                   | 17                   | 17                   | Uniaxial               |
| 4             | 82                   | 18                   | 28                   | Uniaxial               |
| 8             | 87                   | 14                   | 27                   | Uniaxial               |
| 11            | 91                   | 9                    | 52                   | Uniaxial               |
| 14            | 92                   | 8                    | 40                   | Uniaxial               |
| 15            | 92                   | 8                    | 30                   | Uniaxial               |
| 3             | 91                   | 9                    | 24                   | Triaxial 5 MPa         |
| 5             | 91                   | 9                    | 38                   | Triaxial 5 MPa         |
| 7             | 85                   | 15                   | 35                   | Triaxial 5 MPa         |
| 9             | 90                   | 10                   | 43                   | Triaxial 5 MPa         |
| 12            | 88                   | 12                   | 36                   | Triaxial 5 MPa         |
| 6             | 92                   | 8                    | 60                   | Triaxial 10 MPa        |
| 10            | 91                   | 9                    | 48                   | Triaxial 10 MPa        |
| 13            | 91                   | 9                    | 53                   | Triaxial 10 MPa        |

4.2. Trial calculation of various elastic parameter estimation methods

The main mineral crystals that make up the clay rock in the Tamusu pre-selected area for geological disposal of HLW have been studied in detail in (Dortmann, 1985; Tiziana et al., 2003; Deer et al., 2009) and the average
The classical elastic parameter estimation methods of predecessors were used to calculate the theoretical values of bulk modulus and shear modulus of Tamusu clay rock. According to the elastic modulus conversion formula, the theoretical elastic modulus estimates of rock samples under different confining pressures of conventional uniaxial, triaxial 5 MPa, and triaxial 10 MPa are obtained. The specific data and related comparison can be seen in Table 6 and Fig 8.

The test value under normal uniaxial conditions is between 6.08 and 10.27 GPa. The test value under normal temperature triaxial conditions under 5 Mpa is between 5.65 and 9.62 GPa. The normal temperature triaxial conditions under 10 Mpa conditions is between 9.12 and 11.33 GPa. The estimation method proposed by Reuss, which is closest to the actual test value. The estimated value of elastic modulus is between 16.75 and 42.74 GPa under conventional uniaxial conditions. The estimated value is between 16.02 and 21.72 GPa under normal temperature triaxial conditions of 5 MPa. The estimated value is between 16.05 and 17.22 GPa under normal temperature triaxial conditions of 10 MPa.

Table 5 shows the basic elastic parameters of main minerals.

Table 6 presents the comparison of the theoretically estimated elastic modulus (E) and the test result value (unit: GPa) under different experimental conditions.
The theoretical value calculated by the elastic parameter estimation method proposed in this paper is compared with the actual test value. See Table 7 and Fig 9 for details. The estimated values of elastic modulus of

| Sample number | 1 | 2 | 4 | 8 | 11 | 14 | 15 | 3 | 5 | 9 | 12 | 6 | 10 | 13 |
|---------------|---|---|---|---|----|----|----|---|---|---|----|---|---|---|
| Experimental conditions | Uniaxial | Triaxial 5 MPa | Triaxial 10 MPa |
| Actual test value | 6.98 | 6.08 | 7.7 | 9 | 6.93 | 10.27 | 8.44 | 8.4 | 5 | 5.65 | 8.5 | 9.62 | 8.23 | 6.51 | 9.12 | 9.64 | 11.33 |
| Theoretical estimate | 7.16 | 7.31 | 8.8 | 3 | 7.43 | 10.96 | 8.76 | 7.2 | 9 | 5.76 | 8.87 | 10.04 | 9.91 | 7.4 | 12.13 | 10.43 | 11.08 |

Fig9  Comparison of elastic modulus estimation methods and test value under different conditions

Comparing the actual elastic modulus test value with the theoretical value calculated by each elastic parameter estimation method, it can be seen that with the increase of confining pressure, the error of the theoretical value obtained by the classical elastic parameter estimation method is reduced compared with the test value, but the overall error is still large. Under the same test conditions, the estimated value of the rock sample elastic modulus obtained by the elastic parameter estimation method proposed in this paper is more consistent with the actual test value, which can more accurately predict and evaluate the elastic modulus of the clay rock host rock in the geological disposal for HLW.

4.3. Comparison and analysis of errors between theoretical and test values

Table 8 shows the error comparison data between the actual test value of the elastic modulus of the clay rock sample in the Tamusu pre-selected area and the theoretical value obtained by each elastic parameter estimation method. The classical elastic parameter estimation method has a large overall error when estimating the elastic modulus of clay rock samples, the maximum error can reach 788%, the minimum is 46%, and the error range varies greatly. As the confining pressure increases, the sedimentary rock is obviously compacted, which reduces the overall error. The maximum error is reduced to 389% under the condition of normal temperature triaxial 5 MPa, and the maximum error is reduced to 171% under normal temperature triaxial condition of 10 MPa, but there is still a large error compared to the actual test value. Compared with the actual test value of the rock sample, the elastic parameter estimation method established in this paper has the minimum error of only 2% and the maximum error of only 33%, which is more consistent with the actual test value. It is superior to the classical elastic parameter estimation method in the evaluation.

| Estimation methods of various elastic parameters | Uniaxial | Triaxial 5 MPa | Triaxial 10 MPa |
|------------------------------------------------|---------|---------------|---------------|

Table8  The relative error between the estimation method of elastic parameters and the actual test value under different test conditions
5 Conclusion

Through the analysis of rock minerals and mechanical characteristics of the rock samples, it can be known that the main mineral components of the Tamusu clay rock are dolomite, analcime, albite, calcite, quartz, and clay minerals. The rock structure is mainly affected by cementation, and the interstitial material are mainly argillaceous cement and carbonate cement. The conventional uniaxial mechanical strength is relatively low, mainly manifested as elastic deformation, and the failure form is brittle failure. As the confining pressure increases, the rock deformation becomes more obvious plastic deformation, and the failure form is plastic and ductile. When the confining pressure increases to 10 MPa, the rock deformation tends to be more elastoplastic instead.

By distinguishing the structural differences between sedimentary rocks and igneous rocks and other hard rock structures, the soft and hard minerals are classified for the Tamusu clay rock. According to the analysis under the microscope, combined with the material source, sedimentary form and formation environment of the Tamusu clay rock, the main form of cement is determined. Based on the volume average analysis of the mineral properties of sedimentary rocks, and considering the impact of sedimentation on the structure of the rock, a new method for estimating the elastic parameters of Tamusu clay rock is established.

Through the trial calculation of the elastic modulus of each elastic parameter estimation method and the comparison analysis with the actual test value error, it can be seen that the classical elastic parameter estimation method has a large error in estimating the elastic modulus of Tamusu clay rock, with a maximum error of 788%, the minimum is 46%, and the new elastic parameter estimation method established in this paper has a maximum error of only 33% and a minimum error of only 2% when estimating the elastic modulus of rock samples. Compared with the classical elastic parameter estimation method proposed by the predecessors, the error is smaller, and it is more consistent with the actual measured value, which can more accurately estimate and evaluate the elastic modulus parameters of the clay rock in the Tamusu pre-selected area for geological disposal of HLW.

Acknowledgements

This article is one of the phased research results of National Defense Science and Technology Industry Financial Support Project "Research on the Screening and Evaluation of Clay Rock Sections in the Northwestern Region of the Geological Repository for High-level Radioactive Waste" (Second Division of Science and Engineering [2014] No. 1587) and the Jiangxi Province Graduate Student Innovation Fund Project "Research on the Characteristics of Clay Rock/Mudstone Host Rock in the Northwest Preselected Area of the Geological Repository for High-level Radioactive Waste" (YC2019-B107).

References

1. Deer, W.A., Howie, R.A. & Zussman, J. 2009. Rock-forming minerals: Layered silicates excluding micas and clay minerals. London: Geological Society.
2. Dortmann. 1985. Physical properties of rocks and minerals.1th ed. Trans: Jiang Hongyao. Beijing: Science Press.
3. Gong, Y. 2017. Study on regional geological conditions of Tamusu candidate area, inner mongolia-siting of clay rock high-level radioactive waste disposal repository. Dissertation. Nanchang: East China University of technology.
4. Guan, W.C., Liu, X.D. & Liu, P.H. 2014. Geological characteristics of clay rocks in Tamusu area of Bayingobi Basin. World Nuclear Geoscience 31 (02): 95-102.
5. Guo, Q.F., Wu, X., Cai, M.F., Xi, X., Ren, F.H. & Miao, S.J. 2019. Experiment on the strength characteristics and failure modes of granite with pre-existing cracks. Chinese Journal of Engineering 41 (01): 43-52.
6. Hill R. 1952. The elastic behavior of a crystalline aggregate. Proceedings of the Royal Society of London A A65:349-354.
7. Hu, H.Y. 2014. Mechancial properties of clay rocks Tamusu area. Dissertation. Nanchang: East China University of technology.
8. Hu, H.Y., Liu, X.D., Yang, T., Wang, G.B. & Hu, L. 2014. Experimental study and mechanism analysis of mechanical properties of clay rock in Tamusu area. Geotechnical Investigation & Surveying 42 (12): 9-13.
9. Hu, Q.B., Liang, H.A., Yang, T., Liu, X.D, Wang, Y. & Zhang, L.P. 2020. Permeability and Strength Characteristics of Tamusu Deep Clay under Confining Pressure and Osmotic Pressure. Journal of Geophysical Research 125(11):1-12.
10. Huang, H.E. 2018. Study on Hydrogeological Conditions of Clay rock Pre-selected Section of High-level Radioactive Waste Repository-Taking Tamusu and Suhongtu as Examples. Dissertation. Nanchang: East China University of technology.
11. Kumazawa M. 1969. The elastic constant of polycrystalline rocks and nonelastic behavior inherent to them. Journal of Geophysical Research 74: 5311.
12. Laurence S C. 1997. Site selection and characterization processes for deep geological disposal of high-level nuclear waste. Open-file report. Albuquerque Sandia National Laboratories.
13. Li, S.Z. 2018. Geological Characteristics and Comprehensive Evaluation of Clay rock Pre-selected Section of Bayingobi Formation in Ingejing Depression Inner Mongolia. Dissertation. Nanchang: East China University of technology.
14. Li, X.D. 2010. Sedimentary facies analysis of upper member of Bayingobi formation in Tamusu area of Bayingobi Basin. Journal of Henan Polytechnic University (Natural Science) 29 (S1): 177-180.
15. Ma, J.Y., Zhang, H.Y. & Chen, L. 2020 Research status of public participation in high level radioactive waste disposal abroad: a case study of Finland and Sweden. World Nuclear Geoscience 37 (03): 250-256.
16. Pan, Z.Q. & Qian, Q.H. 2009. Strategic Study on geological disposal of high-level radioactive waste. 1th ed. Beijing: Atomic Energy Press.
17. Rao, G.W. 2018. Study on Characteristics of Surrounding Rock of High-level Radioactive Waste Geological Disposal Reservoir: A Case Study of Mudstone in the Upper Part of the BayinGobi Formation in the Preselected Area of Tamusu in Inner Mongolia. Dissertation. Nanchang: East China University of technology.
18. Reuss A. 1929. Berechnung der fließgrenze vom misch kristallen. Journal of Applied Mathematics and Mechanics 9:49-58.
19. Shu, L.S. 2010. Physical Geology. 3th ed. Beijing: Geological Publishing House.
20. Tiziana, V. & Manika, P. 2003 Amos Nur. Elastic properties of dry clay mineral aggregates, suspensions and sdnstones. Geophysical Journal International. 155(1): 319-326.
21. Voight W. 1910. Lehrbuch der Kristallphysik. 1th ed Leipzig: Teubner-Verlag.
22. Wan, C. 2018. A Dissertation Submitted to East China University of Technology for Master's Degree. Dissertation. Nanchang: East China University of technology.
23. Wan, C., Liang, H.A., Wang Y., Chen, Q. & Zhang J. 2017. Study on the Influence of Mineral Composition and Microstructure on the Mechanical Properties of Clay. Construction Quality 35 (06): 78-82 + 86.
24. Wang, J. 2019 Progress of geological disposal of high-level radioactive waste in China in the 21st century. Atomic Energy Science and Technology 53 (10): 2072-2082.
25. Wang, X.L., Han, Z.H., Zhang, L.Q & Zou, J. REGIONAL ENGINEERING GEOLOGY SUITABILITY ASSESSMENT FOR HIGH-LEVEL RADIOACTIVE WASTE DISPOSAL OF PRE-SELECTED ALXA AREA. Journal of Engineering Geology 26 (06): 1715-1723.
26. Wang, Y., Liang, H.A., Hu, Q.B., Cheng, H.K., Wan, C. & Xie, Z. 2018. Study on Correlation Between Mineral Composition and Elastic Modulus of Clay Rock in Tamusu. Chongqing Architecture 17 (03): 18-21.
27. Xiang, L., Liu, P.H., Liu, X.D., Liu, S. & Liang, H.A. 2018. Study on screening of favorable areas for high level radioactive waste claystone/mudstone disposal repository in Yingejing sag. China Sciencepaper 13 (21): 2499-2504.
28. Xue, K.X., Liu, S., Liu, X.D., Hu,Y.X., Tiwari, B., Wei, Y.Q. & Liang, H.A. 2016. Review of the Physical, Mechanical and Engineering Properties of Clay Rocks. Science Technology and Engineering 16 (16): 110-121.
29. Yuan, G.X., Zhang, L.Q., Zheng, Q.L., Huang, Z.Q., Li, J.Y., Wang, H.J & Deng, X.B. 2018. PREDICTION OF ROCK MASS QUALITY IN TARGET DEPTH FOR TAMUSU AREA OF ALXA PRE-SELECTED REGION FOR GEODETICAL DISPOSAL OF HIGH-LEVEL NUCLEAR WASTE. Journal of Engineering Geology 26 (06): 1690-1700.
30. Zhang, C.Y., Nie, F.J., Hou, S.R., Wang, J.L., Zhang, L. & Deng, W. 2015. Ore-Controlling Factors and Metalogenic Model of Tamusu Sandstone Type Uranium Deposit in Bayingobi Basin, Inner Mongolia. Bulletin of Geological Science and Technology 34 (01): 140-147.
31. Zuo, J.P., Chai, N.B., Zhao, C. & Liu, M. 2015. Investigation on the Relationship Between of Micro/meso Mineral Composition and Macro Mechanical Behavior of Moutougou Basalt. Journal of Basic Science and Engineering 23 (05): 97-106.