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

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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, officially approved the construction proposal of the underground laboratory for the geological disposal of high-level radioactive waste in Beishan, Gansu, marking the geological disposal of HLW granite in China has officially entered the underground laboratory stage (Wang, 2019). Clay rock has been recognized internationally as one of the alternative wall rock types for geological repositories of HLW due to its significant advantages in terms of low permeability, strong adsorption, and good self-healing ability. The research on geological repository of HLW clay rock host rock in China is in its infancy. Since 2014, 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

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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 rock during cementation, a new method for estimating the elastic parameters of Tamusu clay rock is established. 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.

$$E = \frac{9KG}{3\mathrm{K} + \mathrm{G}} \tag{1}$$

Table1 Summary of classical elastic parameters estimation methods at home and abroad

Elastic parameter estimation method	Meaning and explanation of formula
Estimation method of elastic parameters proposed by Voigt in 1910	$K_V = \sum_{i=1}^{N} K_i \bullet V_i$, $\mu_V = \sum_{i=1}^{N} \mu_i \bullet V_i$, *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 μ_V.
Estimation method of elastic parameters proposed by Reuss in 1929	$K_R^{-1} = \sum_{i=1}^{N} K_i^{-1} \bullet V_i$, $\mu_R^{-1} = \sum_{i=1}^{N} \mu_i^{-1} \bullet V_i$, *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 μ_R..
Estimation method of elastic parameters proposed by Hill in 1952	$K_{VRH} = \frac{1}{2}(K_R + K_V)$, $\mu_{VRH} = \frac{1}{2}(\mu_R + \mu_V)$, K_V and K_R are bulk modulus parameters obtained by Voigt and Reuss estimation methods respectively, μ_V and μ_R are shear modulus parameters obtained by Voigt and Reuss estimation methods respectively. K_{VRH} and μ_{VRH} are bulk modulus and shear modulus respectively.
Estimation method of elastic parameters proposed by Kumazawa in 1969	$K_{goom}=(K_R \times K_V)^{1/2}$, $\mu_{goom}=(\mu_R \times \mu_V)^{1/2}$, K_V and K_R are bulk modulus parameters obtained by Voigt and Reuss estimation methods respectively, μ_V and μ_R are shear modulus parameters obtained by Voigt and Reuss estimation methods respectively. K_{goom} and μ_{goom} are bulk modulus and shear modulus respectively.
Estimation method of elastic parameters proposed by Jianping ZUO in 2015	$K_{\mathrm{Zuo}} = \alpha K_V + \beta K_R$, $\mu_{\mathrm{Zuo}} = \alpha \mu_V + \beta \mu_R$, α, β 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, μ_V and μ_R are shear modulus parameters obtained by Voigt and Reuss estimation methods respectively. K_{Zuo} and μ_{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 er al., 2015; Guan et al., 2014). The upper member of the Cretaceous Bayin Gobi formation (K_1b^2) 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.

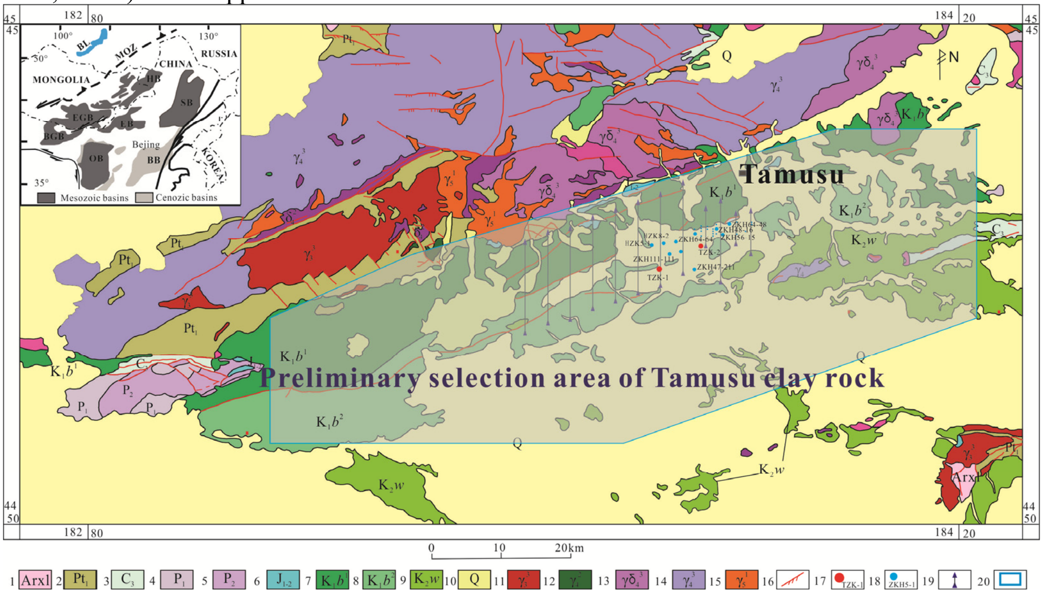


Fig1 Geological sketch of the pre-selected area of the Tamusu clay rock BB = Bohai Basin, EB = Erlian Basin, EGB = East Gobi Basin, HB = Hailar Basin, OB = Ordos Basin, SB = Songliao Basin,BGB = Bayingobi Basin, BL = Baikal Lake, MOZ = Mongol-Okhotsk Zone.
1. Proterozoic; 2. Archean; 3. Carboniferous System; 4. Lower Permian; 5. Upper Permian; 6. Lower middle Jurassic system; 7. Lower Cretaceous Bayingobi formation; 8. Upper section of the Lower Cretaceous Bayingobi formation; 9. Upper Cretaceous Wulansuhai formation; 10. Quaternary; 11. Late Caledonian granite; 12. Middle Variscan gabbro; 13. Late Variscan granodiorite; 14. Late Variscan granite; 15. Indosinian granite; 16. Crack; 17. Project team drilling; 18. Drilling by Nuclear 208 in China; 19. Seismic line-metry; 20. pre-selected area

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 $\leq 0.02°$, the test peak record 2θ angle is 5-70° and the Bruker-Diffrac EVA software was used for semi-quantitative mineral composition estimation.

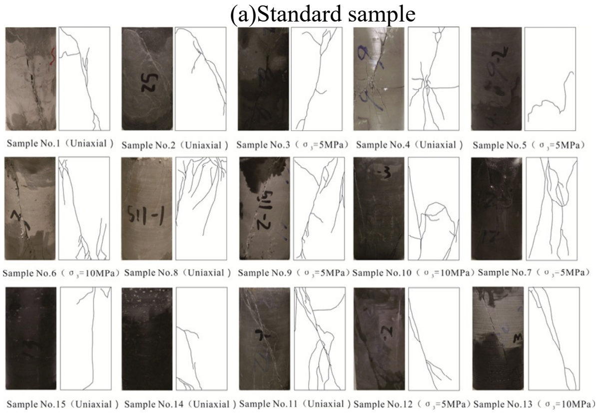
The observation experiment of the rock under the microscope were completed in the State Key Laboratory of Nuclear resources and environment. Selecting broken samples from mechanical testing and send them to Langfang Shangyi Rock and Mine Testing Technology Service Co Ltd to preparation of microscopic 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

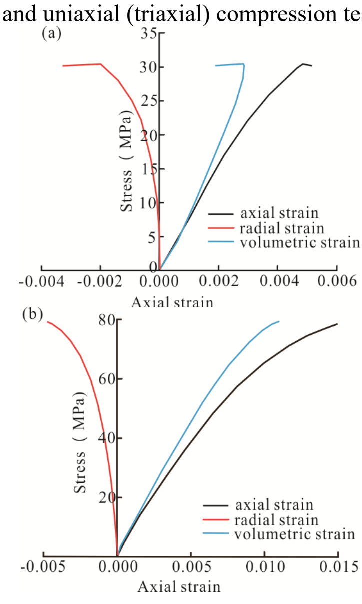
The photos of the clay rock standard samples in the Tamusu pre-selected area and their damaged state are shown in Fig 2. The results of indoor conventional uniaxial, triaxial 5 MPa and triaxial 10 MPa compression tests are shown in Table 2. The stress-strain curves of some rock samples are shown in Fig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

(a)Standard sample



(b)The state and sketch of the sample after destroy

Fig2 Failure diagram of Tamusu clay rock standard sample and uniaxial (triaxial) compression test



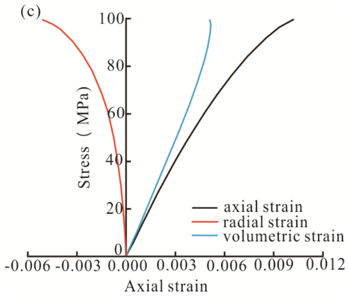


Fig3 Stress-strain curves of some clay rock samples in Tamusu: (a) The uniaxial stress-strain curve of sample No.1; (b) triaxial 5MPa stress-strain curve of sample No.12 at room temperature; (c) triaxial 10MPa stress-strain curve of sample No.13 at room temperature

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.

Table2 Results of uniaxial (triaxial) compression test of clay rock samples in the Tamusu pre-selected area

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

2	255.6	34.46	0.18	6.08	Uniaxial
3	263.5	56.48	0.17	5.65	Triaxial 5 MPa
4	303.2	35.51	0.19	7.79	Uniaxial
5	303.5	66.05	0.22	8.50	Triaxial 5 MPa
6	304.3	71.38	0.18	9.12	Triaxial 10 MPa
7	314.5	60.99	0.18	9.62	Triaxial 5 MPa
8	401.2	37.94	0.25	6.93	Uniaxial
9	401.5	56.98	0.17	8.23	Triaxial 5 MPa
10	401.9	60.94	0.18	9.64	Triaxial 10 MPa
11	403.4	61.56	0.19	10.27	Uniaxial
12	403.6	79.27	0.16	6.51	Triaxial 5 MPa
13	404.8	99.67	0.20	11.33	Triaxial 10 MPa
14	515.4	68.59	0.20	8.44	Uniaxial
15	685.6	81.91	0.23	8.45	Uniaxial

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.

Table 3. Main mineral composition and content of clay rock samples in the Tamusu pre-selected area(%)

Sample number	Quartz	Analcime	Montmoril -lonite	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	6.9	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	5.1	1.7	7.6	27
12	3.6	56.2	—	1.7	2.1	8.4	1.6	7.3	19.1
13	2.9	53.2	—	1.6	2.2	5.3	1.7	7.5	25.6
14	2	39.5	—	0.9	2.7	4.8	—	9.4	40.7
15	1.8	30.4	—	1.4	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.

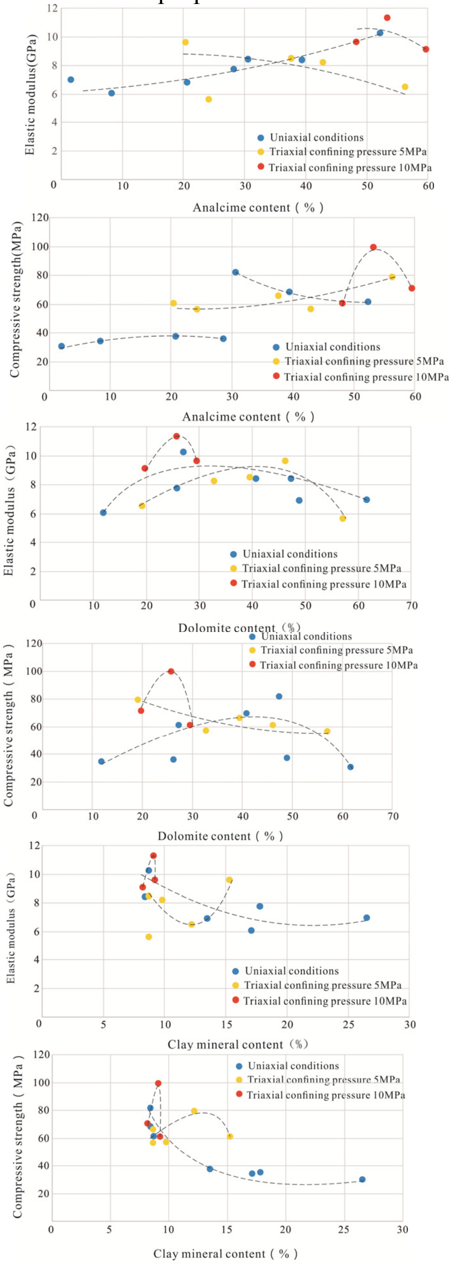


Fig4 Relationship between main minerals and macro-mechanics behavior under different conditions

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). 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).

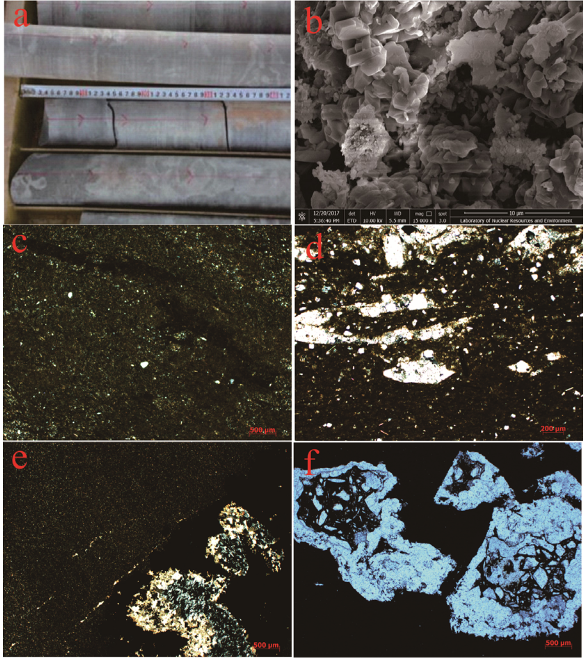


Fig5 Rock and mineral characteristics of clay rock in the Tamusu pre-selected area: (a) Clay rock drill cores in the Tamusu pre-selected area, showing horizontal bedding structures (signs of weak hydrodynamics); (b) Authigenic clay minerals with good self-shape under SEM; (c) Uniform and single argillaceous cement; (d) The secondary large edge structure of carbonate cement (calcite); (e) The cement grows vertically on the surface of the clastic particles in the form of fibers or short columns, showing a comb-like structure; (f) The coarse crystals formed by the crystallization of the cement enclose several dolomites to form an embedded crystal structure

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.

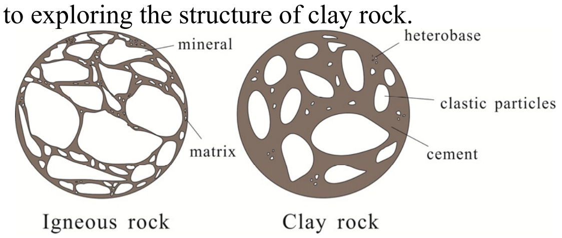


Fig6 Difference between igneous rock and clay rock in cement and matrix

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.

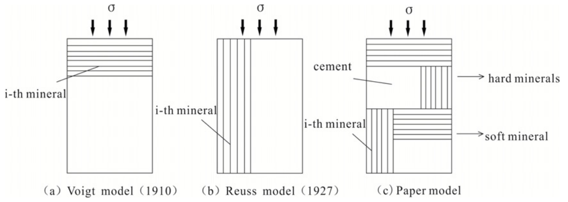


Fig7 Estimation model of rock elastic parameters

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 μ_N are the bulk modulus and shear modulus estimated by the clay rock evaluation method, α and β are the percentages of hard minerals and soft minerals in the entire rock, and γ is the proportion of cement. Table 4 shows the proportion of soft and hard minerals and the percentage of cement in each rock sample.

$$\begin{cases} K_{\mathrm{N}} = \dfrac{(\alpha+\beta)\times(K_V+K_R)}{2} \bullet \gamma \\ \mu_{\mathrm{N}} = \dfrac{(\alpha+\beta)\times(\mu_V+\mu_R)}{2} \bullet \gamma \end{cases} \tag{2}$$

Table4 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 elastic parameters of each mineral are shown in Table 5. Although chlorite is a clay mineral, it is listed separately because of its relatively high bulk modulus and shear modulus. Zeolite is a clay mineral, so analcime (a kind of natural zeolite) with relatively small bulk modulus and shear modulus is classified as clay mineral for analysis.

Table5 Basic elastic parameters of main minerals

Types of minerals	Elastic Modulus *E*/GPa	Poisson's ratio *μ*	Bulk modulus *K*/GPa	Shear modulus *G*/GPa
Clay minerals	12.66	0.27	9	5
Chlorite	72.90	0.35	81	27
Quartz	114.57	0.30	96.4	44.0
Dolomite	23.5	0.26	16.3	9.3
Calcite	68.8	0.31	74.4	26.3
Albite	69.0	0.28	57.0	27

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 5Mpa 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.

Table6 Comparison of the theoretically estimated elastic modulus (E) and the test result value (unit: GPa)

Sample number	Test value	Voigt method	Reuss method	Hill method	Kumazawa method	Jianping Zuo method	Experimental conditions
1	6.98	31.18	22.80	27.01	26.67	28.97	Uniaxial
2	6.08	54.00	31.34	42.74	41.17	50.15	Uniaxial
4	7.79	41.04	21.13	31.11	29.46	37.51	Uniaxial
8	6.93	33.81	21.44	27.64	26.93	32.26	Uniaxial
11	10.27	25.23	16.75	21.00	20.56	24.49	Uniaxial
14	8.44	26.17	18.19	22.19	21.82	25.50	Uniaxial
15	8.45	28.29	19.65	23.98	23.58	28.68	Uniaxial
3	5.65	27.64	20.14	23.89	23.60	26.99	Triaxial 5 MPa
5	8.5	28.65	18.65	23.66	23.12	27.78	Triaxial 5 MPa
7	9.62	35.46	21.72	28.61	27.77	33.37	Triaxial 5 MPa
9	8.23	28.29	18.02	23.16	22.58	27.28	Triaxial 5 MPa
12	6.51	24.83	16.02	20.44	19.95	23.76	Triaxial 5 MPa
6	9.12	24.72	16.05	20.39	19.92	24.01	Triaxial 10 MPa
10	9.64	26.13	17.22	21.69	21.22	25.32	Triaxial 10 MPa
13	11.33	25.06	16.59	20.83	20.39	24.29	Triaxial 10 MPa

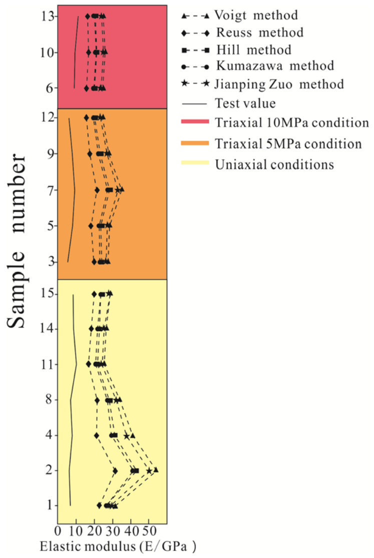


Fig8 Comparison of classical elastic modulus estimation methods and test value under different conditions

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 the proposed method are 7.16 and 10.96 GPa under normal uniaxial conditions, 8.76 and 10.04 GPa at normal temperature triaxial 5 MPa, and 10.43 and 12.13 GPa under normal triaxial 10 MPa conditions.

Table7 Comparison of theoretical estimation value and actual test value based on the proportion of clay rock cement(GPa)

Sample number	1	2	4	8	11	14	15	3	5	7	9	12	6	10	13
Experimental conditions	Uniaxial							Triaxial 5 MPa					Triaxial 10 MPa		
Actual test value	6.98	6.08	7.79	6.93	10.27	8.44	8.45	5.65	8.5	9.62	8.23	6.51	9.12	9.64	11.33
Theoretical estimate	7.16	7.31	8.83	7.43	10.96	8.76	7.29	5.76	8.87	10.04	9.91	7.4	12.13	10.43	11.08

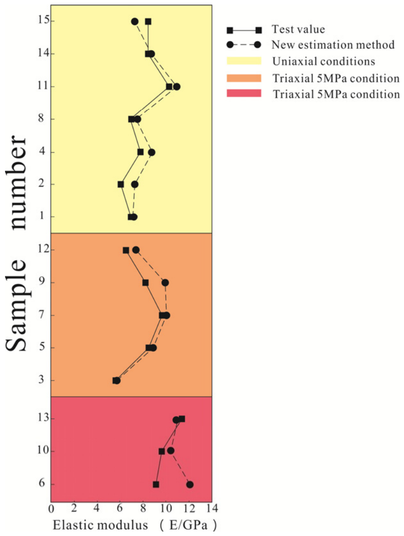


Fig9 Comparison of elastic modulus estimation methods and test value under different conditions

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.

Table8 The relative error between the estimation method of elastic parameters and the actual test value

	Under different test conditions		
Estimation methods of various elastic parameters	Uniaxial	Triaxial 5 MPa	Triaxial 10 MPa

Voigt method	146%~788%	237%~389%	121%~171
Reuss method	63%~415%	119%~256%	46%~79%
Hill method	104%~603%	178%~323%	84%~125%
Kumazawa method	100%~577%	172%~318%	80%~120%
Jianping Zuo method	138%~725%	227%~378%	114%~163%
The method of this paper	3%~20%	2%~20%	2%~33%

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.

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