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Study on Expansion Mechanism of Mudstone Under Structural Strength

Jingyu Liu [1,2], Qianli Zhang[2], Feng Chen[2], Taifeng Li[2]

[1]China Academy of Railway Science, Beijing 100081, China

[2]State Key Laboratory Of Track Technology Of High-speed Railway，China Academy Of Railway Science , Beijing 100081, China

cars-liujy@qq.com

Abstract. As the structural swelling soft rock, mudstone's expansion mechanism is similar to expansive soil, but it has its own particularity. In this paper, based on the analysis of the difference between the undisturbed and remolded samples of mudstone in terms of expansion and deformation, the expansion mechanism considering the strength of mudstone structure was proposed, and the verification test was designed. The following research results were obtained: In judging the potential of mudstone expansion, it is defective to rely solely on the free expansion rate, and its structural strength should be fully considered; The expansive force of mudstone is divided into the external expansive force resisting the external action and the internal expansive force resisting the interaction between internal particles. The external expansive force is the main reason of the increase of the volume of mudstone, and the internal expansive force is related to the cementation strength inside mudstone； The expansion theory based on free expansion rate, expansion force and uniaxial compressive strength is proposed.

1. Introduction

Mudstone, as a kind of textured sedimentary rock contains rich clay minerals, that more than 50% of particles is smaller than 63μm. According to the Code for Investigation of Geotechnical Engineering in China, mudstone belongs to the category of swelling soft rock. Because mudstone contains lots of hydrophilic clay minerals, the change of water content will cause a large volume change. Changes in the physical and mechanical properties of mudstone caused by water immersion seriously affect engineering safety, such as large deformation or even collapse of roadway. As the foundation of high-speed railway, slight volume expansion will cause embankment arch disease, which will seriously influence the operation of high-speed railway. Because China is one of the countries with the widest distribution of mudstone in the world, the study of mudstone has great practical engineering significance. Only by clarifying its expansion mechanism can we take appropriate measures.

Mudstone expansion is mainly divided into two categories, one is caused by the absorption of water by clay mineral. The other kind is caused by crystallized water which produced by the chemical reaction of sulphate mineral water absorption. The swelling mechanism of mudstone is expounded by Tan Ying-jie based on the theory of elastoplastic mechanics. He believed that the non-linearity of the volume expansion of mudstone was an important characteristic of the physical changes of the water absorption process, further more the changing law of elastic modulus(E) and internal friction Angle(φ) with water content(W) of mudstone was given, and a constitutive equation for nonlinear creep materials reflecting the effects of this change was established. Zhu Baolong explained the expansion

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from the perspective of the microscopic morphology, disintegration characteristics, interlamellar spacing and crystallite expansion force of mineral components. There were found that the clayization trend of the mudstone was significant, the microdisintegration was generate, the microporosity ratio was increased, and the interval of the mineral crystal lay was increased,which resulted in the expansion occurred after water immersion. G Anagnostou studied the effect of chemical reactions and ion migration on the expansion of sulphate-bearing mudstones, and he found that under the action of ion concentration gradient and ion diffusion, calcium ions and sulfate ions circulates through pore water. In the process of ion circulation and movement, dissolution of anhydrite and precipitation of gypsum occur simultaneously. K Serafeimidis established a strict anhydrite-gypsum-water thermodynamic equilibrium equation, proving that gypsum formation caused by water absorption of clay minerals is the main process of sulfate-bearing mineral mudstone expansion.

Mudstone contains the structural characteristics of both soil and rock. Under the condition of drying or natural moisture content, mudstone has a large structural strength, and its uniaxial compressive strength is 2MPa. However, when it exposed to water, it became softened and expanded, its strength decreased, completely disintegrated into mud. Due to mudstone is easy to disintegrate in case of water, the judgment of its expansion potential is generally based on the free expansion rate of its powder. This judgment ignores the influence of its structural strength on expansion, so it overestimates its expansion potential and cannot provide accurate reference for engineering construction. Nowadays, the study on the swelling mechanism of mudstone cannot explain the reason why only minor deformation occurs under the condition of high clay mineral content. Therefore, the study on the expansion mechanism of mudstone based on structural strength has important theoretical and practical significance for engineering design and construction.

2. Comparison experiment of expansion between rock original sample and remolded sample

The sample was taken from the red layer mudstone in Xinjiang province, China. The sampling method was geological drilling core sampling, and the sampling depth of the rock sample used in the test was 4 meters. The physical and mechanical parameters of the sample were shown in table 1, where in the uniaxial compressive strength was measured by the drying sample. The water content in table 1 was higher than the natural water content, which was caused by water drilling in the sampling process. The natural water content of the original sample was about 3%. Mineral composition was shown in table 2. Clay minerals were mainly smectite with a content of 25%.

Table 1 Physical and mechanical parameters of undisturbed sample

Depth m	Dry density g/cm^3	Moisture content %	Specific gravity of soil grain	Plastic limit %	Liquid limit %	Plasticity index	Free expansion rate %	Uniaxial compressive strength MPa
4	1.92	11.2	2.72	15.48	42.33	26.85	68	1.89

Table 2 Mineral composition

Quartz	Calcite	Gypsum	Anorthose	Microcline	Chlorite	Mica	Dolomite	Amphibole	Smectite
22%	20%	3%	16%	7%	4%	3%	-	-	25%

After drying 24 hours under 105℃, the mudstone was processed into 61.8mm×20mm ring cutter samples by angular grinder, as shown in figure 1. The rock debris generated in the grinding process was crushed and not screened (ensuring the same composition as the original sample), and remolded into ring cutter samples with a dry density of $1.8g/cm^3$(the maximum density that the remolded sample can achieve under dry conditions), as shown in figure 2. Choosing two flat rocks sample number for C, D, tow powder remolded sample number for C`, D`, to confine free expansion immersion test. Distilled water was used as experimental water to exclude the possibility of other factors. The test results were shown in figure 3.

Fig.1 Undisturbed rock samples

Fig.2 Remolded samples of mudstone

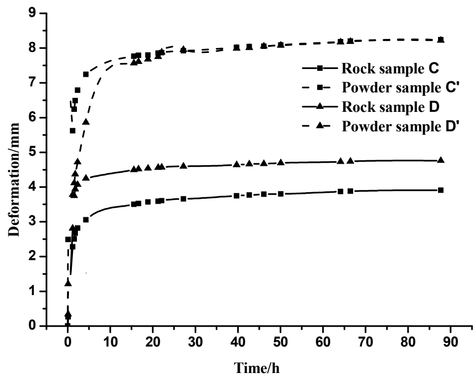


Fig.3 Free expansion test of side limit immersion

It can be seen from figure 3 that the expansion rule of the original rock sample was consistent with that of the remolded powder sample: Both of them expanded rapidly within the first 5 hours, slow down after 5 hours, was basically stable after 10 hours. The average expansion deformation of powder sample was 8mm, rock sample was 4mm. The dry density of powder sample was 1.82g/cm^3, rock sample was 1.92g/cm^3. With the same free expansion rate and mineral composition, the expansion of powder sample was greater than rock sample. The only difference between the two was that the original mudstone samples had certain structural characteristics, the powder samples were unstructured samples formed by compaction of loose particles. Therefore, the conjecture that the expansion mechanism of mudstone had a certain relationship with its structural characteristics was put forward, the test was designed and verified.

3. Verification experiment

3.1. Design of experiment

Pineda studied the internal structure of mudstone by environmental scanning electron microscopy (esem). He proved that clay matrix was loaded with large size minerals, there was a cementing relationship between high activity minerals and low activity minerals. The structural strength was mainly decided by the cementation strength between minerals. The verification experiment was designed based on this theory.

As shown in table 3, bentonite, standard sand and gypsum were mixed in a certain proportion to produce compacted samples with a dry density of 1.8g/cm^3, a size of 50mm×100mm and a size of 61.8mm×20mm. Different gypsum contents represents different cementation strengths. It can be seen from figure 4 that the uniaxial compressive strength of the sample increased linearly with the increase of gypsum content under a certain water content.

Table 3 Experiment group

Groups	Gypsum content %				Standard sand content %	Moisture content %
A	0	5	10	15	40	15
B	0	5	10	15	50	

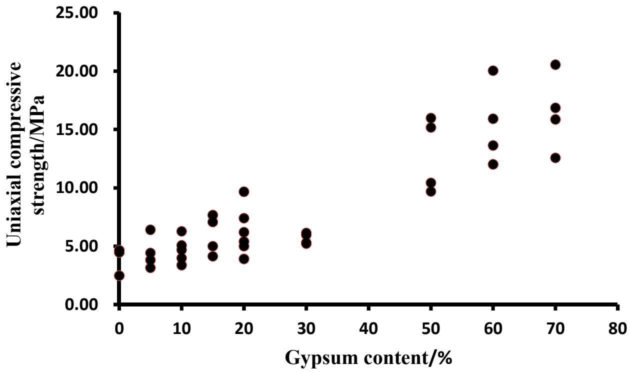


Fig.4 The relationship between uniaxial compressive strength and gypsum content

Table 3 shows the grouping situation of experiments. Two ring-cutter samples and two standard cylindrical samples were prepared for each ratio. After the sample preparation was completed, the samples were wrapped with plastic wrap and maintained in a constant temperature and humidity box for 3 days to ensure sufficient cementation of gypsum. After 3 days, the samples were taken out for uniaxial compressive strength test and lateral limit expansion test under different loads. The test instruments were MTS fatigue test instrument and consolidometer which were calibrated before use.

3.2. Experiment and result analysis

3.2.1. Strength experiment

The uniaxial compressive strength test was carried out on the MTS with the cured standard cylindrical sample, its strength-deformation curve was obtained, taking the 40% content of standard sand as an example, as shown in figure 5. The uniaxial compressive strength of samples with four gypsum contents was 3.9MPa, 3.1MPa, 2.2MPa and 1.2MPa, the strength increased with the increase of gypsum contents. For the samples with gypsum, the strength peak was reached around 2.5mm, while the strength peak of the samples without gypsum was around 5mm. The sample containing gypsum had a substantially uniform tangent slope before reaching the intensity peak, it was larger than the gypsum-free sample, which indicated that the elastic modulus of the sample became larger after the addition of gypsum, but it did not change with increasing content.

After the sample reached the peak strength, the strength droped rapidly, at which time the sample began to destroy and lost its structure. Therefore, uniaxial compressive strength of the sample was adopted to characterize its structural strength. The rock powder was obtained by drying and grinding the debris destroyed by strength test. After the powder was screened by 0.5mm sieve, the free expansion rate was tested to obtain its expansion potential.

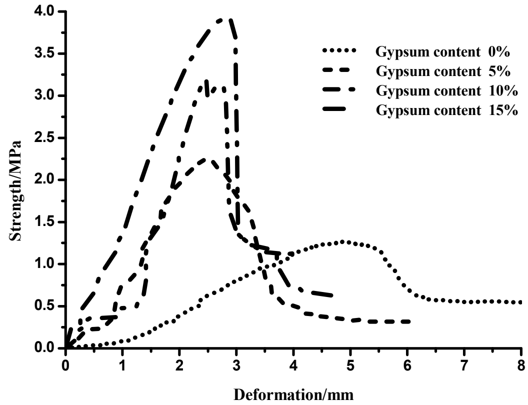


Fig.5 Strength-deformation curve

3.2.2. Expansion experiment

After the maintenance was completed, the ring cutter sample was installed on the consolidation instrument in accordance with the requirements of "Code for Soil Test of Railway Engineering". After 1kpa preloading, the initial reading was recorded, and distilled water was injected after the first level of load was applied. When the deformation was stable(less than 0.01mm every two hours), the expansion deformation value was recorded and the next level of load was applied. A total of four levels of loads (33kpa, 58kpa, 80kpa and 104kpa) were applied to each group of tests. At the end of the test, the swelling deformation under different load conditions was obtained by processing the data according to the calibration value of the consolidation instrument, and the swelling deformation curve was drawn, with 5% gypsum content as shown in figure 6. It can be seen from Fig. 6 that the expansion deformation was linearly related to the load and linearly fitted. The line correlation coefficient was 0.9668. According to the fitting formula, the corresponding load when the expansion deformation was 0mm was calculated, which was considered as the expansion force. The expansion force calculated in figure 6 was 392.44kpa, and the expansion force of other samples was calculated by the same method.

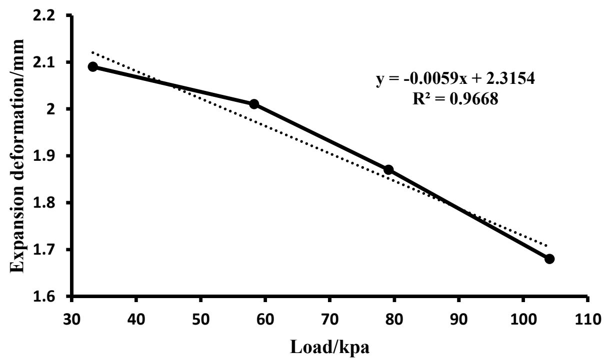


Fig.6 Expansion curve

In the whole process of the test, except bentonite, gypsum and standard sand, no other substances were doped. It was believed that the mineral composition of samples A and B was the same, and no other minerals affected the test results. As can be seen from figure 7, the lower the structural strength was, the greater the expansive force was. There was a certain negative correlation between the structural strength and the expansive force, the correlation coefficient can reached 0.78. The free expansion rate was an important indicator to determine the expansion potential. It can be clearly seen from figure 8 that there was no good relationship between the expansion potential and the expansion force. When the free expansion rate was about 100%, the expansion force can be distributed between 200kpa and 400kpa. It was unreasonable to judge the expansion potential of rock by the free expansion rate. For example, in figure 8, the expansion force of the two specimens with a free expansion ratio of 221.5% and 112% was 271.39kpa and 392.44kpa respectively. The reason why the free expansion rate was high but the expansion force was low, was because the strength of the sample was 6.4MPa, which was higher than the 4.4MPa with the free expansion rate of 112%. Therefore, the structural strength of the rock itself should be fully considered in the judgment of the rock's expansion potential.

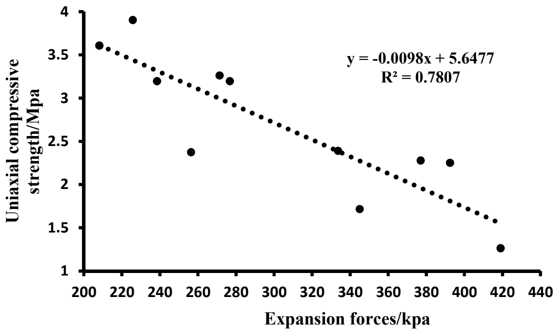


Fig.7 Expansion force-structural strength curve

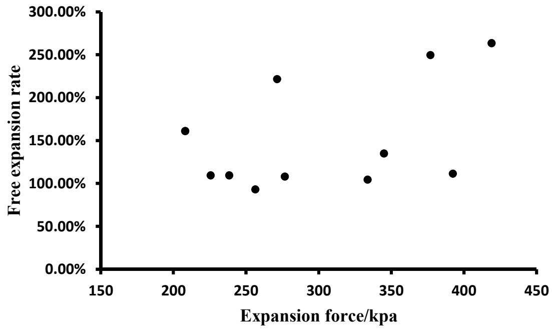
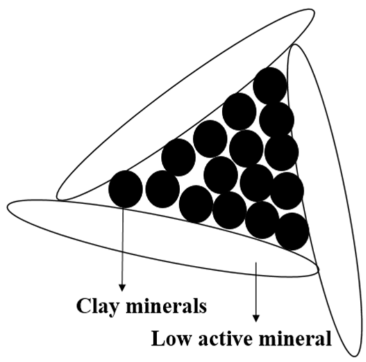


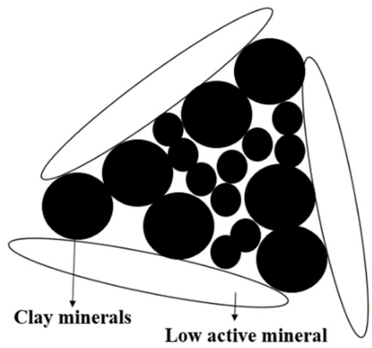
Fig.8 Expansion force-free expansion rate curve

4. Expansion mechanism

The swelling mechanism of mudstone under structural strength was proposed by combining the undisturbed sample test, powder sample test and verification test.



a. Natural state



b. Immerging state

Fig.9 The change of mudstone structure before and after water immerging

Mineral is precipitated in the pores of clastic sediments, in order to form authigenic minerals that will finally be solidified into rocks. As shown in a in Fig. 9, the connection between low active minerals in natural state mainly depends on the cementation of clay minerals. When the cementation is not destroyed, the strength of mudstone structure is high, and the stronger the cementation, the higher the intensity. After the mudstone was immersed in water, the clay minerals between the particles absorb water and cause an increase in volume, and the external force that resists such volume increase was called the external expansion force Py. Py is the expansion force obtained by all indoor or on-site water immersion tests, and it is also the force that can be released by the current expansion potential.

There is also a certain interaction between the particles inside the mudstone structure. From the state a to the state b in Fig. 9, the volume increase firstly overcomes the interaction between the particles, and the force generated by this process is called the internal expansion force Pn. The magnitude of Pn is related to the bond strength and can be characterized by uniaxial compressive strength, as in equation (1):

$$\mathrm{P}_n = \partial\sigma_c \quad (1)$$

Where ∂ is the structural coefficient, which is related to the cementation strength, obtained by experiment; is the uniaxial compressive strength (MPa).

The final expansion force released by the expansion potential should be the sum of the internal and external expansion forces, namely:

$$\alpha F_{\mathrm{s}} = P_y + P_n = P_{\mathrm{y}} + \partial\sigma_c \quad (2)$$

Where, α is the expansion potential coefficient (MPa), which is obtained through experiments. For the expansive soil, the cementation between the particles is weak and the structural strength is low, so the internal expansion force is small and often neglected. At this time, the force released by the expansion potential is equal to the external expansion force. However, for mudstones with obvious structural features, the structural strength is large, and the internal expansion force generated by the interaction between particles cannot be ignored. It can be seen from formula (2) that when the expansion potential is constant, the internal expansion force and the external expansion force are negatively correlated with each other, which is consistent with the conclusion of the verification test.

As a structural expansive soft rock, mudstone has a swelling mechanism similar to expansive soil, and it has its own particularity. After encountering water, the clay mineral molecules in the mudstone swell and generate expansion potential energy. First, within the mudstone, the expanded clay mineral molecules overcome the interaction between the particles and consume a part of the expansion potential energy; Secondly, the expansion potential of the remaining part continues to interact with the mudstone structure, resulting in an increase in the volume of the entire structure.

5. Conclusions

Based on the free expansion test of undisturbed mudstone sample and powder remolded sample, the expansion theory was proposed by considering the strength of mudstone structure in this paper. The following conclusions are mainly drawn:

(1) The expansion mechanism of mudstone is different from expansive soil. There are certain defects in the judgment of mudstone expansion potential through the free expansion rate of mudstone powder. The structural strength of mudstone should be fully considered in the judgment of mudstone expansion potential; There is a negative correlation between expansive force and uniaxial compressive strength when clay mineral composition is consistent.

(2) The mudstone expansion force is divided into an external expansion force against external action and an internal expansion force against internal particle interaction; The external expansion force is the main reason of the increase of mudstone volume, and the internal expansion force is related to the cementation strength inside of mudstone.

(3) The expansion theory is proposed based on free expansion ratio, expansion force and uniaxial compressive strength.

In the natural state, the mudstone fissures are mostly structural fractures, and the structural integrity is good. In the sampling process, secondary fractures will inevitably occur. The influence of the development of the fractures on the model remains to be further studied. Mudstone is mostly in a complex stress environment, and the mudstone expansion under different stress status should be studied in the later stage to correct and improve the expansion theory proposed in this paper.

Acknowledgments

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