The California Bearing Ratio and Pore Structure Characteristics of Weakly Expansive Soil in Frozen Areas

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Abstract: The California Bearing Ratio (CBR) of weakly expansive soil is specially relevant to its expansibility. The mechanisms affecting the bearing strength, in terms of the CBR, of weakly expansive soil that could be used as embankments filler are worth studying. In the present study, the effects of compaction energy on the compaction characteristics and CBR value were investigated. Additionally, the pore size distributions of soils with different compaction degrees were studied with nuclear magnetic resonance (NMR), and the effect of freeze–thaw cycles on the pore size distribution of soils with different compaction degrees was considered. Subsequently, the mechanisms influencing the CBR were analyzed at both the macroscale and microscale. A linear relationship between the CBR value and compaction degree was determined, characterizing the gradual variation of expansive soils with different moisture contents. With increasing freeze–thaw cycles, the volume of micropores decreased and mesopores increased, causing the CBR value to decrease. The expansion was a dominant factor for the CBR values. The CBR values rose with an increase in micropores and decreased with an increase in pore volume. It was considered that the tested weakly expansive soil could be used as an embankment filler in frozen areas.

Keywords: compaction characteristics; CBR; nuclear magnetic resonance; freeze–thaw cycles

1. Introduction

Compaction is considered as a technique for improving the engineering properties of soils, which reduces their permeability and increases their strength [1]. The maximum dry density and optimal moisture content of the soil in both earth filler dams and the foundation backfill for industrial and civil construction projects should be determined. The California Bearing Ratio (CBR) is a critical geotechnical parameter for determining the appropriate thickness of flexible pavements made from subgrade soil. The CBR test is the method most commonly used in developing countries for pavement design [2]. The compaction characteristics and CBR are important due to their implications in transportation construction. Under a given compaction energy, the relationship between the moisture content and dry density (the compaction curve) can be used to represent the compaction characteristics of the soils. The abscissa and ordinate of the peak point of the compaction curve represent the optimal moisture content and maximum dry density, respectively. In early studies, some theories were proposed to explain the compaction characteristics. Proctor [3] thought that water has a dual effect of suction and lubrication; as water increases, the suction decreases. Water also lubricates the particle interaction, giving rise to increased dry density up to the maximum.
Hogentogler [4] thought that soils undergo hydration, lubrication, swelling and saturation stages of wetting during compaction. Similar to Proctor, Hilf [5] proposed an explanation based on unsaturated soil theory. They thought that soil suction reduces with increasing moisture content. As soil reaches the optimal moisture content, air is trapped and cannot escape, as in the case of the dry density optimum. The compaction energy beyond this moisture content increases air pressure, thereby reducing the effectiveness of compaction and dry density. Many scholars proposed models to quickly determine the compaction curves according to massive data [6–8]. In the present research, scholars focused on the compaction and CBR characteristics of mixtures of soil and other materials [9–11]. However, as laboratory CBR tests are laborious and time-consuming, many attempts have been made in the past to predict CBR from simple physical properties such as plasticity index (PI) [12], liquid limit (LL), plastic limit (PL) [13], and strength [12].

The compaction degree $K$ ($K$ is defined as the ratio of dry density to the maximum dry density, as a percentage) of soils to be used as sub-base embankment fillers should exceed 90%, and the CBR value should be at least 3%. Expansive soil is characterized by swelling and shrinkage, over-consolidation and fissures, causing soil particles to be unstable with respect to one another. It is risky to use such material as the filler material when laying the foundations for highways, railways and other infrastructure. Expansive soils, especially strongly and moderately expansive soils, cannot be used directly as embankment fillers [14]. Over the past few years, scholars have tended to use various solid wastes as modifiers for expansive soils, such as lime [15], cement [16,17], fly ash [18], steel slag [19], and polymers [20]. However, these modifiers cause environmental pollution, are costly, and necessitate complex construction procedures. In certain situations (under hydrological conditions and for applications with lower strength requirements, such as for low-grade roads), weakly expansive soil can satisfy the requirements for use as an embankment filler [21]. In non-cold areas, weakly expansive soil can act as an embankment filler or even roadbed filler in scenarios where it is protected from water (e.g., in a closed-over setup with the expansive soil as a core filler, or with an expansive soil layer wrapped in a geomembrane). However, due to variations in geology and climate, significant differences exist between expansive soils in cold and non-cold areas. The applicability of weakly expansive soil as an embankment filler in frozen areas has rarely been reported. As infrastructure has developed, roads in seasonally frozen areas have inevitably had to cross weakly expansive soil, so its compaction and bearing strength characteristics should be studied in depth. The applicability of expansive soils as the embankment fillers in frozen areas should be explored.

Jiamusi in Heilongjiang Province is considered as a vital frontier city in China’s opening up to Russia, as well as an important node city in the development strategy for the land-sea silk road. Jiamusi has a mid-temperate continental monsoon climate, characterized by a long and cold winter and rainy summers. In the low mountains and hilly areas in the southern part of the city, the Cretaceous volcanic rocks are widely exposed, leading to the formation of montmorillonite-based weathered materials. They exhibit a relatively high liquid–plastic limit, obvious expansion, and contraction deformations; these pertain to a weakly expansive soil. As the “Belt and Road” has pressed ahead, and the need for infrastructure construction is rising, a growing number of roads should cross areas of weakly expansive soil. However, there is insufficient high-quality soil to replace expansive soil. In Jiamusi, a better quality (the plastic index of the weakly expansive soil is 16.2%) is found than that of other weakly expansive soils. The weakly expansive soil in this area was used directly without special treatment, but there is no reliable research to evaluate its accuracy. Thus, in terms of economy, convenience, and sustainable development, the applicability of weakly expansive soil in Jiamusi as an embankment filler should be further considered and rigorously studied. Moreover, the freeze-thaw cycles are considered a strong weathering process in seasonally frozen areas [22], which will remold soil structure when soils are exposed [23]. The freeze–thaw cycle effect should be constantly considered in seasonal frozen areas. The negative impact of freeze–thaw cycles on the behavior of expansive soils has been the subject of recent studies [24–27], whereas the CBR characteristic of weakly expansive soil in seasonally frozen areas as embankment filler and its change under repeated freeze–thaw cycles have not been reported. The soil microstructure is the significant
feature regulating the soil’s behavior at the macroscale. It is necessary to study the interaction of the microstructure and CBR value of compacted weakly expansive soil.

As described above, although achievements have been reported in CBR research, most of them focused on the evaluation, prediction and improvement of CBR value; analyses of the CBR mechanism of expansive soil are scarce. The characteristics of expansive soil mean that their CBR mechanism is different from that of other soils. However, few studies have been performed in this regard. Embankment refers to the foundation of the road bearing the vehicle loads; the stability of the embankment is important for driving safety. Considering economy and safety, the behavior of weak expansive soil acting as embankment fillers in frozen areas must be urgently studied. The main objectives of this study were to examine the applicability of expansive soil as embankment fillers in frozen areas through compaction and CBR tests, and to analyze the influence of freeze–thaw cycles on CBR values. More importantly, the study aimed to analyze the CBR mechanism of expansive soil. First, the relationship between deformation and CBR value was analyzed from the macro scale. Then, with the help of advanced nuclear magnetic resonance (NMR) technology, the relationship between pore structure and CBR value was microscopically analyzed. Lastly, according to the test results, the applicability of weakly expansive soil as an embankment filler was discussed.

2. Materials and Test Program

2.1. Materials

The soils were collected from Jiamusi, Heilongjiang Province, China. The soil is yellowish-brown, containing a small amount of black iron-manganese nodules. Table 1 lists its basic physical parameters. The liquid and plasticity limits for the soil were 43.8% and 27.6%, respectively. The free expansion rate $\delta = 55\%$. X-ray diffraction analysis was used to test its composition, and the principal clay minerals in the soil are listed in Table 2. The mineral composition, clay content, and free expansion rate of the soil all satisfied the ranges set out in the evaluation standards for expansion potential, so the soil was categorized as a weakly expansive soil.

| Properties                      | 43.8 | 27.6 | 16.2 | 2.67 | 24.8 | 55 | 5.8 | 54.2 | 40 |
|---------------------------------|------|------|------|------|------|----|-----|------|----|
| Liquid limit (%)                |      |      |      |      |      |    |     |      |    |
| Plastic limit (%)               |      |      |      |      |      |    |     |      |    |
| Plastic index (%)               |      |      |      |      |      |    |     |      |    |
| Particle density (g·cm$^{-3}$)  |      |      |      |      |      |    |     |      |    |
| In-situ moist content (%)       |      |      |      |      |      |    |     |      |    |
| free expansion rate (%)         |      |      |      |      |      |    |     |      |    |
| Grain size distribution (%)     |      |      |      |      |      |    |     |      |    |
| >0.05 mm                        | 5.8  |      |      |      |      |    |     |      |    |
| <0.05 mm                        | 40   |      |      |      |      |    |     |      |    |

Table 1. Basic physical parameters of tested soils.

| Mineral Content (%)               |          |          |          |          |          |          |          |
|-----------------------------------|----------|----------|----------|----------|----------|----------|----------|
| Quartz                           | 31       |          |          |          |          |          |          |
| Feldspar                          | 34       |          |          |          |          |          |          |
| Illite/Smectite                   | 18.9     |          |          |          |          |          |          |
| Montmorillonite                   | 8.4      |          |          |          |          |          |          |
| Illite                            | 6.3      |          |          |          |          |          |          |
| Kaolinite                         | 1.4      |          |          |          |          |          |          |
| Illite/Smectite Ratio             | 67.5     |          |          |          |          |          |          |

Table 2. Mineral composition of test soil samples.

2.2. Compaction Testing

The air-dried soil was used to prepare the compaction samples. The main preparation processes were as follows:
First, the soil was air-dried outdoors and passed through a 20 mm sieve after being pulverized with a hammer. Subsequently, the soil was mixed thoroughly. Lastly, the soils were sealed in a plastic bag for 48 h to ensure that the moisture distribution of the soil was uniform.

The moisture content of the air-dried soil was determined (the natural air-dried soil with a moisture content of 8%). Subsequently, the distilled water needed was calculated according to the initial moisture content, the designed moisture content. The distilled water was then evenly sprinkled on the soil using a spray bottle, stirring the soil meanwhile. The soils were then sealed in plastic bags for 48 h for moisture content homogenization.

The compaction tests were performed with a SKDJ-1 numerical control multi-function electric compactor. The soil was placed in three layers in a mold. Each layer received given blows from a rammer with a mass of 4.5 kg, which was dropped from a distance of 45 cm. The different compaction energies for each of the samples were determined by different hammer blow counts, i.e., 27, 36, 45, 59 and 98 hits. The excess from the last layer was then trimmed, and the total gravity was weighed to calculate the density. The compaction tests were performed according to the Standard for soil test method (GB/T 50123-1999) [28]. The details are presented in Table 3. The samples prepared are listed in Table 4.

### Table 3. Details of apparatus.

| Falling Hammer | Mold | Specimen | Cylindrical Rod |
|----------------|------|----------|-----------------|
| Diameter       | Weight | Diameter | Height | Height | Volume | Diameter | Length |
| 5 cm           | 4.5 kg | 15.2 cm  | 17 cm  | 12 cm  | 2,177 cm³ | 50 mm  | 100 mm |

### Table 4. The samples prepared for tests.

| Moisture Content (%) | 10.5 | 14.0 | 16.4 | 19.0 | 21.7 | 26.4 |
|----------------------|------|------|------|------|------|------|
| Hammer Blow Counts of Each Layer (hits) | 27, 36, 45, 59, 98 |
| Compaction Energy For Compaction Test (kJ·m⁻³) | 771.2, 1028.3, 1285.32, 1685.2, 2799.2 |

### 2.3. California Bearing Ratio (CBR) Testing

#### 2.3.1. CBR Testing for Compacted Soil

The samples used in the CBR test were the compaction samples obtained from the compaction test. The CBR tests were performed according to the Standard for Soil Test Method (GB/T 50123-1999) [28]. In this study, the CBR values were obtained by pressing a cylindrical piston into the soil. Before pressing the piston, the samples were soaked in the water containers for 96 h. First, the samples on the mold were placed onto a rigid porous plastic square board, and the mold and board were tightly linked. We then placed the samples into the water container before adding water. Subsequently, water was poured into the container from the bottom until the height of the water in the container was 25 mm higher than the top surface of the sample. It should be noted that there was a 50 N overhead mass on the samples during the soaking period. Moreover, a dial indicator was used to monitor the expansion of the compaction soils during soaking, as shown in Figure 1a. The cylindrical piston was penetrated into the soaked soil at a speed of 1 mm per min to a maximum penetration of 12.5 mm [29]. Figure 1b shows the CBR testing apparatuses. The CBR value (%) of each soil sample was calculated at penetrations of 2.5 mm by dividing the corrected load by the standard stress. Each experiment was conducted twice to ensure reproducibility. The samples prepared are shown in Table 4. As the compacted samples after the compaction test could be directly used for the CBR test, there were 60 samples in total.
2.3.2. CBR Testing for Soils under Different Freeze–Thaw Cycles

Roads in the seasonally frozen area will be subject to damage from the freeze–thaw cycles. The effect of freeze–thaw cycles on the CBR value was studied. Samples with a compaction degree of 90% (the dry density was 1656 kg·m$^{-3}$) and 100% (the dry density was 1840 kg·m$^{-3}$) were prepared. The moisture contents were 19% and 16.4% for samples with K = 90% and K = 100%, respectively. Note that the degree of compaction K is calculated as the quotient of the dry density of the sample to the maximum dry density obtained by the compaction test at a compaction energy of N = 98; the maximum dry density in this study was 1840 kg·m$^{-3}$. First, the samples were prepared according to the compaction test procedure. The samples were then sealed with plastic wrap, so that there was no increase in or loss of moisture. The samples underwent 0, 1, 2, 4, 6, 8, 10 and 12 freeze–thaw cycles (freezing at $-15^\circ$C for 12 h and thawing at 25°C for 12 h) in a temperature control box operating from $-40^\circ$C to 100°C. Lastly, the samples, after completing the corresponding freeze–thaw cycles, were placed in a water container for soaking, and then CBR tests (as described in Section 2.3.1) were carried out. The expansions produced during the immersion process were also measured. The samples prepared are listed in Table 5.

Table 5. The samples prepared for CBR tests under different freeze-thaw cycles.

| Moisture Content (%) | Compaction Energy (hits) | Compaction Degree (%) | The Number of Freeze–thaw Cycles |
|----------------------|--------------------------|-----------------------|---------------------------------|
| 16.4                 | 98                       | 100                   | 0,1,2,4,6,8,10,12               |
| 19                   | 27                       | 90                    | 0,1,2,4,6,8,10,12               |

2.4. Nuclear Magnetic Resonance Testing

2.4.1. Introduction to Nuclear Magnetic Resonance Testing

In this study, NMR technology was used to investigate the pore characteristics of the compacted expansive soil instead of the more common mercury intrusion porosimetry (MIP). NMR was considered beneficial because the size of the sample used in MIP is small (nearly 1 cm$^3$), meaning that the test result is significantly affected by the sample used in the test and that the results was widely dispersed, especially for heterogeneous soil (with cracks). NMR can test large-sized samples of 60 mm × Φ60 mm and does not damage the soil. It is capable of measuring the same sample multiple times, reflecting continuous changes in the sample’s microstructure. Nuclear magnetic resonance refers to a technology in which the nuclear spin in the low-energy state transitions to a high-energy state by absorbing the energy provided by a radio frequency (RF) field, and the energy change of the nucleus in the magnetic field provides information regarding the nucleus. The free decay curve of the nuclear magnetic signal (FID) was measured by considering that a group of protons with a spin moment in a uniform magnetic field deflects and loses balance under the interference of an RF magnetic field; the group of protons recovers from a non-equilibrium state to an equilibrium state.
when RF interference is stopped. Through Fourier transformation, the $T_2$ time distribution curve of the pore water in the soil samples could be generated. The peak area below the distribution curve represents the nuclear signal corresponding to the $T_2$ range, i.e., moisture content [30,31].

Next, the relaxation rates in soils were simplified as follows [32]:

$$\frac{1}{T_2} = \frac{1}{T_{2s}} = \rho_2 \left( \frac{S}{V} \right)_{\text{pore}}$$  \hspace{1cm} (1)

where $T_2$ is the lateral relaxation time of the water in the pores; $T_{2s}$ represents the surface relaxation time; $\rho_2$ is the surface relaxation coefficient which changes with the surface properties of rock and soil particles, especially the paramagnetic ions on the surface of the soil particles. $S$ is the surface area; and $V$ is the pore volume. Equation (1) can be written as Equation (2) based on the hypothesis that the pores in soils are cylindrical, based on research by Tian et al. [33].

$$\frac{1}{T_2} = \rho_2 \frac{4}{D}$$  \hspace{1cm} (2)

where, $D$ (µm) is the diameter of the pore. $\rho_2$ can be calculated with Equation (3) [34].

$$\rho_2 = (k_s \Phi^4 T_{2LM})^{1/2}$$  \hspace{1cm} (3)

where $k_s$ (µm²) is the permeability of the soil; $\Phi$ denotes the porosity of the soil, and $T_{2LM}$ (ms) denotes the weighted geometric mean value of the $T_2$ spectrum.

Next, the pore volume $V_i$ with a certain diameter is written as follows [35]:

$$V_i = \sum A_i \frac{m_w}{\rho_w} = \frac{\sum A_i (m_s - m_d)}{\rho_w}$$  \hspace{1cm} (4)

where, $A_i$ is the signal intensity at a certain $T_2$, $m_w$ is the mass of water, $m_s$ is the mass of saturated sample, and $m_d$ is the mass of a dry sample.

The nuclear magnetic resonance device applied in the present study was composed of a sample tube, a magnet unit, an RF system, a temperature-controlling system and a data acquisition and analysis system. To generate a stable magnetic field, the temperature of the magnet unit was set to 32 °C, with a variation of ± 0.01 °C [36]. The nuclear magnetic resonance device is illustrated in Figure 2.
2.4.2. Sample Preparation for Soil with Different Moisture contents

Sample preparation: The samples used for nuclear magnetic resonance testing were prepared by the following steps: (1) The expansive soil was first air-dried for about one week and then crushed with a hammer. Then, a 2 mm sieve was used to select the soils. The sieved soil was then humidified with distilled water to achieve the required moisture content. In order to make the water in the soil evenly distributed, the wetted soils were sealed in a plastic bag for 48 h. (2) The soils prepared in Step (1) were compacted by static compaction to the required degree. The diameter and height of the samples were 39.1 and 40 mm, respectively.

Samples with moisture contents of 10.5%, 14%, 16.4%, 19%, and 21.7% were prepared (the compaction degree of the samples was 90%) to analyze the effect of the initial moisture content on the pore structure of the expansive soil. To simulate immersion during the CBR test as effectively as possible, the apparatus and compacted soil were set up as presented in Figure 3. The bottom of the apparatus was a perforated acrylic plate, and the three steel molds were fixed with a steel ring, which resulted in no deformation in the circumferential direction. The upper part of the sample expanded freely. Note that the samples were wetted by immersing the sample in water in the CBR test, the rate of saturation of which was slower than that of the vacuum method. To simulate the state of soil in the CBR test, the immersion method was adopted to saturate the samples with different moisture contents, not the vacuum method. Similarly, the specimens were soaked in water for 96 h before the NMR test.

![Figure 3. The compacted soil and apparatus for saturating the samples.](image)

2.4.3. Sample Preparation for Different Compaction Degrees and Freeze–Thaw Cycles Test

To study the pore distribution characteristics of the samples with different compaction degrees, those with degrees of 80%, 90%, 95%, and 100% were prepared following the steps in Section 2.4.2. The initial moisture content of the samples was 16.4% (16.4% is the optimal moisture content). The specimens had a diameter of 39.1 mm and height of 80 mm. The samples were fixed with saturators and then put in a vacuum bucket, and the air in the bucket was extracted. Subsequently, distilled water was injected into the vacuum bucket until the samples were submerged, in which they were kept for at least 24 h.

Freeze–thaw cycles tests: A temperature control box was used to conduct the freeze–thaw cycles, which could regulate the temperature (−40 °C to +100 °C) and humidity (20–98%). The saturated samples were sealed with plastic wrap to prevent moisture loss. The soil specimens were frozen for 8 h at −15 °C and then thawed for another 8 h at 25 °C. This timing was chosen because the volumes of the specimens became constant after 8 h [26].
3. Results and Analysis

3.1. Compaction Characteristics and Pore Size Distribution

3.1.1. Compaction Characteristics

Figure 4 shows the relationship between the dry density and moist content under different compaction energies. Note that $V_a$ is the contour when the volume of gas in the soil is equal to zero. At the same moisture content, with increasing compaction energy, the maximum dry density increased, and the optimal moisture content decreased. Regarding the compaction curve, with an increase in compaction energy, the range of moisture content with a compaction degree greater than 90% increased. The relationship of the compaction degree $K$ with the compaction energy $N$ varied with the change in moisture content. As Figure 5a illustrates, the impact of the compaction energy on the development of dry density differed according to the moisture contents. Figure 5b indicates that when the moisture contents are less than the optimal moisture content, the compaction degree increases from 82% to 100% with an increase in compaction energy, with a large range of change; when the moisture contents are slightly above optimal (<3%), the compaction degree increases from 91.4% to 96.4% with an increase in compaction energy; this is a small change but satisfies the requirements of embankment compactness. When the moisture contents exceed the optimal content (>3%), the change in compaction degree with the increase in compaction energy is the smallest, and it remains below 90%.

![Figure 4](image1.png)

*Figure 4.* Compaction curves of samples with different compaction energies and moisture contents.

![Figure 5](image2.png)

*Figure 5.* (a) Curves of dry density and stroke numbers with different moisture contents; (b) curves of compaction degrees and stroke numbers under different moisture contents.
3.1.2. Pore-Size Distributions of Soils with Different Compaction Degrees

The pore size distributions of soils with different moisture contents are important for elucidating the characteristics of compacted soil. According to the experimental theory of nuclear magnetic resonance, and considering the reduction in CBR caused by harsh environments, the soil used for studying the pore size distribution by NMR should be saturated. However, expansive soil contains considerable hydrophilic clay minerals (e.g., montmorillonite and illite), which expand when absorbing water. Since the soil with the maximum dry density should be compacted at the optimal moisture content (the initial moisture content of compacted soil with different compaction degrees is 16.4%), the samples should be saturated before NMR testing; the volume will expand, causing the void ratio to become larger than sample in its initial state. Thus, it is necessary to modify the void ratio. Correction was performed by using a vernier caliper to measure the diameter and height of the saturated sample, making multiple measurements until the error fell within the allowable range. Subsequently, the void ratio was calculated and defined as the corrected void ratio. The void ratios before and after correction are illustrated in Figure 6. The void ratio of the saturated samples is obviously greater than the void ratio of the unsaturated sample, suggesting that soil swelled. The void ratio decreased with increasing compaction degree, suggesting the compaction degree of the saturated soil sample decreased. Note that the compaction degree used in this study was the compaction degree before saturation.

![Figure 6. The relation of void ratio e with compaction degree before and after sample saturation.](image)

The $T_2$ value reflects the pore sizes in the sample, i.e., water in large pores has a larger $T_2$ value and the water in small pores has a smaller $T_2$. The pore size distribution curve can directly and quantitatively represent the pore composition and distribution. The $T_2$ time distribution curves of samples with different compaction degrees are plotted in Figure 7, and the $T_2$ time distribution curve shows one to three peaks with an increase in compaction degree. To simplify the analysis, the pores of the Jiamusi expansive soil were classified according to $T_2$ value: the main peak corresponding to micropores, the Sub Peak 1 corresponding to mesopores, and the Sub Peak 2 belonging to macropores. It can be seen from Figure 7 that the main peak is prominent, and the subpeaks are small. The pore size distribution curves with different compaction degrees according to Equations (1)–(4) were calculated (Figure 8). The diameters of the micropores were reduced from 0.28–39.43 µm to 0.0047–0.25 µm, and the mesopores were decreased from 39.43–413.02 µm to 1.75–11.3 µm, suggesting that compaction significantly impacted the pore structure. The macropores of the soil with a compaction degree of 80% could reach 1mm, which might be attributed to fractures produced by damage in the test after saturation. The proportion of pores with different sizes is represented by the ratio of the area corresponding to the peak to the total area of the $T_2$ curve. The proportion of each peak for the samples with different compaction degrees is shown in Figure 9. The main peak of the samples with compaction degrees of 80%, 90%, 95% and 100% take up proportions of 0.77, 0.92, 0.96 and 1, respectively. The difference for soils with different compaction degrees was indicated in the
proportions of pores exhibiting different sizes. As the compaction degree increased, the proportions of mesopores and macropores decreased from 0.12 and 0.11 to 0, and the decrease rate of Sub Peak 2 is higher than that of Sub Peak 1, indicating that compaction significantly affected mesopores and macropores, performing better on macropores. However, it was not suggested that the mesopores were compressed after the macropores disappeared, and the mesopores and macropores were compressed at the same time, but the compression effect on the macropores was more significant. However, Delage [37] confirmed that compression in loose, low plasticity soils can be attributed to the progressive and ordered collapse of pores, starting from the largest existing ones and increasingly affecting smaller pores.

Figure 7. T$_2$ time distribution curves of samples with different compaction degrees.

Figure 8. Pore size distribution curves of samples with different compaction degrees.
3.1.3. Freeze–Thaw Cycles’ Effects on Soils with Different Compaction Degrees

Soil in frozen areas takes up more than 50% of China’s land area; the soil is repeatedly frozen and thawed due to temperature fluctuations. Previous authors have shown that the porosity increases under the effect of freeze–thaw cycles [38–41]. To ensure the stability and safety of the infrastructure in seasonally frozen areas, the freeze–thaw effect should be considered in construction in such areas. Soils with different compaction have different mechanical behaviors as induced by freeze–thaw cycles [42]. The compaction degree of embankment soil is generally greater than 90%. Thus, in the present study, samples with compaction degrees of 90% and 100% as described in Section 3.1.2 were studied; the effect of freeze–thaw cycles on the pore size distributions at different compaction degrees was investigated using NMR. The $T_2$ distribution curves of a loose sample ($K = 90\%$) and dense sample ($K = 100\%$) are presented in Figure 10. Under increasing freeze–thaw cycles, the mesopores and macropores increase, and micropores decrease. Figure 11 illustrates that the pore size distribution curve moves to the right, indicating that the freeze–thaw cycles increase the pore diameter. For loose samples, the diameter of the micropores increases from 0.0266–2.29 µm to 0.04–5.5 µm while the diameter of such increases from 0.0047–0.25 µm to 0.006–0.88 µm for dense samples. Obviously, the first freeze-thaw cycle significantly affected the pore diameter compared with the others. However, the increase in total pore volume was more significant than that in pore diameter for mesopores. The proportions of the peak area in the $T_2$ curve are shown in Figure 12. Since the proportion of Sub Peak 2 is significantly small, only the variations in the mesopores and macropores are discussed here. For the loose sample, under increasing freeze–thaw cycles, the proportion of the main peak gradually declined, from 0.92 to 0.85, while the proportion of the Sub Peak 1 increased, from 0.06 to 0.13. Under the number of cycles $N_{FT} < 8$, the proportion of the main peak decreased and Sub Peak 1 increased with an increase in $N_{FT}$; when $N_{FT} > 8$, the proportions of the two peaks varied slowly. For the dense sample, when $N_{FT} < 4$, the main peak took up over 0.99, and with an increase in freeze–thaw cycles, the proportion of the main peak slightly decreased and Sub Peak 1 increased; when $N_{FT} > 4$, the decrease rate of the main peak and the increase rate of sub peak 1 rises sharply. The proportion of the main peak was reduced from 0.99 to 0.96, and that of the Sub Peak 1 increased nearly 4 fold from 0.007 to 0.027. This accords with the results of Zhang and Bing [41], who reported that macropores are strongly affected by freeze–thaw cycles. In conclusion, dense soil has a small initial void ratio and small and evenly distributed pores, and it exhibits a stable structure that resists damage from the external environment, at the beginning of the freeze–thaw cycles. Accordingly, the freeze–thaw cycle slightly affects the soil structure. However, with a further increase in freeze–thaw cycles, the original structure of the soil varies significantly, the freeze–thaw cycles still significantly affect the pore structure when $N_{FT} = 12$. By contrast, for loose soil, the void ratio is large, and the effect of freeze–thaw cycles on the soil’s pore structure mainly occurs in the early stage of freeze–thaw cycles ($N_{FT} < 8$). The variation of the soil’s pore structure caused by freeze–thaw cycles is slight when $N_{FT} \geq 8$. 
Figure 10. T2 time distribution curves for soils with different freeze-thaw cycles.

Figure 11. Pore size distribution curves for soils with different freeze-thaw cycles.

Figure 12. Relationship between the proportion of the peak area ratio and freeze-thaw cycles.

The pore size distribution reflects the internal adjustment of the pore structure, and the void ratio is a parameter of the pore volume variation at the macroscale. The effects of freeze-thaw cycles on pore volume cannot be ignored. The curve of the void ratio vs. the number of freeze-thaw cycles is shown in Figure 13. It can be seen that the void ratio of the compacted sample increased with the number of freeze-thaw cycles, indicating that the freeze-thaw cycles increased the pore volume in the soil, in accordance with previous research results [43–45]. According to Figure 12; Figure 13, the freeze-thaw cycles had the same effect on the differently compacted soils. When \( N_{FT} < 4 \), there was a slight change in void ratio, which then gradually increased with further freeze-thaw cycles. Freeze-thaw cycles caused the proportion of micropores to decrease, while the mesopores increased. It is worth noting that the void ratio of dense soil increased more. After 12 freeze-thaw cycles, the void ratios of the soils with 100% and 90% compaction degrees increased by 27.5% and 18.3% in an obvious manner. This agrees with Yan [46], who reported that the void ratio of a lime, fly ash and loess mixture increased by about 14% after 10 freeze-thaw cycles. The possible reason is that in the
negative-temperature environment, the water in the pores of saturated soil varies from liquid to solid, thereby causing a change in pore structure and increase in void ratio. If the frost-heaving force is greater than the force between the particles, the expansion of the pores is promoted. Ye et al. [44] make the same point. Ye et al. also believed that the change in particle structure would stop when the frost-heaving force and transfer force were less than the structural strength of the soil. After four freeze-thaw cycles, sub peak 1 of the dense soil began to increase significantly, while the loose soil showed a more gradual change. The difference in the internal pore structure (moisture content, soil structure and pore water distribution) of soils with different compaction degrees caused the macroscale deformation behavior to perform differently faced with freeze-thaw cycles. Compared with loose soil, the soil particles of the dense sample were closely arranged; there was a smaller void ratio and pore size, contributing to the stability of the soil. At the beginning of the freeze–thaw cycles, the adjustment of the pore size distribution was small; with an increase in the number of cycles, the repeated phase change of water in the pores caused the soil pores to increase in number and size. There was space for the adjustment of the soil particles when the soil was loose. As a result, in the early freeze–thaw cycles, the pore size distribution varied, while the void ratio remained constant. However, further freeze–thaw cycles would cause an increased void ratio. When the cycles reached a certain number, the structure of the dense soil gradually approached that of the loose soil, and eventually, the void ratios of the soils with different compaction degrees became closer. Increasing the number of freeze–thaw cycles may lead to the same void ratios for both sample types.

**Figure 13.** The relationship between the void ratio and number of cycles $N_{FT}$.

### 3.2. Bearing Strength Characteristics and Effect of Freeze–Thaw Cycles

Figure 14 shows the CBR test results for Jiamusi expansive soil. To facilitate the analysis, the maximum CBR value under a certain compaction energy was defined as $CBR_{max}$, and the moisture content at the $CBR_{max}$ was defined as $w_{CBR}$. The $CBR_{max}$ and $w_{CBR}$ under different compaction energies are listed in Table 6. It was observed that the $w_{CBR}$ could be divided into two parts according to the compaction energy: ① when the compaction energy was large ($N = 98$), $w_{CBR}$ was 5% higher than the optimal content; ② when the compaction energy was smaller ($N = 59, 45, 36, 27$), $w_{CBR}$ was 3% higher than the optimal moisture content. The CBR values were related to the moisture content in an obvious manner. When $w < w_{opt}$, the CBR values of the Jiamusi expansive soil were less than 3%. At the given moisture content of $w_{opt} \leq w < w_{opt} + 2.6\%$, the CBR values ranged from 3% to 5.2% with the variation of compaction energy; when $w = w_{opt} + 2.6\%$, the CBR values were greater than 5.3%, which could be 6.8% under large compaction energy; when $w_{opt} + 2.6\% < w \leq w_{opt} + 5.3\%$, the CBR value was at least 5%, and the CBR values even reached 6.4% under a compaction energy $N$ of 98.
Figure 14. Curve of CBR values and moisture contents under different compaction energies.

Table 6. Peak CBR values CBRf and corresponding moisture contents under different compaction energies.

| Compaction Energies/Hit | w_{opt}/% | q_{dmax}/(g\cdot cm^{-3}) | CBRmax/% | w_{CBR}/% | Compaction Degree/% |
|-------------------------|-----------|---------------------------|---------|-----------|--------------------|
| 98                      | 16.4      | 1.84                      | 6.44    | 21.7      | 100.00             |
| 59                      | 16.4      | 1.79                      | 6.18    | 19.0      | 97.28              |
| 45                      | 16.4      | 1.76                      | 6.76    | 19.0      | 95.65              |
| 36                      | 19.0      | 1.73                      | 6.28    | 19.0      | 94.02              |
| 27                      | 19.0      | 1.69                      | 5.31    | 19.0      | 91.85              |

Figure 15 plots the curve of the CBR values and compaction degrees K. For the samples with lower than optimal and optimal moisture content, there was a wide range of compaction, depending on the compaction energy. It is interesting to note that the more than optimal and optimal moisture content samples had higher CBR values at the same degree of compaction than the samples with lower moisture content. Since the moisture contents were less than, equal to, and greater than the optimal moisture content, three different straight lines could be fitted. A regression analysis of the three moisture content categories yielded the following equation with a high degree of correlation:

\[
\text{CBR} = 24.77K - 16.85 \quad R^2 = 0.83 \quad 19\% \leq w \leq 26.4\%
\]

\[
\text{CBR} = 8.50K - 4.94 \quad R^2 = 0.84 \quad w = w_{opt} = 16.4\%
\]

\[
\text{CBR} = 9.45K - 6.83 \quad R^2 = 0.97 \quad 10.5\% \leq w \leq 14\%
\]
Based on engineering use and exploratory research, the CBRs of the samples with optimal moisture contents and contents corresponding to the maximum CBR values under different freeze–thaw cycles were studied. The samples with \( K = 100\% \) and \( K = 90\% \) were used in this part; the moisture contents of the samples with \( K = 100\% \) and \( K = 90\% \) were 16.4\% and 19\%. The results revealed that the CBR value decreased with an increasing number of freeze–thaw cycles, as shown in Figure 16. It is interesting that the CBR value of the sample with a compaction degree of 90\% was greater than that of the sample with a compaction degree of 100\%. This could be attributed to the larger expansion strain of the latter, as explained in the following Section. For the sample with the optimal moisture contents, the CBR value decreased from 3.65 to 3.06. Notably, the CBR value decreased from 5.3 to 4.75 for the sample with a moisture content of 19\% and \( K = 90\% \), after 12 cycles. Therefore, it is indicated that the freeze–thaw cycles could cause a loss of strength, while the CBR value would still reach 3\%. Accordingly, weakly expansive soil could be used as an embankments filler. Moreover, it can be concluded that with a moisture content slightly above the optimal, weakly expansive soil could exhibit higher bearing strength and stability, even at a low compaction degree.

4. Discussion

4.1. Mechanistic Analysis of CBR at the Macroscale

Ma et al. [1] conducted CBR tests on loess with different compaction energies and moist contents. The results showed that the water sensitivity was strongly related to the mineralogy and microstructure of the compacted loess. It was recommended to avoid compact soil with extremely
low moist content. For a given compaction energy, the samples with a lower moisture contents expanded more after immersion in water, resulting in more strength loss when soaked in water. Kong et al. [47] studied the bearing mechanism of weakly and moderately expansive soils in the Jingmen area; they supposed that the CBR value depended on the water content, dry density and structural state after the soaking expansion of the compacted expansive soils. However, the mechanisms influencing the CBR of expansive soil were less analyzed. Yu et al. [48] believed that the CBR characteristics of expansive soil were determined by its air and water states of expansive soil under different saturation conditions. These studies analyzed the mechanism of CBR to a certain extent, but CBR is related to the type of soil. The specificity of expansive soil means that its CBR mechanism is different from that of other soils. The increase in volume of expansive soil after absorbing water is the most intuitive aspect that affects the CBR value. Therefore, this paper attempted to explore the effect of expansibility on the CBR value.

The CBR value refers to the ratio of the force per unit area required to penetrate the sample with a standard piston to that required for corresponding penetration in a standard material. In this study, the bearing ratio at 2.5 mm penetration was adopted. Expansive soil swelled upon absorbing water [49–51]; the structure of the expanded soil was loose, which would significantly reduce its strength. In the immersion process during the CBR tests, the soil swelled upon immersion in water. There were restrictions on the bottom and sides of the sample, so only the top could deform. Due to the expansion, it gradually weakened from the top to the bottom, and because of the low permeability of the soil, the soil on the top exhibited the weakest strength with the largest amount of expansion. In the penetration process, the penetration piston is pressed into the top swelled soil; a schematic of the process is shown in Figure 17. The CBR was affected by the expansion of sample, especially for the compacted samples with low moisture contents. This could be verified from the curve of the relationship between the CBR value and expansion strain (the expansion strain is the ratio of expansion deformation to the height of the unsaturated sample), as Figure 18 shows. Under an expansion strain greater than 6%, the CBR values were less than 3%. From Figures 15, 18 and 19a, it can be concluded that the CBR values were affected by the compaction degree and expansion. Given a moist content of $w \leq w_{opt}$, the samples manifested large expansions and low CBR values. In this case, the CBR values of the samples were mainly controlled by the expansion; for samples with moisture contents of $w_{opt} < w \leq 26.4\%$, the expansion measured in the CBR tests were slight, and the compaction degree had an obvious effect on CBR. This could explain why the CBR value of the soil sample with a 26.4% moisture content (small compaction degree) was small, while the expansions were slight. This can also be verified from the expansion strain and CBR value of the compacted soil subjected to freeze–thaw cycles; the CBR value decreased linearly with an increase in expansion strain (Figure 19b). Note that the attenuation amplitude of the CBR value with an initial moisture content of 16.4% is greater than that with a moisture content of 19%. This may be because the expansion of a sample with a low initial moisture content is greater after immersion, and soil with a high compaction degree is more sensitive to freeze–thaw cycles, increasing the damage to the soil.

![Figure 17. Schematic diagram of penetration process.](image-url)
4.2. Mechanistic Analysis of CBR at the Microscale

The expansion deformation of expansive soil is the macroscopic behaviors which affect the CBR, and explains the CBR characteristics of expansive soil to a certain extent. However, the microstructure is considered a vital aspect of in the study of soil, and the macroscale mechanical behavior is affected by the performance of the microstructure. Thus, this paper tries to explain the CBR mechanism of expansive soil from the viewpoint of pore structure based on an NMR test for the first time. The compaction tests show that in the moisture content range of 10.5%–21.7%, the compaction degree can reach 90% with a change in the compaction energy. As discussed above, the CBR is related to the strength of the soil penetrated by the piston. The depth of penetration is slightly greater than 5 mm; soil is saturated and even supersaturated at this depth. The pore structure of the soil at the top of the compacted sample may reflect the actual situation. However, it is hard to determine the pore structure of soil at 5 mm; because it is damaged when removing the soil block used for the NMR test from the sample obtained in the compaction tests. Therefore, small samples (H = 40 mm, D = 39.1) with different initial moisture contents under the same degree of compaction were prepared. The immersion process for the CBR test was then simulated. Subsequently, NMR was conducted on the immersed samples. The test results verified that expansion significantly impacts the CBR value. Figure 20a presents the results obtained by NMR. At the same degree of compaction, the main peak moved upward and the Sub Peak 1 moved downward as the moisture content increased, indicating that the micropores increased and the mesopores decreased, respectively. According to the data shown in Figure 20b, the pore volume of the micropores increased and the pore diameter decreased with an increase in moisture content. The CBR values of the sample with the same compaction and moisture contents in the NMR tests were used. By fitting the experimental data, a linear relationship
between the CBR values and total areas of the $T_2$ distribution curves as well as that between the CBR values and proportions of main peaks, is observed in Figure 21. It is indicated that the CBR value of expansive soil is closely related to the pore distribution which is the dominant factor for the bearing strength. The different expansions caused by various initial moisture contents lead to the differences in pore structure characteristics, which, in turn, affects the bearing strength.

![Figure 20](image_url)

**Figure 20.** (a) $T_2$ time distribution curve for soil with different initial moisture contents. (b) Curve of pore volume and pore diameter of soil with different initial moisture contents.

![Figure 21](image_url)

**Figure 21.** The relationship between the CBR values and total areas of the $T_2$ distribution curve, and that between the CBR values and proportions of the main peak.

In fact, the weakly expansive soil in the non-cold regions of China, such as that in the Baise area [52] and along the Xiang-Jing and Han-Shi expressway [53], has been considered for use as an embankment filler. However, the compaction and CBR value according to the data are insufficient for soil in cold regions. For an upper embankment filler, the CBR values must be greater than 3%; for the lower embankment, they must be greater than 3% for highways and greater than 2% for low-grade highways, according to the Specifications for Design of Highway Subgrades (JTG D30-2015) [54]. The CBR values in this study were all measured on soaked samples. As described, the soaked samples exhibited the lowest bearing strength. The results show that the bearing strength of the soil after immersion in water compacted at the maximum dry density, could still satisfy the requirements for an embankment filler, even after 12 freeze–thaw cycles. The buried depth of the embankment was 0.8m below ground, demonstrating that the expansive soil would not be directly exposed to the environment, and complete flooding and no-load freeze–thaw cycles will be rare. All of these factors contribute to the stability of expansive soil. When the moisture content was slightly greater than the optimal for use as filler, the expansive soil exhibited a higher bearing capacity before and after the freeze–thaw cycles. Thus, weakly expansive soil exhibited enough strength to be used as an embankments filler in a seasonally frozen area.
5. Conclusions

The compaction characteristics and California Bearing Ratio of weakly expansive soil were studied. The pore size distributions of samples with different compaction degrees were determined by NMR; at the same time, the effect of freeze–thaw cycles on the pore size distribution and CBR value was studied.

(1) Based on compaction tests conducted on Jiamusi weakly expansive soil with different moisture contents and compaction energies, it was found that the moisture content corresponding to the maximum CBR value was greater than the optimal moisture content. At the same degree of compaction, the CBR values of the samples with moisture contents above and at the optimum were higher than the CBRs of the samples with lower moisture content. According to whether the moisture content was less than, equal to, or greater than the optimal, three different straight lines could be fitted to describe the change in CBR with compaction. As the number of freeze–thaw cycles increase, the CBR value decreases slightly. After 12 freeze–thaw cycles, the CBR values of the samples with 19% moisture contents and 90% compaction degree decreased by 16%, and the CBR values decreased by 10% for the samples under 100% compaction degree with 16.4% moisture contents.

(2) The mechanism affecting the CBR was analyzed at the macroscale and microscale. From the macroscale perspective, the bearing strength of expansive soil is mainly affected by the expansion and dry density. If the moisture content is slightly greater than optimal, Jiamusi weakly expansive soil has a small expansion strain after immersion (less than 0.83%) and large CBR value. However, too much moisture makes the dry density too low, resulting in a small CBR value, even when the expansion is small. From the microscale perspective, soils with small expansions have more micropores according to the results obtained by NMR. After the freeze–thaw cycles, for the soil with K = 90% and w = 19%, the expansion increased by 65% and the CBR decreased by 10%; the expansion increased by 86% and CBR decreased by 16% for the soil with K = 100% and w = 16.4%. The freeze–thaw cycles decreased the CBR value, because they increased the pore volume. Soils with larger pore volumes experienced greater expansion after being soaked in water.

(3) When subjected to freeze–thaw cycles, soils with different compaction degrees behave differently. When $N_{FT} < 4$, there was little change in the pore size distributions and void ratios of the dense soil. Until $N_{FT} \geq 4$, the pore structure of the soil varied significantly. Space was provided for the adjustment of the soil particles when the soil was loose, causing the pore size distribution to vary in the early freeze–thaw cycles, whereas the void ratio remained constant. For the dense sample, after 12 freeze–thaw cycles, the void ratio and pore size distribution still did not reach a stable state, while the pore size distribution reached a new equilibrium state for the loose sample after eight freeze-thaw cycles.

(4) This study investigated the road performance of weakly expansive soil as an embankment filler under the most unfavorable conditions (e.g., water immersion and freeze–thaw cycles). As suggested from the results, it can sufficiently satisfy the requirements. Compared with the optimal moisture content, the content corresponding to the maximum CBR value can result in higher strength that is better maintained over 12 freeze–thaw cycles.

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