Influence of Moisture Content and Dry Density on the Compressibility of Disturbed Loess: A Case Study in Yan’an City, China

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Abstract: Loess is a kind of soil that experiences a long period of deposition, and it is relatively stable under natural conditions. However, in the process of engineering construction in loess areas, the original soil structures of the loess are destroyed, inducing changes in the composition and water content in the loess. These changes may cause different environmental and engineering geologic problems. To reveal the engineering properties of disturbed losses in the Chinese Loess Plateau, the physical properties of 135 groups of disturbed loess samples in Yan’an City were analyzed statistically, and the compression properties of loess with different moisture contents and dry densities were studied by high-pressure consolidation experiments. We elucidate the compressive deformation law for perturbed solids at different moisture contents and dry densities. The experimental results show that the water content rate for the best compaction performance of the disturbed loess is 16%. The compressive deformation coefficient generally decreases with increasing dry density and water content. However, when the soil moisture is low, a small amount of water and salt is concentrated in the contact position of the powder, and the soluble salt is condensed into cement. The molecular forces between particles and the bonding forces of bound water and capillary water are larger. The soil forms a porous structure with coarse grains as the main skeleton, and the cement bonding strength is strong at the contact points of the coarse grains. As a result, the loess shows high intensity at low-water content. This results in a compression-deformation coefficient that increases with dryness density in the small load range.

Keywords: disturbed loess; consolidation test; compressibility index; remolded soil; moisture content

1. Introduction

With the population growth and society development in the Loess Plateau region, the construction of regional towns accelerated [1]. There are increasingly more engineering constructions in the Chinese Loess Plateau region. The Loess Plateau has a unique topography that is known as “thousands of gullies and ravines”. Its soil is relatively loose. Large areas of loess tableland, girders, and ridges were formed after intense erosion by different surface runoff [2,3]. These gully landforms on the Loess Plateau severely limit population and social development. To address the problem and promote rapid development in the northwest, Yan’an and other cities in China’s Loess Plateau have carried out large-scale mountaintop removal projects to create flat land for urban construction [4]. Consequently, engineering perturbations to loess are common in loess regions. During construction, the original structure of the loess body was destroyed. The compaction of disturbed loess can cause engineering problems such as ground cracking and slope instability [5]. These engineering disasters and geological problems are closely related to moisture in loess [6,7].
Therefore, an in-depth study of the effect of the moisture content on the compaction effect in loess disturbed by engineering construction is of particular importance.

Soil compaction is the process of compacting soil particles to a tighter consistency by manual or mechanical compaction at certain moisture contents [8]. The compressibility of soil refers to the property that the volume of the soil decreases under pressure. Soil compaction can be affected by many factors, such as soil composition, the surface structure of soil particles, and water content [9,10]. Usually, for soils under a certain amount of external pressure, the main factor affecting the degree of compaction is the water content [11]. According to previous research results, when the water content is low, the soil can retain a relatively loose condensed structure due to the gravitational force between the particles. Most of the pores in the unsaturated zone are interconnected and have less water and more air [12–14]. When the moisture content in the loose soil is low, the film lubrication of the strongly bound water forming on the surface of the soil particles is weak at certain external pressures [15], and the relative motion between the soil particles is negligible, which may lead to poor compaction. Moreover, in the presence of the gravitational force among the soil particles, the motion of the soil particles is not significant, resulting in poor compaction of the soil [16]. However, when the water content gradually increases, the water film on the surface of the particles becomes thicker [17]. There is also a corresponding increase in lubrication between soil particles. This results in less friction between particles, easier movement of soil particles, and enhanced compaction effects. As the water content increases, the amount of free water gradually increases in the soil, resulting in an increase in the volume of the pores in the soil and a corresponding decrease in the dryness density [18,19].

A number of studies have investigated the compaction properties of loess. Liu et al. [20] studied the mechanical properties of saturated loess and divided the saturated loess into two categories. The first category is the strongly collapsible loess which is not fully compacted by the long-term overlying pressure. This kind of loess will lose its collapsibility and will have high compressibility after it is soaked (moisture content higher than 80%). When its water content is again reduced to less than 70%, the collapsibility of the loess can be restored to some extent, as most of the pores remain relatively intact. This kind of soil is often in the state of soft plasticity to flow plasticity with low bearing capacity, so this kind of loess is often called “soft loess” [21]. The other category is saturated loess, which was formed long time ago. After sufficient compaction by the overburden pressure, the porosity and compressibility of the loess are completely altered. Even if its water content is restored to less than 70% in the future, its capacity will not be restored. Lei et al. [22] obtained the compression deformation rule of saturated loess with a dry density of 13.42 kN/m$^3$ through a consolidation test. Delage [23] investigated the orderly collapse of compressible pores in loose soils by studying the microstructure changes of clay from Canada during compression. Through a triaxial test on natural loess, Jiang et al. [24] found that loading could cause significant changes in the pores between aggregates but could not change the pores in the aggregates. Perisic et al. [25] conducted indoor compression research on diatomaceous soil and found that the yield stress of diatomaceous soil was much higher than the overburden stress, and it had high compressibility and produced obvious creep strain. The discovery of diatomaceous soils is likely due to the large number of crushed frustules and is significantly more compressible than fine soils of similar geotechnical classification. Thanks to the studies carried out by previous researchers, the hydrodynamic properties and microscopic mechanisms of loess compaction have become fairly well understood. However, little is known about the effect of water content on the properties of compacted disturbed loess, as the water–soil interaction involves both chemical and mechanical processes, which are quite complex. Therefore, relevant experimental studies and analyses are urgently needed. By comparing the physical properties of naturally deposited loess and compacted loess, Zhang et al. [26] found that the liquid limit, plastic limit, plasticity index, clay fraction, silt fraction, sand fraction, and compression modulus of the compacted loess were smaller, and it was more prone to deformation under external forces.
Loess was formed in a semi-arid climate environment, and most of it exists in an unsaturated state in nature. It has strong structural characteristics, high sensitivity to water, and will experience significant changes in compressibility while in contact with water. The compressibility of loess is affected by many factors, such as water content, dry density, structural configuration, particle size distribution, and load intensity. However, considering the water sensitivity and collapsibility of loess, as well as the importance of dry density in engineering applications, this study focuses on the effects of dry density and water content.

In this study, the physical properties of disturbed loess collected from the Yan’an New Area were analyzed by laboratory tests. Distributions of physical indicators such as dry density, porosity, and water content of disturbed loess were analyzed. Several sets of high-pressure consolidation tests were performed on disturbed loess with different dry densities and water contents. The variation in the soil–pore ratio with pressure during the compression of loess has been studied. Variations in the compression coefficient of disturbed loess are revealed in relation to the water content and dryness density of the soil. The relevant results of this study can provide some theoretical guidance for the design, construction, and monitoring of ground subsidence in loess areas where large-scale engineering projects are underway.

2. Study Area
2.1. Location of the Study Area

Yan’an City is located in the northern part of Shaanxi Province, the hinterland of the Loess Plateau, and the middle reaches of the Yellow River. The area is dense with ravines, and the city’s municipal boundary lies between 35°21′ and 37°31′ north latitude and 107°41′ and 110°31′ east longitude, with a total area of approximately 37,000 km². The city is connected to Yulin to the north, Xianyang, Tongchuan, and Weinan to the south, Linfen and Lviang in Shanxi Province to the east, and Qingyang in Gansu Province to the west. The construction area of Yan’an New City is located in the northern part of Yan’an City, and the geomorphology is mainly characterized by well-developed gully areas [27].

2.2. Meteorological and Hydrological Features

Yan’an has a warm, semi-arid continental monsoon climate [28]. According to data from the Yan’an meteorological station from 1951 to 2013, the average annual maximum temperature in Yan’an is 11.5 °C. The average monthly maximum temperature is usually approximately 23 °C in July, and the average monthly minimum temperature is −5.8 °C in January. The multiyear average precipitation in Yan’an is 537.87 mm, with a maximum of 959.1 mm and a minimum of 330 mm. With an average precipitation of 481.77 mm over the past 20 years, precipitation in Yan’an is mainly concentrated from June to September, accounting for approximately 70% of the annual precipitation. The annual average evaporation in Yan’an is 1605.8 mm, with the highest evaporation of 1929.5 mm and the lowest evaporation of 1265.7 mm, with most of the evaporation occurring from April to August, accounting for 66% of the annual evaporation rate. The main river in the study area is the Yan River. The Yan River originates in Zhoushan, Tianzhiwan Township, Jingbian County, and runs from northwest to southeast, joining the Yellow River near Lianshui Bank, Nanhegou Township, Yanchang County. The total length of the mainstream of the Yan River is 286.9 km, with a total average annual runoff of 294 million m³, a total river drop of 860 m, and an average specific rainfall of 3.3‰. The length of the river in the study area is 15.1 km, and the slope of the riverbed is 27 m, with an average slope drop ratio of approximately 1.8‰. In addition, there are two small ditches, Dujiaogou and Qiaogou, both tributaries of the Yanhe River, in the study area.

2.3. Geology and Hydrogeology Conditions

The stratigraphy of the study area is Quaternary, Neoproterozoic, and Jurassic, from new to old. Among the strata in the area, Jurassic strata are mainly distributed in Qiaoligou and both sides of the Ijagou valley, and only sporadic outcrops occur in the rest of the
area [29]. The Neoproterozoic is not exposed in the study area. Quaternary deposits are widely developed in the study area. The thickness of stratigraphic deposits varies greatly under the influence of running water and other influences. According to the sedimentary time from old to new, it is middle Pleistocene Lishi loess, upper Pleistocene Malan loess, Holocene landside deposits, and diluvial deposits. This area is mainly Quaternary wind sedimentary loess [30]. The types of disturbed loess in the Yan’an New District are mainly Lishi loess (Q_{p2}) and Malan loess (Q_{p3}).

Middle Pleistocene Lishi loess (Q_{p2}) is mainly distributed in the Loess Mountains area and is the main body of the Loess Mountains. The lithology is brownish-yellow, brownish-red, and light brownish-yellow powdery clay with a sand layer; vertical joints are developed, and layers of calcareous nodules and calcareous plates are interspersed in the middle and lower parts [31,32]. Affected by the ancient terrain, the thickness of the Lishi loess varies greatly, between 30 m and 50 m, and the local thickness is more than 100 m. The upper Pleistocene Malan loess (Q_{p3}) is distributed on the top of the loess hills. The lithology is grayish-white silty clay and chalk, and the thickness varies greatly, generally 10–20 m.

The hydrogeological structure of the study area is generally characterized by the spreading of the upper permeable nonaqueous layer and aquifer and the lower relatively intact bedrock water barrier. The permeable nonaqueous layer is distributed in the loess mount area and consists of the upper Pleistocene wind-deposited loess of the Quaternary system, the middle Pleistocene wind-deposited loess, and the Neoproterozoic system; the aquifer is composed of the local Holocene alluvium of the Quaternary system and the weathered crust of the sand mudstone of the Jurassic Yan’an group in the valley area, which is a unified water-bearing body of double media [33,34]. The water barrier is the base of the aquifer and consists of the sandy mudstone of the Yan’an formation [35].

3. Materials and Methods
3.1. Sampling and Analysis

The loess samples used in this experiment were collected from the Kangjiagou area of the “Land Creation Project” in Yan’an City, and the sampling locations are shown in Figure 1. The Kangjiagou valley area is approximately 0.5 km wide and 1 km long, with elevations ranging from 970 to 1110 m. To ensure the objectivity of the sampling analysis, 13 sampling points were set up in the study area, which covered the whole construction area, and undisturbed sampling was carried out at different heights of each point according to the construction progress. The horizontal distance between each pair of sampling points is approximately 100–200 m, and the vertical distance between each pair of vertical samples is 10 m. A total of 8 samples were collected vertically at each sampling point. Soil samples were taken by exploratory wells and dug manually. To ensure stable soil properties, the removed loess was sealed and fixed using black plastic bags and transported to the laboratory. The disturbed loess taken was subjected to dry density, volumetric moisture content, mass moisture content, and porosity.

In this study, the dry density, mass water content, and volumetric water content of the soil were determined in the laboratory with the drying and weighing method. To obtain this, the loess specimens were prepared with a cutting ring with an inner diameter of 70 mm and a height of 52 mm. As the specimens were sampled in the field, different specimens have different water contents; thus, the weights of the specimens are diverse. The total weight of the cutting ring and the soil specimen (m) was weighed using a balance with an accuracy of 0.01 g. Soil samples were then dried at 105–110 °C to a constant weight (m_d) using a 101-2A electric blast dryer. The measurements were performed three times to ensure accuracy of the measurements. The average of the triplicate measurements was used as the final measurement. Equations (1)–(3) were used to calculate the dry density, volumetric water content, and mass water content of the collected soil samples. The specific gravity of the soil (G) was determined using the specific gravity bottle method. To do this, soils air-dried and filtered through a 1 mm diameter sieve were weighed (m_s) and then
poured into a specific gravity bottle, which was filled with distilled water to one-third of the bottle volume. Then, the bottle was heated until the water was boiling and continued heating for at least 30 min to remove the air in the soil and water. After the bottle cooled, it was filled with distilled water to the bottle neck and then weighed \((m_a)\). The same specific gravity bottle was washed and filled with distilled water with air removed to the bottle neck and weighed \((m_b)\). Equations (4)–(6) were used to calculate the specific gravity, porosity \((n)\), and void ratio \((e_0)\) of the soil.

\[
\rho_d = \frac{m_d}{V} \tag{1}
\]
\[
\omega = \frac{m - m_d}{m_d} \times 100\% \tag{2}
\]
\[
\theta = \frac{m - m_d}{\rho_w V} \tag{3}
\]
\[
G = \frac{m_a}{m_a + m_b - m_d} \times d_w \tag{4}
\]
\[
\begin{aligned}
\quad n &= 1 - \frac{\rho_d}{G} \\
\quad e_0 &= \frac{G}{\rho_d} - 1
\end{aligned} \tag{5, 6}
\]

where \(\rho_d\) is the dry density of soil \((g/cm^3)\), \(m\) represents the original soil weight, \(m_d\) denotes the mass of soil after drying \((g)\), \(V\) indicates the volume of loess specimen \((cm^3)\), \(\omega\) signifies the mass water content, \(\theta\) is the volumetric water content, and \(\rho_w\) is the density of water, which is taken as 1.0 \(g/cm^3\) in this study. \(G\) indicates the specific gravity of soil \((g/cm^3)\),

Figure 1. Study area and sampling locations.
\( m_s \) is the weight of the soil particles, \( m_a \) is the weight of a gravity bottle filled with water and soil (g), \( m_b \) is the weight of the specific gravity bottle filled with water (g), \( d_w \) is the specific gravity of distilled water, \( n \) signifies the soil porosity, and \( \rho_0 \) is the wet density of the soil. In practical engineering activities in Yan’an City, the main type of loess involved is Qp2 loess, so the analysis of the compressibility of the loess in this study focused on only Qp2 loess.

### 3.2. Fast Consolidation Test

As China’s Loess Plateau has experienced many large-scale construction projects, disturbed loess is widely distributed in the study area [4]. During engineering construction, disturbed loess is compacted with mechanical machines. The stress state that the loess is subjected to is similar to that of the one-dimensional consolidation test specimen, so the one-dimensional high-pressure consolidation test was used to study the compressibility of the disturbed loess in the study area [36]. Previous studies have shown that the fast consolidation test method gives similar results to the conventional consolidation test. The fast consolidation test method is more suitable for high-pressure tests and can greatly reduce the test time, so the fast consolidation test was used in this study [37]. Qp2 loess samples were taken from the construction area of the Yan’an New District and were crushed manually, after which the crushed loess samples were passed through a 2 mm sieve and dried to prepare five groups of soil specimens with moisture contents of 7%, 10%, 13%, 16%, and 19%, respectively. All prepared specimens with different moisture contents were placed still for 24 h and weighed to fine-tune the moisture contents. According to the Chinese geotechnical test method standard (Ministry of Housing and Urban–Rural Development of the P. R. China 2013), a JDS-1 CNC electric compaction instrument was used to obtain soil specimens with dry densities of 1.55, 1.60, 1.65, 1.70, and 1.75 g/cm\(^3\) under each moisture content, respectively [38]. These samples were then prepared for a high-pressure consolidation test. A high-pressure consolidation apparatus with a maximum load of 4 MPa was used for the high-pressure consolidation test [39]. The applied loads were selected as 25, 50, 100, 200, 400, 800, 1600, and 3200 kPa, and the loads were increased step by step. When the deformation under the current load was stabilized at 0.01 mm/h, the next level of the load was applied to the soil specimen. When the last reading was over, the specimen was left for 24 h to obtain the final stable deformation.

### 3.3. Calculation of the Compression Deformation Coefficient

In the land construction project of the Yan’an New Area, the compaction rolling method is adopted for the loess foundation in the construction area. This process will cause ground compression. It is necessary to understand the relationship between compaction and compression to provide theoretical guidance for practical engineering applications.

The compression deformation coefficient (\( \delta_p \)) and soil pore ratio (\( e_i \)) were used to investigate the relationship between soil compression deformation and soil moisture content and dry density under different loads. The percentage between the shape variable of the sample and the height of the sample before compression and the soil pore ratio during the compression process can be expressed by Equations (7) and (8). The compressibility and its variation rule under different conditions can be easily and intuitively judged by the compression deformation coefficient.

\[
\delta_p = \frac{H_0 - H_i}{H_0} \times 100\% \quad (7)
\]

\[
e_i = e_0 - \frac{1 + e_0}{H_0} \times (H_0 - H_i) \quad (8)
\]

where \( \delta_p \) indicates the compression deformation coefficient, \( H_0 \) indicates the height of the sample before compression (mm), and \( H_i \) indicates the final stabilized height (mm) of the sample after deformation.
4. Results and Discussion

4.1. Compressibility Analysis of Disturbed Loess

From Table 1 and Figure 2, the dry density of 135 disturbed loess samples was distributed between 1.29 and 1.83 g/cm³, with a mean value of 1.56 g/cm³, and the dry density was 1.56 ± 0.021 g/cm³ at the 95% confidence level. The dry density of most samples ranges from 1.45 g/cm³ to 1.6 g/cm³, accounting for approximately 50% of the total soil samples. The minimum and maximum coefficients of volume compressibility of disturbed loess are similar to the minimum value of the undisturbed Q_p3 loess and the maximum value of the undisturbed Q_p2 loess, respectively, and the mean values are also between the mean values of the compactness indices of these two kinds of loess.

<table>
<thead>
<tr>
<th>Physical Index</th>
<th>Dry Density (g/cm³)</th>
<th>Moisture Content (%)</th>
<th>Specific Gravity (g/cm³)</th>
<th>Void Ratio</th>
<th>Degree of Saturation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size</td>
<td>1150</td>
<td>1150</td>
<td>1150</td>
<td>1150</td>
<td>1150</td>
</tr>
<tr>
<td>Max</td>
<td>1.510</td>
<td>16.6</td>
<td>2.71</td>
<td>1.153</td>
<td>50</td>
</tr>
<tr>
<td>Min</td>
<td>1.265</td>
<td>10.2</td>
<td>2.7</td>
<td>0.786</td>
<td>27.2</td>
</tr>
<tr>
<td>Mean</td>
<td>1.392</td>
<td>12.748</td>
<td>2.703</td>
<td>0.941</td>
<td>36.715</td>
</tr>
<tr>
<td>SD</td>
<td>0.038</td>
<td>1.248</td>
<td>0.004</td>
<td>0.054</td>
<td>3.963</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>0.027</td>
<td>0.097</td>
<td>0.001</td>
<td>0.057</td>
<td>0.107</td>
</tr>
</tbody>
</table>

| Sample size   | 2446                | 2446                 | 2446                    | 2446       | 2446                     |
| Max           | 1.816               | 26.8                 | 2.71                    | 0.908      | 100                      |
| Min           | 1.418               | 12.7                 | 2.7                     | 0.491      | 47                       |
| Mean          | 1.616               | 18.466               | 2.705                   | 0.679      | 74.011                   |
| SD            | 0.067               | 2.586                | 0.004                   | 0.067      | 13.15                    |
| Coefficient of variation | 0.041               | 0.14                 | 0.001                   | 0.099      | 0.177                    |

| Sample size   | 135                 | 95                   | 95                      | 135        | 95                       |
| Max           | 1.883               | 24.902               | 2.71                    | 0.548      | 89.389                   |
| Min           | 1.293               | 5.271                | 2.7                     | 0.308      | 13.529                   |
| Mean          | 1.562               | 12.896               | 2.705                   | 0.439      | 46.72                    |
| SD            | 0.125               | 4.147                | 0.004                   | 0.049      | 18.377                   |
| Coefficient of variation | 0.043               | 0.129                | 0.001                   | 0.075      | 0.143                    |

Figure 2. Histogram for the physical indices of disturbed loess. (a) histogram of dry density, (b) histogram of moisture content, and (c) histogram of degree of saturation.
By analyzing the relationship between the compaction effect and the water content of loess in this research, the relationship between dry density and the water content of loess is drawn in Figure 3. It shows that with the increase of mass water content, the dry density of the disturbed loess shows an initial increase and then decrease trend, and the dry density reaches the maximum when the mass water content is around 16%. Therefore, when the water content of the filled material is adjusted to about 16%, the best compaction effect can be achieved in practical engineering. This finding can be useful in instructing practical compaction engineering so that the loess can achieve the highest compaction effect. In addition, this finding can also facilitate the preparation of laboratory loess specimens.

![Figure 3. Relationship between dry density and mass moisture content of disturbed loess.](image)

In this paper, the effective pressure and pore ratio during the compression of disturbed loess were analyzed. The pore ratio versus effective pressure curves ($e$-$p$) and pore ratio versus effective pressure logarithmic relationship curves ($e$-$\lg p$) under different water content conditions are shown in Figure 4. Figure 4a shows that with increasing compression load $p$, the loess samples are gradually compacted, and the void ratio $e$ decreases. With increasing water content, the deformation resistance is obviously weaker, and the void ratio decreases more and more. Therefore, the lower the $e$-$p$ curve is, the higher the soil water content and the greater the compressibility. In situ loess is a kind of under-compacted soil with low structural strength. Due to the influence of human activities, disturbed loess destroys the original structure of loess by filling and compaction, forming a new secondary structure [40].

From Figure 4b, with increasing compressive load, the slope of the $e$-$\lg p$ curve increases gradually. When the load increases to a certain extent, the slope of the curve remains unchanged and begins to enter a straight line. In this process, there is an inflection point of curvature mutation on the $e$-$\lg p$ curve, but this is not due to the destruction of the primary structure but to the reflection and expression of the secondary structure strength [41]. Compared with the primary structure, the structural strength of the secondary loess is weak. When the applied load is less than the sum of the structural strength of the secondary loess and the previous consolidation pressure, the structure of the secondary loess is not destroyed, the soil compressibility is small, and the curve is gentle. However, once the applied load exceeds the sum, the soil structure is destroyed, the compressibility increases suddenly, structural compression yielding occurs, and the curve becomes steeper [42]. Therefore, the pressure corresponding to the turning point of the disturbed loess compression curve contains not only the prior consolidation pressure but also the structural strength at the time of secondary structural damage of the loess under compression conditions [43]. Compared with the compression yielding of the undisturbed loess, the compression yielding of the disturbed loess secondary structure is not obvious.
Figure 4. Relationship between the pore ratio and pressure value of compressed specimens under different water contents.

4.2. Effect of Moisture Content on Compressibility

Figure 4 also shows that the pore ratio gradually decreases with increasing pressure. Under low pressure \((p < 800 \text{ kPa})\), the \(e\)-\(p\) curves of disturbed loess specimens become increasingly steep, indicating that the compressibility of disturbed loess increases with increasing initial water content. Under the action of high pressure \((p > 1000 \text{ kPa})\), the slopes of the \(e\)-\(p\) curves for water contents of 7%, 10%, 13%, 16%, and 19% are closer, and the changes in the pore ratio are not obvious, especially in the small pressure range. This indicates that the effect of water content is not significant in the initial stage of compressive deformation of disturbed loess [44]. At pressures less than 1000 kPa, the \(e\)-\(p\) curve is hyperbolic in shape, and at pressures greater than 1200 kPa, the \(e\)-\(p\) curve relationship is close to linear. In Figure 4b, the \(e\)-\(\log p\) curve is convex at a water content of 7%, but when the water content is greater than 7%, the \(e\)-\(\log p\) curve is close to a linear variation. This indicates a larger pore-ratio coefficient and a higher strength of the soil sample when the water content of the disturbed loess is 7%. For water contents greater than 10%, the decrease in the ratio of the pore size to the vertical pressure of the disturbed loess is more pronounced than for water contents greater than 7%, indicating that the compressibility of the disturbed loess is greater at higher water contents. The fact that the pore ratio is larger at low water content and smaller at high water content proves that the variability of the pore ratio is necessarily related to the amount of water content. The high water content causes the structural properties of the loess to be destroyed and the soil to be more compressible. This suggests that the increased wetting and sinking of loess is caused by the softening of the loess structure by water and the resulting reduction in strength [45].
This phenomenon is due to the fact that loess at low humidity has a pronounced strength and low compressibility; once immersed in water or even moistened, however, it exhibits a marked sudden decrease in strength and a marked sudden increase in deformation [46].

Figure 5 shows the relationship of the compression deformation coefficient with sample moisture content under different loads. Figure 5 indicates that under dry density, when the water content is less than 10%, the compression coefficient increases rapidly with the water content, and when the water content is greater than 10%, the compression coefficient increases slowly with the water content. Because the sample is disturbed loess, when the loess skeleton with weak strength is formed inside the soil sample, the water content is small, and large pores are formed inside the soil sample, resulting that the sample can withstand less external load [47]. Under certain loading conditions, the loess skeleton is destroyed, accompanied by a relative slip between the particles; local small particles fall into the pores, and the soil immediately disintegrates, destroying the entire structure [48].

![Figure 5. Curve of compression deformation coefficient versus sample moisture content under different loads.](image-url)
Under larger dry-density conditions, the compression coefficient gradually becomes larger with the water content, but after the water content is greater than 16%, the compression coefficient increases rapidly, and at a water content of 19%, the soil becomes softer and more easily compressed [49]. This is mainly because the water film on the surface of soil grains is thin when the water content is small, the linkage between soil grains is strong, and the soil skeleton composed of soil grains, intergrain cement, and shrinkage film is not easily deformed under the action of additional pressure, the structure of the soil sample is not destroyed, the compressibility of the soil is not great, and the soil is in the elastic stage [50]. When the water content continues to increase, the water film on the surface of soil grains thickens, the linkage between soil grains is weakened, the loess skeleton is easily deformed under the action of additional pressure, the compressibility of the structural soil increases sharply, and the soil sample gradually becomes softer during the compaction process but shows the characteristics of easy compression [51].

4.3. Effect of Dry Density on Compressibility

Figure 6 shows the relationship between the compressive deformation coefficient and the dry density of soil under different moisture contents. The compressive deformation coefficient as a whole showed a decreasing trend with increasing dry density, and the decreasing trend gradually became slower [52]. This indicates that as the water content increases, the cohesive structure in the specimen gradually decreases, and the number of pores in the specimen gradually becomes the main factor affecting the compressive deformation coefficient. When the water content is small, the variation in the compression deformation coefficient with dry density shows a trend of first increasing and then decreasing. The main reason for the above is that when the water content is low, the loose soil is apt to form a cohesive structure, and when the external force is small, the cohesive state is not easily destroyed, and the experimental sample is not easily compressed [53,54]. When the water content is lower than the optimum water content, the compression coefficient of disturbed loess under low-pressure conditions, such as Figure 6d, does not change with increasing dry density because the load on disturbed loess is less than the sum of the structural strength of soil and prior consolidation pressure, and the structure produced by disturbed loess accumulation has not yet been destroyed, so the compression coefficient remains relatively consistent [55,56]. When the disturbed loess is subjected to a higher pressure, the load exceeds the capacity of the soil structure of the loess at each moisture content, the secondary structure is destroyed, and the compression coefficient of the soil sample becomes larger. The soil sample dry density increased from low to high, soil gradually compacted, soil porosity gradually reduced, soil particles formed soil–particle skeletal structure increased, providing more support for soil sample compression, as shown by the compression coefficient gradually decreasing with increasing dry density [57,58].

When the water content is high, the clay particle diffusion layer is fully developed, the thickness of the hydration film increases, and the strength of the agglomerate structure weakens, resulting in a small resistance to deformation of the soil, at which time the effect of dry density on the soil compression coefficient is weaker [28].

When disturbed loess is subjected to a smaller external load, the air between the soil particles is expelled more rapidly at the initial stage, followed by the completion of the soil drainage consolidation process. At this point, the load is mainly carried by the cementation strength of the particles, and even if the pore size is large, the load has a smaller break on the cementation strength. However, the creep and spatial rearrangement of the soil particles are hindered by cementation between the particles and lead to a small compression factor. As the load increases, the breakdown of the structural strength becomes progressively larger, and this reduced hindrance and destruction of the pores result in a rapid decrease in the soil–pore ratio. At high stress, the soil–pore space becomes very small, the secondary structure has completely yielded, and the movement of the soil particles is greatly impeded and stabilized. Theoretically, in an engineering sense, the pressure on a soil sample can increase indefinitely without strength damage [24]. Thus, under engineering conditions, to
ensure stable engineering properties, the involved perturbed loess should be compacted until the density of the perturbed loess is increased, and the pore space is reduced to a relatively stable state, and the tendency of the particles to move is substantially reduced.

Figure 6. Variation in the compression deformation coefficient with dry density under different loads.

In the compression process of disturbed loess, when the water content is less than the optimal water content, the viscous particle-diffusion layer cannot be fully developed, the hydration-film-wedging force between the particles is smaller and the adsorption force is larger, so the structural strength of the agglomerate itself is high, and the interagglomerate force is strong, resulting in the soil resistance to deformation; when the water content is larger than the optimal water content, the viscous particle-diffusion layer is fully developed, the hydration-film thickness increases, and the structural strength of the agglomerate is weakened, resulting in the soil resistance to deformation being small. At the same time, the diffusion layer of clay particles fully develops, the thickness of the hydration film
increases, the strength of the agglomerative structure weakens, and the resistance of the soil to deformation is small. To reduce perturbative deformations, the water content should not exceed the optimal water content. For disturbed soils of engineered nature, the water content of the disturbed soil should be more strictly controlled.

Water is not only an important resource for various uses in loess areas but also a significant factor affecting the stability of constructions [59]. In summary, in the practical construction project in loess areas, the original loess will usually be excavated to form the foundation, and then the disturbed loess will be filled back and compacted in multiple layers. In the process of compaction, the moisture content of the disturbed soil should be configured to 16% so that the compaction can achieve the best quality. Even so, sensors are suggested to be installed inside the backfilled loess to monitor the changes in moisture content and pressure of the compacted loess, warning of possible deformation of the loess soil. There are many factors affecting the compression characteristics of loess, such as water content, dry density, structural configuration, particle size distribution, and load intensity, and only two of the most important ones were considered in this research. However, the influence of other factors on the strength of loess is also important, and it is important and necessary to consider all these factors in future studies to achieve a full understanding of how these factors can conjunctively affect the compression characteristics of loess.

5. Conclusions

In this research, the physical properties of 135 groups of disturbed loess in Yan’an were statistically analyzed, and the distribution pattern of physical and mechanical indices of the disturbed loess was investigated. High-pressure consolidation experiments were carried out for the disturbed loess, and the compression characteristics and compression ratio of the disturbed loess were explored. The following main conclusions were obtained:

1. With increasing compression load, the loess specimens are gradually compacted, and the pore ratio decreases. When the water content of the disturbed loess is 7%, the pore ratio coefficient is the largest, and the strength of the soil sample is the highest. When the water content is greater than 10%, the decreasing rate for the pore ratio of disturbed loess increases significantly with the increasing pressure. At a pressure less than 1000 kPa, the e-p curve is hyperbolic, and at a pressure greater than 1200 kPa, the e-p curve relationship is close to linear. In contrast to in situ loess, the compression process in perturbed loess is relatively homogeneous, and there is a compression-yielding phenomenon, which is weaker than the yield stress performance of in situ loess.

2. The compression coefficient of disturbed loess showed an initial increasing and then decreasing trend with increasing mass water content. At low dry density, the compression coefficient of the specimen increases more rapidly with the water content up to 10%. When the water content is larger than 10%, the growth rate of the compression coefficient of the disturbed loess becomes slower. The dry density reaches its maximum at a mass water content of approximately 16%. That is, the best compaction is achieved when the moisture content of the filled loess material is adjusted to approximately 16% in a practical engineering project.

3. The compressive deformation coefficient generally decreases with increasing dry density and increases with increasing water content under different loading conditions. However, in the case where both the dry density and the water content are small, the compression coefficient increases with the dry density for a range of dry densities due to the easy formation of cohesive structures in soil. In the case of a larger dry density and water content, the compressibility rapidly becomes larger as the dry density and water content increase since it is closer to saturated soft loess.

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