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The Parameter of Soil Structural Properties and Their Relationship to Grain Size, Density, and Moisture Content

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Abstract: In this paper, a new definition of a structural parameter for soil is given to characterize the mechanical properties of soils and their changing patterns. The soil structural parameter is a quantitative descriptor of soil structural properties. Structural parameters are related not only to the grain size, density, and moisture content of the soil material composition and state, but also to the spatial arrangement of soil particles in the soil skeleton structure and the characteristics of intergranular associations. The new definition of the structural parameter, established from the comparison of loess structural stability and variability, is defined as the ratio of the shear strength of undisturbed loess to that of remodeled saturated loess. The patterns of moisture content, confining pressure, and dry density on structural properties were analyzed and the degrees of influence of each factor on structural properties were quantified. By analyzing the change rule of the structural parameter of loess with the difference of moisture content and plastic limit, its change rule with plastic limit and liquid limit, and the change rule of the structural parameter with the liquidity index, the essential relationship between the structural parameter and grain size, density, and moisture is revealed. The essential relationship between the structural parameter and grain size, density, and moisture were also revealed.

Keywords: structure; structural parameter; particle size; density; moisture

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1. Introduction

Loess is a loose accumulation formed in the Quaternary period. Loess and loess-like soils cover more than 9.3% of the world's continental area, with a total area of about 13 million km^2 [1]. The distribution of loess is characterized by wide coverage, large thickness, and large continuous area, which greatly increases the complexity of loess engineering problems [2]. The concept of the structural nature of soil was first proposed by Tyshaki [3]. Since then, it has been emphasized by scientists. The structural property of soil is the embodiment of the physical state of the soil, which is another important physical property in addition to particle size, density, and moisture. Different combinations of mineral composition, particle characteristics, pore characteristics, and moisture content cause the soil to have different structural properties. Structural properties are the most fundamental internal factors controlling the nature of soil mechanics. The study of loess structural properties and its change law under the action of force and water has a very important role in the radiation of the whole research object of soil mechanics [4]. As an internal factor, the structural property of soil is the dominant factor in the mechanical properties of soil. The structural property of soil is recognized as one of the essential properties of soil, and its related research is also considered as "the core problem of soil mechanics in the twenty-first century" [5–7].

The core objective of soil structural research is to establish the quantitative relationship between structural properties and macromechanical behavior to realize the purpose of theoretical guidance of practical engineering. The prerequisite for establishing this quantitative relationship is the quantitative characterization of soil structural properties [8,9]. Therefore, the study of quantitative structural indices has become the focus of current research. There are three ways to study the structural properties of loess: the fine morphology way [10,11], the solid mechanics way, and the soil mechanics way [12,13]. At present, the quantitative study of loess microstructure mainly focuses on the relationship between microstructural parameters and macroscopic properties, such as physical and mechanical properties [14]. The application of damage theory to the study of soil structure was first proposed by Shen Zhu-jiang [6], who not only reasonably described the destructive process of soil structure but also provided a new way to investigate the structural properties of loess. The core idea of the soil mechanics method to study the structural properties of loess is to investigate the relationship between the engineering properties and the structural properties of loess, and its ultimate goal is to seek quantitative indices that can comprehensively reflect the structural properties of loess and introduce them into the stress-strain relationship so as to establish the structural ontology model of loess [15]. This method has greater potential and better application prospects in the study of soil structure. Based on the structural stability and variability of soil, Xie Ding-yi [16–18] introduced an integrated structural potential that quantifies the structural properties of soil under disturbances, loading, and immersion. This parameter is both concise and practical, serving as a crucial tool for studying soil structure and providing a robust foundation for investigating the structural characteristics of loess and their evolution. However, this parameter can increase its pressure infinitely when the amount of compression deformation is basically stable and there is no strength damage in the engineering sense. The relationship between the axial pressure on the specimen and the amount of compression deformation shows a strain-hardening type curve, which is quite different from the shear damage pattern of soil. Therefore, based on the uniaxial compressive strength of undisturbed loess, remodeled loess, and saturated loess, Shao Sheng-jun [19] applied the integrated structural potential approach to establish a structural index that describes the structural properties of loess. Additionally, using the comprehensive structural potential method, the intrinsic model and strength laws that consider the structural characteristics of loess were investigated. Therefore, based on particle size, density, and moisture describing soil mechanical properties, the structural degree index can be introduced to improve the understanding of the physical nature of soil mechanical properties. However, the constitutive index is a structural parameter obtained under the uniaxial stress state of the soil body, so the structural parameter of the soil obtained in the uniaxial compressive strength test cannot be directly applied to the triaxial stress state. This is inconsistent with the stress state of the soil body in actual engineering, and the engineering applicability of this parameter is poor [20–22].

Based on the above theory, this article inherits the theoretical core of previous research and explores a new definition of structural parameters that can be applied to complex stress states. To break through the limitations of the structural parameter in complex stress states and to expand te application space of the soil structural parameter, the relationship between structural parameter and grain size was analyzed. The relationship between the structural parameter and the indices of grain size, density, and moisture is also analyzed, and the reliability and rationality of the structural parameter are demonstrated.

2. Materials and Methods

2.1. New Definition of Structural Parameter

When natural loess is not disturbed by external influences, it exhibits inherent structural properties. The strength of the soil structure is mainly manifested in the arrangement and connection of the soil particles. Loading, disturbance, and immersion in water can alter or destroy the original structural form of the soil. Loading can change the arrangement and association characteristics of soil particles. Disturbance can weaken and break the cementation between soil particles. Immersion does not only dissolve and weaken the chemical composition of the soil, so that the suction in the soil disappears and the water film thickens, but also releases the expansion and contraction potential of the soil [23–28]. Xie Ding-yi [16,17] first proposed to seek a quantitative index of soil structural properties by releasing the structural potential, i.e., the structural properties of undisturbed soil are completely released by loading, disturbing, and immersion methods. Based on the idea of integrated structural potential, many scholars have conducted substantial research [29–31]. Shao Sheng-jun [19] obtained the difference of principal stresses of three given strains from the stress-strain curves of undisturbed loess, saturated loess, and remodeled loess under the condition of consolidated drainage triaxial shear. The ratios of principal stress difference between undisturbed and remodeled loess and between primary and saturated loess define the structural parameter of the soil. It comprehensively reflects the structural characteristics of soil particle arrangement and particle bonding. Luo Ya-sheng [32] defined the strain-structure parameters of soils by the shear strengths of undisturbed, remodeled (wet compacted state is kept the same as undisturbed), and saturated soils under triaxial stresses for a given strain. The ratio of strength between undisturbed soil and saturated soil, as well as the ratio of strength between undisturbed soil and remolded soil, comprehensively reflects the arrangement and connection characteristics of soil particles. The structural parameter defined above shows good sensitivity, stability, and rationality. However, in the testing process, it is necessary to test the as-is, remodeled, and saturated samples, and the workload is relatively large. Therefore, this paper combines the triaxial shear test and takes Shaanxi undisturbed loess as the research object to give a structural parameter that is applicable to complex stress states and does not require too much workload, is achievable through a relatively simple test, and is easy and convenient to obtain. The defined structural parameter m_τ is:

$$m_\tau = \frac{\tau_o}{\tau_{rs}} \quad (1)$$

In Formula (1), τ_o represents the shear strength of intact loess and τ_{rs} represents the shear strength of remolded saturated loess. From the definition of m_τ, it can be seen that the greater the strength of the association between soil particles, the more unstable the arrangement, and the lower the strength of the soil body under external load after disturbance and saturation by water immersion, i.e., the greater the structural parameter.

The definition of the structural parameter is expressed in terms of shear strength, which proves that the parameter is a material constant that is a composite response to the strength of the earth material, and that the definition is more standardized and widely applicable. Furthermore, the new definition utilizes the strength parameters of remolded saturated soil rather than those of both saturated and remolded soil, which simultaneously addresses the structural stability and variability of the soil. This approach simplifies the testing conditions and reduces the required sample size. Moreover, the novel definition characterizes structural parameter based on shear strength, which can be assessed through intricate stress state tests, including triaxial shear tests, direct shear tests, and even in situ testing experiments, thereby enhancing the flexibility of the testing methods. Ultimately, the introduction of these new parameters facilitates not only the investigation of

loess, a more cohesive soil type, but also the structural attributes of soils that cannot be formed into uniaxial specimens, such as sandy soils and soft clays, thus enabling a more comprehensive analysis.

2.2. Test Materials and Test Program

2.2.1. Basic Physical Property Indicators of Sampled Loess

The soil samples were taken from a construction site in Pucheng County, Weinan City, Shaanxi Province, and the vegetation was developed at the sampling site. The exploration well sampling method is used to dig the exploration well to the required sampling depth, and then the manual sampling is carried out at a depth of 1 m on the side wall. Wrap the extracted undisturbed soil blocks with cling film and seal them with tape to prevent moisture loss. Mark the upper surface of the soil sample on the wrapped soil blocks to determine the direction of the soil sample during testing and avoid the influence of anisotropy. The soil samples were taken from 3 m underground, and then deeper soil samples were taken every 1 m, for a total of five undisturbed soil samples at different depths. The soil sample is yellow brown in color, with insect holes and plant root holes distributed throughout, accompanied by snail shells, plant roots, and a few stones. According to the "Standard for Geotechnical Test Methods" (GB/T50123-2007) [33], the physical properties of soil samples at different depths were determined, and the test results are shown in Table 1.

Table 1. Indicators of Loess Physical Properties.

Extraction Depth (m)	d_s (g/cm^3)	w (%)	w_l (%)	w_p (%)	I_p	ρ (g/cm^3)	ρ_d (g/cm^3)	e
3.0	2.70	9.2	30.6	18.3	12.3	1.48	1.35	1.00
4.0	2.70	11	27.6	16.8	10.8	1.57	1.41	0.92
5.0	2.70	17	34.6	16.6	18	1.66	1.42	0.91
6.0	2.70	16.6	28	17	11	1.59	1.36	0.92
7.0	2.70	16.7	34.8	23.5	11.3	1.49	1.28	1.12

The particle size distribution of soil samples with depths of 3 m, 5 m, and 7 m were determined by sieve analysis and density meter methods. The particle size composition of the test soil samples is shown in Table 2. The particle size composition of the soil sample is mainly composed of silt particles (0.005–0.075 mm), with a content of over 70%, followed by clay particles (<0.005 mm) and finally sand particles with the lowest content (0.075–2 mm).

Table 2. Grain Size Composition of Loess.

Content of Different Particles (%)				Types of Soil
Extraction Depth (m)	Clay Particle (mm) <0.005	Silt Particle (mm) 0.005~0.075	Sand Particle (mm) 0.075–2	
3 m	18.97	80.28	0.75	silty clay
5 m	17.68	80.82	1.5	silty clay
7 m	19.8	77.35	2.85	silty clay

2.2.2. Experiment Scheme

According to the "Standard for Geotechnical Test Methods" (GB/T50123-2019), the test shear strain rate is 0.5%/min, that is, 0.4 mm/min, and the test is stopped when the shear strain is 20%. The instrument used in the test was an SY10-2 strain control triaxial instrument.

In accordance with the "Standard for Geotechnical Test Methods" (GB/T50123-2019), the undisturbed soil blocks were cut into cylindrical soil samples (d = 39.1 mm, h = 80 mm) required for the test. The remolded soil samples were also made into the size of this specification.

Prepare undisturbed and remolded soil samples with different moisture contents (6%, 11%, 16%, 21%, 26%, 31%, and 36%) to study the structural changes of loess with different moisture contents and the relationship between loess structure and loess moisture. The undisturbed saturated sample and remolded saturated sample were prepared by the vacuum saturation method, while other moisture content soil samples were prepared by the following methods.

(1) Preparation method of undisturbed soil samples with different moisture contents

To prepare undisturbed loess samples with different moisture contents and evenly distribute moisture in various parts of the soil, the "water film transfer method" and "natural wind dry method" were used to control the required initial moisture content of the samples. For samples with a target moisture content higher than the natural moisture content, the first step is extraction saturation. The quality of the sample when the target moisture content is reached is calculated by Formula (2), and then the sample is naturally air-dried to the target weight. For samples whose target moisture content is lower than the natural moisture content, the natural air-dried method is directly used to air dry them to the target quality, and the target quality is also calculated by Formula (2). Finally, the sample was sealed with plastic wrap and placed in a moisturizing cylinder for 3–5 days, and the test was carried out after the water inside the sample was evenly distributed.

$$m_t = \frac{m_o}{1 + 0.01 w_o} \times (1 + 0.01 w_1) \tag{2}$$

In Formula (2),

m_o: quality of natural moisture content samples (g),

w_o: natural moisture content of the sample $(\%)$,

w_1: target moisture content of the sample $(\%)$,

m_t: the quality of the sample when the target moisture content is reached (g).

(2) Preparation method of remolded samples with different moisture contents

First, the remaining soil during the preparation of the undisturbed sample is air-dried and crushed, and the quality of the required air-dried soil is calculated according to the air-dried moisture content and natural dry density.

$$m_0 = (1 + 0.01 w_0) \rho_d V \tag{3}$$

In Formula (3),

m_0: quality of air-dried soil sample required for sample preparation (g),

w_0: air-dried moisture content $(\%)$,

ρ_d: dry density required for soil sample $\left(\mathrm{g/cm^3}\right)$,

V: volume of soil sample $\left(\mathrm{cm^3}\right)$.

Add different volumes of water to the air-dried soil to obtain the predetermined moisture content. The prepared soil sample is sealed in a plastic bag, and then the sample is placed in a closed curing tank for 3–5 days.

The number of samples required for this test is shown in Table 3.

It can be determined from Table 3 that 48 undisturbed soil samples and 48 remolded soil samples are required. To ensure the accuracy of the experiment and consider inevitable errors, two additional undisturbed and remolded soil samples with different moisture contents and dry densities are prepared as backups. Therefore, a total of 72 undisturbed and 72 remolded soil samples need to be prepared.

Table 3. Number of Test Samples.

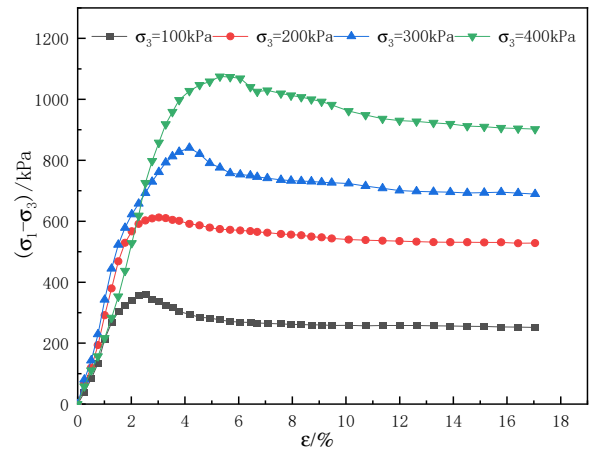
Sample Type	ρ_d (g/cm^3)	w (%)	Confining Pressure (kPa)	Amount
undisturbed sample	1.35, 1.41, 1.42, 1.36, 1.28	36, 31, 26, 21, 16, 11, 6	100, 200, 300, 400	5 × 4 + 7 × 4
remolded sample				5 × 4 + 7 × 4

3. Results

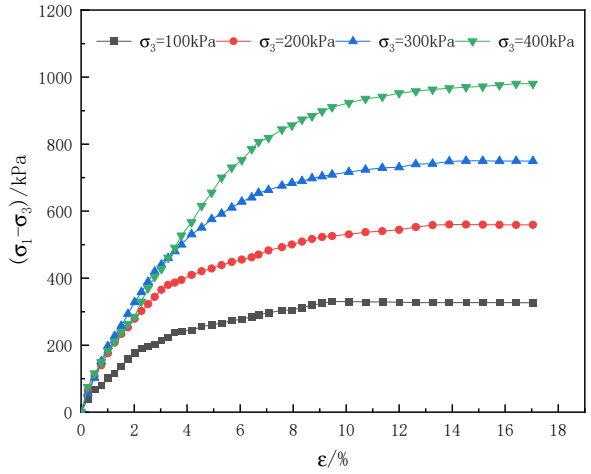
3.1. Analysis of Stress-Strain Characteristics of Loess Soil Samples

3.1.1. Analysis of Stress-Strain Characteristics of Undisturbed Soil

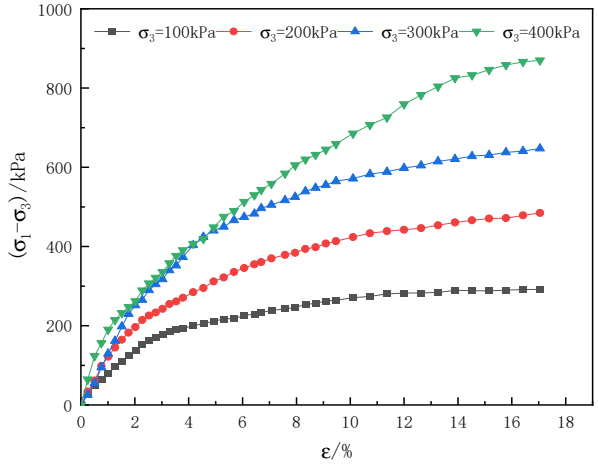
The test data were sorted and the curves of the difference in principal stress with axial strain for the undisturbed soil samples and the remolded soil samples with different moisture contents were plotted, as shown in Figure 1. The following patterns can be obtained from Figure 1.



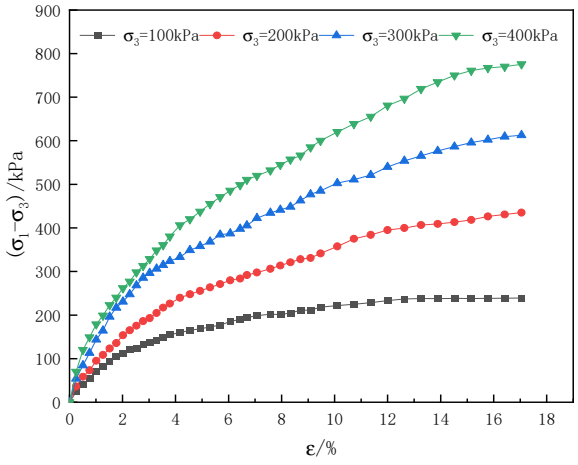
(**a**) w = 6%



(**b**) w = 11%



(**c**) w = 16%



(**d**) w = 21%

Figure 1. *Cont.*

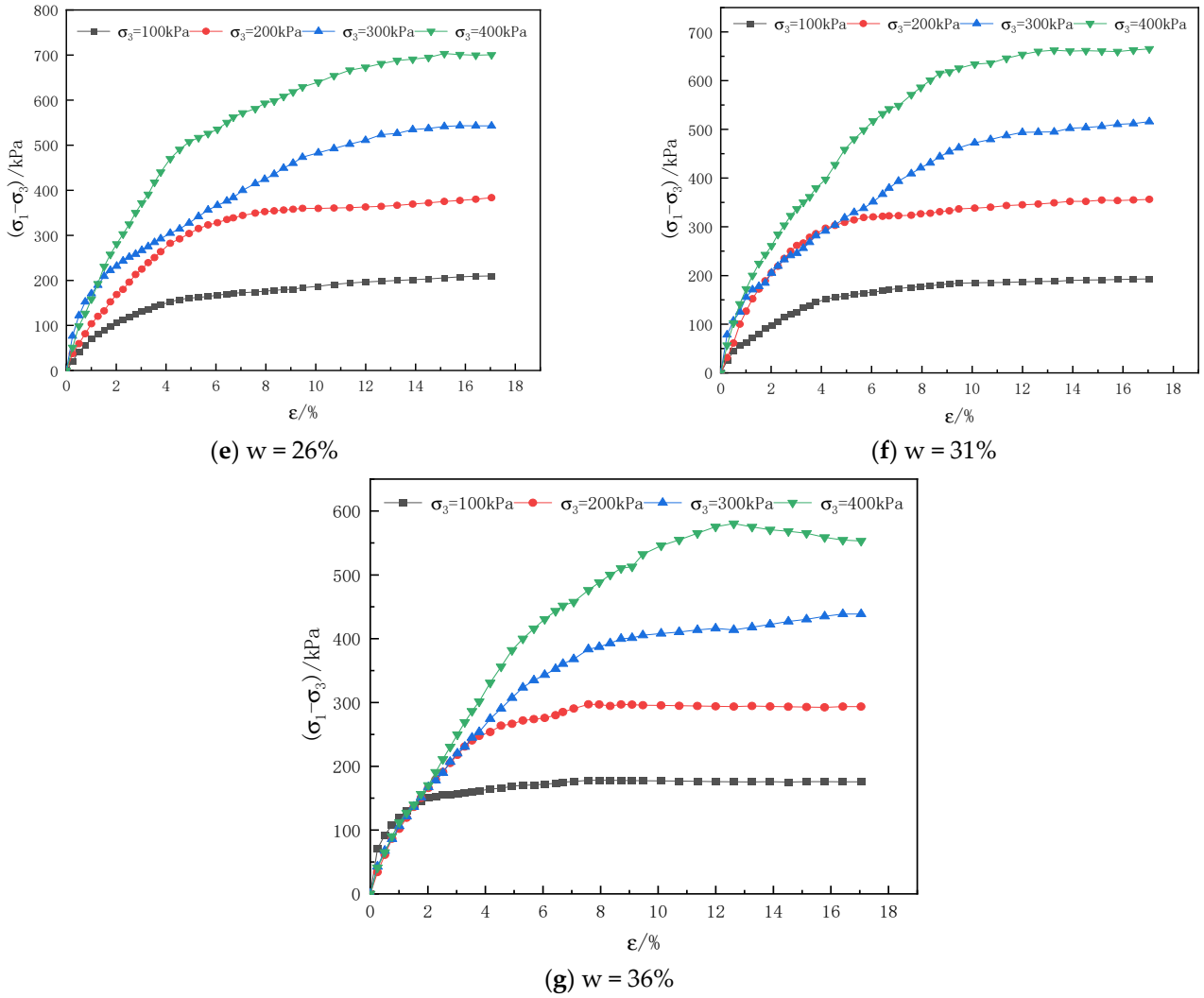


Figure 1. Stress strain curves of undisturbed loess under different confining pressures.

(1) When the moisture content of the soil sample is the same, the greater the confining pressure, the greater the strength, and the larger the elastic modulus in the initial rising stage of the stress-strain curve. The action of force disrupts the original internal structure of the undisturbed loess when the confining pressure increases, causing relative movement between the soil particles and achieving the effect of consolidation and densification. The soil particles are rearranged again. Macroscopically, the strength of the soil gradually increases with the consolidation effect of the vertical pressure.

(2) When the water content is 6%, the stress-strain curve shows a strain softening type. As the confining pressure increases, the degree of strain softening in the curve gradually weakens. This is because when the confining pressure is relatively small, the structural strength of the soil mass is greater than the confining pressure. Therefore, the structural strength within the soil mass can resist the action of the confining pressure. Thus, after the soil strength reaches its peak, the loss of strength becomes more obvious. However, as the confining pressure increases, the internal structural strength of the soil gradually fails to resist the action of the confining pressure. Therefore, the soil structure will gradually deteriorate under the action of the confining pressure, and the stress-strain curve of the soil will gradually transform into a hardening type.

(3) After the moisture content increases, the stress-strain curve of the original soil becomes a hardened type, without obvious peak strength and inflection point, and it belongs to plastic failure. During the initial elastic deformation stage of the curve, the

greater the confining pressure, the greater the growth slope of the elastic deformation. This is because in the low confining pressure state, the initial structural stability of the soil is relatively stable, and the relative sliding between soil particles is smaller, thus resulting in a larger linear elastic deformation. As the confining pressure increases, the initial structural failure of the soil mass becomes more severe, thereby leading to an increase in the sliding deformation between soil particles. This disrupts the original connections between soil particles, causing micro-cracks to appear in the soil skeleton and gradually expanding as the axial strain increases. As a result, the linear elastic deformation is relatively small.

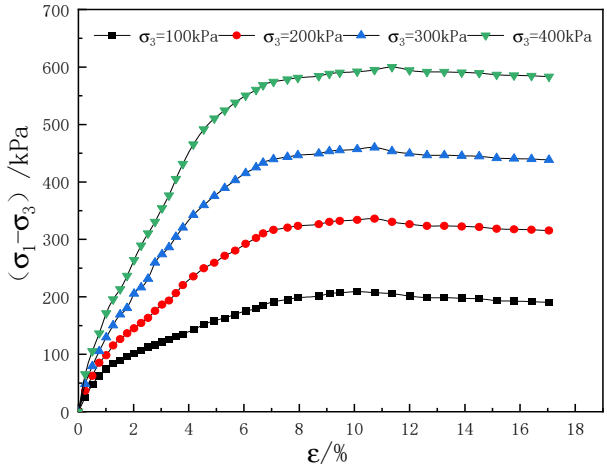
3.1.2. Analysis of Stress-Strain Characteristics of Remolded Soil

Figure 2 shows the stress-strain relationship of remolded loess under different confining pressures of soil samples with the same moisture content, and the following rules can be obtained.

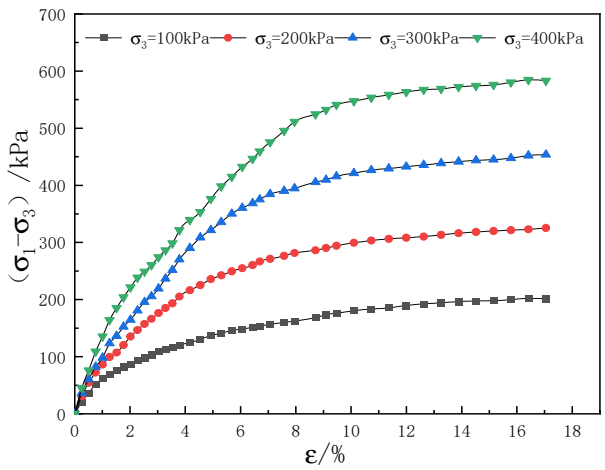
(1) At the same moisture content, the higher the confining pressure, the greater the shear strength of the soil, the greater the slope of the stress-strain curve in the rising stage, and the higher the peak strength of the shear stress.

(2) When the water content is 6%, the stress-strain curve of the soil sample shows a strain softening type. However, compared with the stress-strain curve of the undisturbed soil, the peak strength of the strain curve of the remolded loess is relatively lower, and the degree of strength decline after reaching the peak strength is also relatively slower compared to the undisturbed soil sample. As the confining pressure increases, the peak strength of the stress-strain curve is reached, and the corresponding shear strain also gradually increases. This is because when the moisture content is relatively low, the effective stress between the soil skeleton is greater. Under the consolidation effect of confining pressure, the soil skeleton can withstand a greater shear stress. Therefore, as the confining pressure increases, the corresponding shear displacement when the soil sample fails becomes larger, and the higher the confining pressure, the greater the peak strength.

(3) As can be seen from Figure 2g, the curve basically shows a trend of weak hardening. This is because the soil samples were soaked in water and disturbed, which simultaneously disrupted the connection mode, arrangement combination, and chemical action of soil particles. With the increase of axial strain, secondary structural formation gradually occurs. However, due to the excessive water content, the secondary structural strength cannot continue to increase. Therefore, as the strain increases, the principal stress difference cannot continue to grow and shows a trend of weak hardening.



(**a**) w = 6%



(**b**) w = 11%

Figure 2. *Cont.*

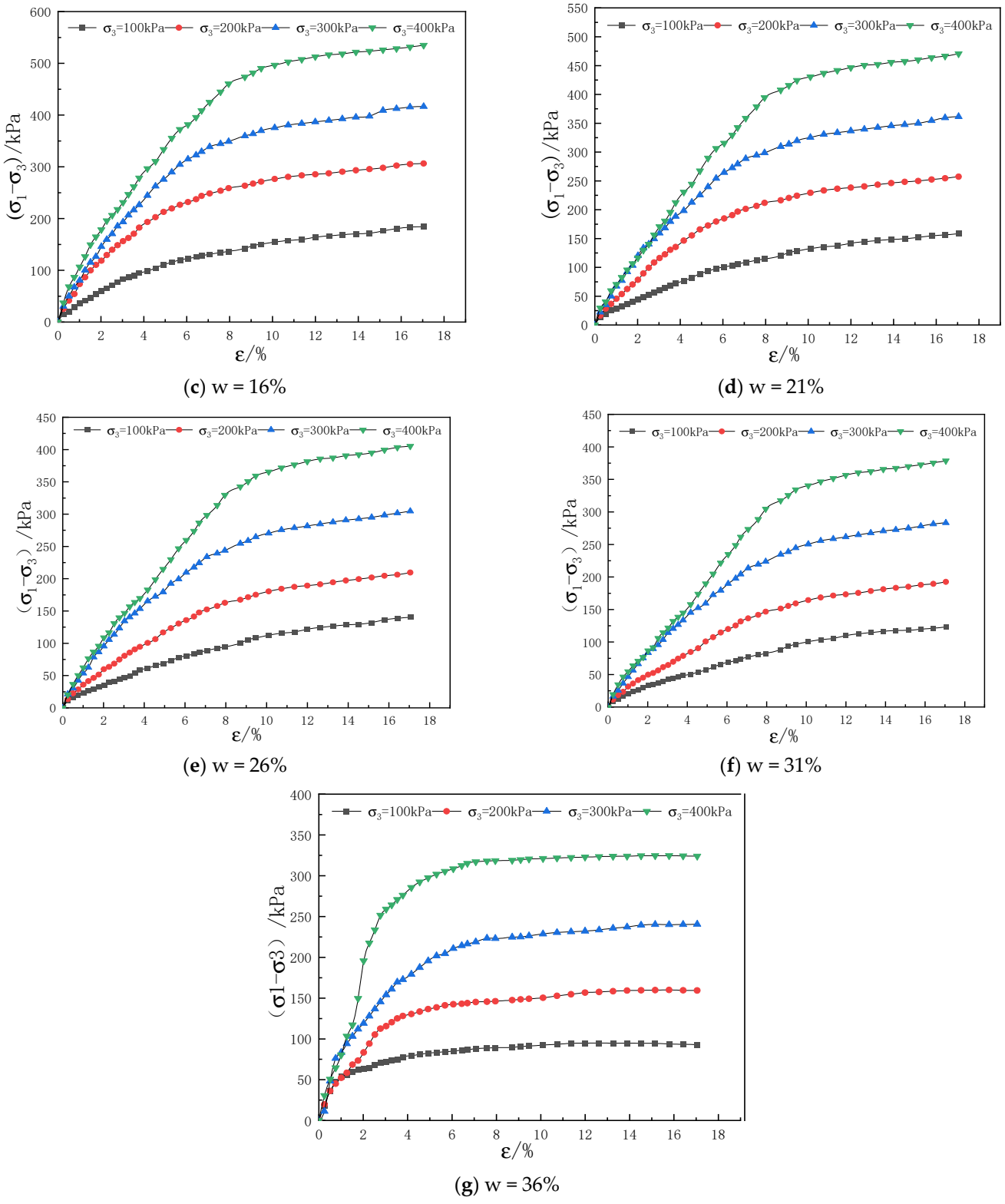


Figure 2. Stress strain curves of remolded loess under different confining pressures.

3.2. Analysis of Structural Changes in Loess Soil Samples

3.2.1. Relationship Between Confining Pressure and Structural Parameter

Generally, an increase in consolidation pressure leads to a reduction in the variability of loess structure and an enhancement in structural stability when the soil is compacted. However, the asynchronous nature of these effects—faster reduction in variability and slower increase in stability—results in an overall weakening of the soil's structural perfor-

mance as pressure increases. Nevertheless, if the soil initially possesses strong structural strength and low consolidation pressure is insufficient to compromise this strength, the increase in consolidation pressure can have dual effects: it can enhance the soil's structural stability through densification while simultaneously increasing the variability of the soil structure due to particle movement and colloid damage [34–37]. Shear stresses, however, predominantly reduce structural stability, facilitating the destruction of initial structural strength and the manifestation of variability.

According to the triaxial test, the shear strength of undisturbed soil samples with different moisture content and saturated remolded soil was obtained, and then its value was substituted into Formula (1) to obtain the corresponding structural parameter values. The calculation process and results are shown in Table 4, which is plotted as the change trend of the structural parameter with confining pressure, as shown in Figure 3.

Table 4. Shear Strength Values and Structural Parameter Values of Soil Samples with Different Moisture Contents under Various Confining Pressures.

w (%)		6%	11%	16%	21%	26%	31%	36%
100	τ_o(kPa)	153.38	142.22	110.91	111.52	94.78	87.32	84.12
	τ_{rs}(kPa)				43.58			
	m_τ	3.52	3.26	2.87	2.56	2.17	2.00	1.93
200	τ_o(kPa)	255.82	236.16	180.7	190.79	168.75	158.7	154.25
	τ_{rs}(kPa)				79.31			
	m_τ	3.22	2.98	2.64	2.41	2.13	2.00	1.94
300	τ_o(kPa)	354.89	324.27	245.68	268.12	239.04	229.55	223.08
	τ_{rs}(kPa)				116.67			
	m_τ	3.04	2.78	2.48	2.30	2.05	1.97	1.91
400	τ_o(kPa)	444.61	415.37	319.22	344.5	312.57	299.03	290.36
	τ_{rs}(kPa)				154.38			
	m_τ	2.88	2.69	2.44	2.23	2.02	1.94	1.88

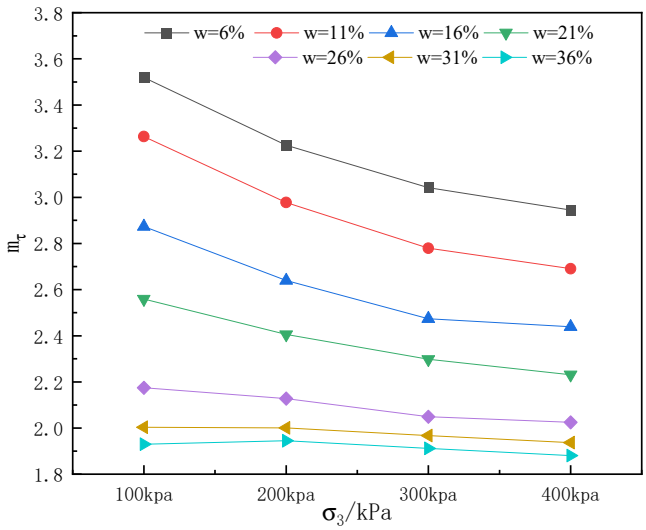


Figure 3. Variation curves of the structural parameter with confining pressure for specimens with different moisture contents.

It can be seen from Figure 3 that the structural parameter of the soil samples with different moisture contents gradually decreases with the increase of the perimeter pressure. The reduction in the structural parameter is relatively large at lower boundary pressures, while the reduction in structural parameter is smaller at higher boundary pressures. The reason for this phenomenon is that when the circumferential pressure is small, the squeezing effect of the circumferential pressure on the soil samples is weaker, and the structure of the soil body is looser, so it has stronger structural properties. After the boundary pressure increases, the initial structure of the soil sample is destroyed during consolidation, i.e., the primary structure is rapidly destroyed at low strains. In the process of increasing deformation in the later stage, the internal particle arrangement and cementation structure are continuously adjusted, and the soil samples gradually form a certain secondary structure under the compacting effect of high peripheral pressure. At this time, the strength of the primary structure is reduced, but the healing of the soil structure presents a dominant role due to the formation and slow increase in strength of the secondary structure, so that the magnitude of changes in the structural parameter of soil samples after large perimeter pressures and strains is significantly reduced. In the later stages of the change, the formation of secondary structures in the soil inhibits the further weakening of the soil structural properties by the structural damage factors, allowing the parameters of the structural properties to stabilize with strain.

3.2.2. Relationship Between Moisture Content and Structural Parameter

In loess engineering, moisture content is generally considered to be a broad force that weakens and dissolves the chemicals in the soil, weakening the structural properties of the loess as the moisture content increases. Loess is particularly sensitive to water. Once immersed or even moistened, there is a significant reduction in strength and a significant increase in deformability [38,39].

The shear strength values of undisturbed and reshaped saturated soil samples with different moisture contents and the structural parameter of soil samples with different moisture contents are shown in Table 4, and the change trend of the structural parameter with moisture content is shown in Figure 4.

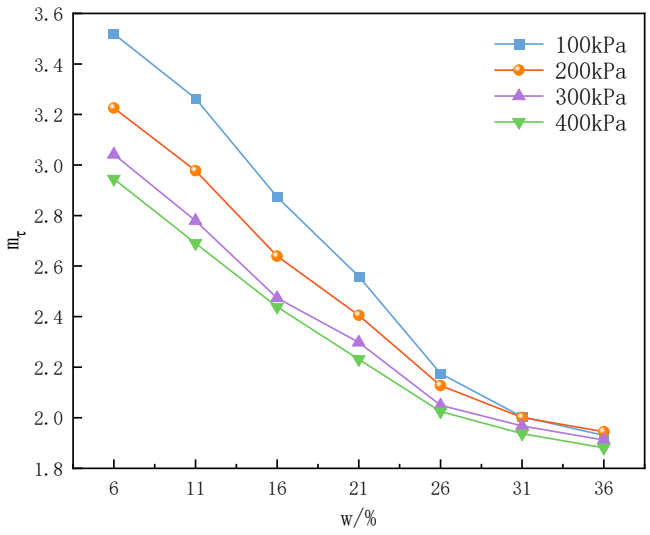


Figure 4. Variation curves of structural parameter with moisture contents.

It can be seen from Figure 4 that under the condition of controlling variables, the influence law of moisture content on soil structural properties is basically similar to that of perimeter pressure on soil structural properties, i.e., the value of the structural parameter

of loess gradually becomes smaller with the increase of moisture content. The structural parameter as a whole decreases with increasing moisture content, and the lower the moisture content, the higher the corresponding structural parameter at the same pressure. The magnitude of decrease in the structural parameter is greater at lower moisture content intervals, while the magnitude of change in the structural parameter decreases significantly as the moisture content increases to a saturated moisture content (36%). This suggests that for undisturbed loess, changes in moisture content have the most dramatic effect on loess structural properties at low moisture content intervals, and that a small increase in moisture content in this region can lead to a sudden decrease in loess structural properties. The structural nature of the undisturbed loess was effectively destroyed at higher moisture contents, when the sensitivity of the structural parameter to changes in moisture content and pressure was greatly reduced.

As a result of long-term physicochemical action, loess has developed a structure of porous and vertical joints and the formation of carbonate-based cementing material between soil particles, which not only gives it strong structural properties but also makes it particularly sensitive to water. The underlying causes of the above phenomenon are as follows. ① The cementing material in loess is dominated by soluble carbonates, and the water in loess causes some of the cementing material between particles to dissolve, weakening the cementing effect. This resulted in a reduction in the strength of the cementitious bonds between the soil particles, and this weakening effect continued to increase with increasing moisture content, with a significant reduction in the strength of the soil samples. ② As the moisture content increases, the bonded water film between the particles thickens. At this time, the sample may change from strong bonded water association to weak bonded water association until free water appears, the bond strength is reduced, and the thickening of the bonded water film reduces the friction between particles, which ultimately leads to the weakening of the soil samples [40]. ③ An increase in the moisture content of the soil will result in a decrease in matrix suction, leading to a weakening of the mosaic between soil particles and a reduction in the strength of the soil sample. Based on the new definition of the structural parameter, it was discovered that the reduction in strength of the undisturbed soil samples resulted in a decrease in the structural parameter, which is consistent with the test results.

3.2.3. Relationship Between Dry Density and Structural Parameter

Soil is a collection of loose particles, and the connections between soil particles are much smaller than the connections between the particles themselves, so the strength of the soil is mainly determined by the interaction force between soil particles. Different dry densities of the same loess determine the size of the pore ratio and thus the force between particles. From another point of view, dry density also determines the degree of occlusion between soil particles. Dry density is one of the factors that influence the structural properties of the soil. The increase in density reduces the structural variability of the loess and increases its structural stability. The combined effect of these two factors ultimately results in structural changes.

According to the triaxial test, the shear strength of undisturbed soil samples with different dry densities and saturated remolded soil was obtained, and their values were substituted into Formula (1) to obtain the corresponding structural parameter values. The calculation process and results are shown in Table 5, which is plotted as the change trend of structural parameter with dry density, as shown in Figure 5.

Table 5. Shear Strength Values and Structural Parameter Values of Soil Samples with Different Dry Densities under Various Confining Pressures.

ρ_d (g/cm^3)		1.28	1.35	1.36	1.41	1.42
100	τ_o(kPa)	135.61	141.33	142.22	147.02	148.99
	τ_{rs}(kPa)	37.88	40.15	43.58	48.52	50.85
	m_τ	3.52	3.52	3.26	3.03	2.93
200	τ_o(kPa)	220.15	233.58	236.16	256.39	254.02
	τ_{rs}(kPa)	66.31	72.54	79.31	94.26	95.14
	m_τ	3.32	3.22	2.98	2.72	2.67
300	τ_o(kPa)	292.91	320.36	324.27	341.73	339.86
	τ_{rs}(kPa)	96.67	105.38	116.67	130.43	133.28
	m_τ	3.03	3.04	2.78	2.62	2.55
400	τ_o(kPa)	414.12	420.05	415.37	430.37	430.97
	τ_{rs}(kPa)	140.38	145.85	154.38	170.78	175.19
	m_τ	2.95	2.88	2.69	2.52	2.46

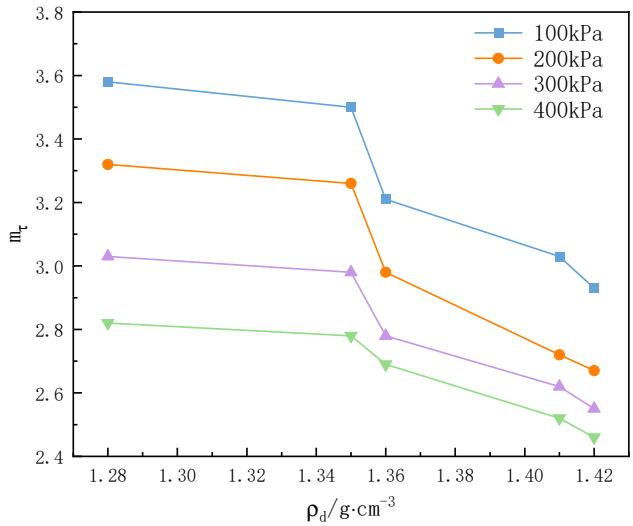


Figure 5. Variation curves of structural parameter with dry density.

As can be seen in Figure 5, the structural parameter decreases with increasing dry density. At low circumferential pressures (100~200 kPa), the structural parameter varies more with dry density and is highly sensitive to dry density. At high circumferential pressures (300~400 kPa), the structural parameter varies less with dry density and is less sensitive to dry density. Soils with low dry density have high pore ratios, low compaction, and higher structural stability corresponding to the particle bonding characteristics and structural variability corresponding to the particle arrangement characteristics of the soil. The combined structural potential released by the soil body under load, immersion, and disturbance is large, and the loss of structural strength corresponds to a large structural parameter. When the dry density of the loess is relatively high, the loess is more stable, the variability has been relegated to a secondary position, the void between the particles of the soil body is small, and the strength of the connection between the particles is low. At this time, the particle arrangement of the soil body is in a relatively stable state and the loess is weakly structured, corresponding to a small structural parameter. Overall, changes in loess dry density have a greater effect on loess structural variability than on stability. Therefore,

with the increase of dry density, the weakening of structural variability is greater than the strengthening of structural stabilization in the corresponding situation, and the structural properties of loess are also weakened from strong to weak accordingly.

3.3. Quantitative Evaluation of Structural Influencing Factors

In this section, based on the study of the influencing factors on the structural properties of loess, the coefficient of variation method is used to statistically analyze the data on the structural parameters of each sample. This can further clarify the degree of influence of each influencing factor on the structural properties and finally determine the weights occupied by each factor.

3.3.1. Concept of Coefficient of Variation Method

The coefficient of variation, that is, the coefficient of standard deviation, reflects the total unit sign value, the degree of difference, or the degree of dispersion, and is one of the indicators used to reflect the distribution of data. The coefficient of variation is a relative dimensionless quantity, reflecting the degree of dispersion in the unit mean, so it is more convenient for practical application. In probability theory and statistics, the coefficient of variation [16,17] is a statistical indicator that measures the difference in the degree of variation of various observed values in data. It describes the degree of deviation of the measurement results, and its formula is:

$$V_i = \frac{s_i}{\overline{x_i}} (i = 1, 2, \cdots, n) \tag{4}$$

In Equation (4), V_i is the coefficient of variation of item i, also known as the standard deviation coefficient; s_i is the standard deviation of item i; and x_i is the mean of item i.

The formula for calculating the weight of each indicator, W_i, is shown in Equation (5):

$$W_i = \frac{V_i}{\sum_{i=1}^{n} V_i} \tag{5}$$

3.3.2. Calculate the Weight of Structural Factors

In this section, the different levels under each factor are first analyzed for weights to determine the weights that each factor individually contributes to a particular level. The factors are then aggregated to calculate the weight assigned to a particular factor.

- Moisture content

The structural parameters of the specimens with different moisture contents at each circumferential pressure were plotted and are shown in Table 6.

Table 6. Structural Parameters of Specimens with Different Moisture Contents at Different Boundary Pressures.

Confining Pressure	Structural Parameters of Soil Samples with Different Moisture Contents						
	6%	11%	16%	20%	26%	31%	36%
100 (kPa)	3.5	3.26	2.87	2.48	2.17	2.02	1.91
200 (kPa)	3.21	2.98	2.64	2.38	2.13	2.01	1.86
300 (kPa)	3.03	2.78	2.47	2.29	2.07	1.98	1.84
400 (kPa)	2.93	2.71	2.44	2.23	2.03	1.94	1.83

Calculate the coefficient of variation and weight value of different moisture contents under this factor using Formula (2) and Formula (7), respectively, as shown in Table 7.

Table 7. The Weight of Soil Samples with Different Moisture Contents Under Various Confining Pressures.

Moisture Content	6%	11%	16%	20%	26%	31%	36%
coefficient of variation	0.019	0.018	0.03	0.047	0.076	0.079	0.084
weight value	0.054	0.051	0.084	0.132	0.215	0.224	0.239

As can be seen in Table 4, the lowest weight value is assigned when the moisture content is 11% (natural moisture content) and the highest weight value is assigned when the moisture content is 36% (saturated moisture content). This point proves that when the moisture content is low, the dissolving effect of water on the cementing material in the soil is weak, the bond between the soil particles is strong, and the coefficient of variation is small. On the other hand, when the moisture content is high, the dissolving effect of water on the cementing material is strong, so the bond between the soil particles is weakened, the coefficient of variation gradually increases, and the effect of water on the structural properties is enhanced. The data in Table 4 show that the weight value occupied by each moisture content rate of soil samples with higher moisture content is generally higher than that occupied by soil samples with lower moisture content, which indicates that the dissolving effect of water immersion on the internal cementing material of soil samples is greater than the change in the structure of soil samples by water loss and contraction, which fully reflects the characteristics of the weakened structure of loess in contact with water.

- Dry density

Create a table showing the structural parameter values of soil samples with different dry densities under different confining pressures, as shown in Table 8.

Table 8. Structural Parameters of Specimens with Different Dry Densities at Different Confining Pressures.

Confining Pressure	Structural Parameters of Soil Samples with Different Dry Densities				
	1.28 g/cm^3	1.35 g/cm^3	1.36 g/cm^3	1.41 g/cm^3	1.42 g/cm^3
100 (kPa)	3.58	3.5	3.21	3.03	2.93
200 (kPa)	3.32	3.26	2.98	2.72	2.67
300 (kPa)	3.03	2.98	2.78	2.62	2.55
400 (kPa)	2.82	2.78	2.69	2.52	2.46

Calculate the coefficient of variation and weight value of different dry densities under this factor using Formula (2) and Formula (7), respectively, as shown in Table 9.

Table 9. The Weight Value of Soil Samples with Different Dry Densities under Various confining pressures.

Dry Density	1.28 g/cm^3	1.28 g/cm^3	1.28 g/cm^3	1.28 g/cm^3	1.28 g/cm^3
coefficient of variation	0.104	0.101	0.079	0.081	0.077
weight value	0.236	0.228	0.179	0.183	0.174

As can be seen from Table 6, the coefficient of variation and weight value decrease overall with increasing dry density, except for a slight increase for the soil sample with a dry density of 1.41 g/cm^3. This indicates that soil samples with lower dry densities have a larger coefficient of variation and higher weight value compared to soil samples with higher dry densities, which have a greater effect on the structural properties of the soil. The

reason for this is that the structure of the soil sample with a smaller dry density is loose, the structural variability is stronger, and the stability is weaker, so the structural properties are also stronger, and the influence of external forces on the structural properties is larger. Meanwhile, when the dry density is larger, the soil sample is relatively dense, the structural properties of the soil body are weaker, and the influence of external forces on the structural properties of the soil body is also smaller.

- Confining pressure

Calculate the weight values of different confining pressures under the influence of moisture content using Formulas (1) and (7), as shown in Table 10.

Table 10. The Weight Value of Different Confining Pressures under the Influence of Moisture Content.

Confining Pressure	100 kPa	200 kPa	300 kPa	400 kPa
coefficient of variation	0.24	0.206	0.185	0.179
weight value	0.299	0.255	0.229	0.22

As can be seen from Table 7, the coefficient of variation gradually decreases with the increase of the confining pressure. When the circumferential pressure is small, the structural property of soil samples can be realized, and the coefficient of variation reaches the maximum value at this time, which occupies the largest weight value, and the effect of this level of pressure on the structural property is also the most significant. After that, as the circumferential pressure continues to increase, the coefficient of variation gradually decreases and the occupied weight value also decreases accordingly, which proves that the influence of the circumferential pressure on the structural property is weakened.

Calculate the weights of different confining pressures under the influence of dry density using Formulas (1) and (7), as shown in Table 11.

Table 11. The Weight Value of Different Confining Pressures under the Influence of Dry Density.

Confining Pressure	100 kPa	200 kPa	300 kPa	400 kPa
coefficient of variation	0.088	0.1	0.076	0.06
weight value	0.271	0.309	0.235	0.185

From Table 8, it can be seen that when the circumferential pressure is small, the coefficient of variation is larger and occupies a higher weight value, which has a greater influence on the structural properties. When the circumferential pressure is 200 kPa, the coefficient of variation reaches the maximum value and the occupied weight value is the largest, which has the greatest influence on the structural properties. After that, the coefficient of variation and the weight value gradually decrease with the increase of the circumferential pressure, and the influence on the structural property is weakened.

3.3.3. The Weight Values of Each Influencing Factor

Calculate the weights of each factor using Formulas (1) and (7), as shown in Table 12.

As can be seen from Table 8, the moisture content has the largest coefficient of variation and the largest weight value, and the structural parameters with different moisture contents have a range from 1.83 to 3.5, with an extreme deviation of 1.67, a coefficient of variation of 0.579, and a weight value of 0.51. This indicates that the structural parameters of loess vary

more under the influence of different moisture contents, and that the data are extremely well dispersed and have a greater influence on the structural properties. On the other hand, the structural parameters of different dry densities are relatively steady, with a range of 2.46 to 3.58 and an extreme value difference of 1.12. This is significantly weaker than the influence of moisture content, with a coefficient of variation of 0.268 and a weight value of 0.236, which is much smaller than the extent of influence of moisture content on structural properties. The degree of influence of the confining pressure on the structure lies between these two.

Table 12. The Weight Values of Different Influencing Factors.

Interfering Factor	Confining Pressure	Moisture Content	Dry Density
coefficient of variation	0.288	0.579	0.268
weight value	0.254	0.51	0.236
ranking of evaluation indicators	2	1	3

4. Discussion

The mechanical properties of soils in general are closely related to their grain size, density, moisture content, and structure. The mechanical properties of soils with different structures are different and result from the influence of factors inherent in the structural nature of the soil. Soil particle size refers to the degree of coarseness or fineness of the soil particles and includes not only the particle gradation of the soil, but also the mineralogical composition associated with the fine particle size [38]. Fine-grained soils can be described quantitatively by the liquid and plastic limits and the plasticity index. Soil density refers to the degree of compactness of the soil, which can be described quantitatively by dry density, void ratio, porosity, and specific volume; soil moisture refers to the degree of moisture content of the soil, which can be described quantitatively by moisture content, saturation, and other indicators.

4.1. Relationship Between Structural Parameter and Density

Soil density is a class of indicators that reflect the relative mass and volume content of the soil's three-phase material. When there are only solid and gas phases in the soil, the density of the soil is called the dry density, which reflects the mass of the soil particle skeleton per unit volume of soil. The dry density of the soil includes the effect of the material composition of the soil particles. In addition to dry density, void ratio and porosity also reflect the compactness of the soil. The pore ratio is the size of the pore volume gap per unit volume of soil particles, and its reciprocal is the volume of soil particles per unit volume of pore space. Together they give a fuller picture of the tightness of the soil's skeleton. The lower the dry density of the soil, i.e., the higher the pore ratio, the more unstable the particle arrangement and association. The changes in soil structure after disturbance and immersion are more pronounced, with the soil showing stronger structure and greater structural parameter.

To reveal the effect of soil density on its structural properties, the relationship between the structural parameter and the ratio of dry density and pore ratio was analyzed by reflecting the dry density of soil per unit volume of soil particle mass and the volume of soil particles corresponding to unit pore volume to synthesize the degree of soil compaction, as shown in Figure 6. It shows that the structural parameter of loess with different moisture contents generally show a decreasing trend with an increasing ratio of dry density to pore space ratio. The lower the dry density of the soil, the higher the pore ratio, the

greater the changes in the arrangement and association characteristics of the soil skeletal particles subjected to the effects of immersion and disturbance, and the greater the structural parameter of the soil. The greater the dry density of the soil, the smaller the pore ratio, the less the changes in the arrangement and association characteristics of the skeletal particles subjected to the effects of immersion and disturbance, and the smaller the structural parameter of the soil.

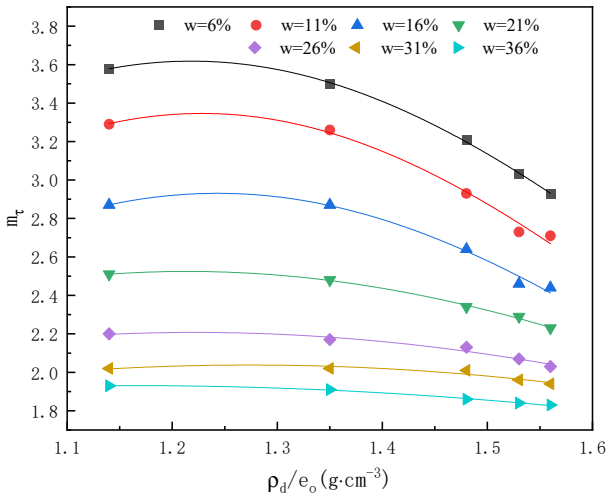


Figure 6. Variation of structural parameter with ratio of density to void ratio.

Figure 6 also shows that the structural parameters are more discrete with respect to the pattern of change in the dry density and pore ratio ratios. Given the same soil source and moisture content, the structural parameters of loess are affected not only by dry density and void ratio, which reflect soil compactness, but also by other physical properties of loess.

4.2. Relationship Between Structural Parameter and Particle Size

Loess is a fine-grained soil, and the moisture content has a very important effect on its mechanical and strength properties. The plastic limit of soil is an index of the soil reaching the plastic state. The liquid limit of soil is the moisture content of the boundary of the soil required to reach the liquid-plastic state. The plasticity index is the range of change between the upper and lower limits of the plastic state of soil, which mainly reflects the water-holding capacity of soil particles. The finer the soil grain, the greater the ability to absorb and hold water, and the greater the plastic limit, liquid limit, and plasticity index of the soil. The structural parameter m_τ is closely related to the strength of loess. When the moisture content of the soil is close to the plastic limit, the soil is prone to plastic deformation, and the loess suffers less sensitivity to the effects of immersion and therefore less structural parameter. When the natural moisture content of loess is less than the plastic limit, the sensitivity of loess to soaking increases. Therefore, the difference between plastic limit and natural moisture content of loess soil samples was taken to investigate the effect of plastic limit on the structural properties of loess. The difference in moisture content is defined as follows:

$$\Delta w = w_p - w \tag{6}$$

Based on the test results of the structural parameter m_τ with moisture content in Section 3.2.2, the relationship between m_τ and moisture content difference was analyzed, as shown in Figure 7. The pattern of change of structural parameters with moisture content difference for different depths of Weinan loess samples from loess 1 to loess 5 shown in Figure 7 is approximately the same. The greater the difference between the plastic limit and the moisture content, the greater the value of m_τ; conversely, the smaller the value

of m_τ. When the moisture content is less than the plastic limit, the value of the structural parameter of loess is greater. The lower the plastic limit of the soil sample, the larger the slope of the change curve of moisture content difference with structural parameters, and the smaller the range of structural parameters. On the contrary, the smaller the slope of the change curve of moisture content difference with structural parameters, the smaller and larger the change range of structural parameters.

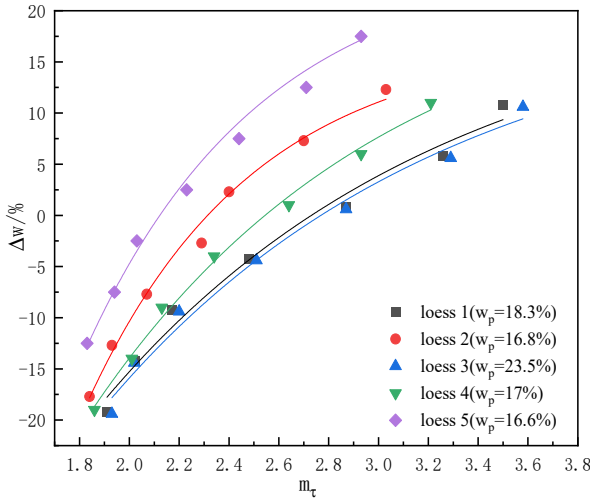


Figure 7. Variation of structural parameter with difference between plastic limit and natural moisture content.

A comparison of the structural parameters of the five soil samples as a function of the difference between the plastic limit and the moisture content is shown in Figure 8. It can be seen from Figure 8 that the growth rate of m_τ with decreasing moisture content is smaller when the difference between plastic limit and moisture content is less than 7.5%. The growth rate of m_τ with decreasing moisture content is greater when the difference between the plastic limit and moisture content is greater than 2.5%. At the same time, the test results of the change pattern of m_τ with the difference of plastic limit and moisture content are more discrete. This shows that there are other factors besides moisture content (such as differences in density and structure of different loess) that can affect structural properties.

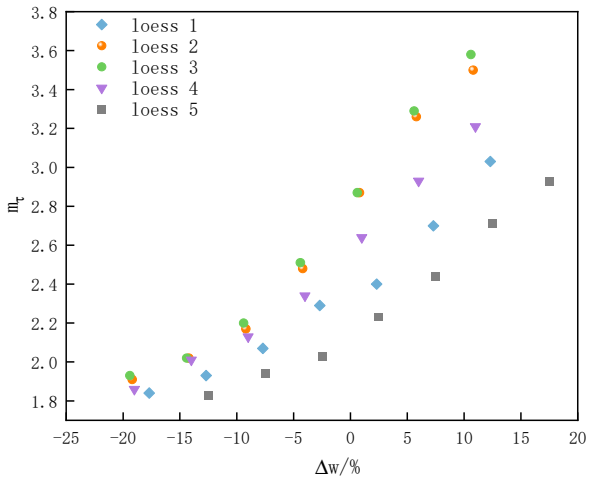
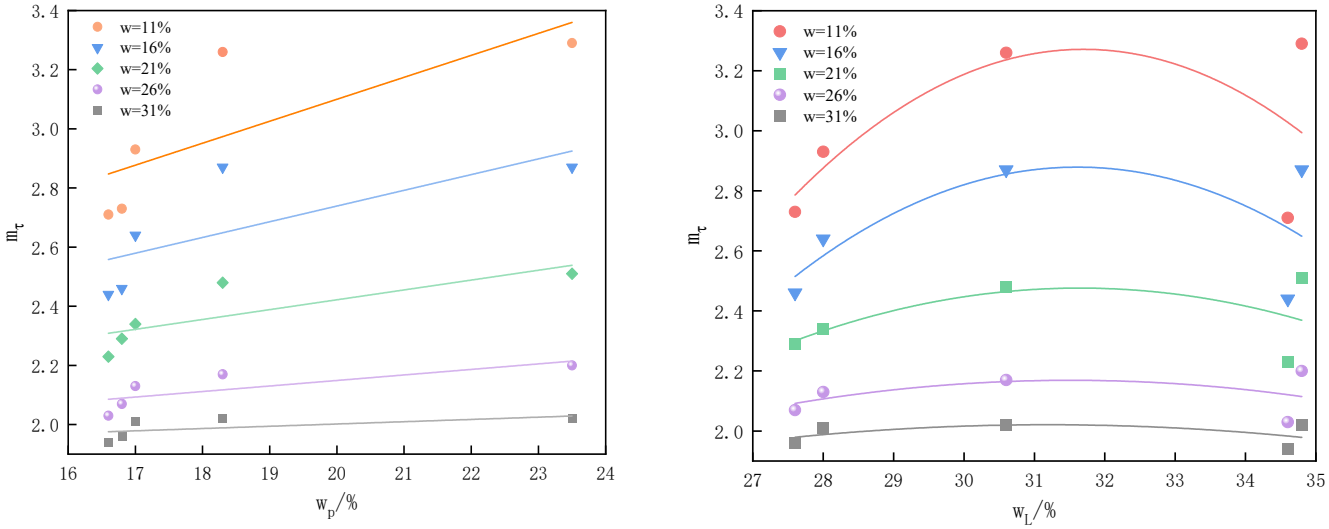


Figure 8. m_τ-Δw of different loess samples.

To consider the effect of plastic limit and liquid limit on the structural properties, the test results of the variation of the structural parameters of plastic limit and liquid limit soils

under different moisture content conditions are analyzed in Figure 9. It can be seen from Figure 9a that the structural parameters of loess generally show a monotonically increasing rule of change with increasing plastic limit. As can be seen from Figure 9b, the increase of liquid limit of structural parameters presents a non-monotonic change rule.



(**a**) relationship curve of m_τ-w_p (**b**) relationship curve of m_τ-w_L

Figure 9. Variation of structural parameter with plastic and liquid limits.

4.3. Relationship Between Structural Parameter and Consistency State

Soil Consistency: The Liquidity Index combines the effects of soil moisture and grain size. The variation of the soil structural parameters with the liquidity index is shown in Figure 10. It can be seen from Figure 10 that the soil structural parameters gradually decrease with the increase of the liquidity index. The structural parameters of soil are relatively large when the liquid index of soil is less than zero, and the structural parameters of soil are relatively small when the liquid index of soil is greater than zero. However, when the liquidity index is similar, there are still significant differences in the structural parameters of different loess soil samples, and the distribution of their structural parameter values is relatively scattered and not concentrated in a single variation area. This proves that besides humidity and particle size, there are other factors that affect the structural characteristics of loess, which is consistent with the research results of this article.

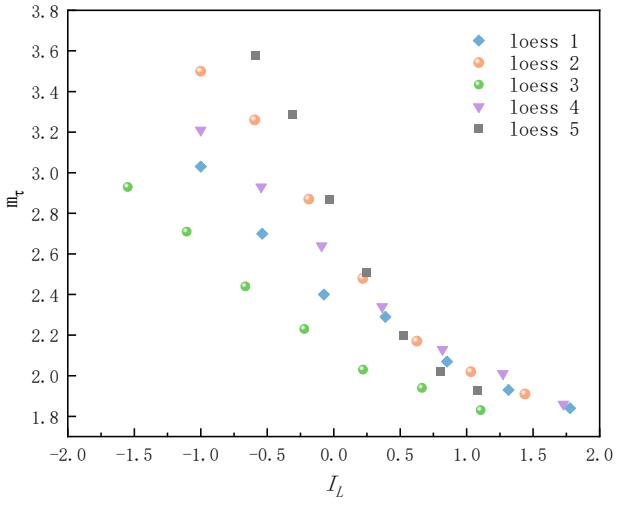


Figure 10. Variation of structural parameter with liquidity index.

5. Conclusions

(1) The arrangement of soil particles and the intergranular associations of the soil skeletal structure are stabilized against external loads and variables against damage. Based on the ratio of undisturbed soil shear strength and saturated remodeled soil shear strength, the stabilizability and variability of loess structures are integrated. The established structural parameter mainly includes immersion sensitivity and disturbance sensitivity, revealing the change rule of immersion sensitivity and disturbance sensitivity. The soaking sensitivity of loess varies greatly with natural moisture content, while the disturbance sensitivity varies less with natural moisture content, reflecting the water sensitivity of loess.

(2) The structural characterization parameters given in this paper are defined in terms of shear strengths of undisturbed soil and remodeled saturated soils, which at once releases the integrated structural potential of the soil and reflects the strength characteristics and essential properties of the soil. The structural parameters of loess gradually decrease with the increase of confining pressure (consolidation pressure), moisture content, and dry density. The quantitative analysis of the influencing factors of the structural parameters led to the conclusion that the moisture content has the greatest influence on the structural properties, the dry density has the least influence, and the degree of influence of the peripheral pressure is in the middle.

(3) The effects of grain size, density, and moisture on the structural properties of loess were revealed by analyzing the relationships between the structural property parameters and the ratio of dry density to porosity ratio, between the structural property parameters and the difference between the plastic limit and moisture content, between the structural property parameters and the liquid and plastic limits, and between the structural property parameters and the liquidity index. It is shown that the structural property decreases with the increase of the ratio of dry density and porosity with the increase of the difference between plastic limit and moisture content; increases with the increase of the plastic limit; and, at low moisture content, shows a peak variation curve relationship with the increase of the liquid limit. The correlation between them shows that the new structural parameters of loess can comprehensively reflect the physical properties, such as particle size, density and moisture; the discrete nature of the different correlations between them indicates the structural differences in the arrangement of soil particles in the soil skeleton and the intergranular association characteristics.

(4) A physical characterization measure that integrates particle size, density, and moisture has been established by the liquidity index, dry density ratio, and pore ratio. Under the condition of approximate consistency of dry density, there is a monotonically varying relationship between the parameters of structural properties of loess and the integrated physical characteristic quantities. This indicates both that the liquid-plastic limit, moisture content, dry density, and pore ratio of loess, as reflected by grain size, density, and moisture, have a significant effect on its structural properties, and that loess with the same degree of conformation may have different indices of grain size, density, and moisture properties.

(5) The particle size, density, moisture content, and structural properties of soils are inherent indicators of their material composition and state characteristics, which are used to characterize the mechanical properties of soils and their patterns of change. Structural parameters are quantitative indicators of the structural properties of the soil body, which are related not only to the composition and state of the soil material in terms of grain size, density, and moisture, but also to the characteristics of the spatial arrangement of soil particles in the soil skeleton structure and intergranular associations. This proves the reliability and rationality of the structural parameters proposed in this paper.

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