Analysis of water sensitivity and microstructure for silt in Zhengzhou area

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Abstract; In order to study the evolution mechanism of Zheng Han Gu Cheng, direct shear tests and disintegration test were carried out by using the scattered soil of Zheng Han Gu Cheng to prepare the samples with different water content, and the microscopic mechanism of water sensitivity characteristics for silt was analyzed by field emission scanning electron microscope. The test results show that the stress-strain curve of silt behaves as hardening type based on different water content, and with the increase of water content, the shear stress increases first and then decreases, and reaches the maximum at the optimum water content. The variation on shear strength with water content is consistent with that of shear stress. With the change of water content, the cohesion reaches its peak at the optimum water content, while the internal friction angle changes little, and the difference is about 1.7 degrees. With the increase in water content, the disintegrating rate of specimen decreases gradually due to the influence of water film. From the SEM images of different water content, it can be seen that silt has the least pore size, dense grain arrangement and mosaic structure under the optimum water content, which greatly improves the strength of soil samples. With the change of water content, the micro-structure of soil gradually develops from loose structure of dense structure, then to mosaic mechanism, and finally to directional arrangement structure. The above research results can provide a theoretical basis of the protection and reinforcement of ancient city walls.

1. Introduction

In recent years, the protection of city walls, various sites and other cultural relics has been paid more and more attention by the academic circles. The city walls and other sites not only have cultural, historical and scientific value, but also are the symbol of the spiritual civilization of the Chinese nation [1]. He-Nan is a large province of cultural relics, the city wall earthen sites are widely distributed in the impact plain area of the Yellow River in He-Nan Province. The main structure of the city wall is silt. Silt refers to particles with particle size greater than 0.075mm, whose content does not exceed 50% of the total mass and plastic index is less than 10. Its characteristics are mainly silt, low bonding force and low plastic index. The water sensitivity of silt is strong, which shows the phenomenon of decomposition and collapse in the event of water humidification. Due to its special geographical location and the special engineering nature of silt, the rainy season is often eroded by rainwater, which makes the wall prone to cracks, collapses, root erosion and other diseases [2]. Therefore, it is of great significance to study its water sensitivity characteristics and physical and mechanical properties in depth.

Many scholars have made a thorough inquiry into the characteristics of silt. Tan et al. [3], Xiao et al.
[4], Zhang et al. [5], the effects of different water content on the strength indexes and deformation character of silt were discussed through laboratory experiments, and the results showed that the moisture content had a significant effect on the shear strength index, especially the effect on the adhesion force was obvious, and the adhesion force at the optimal water content was the greatest. Liu et al. [6], through the collapse, penetration and so on tests to study disintegration, permeability of silt, the results show that its water sensitivity characteristics have a direct impact on its strength, physical properties. There is an interdependent dialectical relationship between the macroscopic characteristics of soil and microstructure, the macroscopic physical and mechanical properties of soil are influenced by its microstructure in essence, and the evolution mechanism of microstructure is embodied in the macroscopic deformation of soil [7-8]. Therefore, it is very important to study the microscopic evolution mechanism of soil to reveal its macroscopic deformation characteristics. Zhou et al. [9], the microstructure of low liquid limited powder soil was studied by X-ray diffraction test and SEM test, and the morphological distribution and coupling form of soil composition and particles were analyzed from two aspects of mineral composition and microstructure. Zhang et al. [10], on the basis of SEM test, the strength of different freeze-thaw circulating powdery clay was analyzed, and the microscopic structure of soil microstructure images was quantitatively studied to study the microscopic evolution mechanism between freeze-thaw cycles and intensity. The above research is a profound summary of the characteristics of silt, which provides a basis for the future research of silt, and has a guiding effect on its engineering application. However, silt has typical regional characteristics, so it is very meaningful to carry out regional research.

Taking the scattered soil of Zheng Han Gu Cheng wall as the research object, this paper emphatically discusses the influence law and disintegrating effect of different water content on the strength parameters of silt, and uses field emission scanning electron microscope to analyze the water sensitivity characteristics of soil particles from the shape and arrangement of microstructure.

2. Test materials and schemes

2.1. Physical and Mechanical Properties of Silt

The soil used in this experiment was taken from the scattered soil of Zheng Han Gu Cheng wall in Xinzheng City, and its basic physical properties were obtained according to the Geotechnical test method standard (GB/T 50123-1999) [11], as shown in Table 1. X-ray diffractometer is used for qualitative and quantitative analysis of minerals in the returned soil samples. The X-ray diffractometer adopts the CBO cross-optical system originally invented by Japanese Neo-Confucianism Company. The equipment can accurately study multi-crystals such as powder samples and bulk samples. Test method: (1) air-drying the soil sample and grinding it into powder, (2) placing the sample on the sample plate, pressing it with the compact plate, (3) putting it into the diffractometer for diffraction test. The results of mineral analysis are shown in Table 2. As can be seen from Table 2, the mineral composition of the wall silt includes primary minerals and clay minerals, of which the primary mineral content is 79.5% (including quartz, feldspar and calcite) and clay mineral content is 20.5% (including illite, kaolinite and montmorillonite).

| Liquid limit /% | Plastic limit /% | Plasticity index | Proportion |
|----------------|-----------------|------------------|------------|
| 27.7           | 18.45           | 9.25             | 2.68       |

Table 2 Mineral content

| Primary mineral /% | Total amount of clay |
|--------------------|----------------------|
Quartz  |  Feldspar  |  Calcite  |  minerals /%
--- | --- | --- | ---
44.3  |  27.8  |  7.4  |  20.5

2.2. Compaction characteristics of silt
The relationship between dry density and water content was measured by wet soil compaction test as shown in Figure 1. As can be seen from Figure 1, the maximum dry density of soil is 1.82 g/cm³, the optimal water content is 14.2%, and the compaction curve shows an obvious asymmetric shape. With the optimal water content as the boundary, the dry density on the left side of the optimal water content increases slowly with the increase of water content, exceeding the optimal water content, and the dry density decreases rapidly with the increase of water content, showing a strong water sensitivity. In the compaction process, the soil sample is loose and easy to splash out from the cylinder at low water content, and the surface layer is easy to peel. At high water content, the soil sample has too much water and overflows from the bottom of the cylinder, which makes it difficult to compact. This is consistent with the results of Xiao [4].

Fig. 1 Compaction curve of silt

2.3. Test scheme
Considering the influence of water content on silt and the compaction degree of wall body, silt samples with different water content (4.8%, 7.9%, 11.1%, 14.1%, 16.7%, 20.2%) under 1.75 g/cm³ dry density were prepared for direct shear test. The main steps of the experiment are as follows: the soil samples with different water content were put into the straight shear box in turn, and consolidated under 50, 100, 200 and 400 kPa axial pressure. After consolidation, shear was carried out at a rate of 2.4 mm/min and the shear stop was based on the shear deformation of the sample to reach 6 mm. When the peak value of shear stress is uncertain with the increase of shear displacement, the shear stress of 4 mm shear displacement is taken as the shear strength. In order to ensure the accuracy of the test, at least three repeat tests were carried out in each group of specimens, and the moisture content of the shear surface was checked after the test, and the error was controlled at 0.5%.

3. Results and analysis of direct shear test

3.1. Analysis of stress-strain characteristics of different water content
The stress-strain relationship curve of silt and the relationship curve between shear strength and water content can be obtained by direct shear test (limited to length, taking normal stress of 100kPa as an example). Fig. 2 is the stress-strain relationship curve, fig. 3 is the relationship curve between water content and shear strength, and table 3 is the fitting equation of shear strength and consolidation stress of silt.

From Figure 2, it can be seen that the stress-strain curves of silt at different water content behaves as
hardening type. With the increase of shear displacement, the shear stress tends to increase. Before the shear displacement reaches 1mm, the shear stress increases rapidly and tends to be stable after reaching the peak value. The shear stress increases first and then decreases with the increase of water content, and reaches the maximum at the water content of 14.1% (near the optimal water content).

As shown in Figure 3, the shear strength of silt increases first and then decreases with the increase of its moisture content, that is, there is a critical water content, less than the critical water content, the shear strength increases with the increase of water content, and the shear strength decreases with the increase of water content when it is greater than the critical water content. According to the experimental law, the critical water content is the best water content, the sample structure reaches the most stable state under the optimal water content, the minerals in the soil strengthen the bonding between particles under the optimal water content, and the coupling force between particles reaches a strong state, which is reflected in its shear strength. As can be seen from table 3, the shear strength envelope of silt is in accordance with the molar Coulomb's law at different water content, and the correlation coefficient of the fitting equation is more than 0.99.

![Fig. 2 Relationship between stress and shear displacement](image1)

![Fig. 3 relationship between shear strength and water content](image2)

| Water content (%) | Fitting equation | $R^2$ |
|-------------------|------------------|-------|
| 4.8               | $\tau_f = 0.467\sigma + 12.55$ | 0.9993 |
| 7.9               | $\tau_f = 0.478\sigma + 22.16$ | 0.9998 |
| 11.1              | $\tau_f = 0.480\sigma + 29.53$ | 0.9998 |
| 14.1              | $\tau_f = 0.499\sigma + 39.04$ | 0.9993 |
| 16.7              | $\tau_f = 0.496\sigma + 26.65$ | 0.9983 |
| 20.2              | $\tau_f = 0.462\sigma + 18.38$ | 0.9985 |

Note: "$\tau_f$" for shear strength, "$\sigma$" for consolidation stress

3.2. Relation between water content and shear strength index

3.2.1. Cohesion

Fig. 6 (a) shows the relationship between water content and cohesion. From the figure, it can be seen that cohesion increases first and then decreases with the increase of water content. The maximum cohesion corresponds to the optimal water content, which is consistent with the results of Lin [12]. The reason is that according to the particle size distribution of silt, the particle size of silt is mainly concentrated in the silt group (0.005-0.075 mm), and the clay content is very small, so its cohesion
mainly depends on the bonding mode between the soil particles. The cohesive force is also considered to include the true cohesive force and capillary force formed by cementation with electrostatic attraction, and the false cohesive force formed by apparent mechanical biting. In the case of low water content, there is less free water in the soil, and the binding force produced by capillary action is relatively weak, which leads to its small cohesion; with the increase of water content, the bonding force produced by capillary action increases relatively, the bonding force between soil particles increases, and the cohesion increases; when the optimum water content is reached, on the one hand, the capillary effect is further enhanced, on the other hand, the bonding force is enhanced by the bonding effect of water film between silt particles. The bonding effect produced by the bonding water film has a certain viscosity and shear resistance, thus increasing the cohesive force; when the optimum moisture content exceeds, the combined water film thickness increases further, and the viscous property decreases with the increase of the water film thickness. At the same time, the capillary effect disappears gradually, the lubrication between soil particles is strengthened by the introduction of a large amount of water, and the mechanical biting force between particles is weakened. The structure between particles is loose, the strength is reduced, and the cohesion becomes smaller. Therefore, it is necessary to strictly control the construction water content in the process of city wall repair or reinforcement.

3.2.2. Internal friction angle
Fig. 4 (b) shows the change regulation of internal friction angle with water content. Fig. 4 (b) shows that the change of internal friction angle is very small with the increase of water content, which is due to the fact that the particle size of silt is mainly concentrated between 0.005 mm and 0.075 mm, and the particle size is relatively single. It can also be seen in the figure that with the increase of moisture content there is a certain change in the internal friction angle, which is the water between the particles to play a lubrication role, its impact range is certain. In the course of the change of moisture content, the variation difference of internal friction angle is about 1.7°.

4. Disintegration test
According to the Standard of Geotechnical Test Method (GB/T 50123-1999), wetting (disintegration) tests of different water content samples was carried out, the sample disintegration process is shown in Fig. 7. From Fig. 7 (a), it can be seen that the soil samples with lower than the optimal water content have bubble overflow in the early stage after water encounter, and the surface and edge particles rapidly collapse and annual ring cracks appear; in the mid-term, silt has been soaked and softened, with small bubbles overflowing, some particles are peeled off by bubbles at the outlet of bubbles, a large number of particles at the bottom of the soil sample are separated from the sample, and part of the soil sample area collapses; at the later stage of the test, the pore of the sample was filled with water, and there were
still dense small bubbles overflowing, the disintegration of the sample began to separate by sliding and collapse. From Fig. 5 (b), it can be seen that a small amount of bubbles overflow in the early stage of soil sample with optimal water content, and the edge particles and bottom particles break up in granular form without annual ring cracks, in the mid-term, the silt has more dense small bubbles overflowing, the edge particles rapidly disintegrate from the soil sample, and the bottom particles detach from the sample, resulting in rapid turbidity of water; at the later stage, a large number of small bubbles overflowed and the sample began to slide and collapse rapidly. It can be seen from Fig. 5 (c) that the soil samples with higher than the optimum moisture content peel off the parent body with single or granular particles in the early stage after water encounter, and there is no annular crack.; in the medium term, the soil sample has a small bubble overflow, the surface soil is layered peeling soil sample, the soil samples began to collapse with aggregates or granules; at the later stage of the test, cracks and small bubbles still appeared on the surface of the soil sample, and the soil collapsed slowly in groups.

Fig. 5 Disintegrating process of samples with different water content
Table 4 Wetting test results of specimens with different moisture content

| Water content /% | A_15 | A_30 | A_45 | A_60 | A_75 | A_90 | A_120 | A_150 | A_180 | A_200 | Disintegration duration /s |
|------------------|------|------|------|------|------|------|-------|-------|-------|-------|-----------------------------|
| 4.8              | 30.24| 41.16| 82.46| 93.78| 104.22| ---  | ---   | ---   | ---   | ---   | 78                          |
| 7.9              | 27.85| 40.18| 82.43| 96.62| 106.52| ---  | ---   | ---   | ---   | ---   | 81                          |
| 11.1             | 26.66| 42.17| 86.67| 99.84| 106.84| ---  | ---   | ---   | ---   | ---   | 82                          |
| 14.1             | 22.79| 37.22| 78.38| 94.61| 102.34| 110.58| ---   | ---   | ---   | ---   | 93                          |
| 16.7             | 18.26| 34.46| 65.81| 88.44| 101.21| 111.47| ---   | ---   | ---   | ---   | 104                         |
| 20.2             | 12.35| 26.28| 42.16| 60.33| 78.49 | 84.82 | 98.27 | 108.45| 118.63| ---   | 192                         |

Note: A_t is the disintegration amount of soil sample at t

Table 4 shows the wetting test results of samples with different moisture content. Table 4 shows that the disintegration rate decreases with the increase of water content. The water content of the sample is small. Because the sample is dry, the mechanical biting force is the main force between particles and the X-ray diffraction results show that there is a certain amount of clay minerals in the soil sample, which will expand after meeting water and make the cementing force weaken sharply and accelerate the disintegration of the soil sample; at the optimum water content, the disintegration rate slows down slightly; when the water content of the sample is greater than the optimum water content, the disintegration rate slows down gradually, on the one hand, the higher water content in the sample with high water content makes the bound water film between particles thicker, and the pore between particles is filled by water molecules in the sample, on the other hand, the clay minerals in the sample have expanded and the volume of the increase occupies a certain pore, and the residual swelling force becomes smaller, therefore, the disintegration becomes slow when it is re-immersed. The disintegration of soil sample is shown as the anti-erosion ability of soil and the results of disintegration rate of soil sample have certain guiding significance for the study of soil and water conservation.

5. Results and analysis of field emission electron microscope test

The change of macro-mechanical properties of soil is fundamentally due to the change of soil microstructure. Therefore, it is of great significance to study the apparent characteristics of soil particles, particle size, arrangement, pore morphology and the connection mode between particles. In this experiment, field emission scanning electron microscopy (FESEM) produced by Zeiss Company of Germany was used to observe the microstructures of samples with different moisture content, for the convenience of comparative analysis, the image was magnified by 500 times, as shown in Figure 8.
Fig. 6 is a SEM image with different water content. From Figure 6, it can be seen that the macropore decreases and the micropore increases with the increase of water content. When the water content exceeds the optimal water content, the mesopore increases to a certain extent, with the increase of water content, the arrangement of particles is more orderly, and the microstructures gradually develop from loose structure to dense structure. From Figure 6 (a), it can be seen that under 4.8% water content, the particles are mainly single and flaky, arranged loosely and distributed in disorder, there are a lot of overhead voids among the particles, and the shape of the particles is very irregular, forming a loose single-grain structure. There is less clay in the soil, only a small amount of clay is scattered on the surface of silt particles, which can not form a better connection, the main forms of connection between particles are edge-to-edge contact, point-to-surface contact and point-to-point contact, which are easy to fracture. As shown in figs. 6 (b) and (c), with the increase of water content, the overhead voids between grains decrease gradually, and the average voids of soils decrease gradually, changing from loose structure to cohesive structure, and the arrangement of grains has certain directionality. More clay particles adhere to the surface of the powder particles, and the bonding strength between the particles is enhanced to a certain extent. At this time, the edge-to-surface contact and the surface-to-surface contact are the main contacts. At the optimum water content, as shown in Figure 8 (d), the particles form a whole, closely arranged together, and the porosity between the particles decreases significantly. The optimum water content of the soil not only achieves the maximum compactness, but also makes it easy to compact between particles. The clay particles are pressed into the interspace of silt particles to form a mosaic structure, which improves the strength of inter-particle bonding, the surface-to-surface contact between particles and the overall strength of soil samples. After exceeding the optimal water content, as shown in figs. 6 (e) and (f), due to the increase of water content, the force between particles decreases, a large number
of aggregates are extruded, and their structural strength decreases, forming a directional arrangement structure. Generally speaking, with the increase of water content, the micro-structure of soil samples gradually develops from loose structure to dense structure, further into mosaic mechanism, and finally to directional arrangement structure [13].

6. Conclusion
(1) The stress-strain curves of silt at different water content show hardening type, the shear stress of silt increases first and then decreases with the increase of water content, that is to say, there exists a critical water content (optimal water content), when the water content is less than the critical water content, the shear stress increases with the increase of water content, but decreases with the increase of water content when the water content exceeds the critical water content. The change regulation of shear strength with water content is the same as that of shear stress, the envelope of silt shear strength under different water content is consistent with Mohr-Coulomb's law, and the correlation coefficients of the fitting equation are all above 0.99.

(2) The cohesion increases first and then decreases with the increase of water content, and the peak cohesion corresponds to the optimal water content; with the change of water content, the angle of internal friction changes to a certain extent, and the variation difference of the angle of internal friction is about 1.7 degrees.

(3) The disintegration rate of soil samples decreases with the increase of water content. The clay minerals in low water content soil samples will expand when they meet with water, which makes the cementation strength weaken sharply and accelerates the disintegration of soil samples; the higher water content in the sample with high water content makes the bound water film between particles thicker, the pore between particles is filled by water molecules in the sample, the clay minerals in the sample have been expanded and the residual expansion force has been reduced, therefore, the sample disintegration is slow when the sample is re-immersed.

(4) Under the optimum water content, silt has the least pore space, dense particle arrangement and greatly improved the strength of soil samples. With the increase of water content, the microstructures gradually change from loose structure to dense structure, then to mosaic mechanism, and finally to directional arrangement structure.

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