Characteristics of the Microstructure and Mineral Composition of Completely Decomposed Migmatitic Granite

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Abstract: Based on the characteristics of special mineral composition, complex internal structure and remarkable water effect of completely decomposed migmatitic granite (CDMG), the mineral composition distribution was obtained by X-ray powder diffraction (XRD), and the microstructure of CDMG with different water content was studied by using scanning electron microscope (SEM). The following new progress was made: The mineral composition of the rock samples is mainly quartz, feldspar, montmorillonite, illite and kaolinite. The microstructure of the sample is composed of coarse-grained quartz and feldspar as the framework, and laminated and fragmental clay minerals as the filling materials, forming a relatively dense framework filling structure. Through statistical analysis of the particle morphology and pore distribution data of CDMG samples, it is found that with the increase of moisture content, the filling structure changes from dense to loose. Because of the swelling potential induced by water absorption of hydrophilic clay minerals, and the uneven distribution of clay minerals such as montmorillonite, the filling materials are not uniformly expanded, which eventually leads to the destruction of the original filling structure and the decrease of the density.

Key words: completely decomposed migmatitic granite; microstructure; mineral composition; water sensitivity

1. Introduction

As weathering product of migmatitic granitic crust, completely decomposed migmatitic granite (CDMG) distributes in Lincang area, Yunnan Province, China, and its weathering depth is 30m on average. In the process of weathering, the original mineral components and rock mass structure of the
parent rock are gradually destroyed and lose their characteristics, mica and some feldspar are weathered into clay minerals, and the overall structure incrementally changes from dense to loose state. Under the constant leaching of precipitation and groundwater, the mineral composition and pore structure characteristics of the parent rock become more complex, which eventually leads to the significant water sensitive property and special mechanical property of CDMG, thus affecting the engineering construction industry. The water-bearing state is an important factor affecting the microstructure and mechanical properties of CDMG[1,2]. Explore the structural characteristics of particles and pores and the distribution of mineral composition under different water-bearing states is the key to understand the evolution of mechanical properties of CDMG.

As a geological body with a special genesis and only distributed in a certain area, there are few studies on CDMG, most of which focus on the mechanical properties and microstructure of granite residual soil. Wang[3] systematically studied the microstructure and pores of the granite residual soil(GRS), and found that the main component of the soil structure when the edge and surface contact. Wu[4] found through particle separation test and scanning electron microscope test that the granule composition of GRS contains a high content of coarse and clayey particles, and its microstructure characteristics are greatly different from those of common clayey soil and sandy soil. Through microstructure analysis, Gutierrez et al.[5] pointed out that the structural strength of Brazilian residual soil mainly came from the residual structure of parent rock and the cementation effect of free oxides. Li et al.[6] studied the granite residual soil by scanning electron microscopy and observed the fine grain structure. Kong et al.[7] conducted a detailed study on the pore size distribution characteristics of GRS by using NMR test, and discussed the relationship between soil-water characteristic curve and T2 distribution curve. Sun et al.[8] carried out CT scan test on remolded GRS samples, and observed that the porosity varied with water content to some extent, and believed that this phenomenon was mainly related to the expansion characteristics of hydrophilic minerals in the soil when they met water. Li, et al.[9] studied the disintegration process of the GRS through staged CT scanning, and found that the hydraulic impact at the initial stage of disintegration had serious damage effect on the pore structure. The above research reflects that the products of granite weathering and accumulation have complex microstructure characteristics and special mineral composition, in addition, they also have poor water retention and strong water sensitivity.

However, CDMG is a semi-diagenetic rock between rock and soil. Compared with the GRS, CDMG has a great difference in mineral composition, grain size distribution and microstructure. In this paper, XRD and SEM were carried out on CDMG in Lincang, in order to explore the mineral composition distribution of CDMG. By finely segmenting the SEM images, the parameters of particle and pore structure were extracted, and the microstructure evolution of CDMG under different water content conditions was analyzed.

2. Materials and methods

2.1 Sample and its basic physical properties

CDMG were taken from the engineering construction site in the mountain area in the southwest of Lincang, Yunnan. Figure 1 shows the specific location of the sampling points. The parent rock of CDMG in this area is extremely complex, mainly composed of two types of rocks, biotite monzogranite and biotite mixed granite. Under the combined action of multi-stage mixed lithitization and granitization,
the matrix and vein cannot be distinguished. After different degrees of weathering, CDMG shows more complex particle distribution, mineral composition and overall structure. As a result, CDMG has some special properties, such as strong water sensitivity, poor water retention and loose structure. The basic physical properties of CDMG are determined according to the standard for Soil Test Method of P. R. China. The results are shown in Table 1.

| Property                          | Value  |
|----------------------------------|--------|
| Specific gravity                 | 2.72   |
| Natural density (g/cm³)          | 1.89   |
| Natural moisture content (%)     | 17.5   |
| Standard compaction test         |        |
| Maximum dry density (g/cm³)      | 1.86   |
| Optimal moisture content (%)     | 12     |
| Grain-size distribution          |        |
| Gravel(%)                        | 11     |
| Sand(%)                          | 70.4   |
| Silt(%)                          | 15.7   |
| Clay(%)                          | 2.9    |

**Figure 1.** Sampling site

2.2 Sample preparation

According to relevant test methods [10], powder samples of 325-mesh sieve were obtained by conventional mechanical grinding method during XRD analysis. The CDMG sample was air-dried, ground, screened and dried, as shown in Fig. 2. For SEM tests, CDMG was remolded into ring samples with a certain dry density (1.80g/cm³) and different moisture content (6%, 8%, 10%, 12%, 14%).
Figure 2. Preparation of CDMG sample mineral composition test

2.3 Mineral composition and microstructure test

The mineral composition of CDMG was determined based on X powder crystal diffraction test. Due to the complex mineral composition of the samples, three groups of parallel tests were designed, and the average value of the mineral composition distribution of the three groups of test results was taken. The D8 Advance X-ray system was used.

After the sample is completely air dried, it is carefully broken, and the representative fresh surface is selected as the test surface. The sample is sliced and the microstructure image of the sample is taken by means of SEM. With reference to the existing micro image processing experience of soil mass [11,12], Image-J software was used to filter, calibrate and segment 800X SEM micro image (see figure 3), identify and extract the number, area, Angle, diameter and other geometric morphological information of particles, eliminate the overlapping part, and then quantitatively analyze the evolution of particle morphology and arrangement.

Figure 3. SEM image (a) filtering (b) binarization

3. Test results

3.1 Mineral analysis test results

Table 2 shows the mineral composition test results of three parallel samples. The results show that the mineral composition of CDMG is dominated by feldspar and quartz, with an average content of 44.26% feldspar, 28.09% quartz, and 27.65% clay minerals. Among the clay minerals, montmorillonite with strong hydrophilicity is the main one. Figure 4 shows the mineral composition distribution of completely decomposed granite (CDG) and GRS in different regions[13,14]. It can be found that the content of CDMG feldspar in Lincang area is significantly higher than that in southeast coastal areas, while the content of clay minerals is lower In the GRS with more thorough weathering degree, feldspar is basically weathered into clay minerals with low content, but the distribution of quartz content is relatively stable.
Table 2 CDMG mineral composition distribution

| Sample | Quartz (%) | Feldspar (%) | Montmorillonite (%) | Kaolinite (%) | Illite (%) |
|--------|------------|--------------|---------------------|--------------|-----------|
| 1-1    | 24.52      | 46.81        | 18.84               | 3.13         | 6.68      |
| 1-2    | 31.14      | 42.35        | 19.56               | 1.92         | 5.03      |
| 1-3    | 28.62      | 43.58        | 19.79               | 3.55         | 3.27      |
| Average| 28.09      | 44.26        | 19.79               | 2.87         | 4.99      |

Figure 4. Mineral distribution of weathered granite in different areas

As can be seen from the mineral composition, the particularity of Lincang CDMG is manifested in two aspects: First, feldspar content is high and quartz content is relatively low, which is related to the formation process and weathering process of the parent rock. Migmatitic granite is mainly formed by the intrusion of basic-basic-magma into the shallow strata and the dissolution, metasomatism and condensation of the shallow strata. The silica (quartz) content of the migmatitic granite is lower than that of ordinary granite, and the later weathering intensity is far lower than that of the southeast coastal areas. As a result, the relatively difficult weathering minerals such as feldspar can be retained in large quantities. The huge difference in mineral composition directly leads to the difference in particle size composition and microstructure of CDMG; Second, the content of montmorillonite in the CDMG clay minerals is high and the water sensitivity is strong. Different water-bearing states and the inhomogeneity of hydrophilic montmorillonite distribution will induce differential expansion potential in CDMG, which makes the pore structure of CDMG particles show a more complex state.

3.2 CDMG microstructure

3.2.1 Overall structure of CDMG sample

In order to ensure the overall range of view, SEM images with relatively low magnification were selected for analysis. In figure 5, a, b, c and d are SEM images at 800X with water content of 6%, 8%, 12% and 14%, respectively.

By observing figure 5a,b, it can be found that in the state of low water cut, the microstructure of the sample takes coarse quartz and feldspar as the skeleton and laminated and granular clay minerals as the filling material to form a dense skeleton-filling structure. Large particles are mainly irregular angular and sub-angular, and the arrangement of particles is relatively close and firm. The pores are mainly micropores and small pores, and relatively few macropores and connected pores. As can be seen from
figure 5c,d, the original dense filling structure of the sample under the condition of high water cut has changed greatly. In the field of view, the arrangement of small clay minerals became disorderly, and some clay particles formed larger aggregates when they encountered water. The original granular and laminated clay minerals absorbed water and swelled, and the morphology changed greatly, showing flocculating and filamentous characteristics. The intergranular pores are connected, and the content of macropores and connected pores increases obviously, and most of them are concentrated near clay minerals. The compacted filling structure of the sample is lost and the overall structure becomes loose.

3.2.2 Microscopic pore structure

The pore diameters of CDMG samples with different water content were calculated and counted, and the results were shown in figure 6a. According to the existing experience of pore division in sandy soil [15], the pore structure size of CDMG sample is divided into micropores (<80um), small pores (80-150um), mesoporous (150-300um) and macropores (>300um) according to their equivalent diameter. With the increase of moisture content, the pore diameter distribution changes. The proportion of micropores and small pores decreased significantly, while that of macropores increased markedly. When the moisture content increases from 6% to 10%, the micropores and small pores decrease by 7.22% and 4.11%, while the mesopores and macropores increase by 2.71% and 8.62%, respectively. When water content increased from 10% to 14%, micropores and small pores decreased by 3.81% and 0.68%, mesopores and macropores increased by 1.47% and 3.05%, respectively.

Figure 6. Pore diameter, porosity and pore connectivity of CDMG sample

The division of pore connectivity is mainly based on the contact relationship between pores and cavities. With reference to the existing experience [16], the connectivity of pores is divided according to the surface contact between cavities. The calculation formula of pore connectivity $p$ is as follows:

$$p = \frac{n_i}{n} \times 100\%$$  \hspace{1cm} (1)

Where, $n_i$ is the number of connected pores, and $n$ is the total number of pores. The number of connected
pores and total pores was identified and extracted by the automatic pore contour tracking function of image-J software according to the segmentation results of SEM images. The incomplete or overlapping parts were removed manually, and then the evolution characteristics of pore size were quantitatively analyzed. Figure 6b reflects the evolution of the overall porosity and pore connectivity of CDMG samples with the increase of moisture content. When the moisture content of the sample increases from 6% to 8%, the porosity and connectivity of the sample increase not significantly, and both increase by 0.7%. As the moisture content continues to increase, the porosity and connectivity of the samples increase rapidly. When the moisture content increases from 8% to 14%, the porosity of the samples increases from 22.8% to 31.4%, and the connectivity increases from 84.2% to 97.3%.

The influence of the difference of moisture content on the pore structure of CDMG samples is mainly manifested in two aspects: (1) With the increase of moisture content, some micropores are filled with water, resulting in the decrease of the proportion of micropores and small pores; (2) When the moisture content increases, the clay minerals between the framework of large particles absorb water and expand, accelerating the structural damage and loosening of the surrounding particles and fillings, resulting in the coarsening and connectivity of a large number of micropores, forming larger mesopores or macropores, further increasing the connectivity of pores.

### 3.2.3 Microscopic particle structure

The difference of moisture content mainly has a strong reformation effect on the filling materials with fine particles (diameter less than 0.25mm) such as clay minerals, but has little effect on the skeleton of large quartz feldspar. By segmenting and counting the data of fine particles in SEM images, the structure of fine particles was quantitatively studied from two aspects: particle arrangement (directional frequency) and particle size (particle size distribution). The basic parameters of fine particles of CDMG samples with different moisture content were summarized in Table 3.

#### Table 3. Extraction results of particle parameters from SEM images with different water content

| Moisture content/% | Total number of particles | Average particle size/μm | Particle average circumference/μm | Average particle area/μm² | Particle area ratio/% |
|--------------------|---------------------------|--------------------------|----------------------------------|--------------------------|---------------------|
| 6                  | 982                       | 21.53                    | 22.35                            | 164211.56                | 63.46               |
| 8                  | 1035                      | 23.60                    | 23.63                            | 157563.24                | 60.26               |
| 10                 | 863                       | 27.33                    | 26.96                            | 150254.93                | 55.32               |
| 12                 | 855                       | 31.87                    | 33.67                            | 145321.75                | 52.97               |
| 14                 | 812                       | 31.21                    | 32.18                            | 138723.52                | 47.85               |

The directional frequency of particles in the sample represents the disorder degree of the arrangement of particle units, and the calculation formula is as follows [17]:

\[
F_i(\alpha) = \frac{N_i}{N}
\]  

(2)

Where: \(N_i\) is the number of particles in azimuth \(i\); \(N\) is the total number of particles. \(\alpha\) is the unit location Angle divided equally between 0° and 180° in the particle alignment direction. In this study, 15° is used as the unit Angle to divide, that is, \(\alpha=15^\circ\). Assume that the directional frequency of particles in the range of 180° ~ 360° is symmetric with that of particles in the range of 0° ~ 180°. The directional frequency distribution of samples with different moisture content is calculated and counted, as shown in figure 7.
Figure 7. Directional frequency distribution of particles with different moisture content

By observing figure 7, it can be found that the particle orientation frequency distribution of the sample in different angle ranges is more balanced, but there are obvious differences in local angle ranges. Under the condition of low moisture content (6%, 8%), the directional frequency of particles always has a higher distribution near the polar Angle (0°, 90°, 180°, 270°), while the distribution is more uniform in other intervals. Under the condition of high moisture (10%, 12%, 14%), the directional frequency of the particles had no obvious distribution orientation, and the arrangement of the reaction particles tended to be disordered. The variation of particle directional frequency distribution is mainly affected by two reasons: One is that when the sample is pressed, some particles will be adjusted to the horizontal direction, and the fine particles of clay minerals filled between the large particles of the skeleton shows intractable; Second, with the increase of water content, the clay minerals absorb water and expand to squeeze the adjacent particles, forcing the fine particles near the polar Angle to rotate and adjust to a stable state. This phenomenon is called “depolarization” [18], and eventually leads to a relatively disordered state of the directional frequency of particles.

The traditional sieving method and sedimentation analysis method can not study the change of particle size distribution under different moisture content. In this study, SEM image digital processing was used to calculate the fine particle size distribution information, so as to explore the evolution characteristics of fine particle size of CDMG sample. Due to the limitation of the SEM resolution and the scale of the image, the size information of samples with different moisture content can be obtained from 0.001-0.25mm, and the results are shown in figure 8.
Figure 8. Particle size distribution of fine particles under different moisture conditions

On the whole, the content of clayey particles (0.001-0.005mm) was close to that of fine particles (0.005-0.01mm), both at about 20%. The content of coarse silt (0.01-0.075mm) was the most, accounting for about 40%, and the content of fine sand (0.075-0.25mm) was the least, accounting for about 15%. The change of moisture content has a certain influence on the distribution of particle size. When the moisture increased from 6% to 14%, the clay particles decreased by 4.97% and the coarse silt particles increased by 5%. Combined with the changes of particle morphology in SEM images, it is considered that the changes of particle size are mainly affected by two aspects: The first is that the clay particles absorb water and expand, which increases the volume of clay particles. The second is that the increase of moisture content will promote the dispersed clay particles to gather together and form larger aggregates.

4. Discussion on mineral composition and microstructure of CDMG

By measuring the mineral composition of CDMG and analyzing the microstructure of CDMG sample, it can be found that the evolution of the microstructure of CDMG sample under the change of the water-endowed state is a complex process, which involves water, the physical and chemical properties of and mineral as well as the mechanical properties between particles. When the sample is pressed, the particle size component of CDMG determines the overall structure of the sample as a skeleton-filling structure, and the particles show irregular morphology, so that the particles interlock and rub with each other to reach a stable equilibrium state. Under certain moisture content condition, the stable skeleton-filling structure is compact. However, this compact state is easy to be broken when the moisture content changes. The reason is that the filling structure of CDMG is rich in hydrophilic clay minerals, which leads to a certain expansion and contraction property. When the moisture content is high, the water molecules enclose the hydrophilic clay minerals, forming a thicker bound water film, resulting in intergranular expansion, and then the volume of clay minerals expands to open the adjacent pores, making the intergranular pores coarser and connected continuously, leading to the destruction of the original dense filling structure. Secondly, the uneven distribution of clay minerals causes the differential expansion potential in the sample. Finally, the distribution of pores between grains tends to be complex, and the overall structure of the sample produces uneven damage and deterioration.
5. Conclusion
In this paper, the mineral composition and the microstructure of CDMG under different moisture content conditions were studied and analyzed in detail by means of XRD and SEM, and the following conclusions were drawn:

1. The main mineral composition of CDMG is quartz feldspar, with an average content of 28% and 44%, respectively. The rest are clay minerals, in which the majority of the clay minerals are montmorillonite with strong hydrophilicity, which is the material basis of CDMG showing strong water sensitivity;
2. With the increase of moisture content, the microstructural deterioration of CDMG is significant. The pore structure among the fine particles is characterized by the coarsening and coalescence of micropores and small pores, forming mesopores and macropores, and the pore connectivity is increased. The change of pore distribution is the most important factor to induce the deterioration of filling structure.
3. In the process of moisture content increasing, the variation range of particle size distribution is small, but the directional distribution of particles has a greater impact, and the arrangement and contact of particles become disordered and disordered, showing the characteristics of "depolarization".
4. The main factor of CDMG's strong water sensitivity is the swelling potential induced by water absorption of hydrophilic clay minerals, which leads to the coarsening and coalescence of intergranular pores in the filling structure, the disorder of particle arrangement and the adjustment of particle size. The dense filling structure was destroyed and the CDMG microstructure became loose.

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