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Original Research

Study on The Influence of Grain Size Composition on Engineering Properties of Granite Residual Soil

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Abstract

The parent rock properties, weathering degree and soil formation conditions of soil in different regions and different levels are different, which results in the obvious difference of grain size composition of soil. At present, the research on granite residual soil often ignores the mechanism of its grain size composition on engineering properties. In this study, a series of soil samples with different grain size composition were configured based on the content of gravel grain in the granite residual soil. This paper mainly studies the influence of the content of gravel grain group and fine grain group of the compaction and strength of granite residual soil. The results show that the optimal moisture content and cohesion of granite residual soil are mainly controlled by the content of fine grain, and the maximum dry density and internal friction angle are mainly controlled by gravel grain. For each 1% increase in the fine grain content of the soil, the optimal moisture content of the soil will approximately increase by 0.11%, and correspondingly, the cohesion of the soil will approximately increase by 0.27 kPa. In addition, the engineering properties of granite residual soil with different grain size composition are also affected by soil structure. Finally, based on the microstructure characteristics of granite residual soil, three different aggregates are proposed, and seven micro models with different structural characteristics are established. Micro models established by different aggregates can control different engineering properties of soil. The research results are helpful to understand the relationship between the engineering properties and grain size composition of granite residual soil and provide reference for the refinement of its engineering classification.

Keywords: granite residual soil, grain size composition, compaction characteristics, strength characteristics

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Introduction

Granite residual soil is not only widely distributed in China, but also in other places such as Korea, Singapore, and Japan [1-5]. The unique genesis, composition and internal structure of granite residual soil lead to its obvious particularity in engineering properties. Many scholars at home and abroad attach great importance to its engineering properties [6-12]. The granitic residual soil of different regions and different levels have obvious differences in grain size composition due to the different nature of parent rock, weathering degree and soil formation conditions [13-15]. With the development of infrastructure, more and more engineering practices are carried out in this kind of soil, and the research on its engineering properties is more important. Generally, the granite residual soil is classified with the content of gravel grain (>2 mm) as the boundary value. This classification method is simple and practical, which fully illustrates the importance of gravel grain content to its engineering properties, but the specific rules of the impact of grain size composition on the engineering properties of granite residual soil are still unclear.

The grain composition of naturally distributed granite residual soil is quite different (Table 1), and the weathering degree of granite residual soil is obviously different due to different climatic conditions in different regions [16-19]. The difference of parent rock type and weathering degree in different regions jointly results in the obvious regional characteristics of grain size composition of granite residual soil. Even in the same area, due to the weakening of the top-down weathering degree, the grain size composition is also very different [20-23]. The difference of grain size composition has a significant impact on the structure and engineering properties of granite residual soil, but there is a lack of targeted research [24]. At present, granite residual soil is generally divided into three types based on the content of gravel grain (>2 mm grain size) as the boundary value. Cohesive soil, without gravel grain; Sandy cohesive soil, gravel grain content ≤20%; Gravelly cohesive soil, gravel grain content>20%. This classification scheme is more practical, and can highlight the importance of gravel grain on the engineering properties of granite residual soil. However, the range of gravel grain content specified by the method is too large, and the influence of content of other particle groups is ignored, which cannot fully reflect the actual engineering properties of soil. Therefore, the engineering classification of granite residual soil should be based on the content of gravel grain group, while taking into account the influence of the content of other grain groups. At present, the research on the influence of grain size composition on the soil properties of granite residual soil is limited to the test analysis of adding other types of soil or other material particles [25]. Most of these studies are conducted from the perspective of soil improvement, but ignore the obvious difference of grain size composition of granite residual soil itself.

Scholars at home and abroad have done a lot of work on the impact of grain size composition on other soil engineering properties [26-30]. Thevanayagam and Mohan [31] studied the influence of fine grain content on the engineering properties of sand, and proposed to describe the stress-strain relationship of sand by using the inter particle void ratio and state parameters. Ahsan et al., [32] studied the influence of different particle gradation on shear strength through direct shear tests and established calculation models for non-uniformity coefficient, curvature coefficient and direct shear strength. Wu et al., [33] studied the influence of different graded areas of coarse grained soil on its maximum dry density, and proposed a method to design the optimal graded distribution of soil. Bao et al., [34] studied the influence of grading on the permeability coefficient of coarse grained soil, and found that the smoother the grading curve is, the larger the area is, and the smaller the permeability coefficient is. However, the existing studies often screen out the>2 mm particles in the granite residual soil for test analysis. The characteristics of granite residual soil containing a large number of gravel grains are ignored, which cannot fully reflect the compaction and strength characteristics of the real granite residual soil. Previous studies on the influence

Table 1. Grain size composition of different regions.

Region	Gravel grain (>2 mm) content/%	Coarse sand (0.5-2 mm) content/%	Medium sand (0.25-0.5 mm) content/%	Fine sand (0.075-0.25 mm) content/%	Fine grain (≤0.075 mm) content/%
Zhuhai	19.48	25.91	5.45	11.65	38.5
Guangzhou	16.30	17.48	5.79	6.88	55.01
Xiamen	30.15	29.08	9.20	8.86	22.71
Haikou	2.41	10.49	17.70	10.09	59.31
Qingdao	50.78	20.8	7.65	8.73	13.04

Note: Due to the limited samples taken from various regions, although the data in the table cannot fully represent the grain size composition of granite residual soil in this region, it can indicate that the grain size composition of granite residual soil in different regions varies greatly of grain size composition of soil often only focus on the change of its macroscopic engineering properties, and the difference of the microscopic model of soil under different grain size composition is the fundamental reason for its engineering geological change.

Based on this, this paper configures a series of soil samples with different grain size composition based on the gravel grain content of granite residual soil. The macro engineering properties of compaction and strength of granite residual soil with different gravel grain group content and fine grain group content were studied, and the micro models with different structural characteristics were established. This study provides a basis for the refinement of engineering classification of granite residual soil.

Materials and Methods

Materials

The soil samples used in this study were taken from a foundation pit in Xiangzhou District, Zhuhai City, as shown in Fig. 1a). The granite residual soil widely distributed in Zhuhai is mainly formed by long-term physical and chemical weathering of Yanshanian medium coarse grained granite in a humid and warm environment. After the original soil sample is crushed and air dried, take a proper amount of representative soil sample and put it in a bucket. Add a proper amount of water and dispersant (Sodium hexametaphosphate) to completely separate the coarse and fine grains in the soil sample. The sieve analysis method is used for soil samples larger than 0.075 mm, and the standard densitometer method is used to determine the grain size composition of soil samples smaller than 0.075 mm. The grain size grading curve of the original granite residual soil sample is shown in Fig. 1b). The gravel grain content of the original soil sample taken in this study is 19.6%, which is named sandy cohesive soil. The content of particles in sand group and fine grain group is 41.8% and 38.6% respectively.

Based on the gravel grain content of granite residual soil, a series of soil samples with different grain size composition are prepared. The content of each grain size composition of different soil samples is shown in Table 2. This study is based on the commonly used engineering classification scheme of granite residual soil, which is divided into three types according to the gravel grain content in the soil. Then, in each type of soil, three soil samples with different grain size composition were allocated, totaling 9 soil samples.

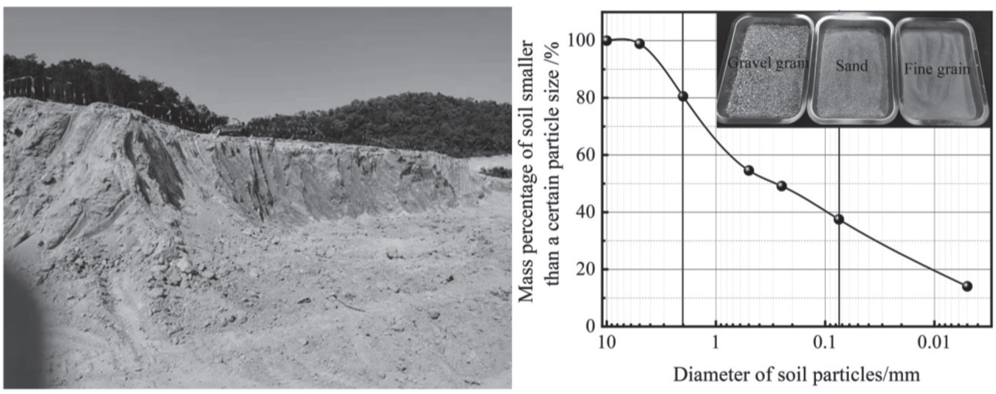
Test Procedure

Compaction Test

In this study, light standard compaction test is used to test the optimal moisture content and maximum dry density of each soil sample. According to the standard GB/T50123-2019, take 20 kg of prefabricated soil samples from No. 1-9 soil samples respectively, estimate the optimal moisture content according to the plastic limit of soil samples, and allocate 5 soil samples with different water content. Among them, the moisture content of one soil sample is close to the plastic limit; The moisture content of two soil samples is higher than the plastic limit; The moisture content of two soil samples is lower than the plastic limit. The difference between the two adjacent moisture contents is 2%-3%. Weigh the same amount of soil samples for each layer, compact them in three layers, and roughen the soil between each layer. The soil samples with different moisture content and grain size composition shall be compacted according to the above steps in order to obtain the corresponding moisture content and dry density of each soil sample under different conditions.

Triaxial Test

In this test, the compactness of soil samples from triaxial tests with different grain size components is 95% of the soil samples with their respective grain size components, and the moisture content is the



(a) (b)

Fig. 1. Soil sample information a) Sampling points b) Grain gradation curve of soil sample.

Table 2. Grain size composition of each soil sample.

Soil type	Soil sample No.	Gravel grain (>2 mm) content/%	Sand (0.075-2 mm) content/%	Fine grain (≤0.075 mm) content/%
Cohesive soil (without gravel grain)	1	0	30	70
	2	0	50	50
	3	0	70	30
Sandy cohesive soil (0<gravel grain content<20%)	4	5	47.5	47.5
	5	10	45	45
	6	15	42.5	42.5
Gravelly cohesive soil (20% ≤ gravel grain content)	7	25	37.5	37.5
	8	35	32.5	32.5
	9	45	27.5	27.5

optimal moisture content of their respective grain size components. The soil sample is made into a cylinder with a diameter of 5 cm and a height of 10 cm by the layered compaction method, and the consolidated undrained triaxial shear test is carried out. This test procedure is mainly divided into soil sample saturation, consolidation and shear. According to the standard GB/T50123-2019, after the soil sample has completed vacuum saturation and back pressure saturation, the confining pressure is increased by injecting water into the pressure chamber. The confining pressure of each group of soil samples is controlled at 100, 200 and 300 kPa respectively. Shear is carried out by controlling the strain rate and keeping the drain valve closed. The loading rate of axial strain is 0.3%/min.

Scanning Electron Microscopy (SEM) Test

The microstructure characteristics of vertical and horizontal cross sections of soil samples with different grain size components was observed using a SEM.

Results and Analysis

Compaction Characteristics of Different Grain Size Components

Fig. 2 shows that the optimal moisture content of cohesive soil (No. 1-3 soil sample) increases with the increase of fine grain content; The optimal moisture content of sandy cohesive soil (No. 4-6 soil sample) and gravelly cohesive soil (No. 7-9 soil sample) still increases with the increase of fine grain content. This is due to the large specific surface area of the fine grains in the granite residual soil and the strong hydrophilicity of the clay minerals contained therein. Therefore, on the whole, the optimal moisture content of granite residual soil increases with the increase of fine grain content. Only the optimal moisture content of No. 3 soil sample (30% fine grain content) is greater than that of No. 8 soil sample (32.5% fine grain content), which is due to the loose structure of gravel grains in No. 8 soil sample compared with that of No. 3 soil sample, and the total content of hydrophilic minerals in No. 8 soil sample is less than that of No. 3 soil sample. It can be seen that the optimal moisture content of granite residual soil is also affected by its structure. For each 1% increase in the fine grain content of the soil, the optimal moisture content of the soil will approximately increase by 0.11%. It can be seen from Fig. 3 that the maximum dry density of sandy cohesive soil (No. 4-6 soil samples) basically increases linearly with the increase of gravel grain content. However, the maximum dry density of gravelly cohesive soil (No. 7-9 soil samples) first increases with the increase of gravel grain content, but when the gravel grain content reaches a certain value, its maximum dry density decreases with the increase of gravel grain content. The maximum dry density of granite residual soil first increases and then decreases with the increase

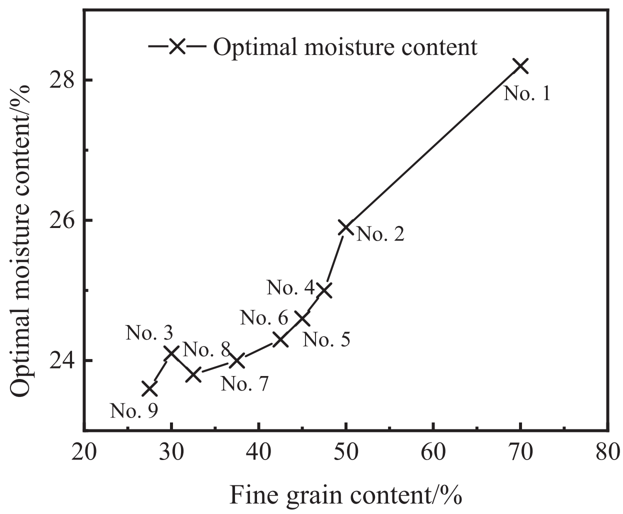


Fig. 2. Relation curve of optimal moisture content of different fine grain content.

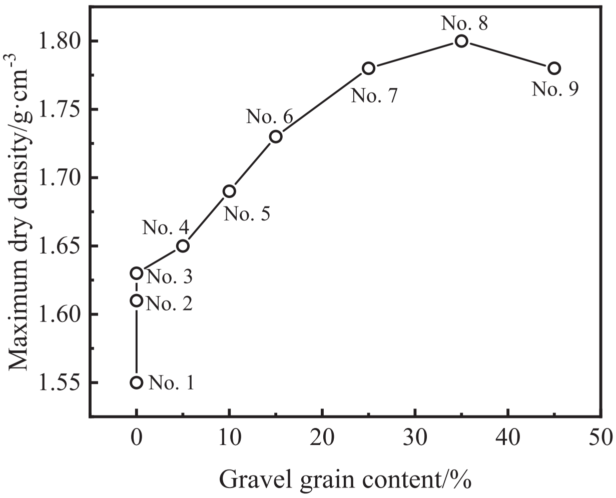


Fig. 3. Relation curve of maximum dry density of different gravel grain content.

of gravel grain content. When the gravel grain content is 35%, the maximum dry density is obtained.

Strength Characteristics of Different Grain Size Components

It can be seen from Fig. 4 that under the same confining pressure, the peak strength of granite residual soil increases gradually with the increase of gravel grain content, and the greater the confining pressure, the greater the slope. However, when the gravel grain content reaches 35%, the peak strength of soil decreases with the increase of gravel grain content. Therefore, the peak strength of granite residual soil does not increase monotonously with the increase of gravel grain content. The reason is that with the increase of gravel grain content, the content of other particle groups will decrease, which leads to the corresponding changes in the occlusal force, cohesion and skeleton structure between soil particles.

As shown in Fig. 5, the cohesion of granite residual soil increases with the increase of fine grain content. The mineral components of gravel grain and sand are mainly primary minerals such as quartz and feldspar, which can provide less cohesion. The fine grains contain a lot of cohesive minerals such as kaolinite, which can produce high cohesion. Only the cohesion of No. 3 soil sample (30% fine grain content) is greater than that of No. 8 soil sample (32.5% fine grain content). This is because the gravel grain content (35%) in No. 8 soil sample is much higher than that in No. 3 soil sample (0%). The existence of gravel grains leads to larger pores in No. 8 soil sample. The fine grains form more fine aggregates to fill the pores, which is not sufficient for cementation of soil skeleton. Therefore, the cohesion of No. 8 soil sample is smaller than that of No. 3 soil sample with lower fine grain content. Since the existence of gravel grains will reduce the cohesion of granite residual soil, it is reasonable to take gravel grain content as the classification index of granite residual soil from the perspective of cohesion. With the increase of fine grain content, the total specific surface area is larger, and the mutual attraction between particles is enhanced. The cementation of clay minerals and free oxides on the soil skeleton is more obvious, and the resulting cohesion is greatly enhanced. For each 1% increase in the fine grain content of the soil, the cohesion of the soil will approximately increase by 0.27 kPa.

Fig. 6 shows that the internal friction angle of granite residual soil does not increase monotonously with the increase of gravel grain content. When the gravel grain content is ≤35%, the internal friction angle increases with the increase of gravel grain content, but its growth rate is slowed down. When the gravel grain content is more than 35%, the internal friction angle decreases with the increase of gravel grain content. It can be seen

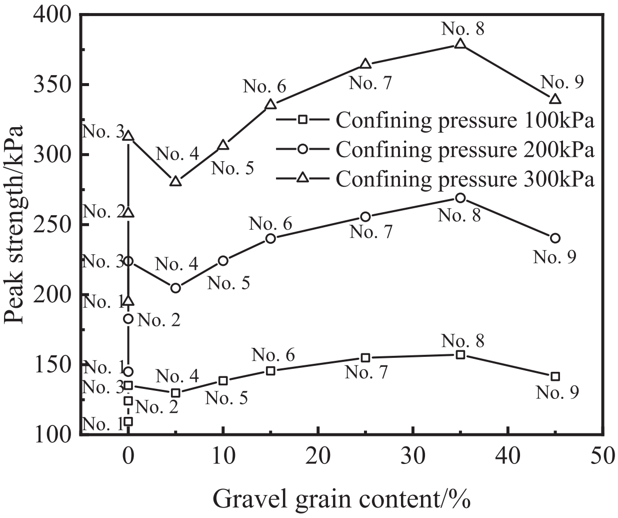


Fig. 4. Relationship between peak strength and gravel grain content.

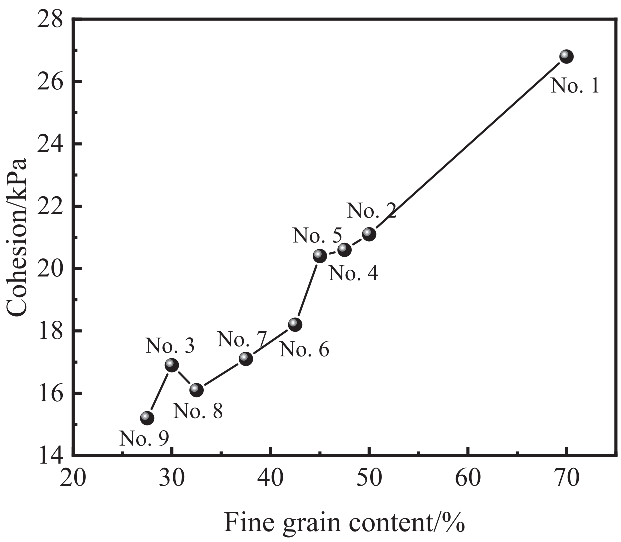


Fig. 5. Relationship between cohesion and fine grain content.

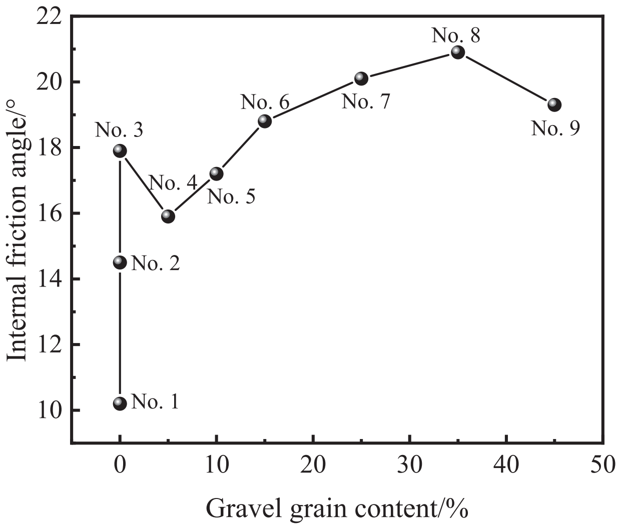


Fig. 6. Relationship between internal friction angle and gravel grain content.

from the analysis of particle characteristics of each particle group that the gravel grain size is large and the bite between particles is deep, so the energy consumed by the movement, pullout and rotation of soil particles under the action of shear stress is greater, which leads to the increase of the bite friction [12]. At the same time, the dilatancy effect of gravel grains is more obvious, which requires more energy, which is also of positive significance for improving the internal friction angle of soil. Therefore, when the gravel grains increase in a certain range, the internal friction angle also increases accordingly.

Discussion

Microstructure Characteristics

According to the SEM test, the overall appearance of the original soil sample is shown in Fig. 7. As shown

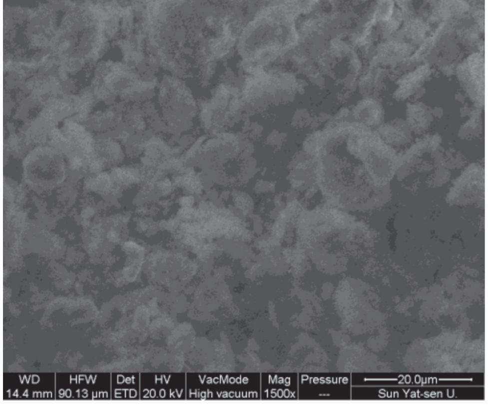


Fig. 7. Overall appearance of original soil sample.

in Fig. 7, the overall structure of the original soil sample shows that large particles (mainly gravel grain and medium coarse sand) are distributed dispersedly, arranged unevenly, and inlaid with each other. The free oxides in fine grains and clay minerals in the edges and pores of large particles connect the coarse grains to form a soil skeleton through cementation. The pores inside the skeleton are filled with fine grains, and the overall structure is relatively dense.

It can be seen from Fig. 8 that the gravel grain, sand and fine grain groups in the soil are connected to form aggregates, and the aggregates are arranged to form the soil structure. There are three types of aggregates, namely, fine grain aggregate, fine grain wrapped coarse grain aggregate and coarse grain bite aggregate. Fine grain aggregate (Fig. 8a) is formed by clay minerals and free oxides, which can aggregate fine grains together and play a cementing role in the skeleton pores and the edges of large particles, with micro pores inside. The content of fine grains determines the soil cohesion. Fine grain wrapped coarse grain aggregate (Fig. 8b), which are composed of fine grains and coarse grains. Fine grains are wrapped around coarse grains in flocculent form. There are two types of fine grain wrapped gravel grain and fine grain wrapped sand, which mainly exist in granite residual soil with more fine grains. Coarse grain bite aggregate (Fig. 8c) is composed of gravel grains and medium coarse sands, which can form a soil skeleton with macropores. Its content determines the soil friction. The contact types are gravel-gravel contact, gravel-sand contact and sand-sand contact. The gravel-gravel contact is deep, forming a relatively large soil skeleton.

Structural Model

According to the content of each grain group of No. 1-9 soil sample and the shape of each aggregate, the microstructure model diagram of each soil sample is obtained. Different microstructures of soil will lead to different engineering properties of soil [12, 35]. As shown in Fig. 9, seven structural types (flocculation structure, flocculation skeleton structure, uniform skeleton structure, uneven skeleton structure, skeleton dense structure, skeleton virtual filling structure and skeleton pore structure) can be obtained according to the structural characteristics of No. 1-9 soil samples. The cohesive soil is mainly divided into flocculation structure, flocculation skeleton structure and uniform skeleton structure. Fig. 9a) shows that No. 1 soil sample has a flocculation structure. The content of gravel grain and sand in the soil is small. The clay minerals and free oxides make the fine grains gather together to form fine grain aggregates, forming the soil matrix. Sand particles float in it and are wrapped by fine grains, forming fine grain wrapped sand particles, and it is difficult for coarse grains to directly contact with each other. No. 2 soil sample has a flocculation skeleton structure (Fig. 9b), with less gravel grain and more sand in the

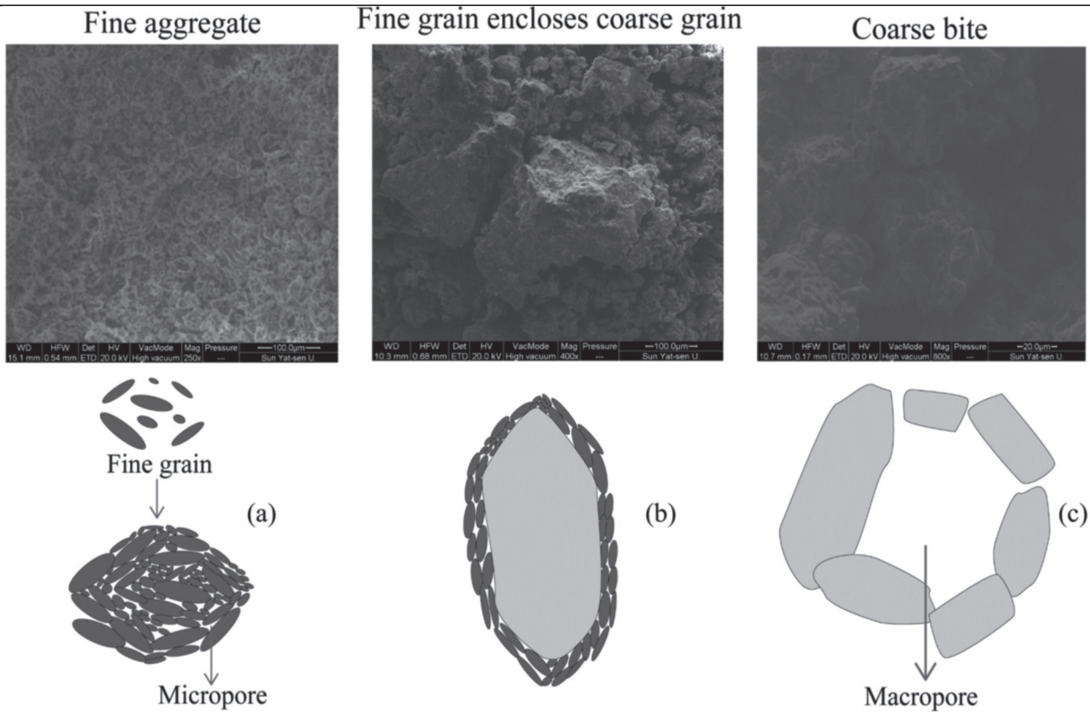


Fig. 8. Micromodel of three aggregates a) Fine grain aggregate b) Fine grain wrapped coarse grain aggregate c) Coarse grain bite aggregate.

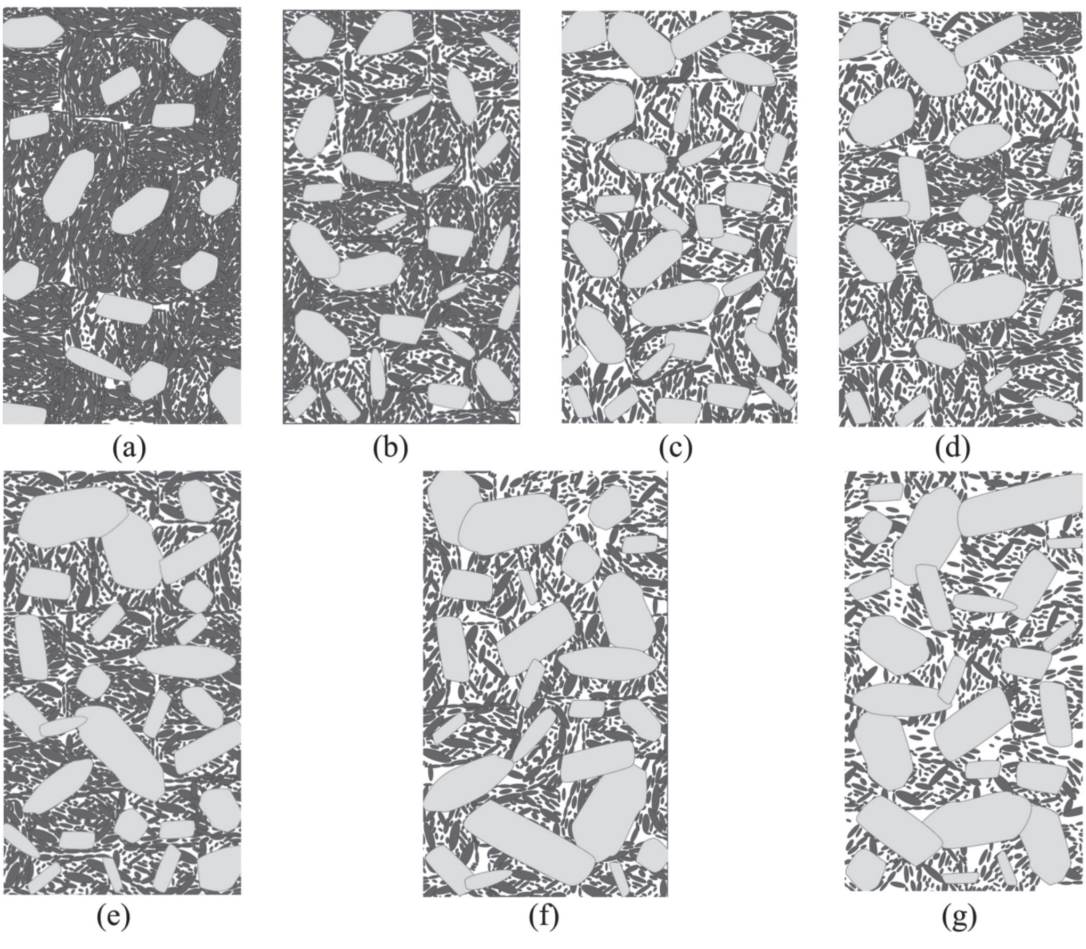


Fig. 9. Microstructure model of No. 1-9 soil sample a) Flocculation structure: No. 1 b) Flocculation skeleton structure: No. 2 c) Uniform skeleton structure: No. 3 d) Uneven skeleton structure: No. 4-6 e) Skeleton dense structure: No. 7 f) Skeleton virtual filling structure: No. 8 g) Skeleton pore structure: No. 9.

soil. The fine grain aggregate is flocculent, and the structural unit appears coarse grain bite aggregate, which can realize direct contact or indirect contact through the fine grain aggregate. At this time, coarse grain bite aggregate forms the soil skeleton, but the content is small. The fine grain aggregate is filled in, with less macropores and more micropores. Coarse grain bite aggregate is mainly sand-sand contact with shallow occlusion. No. 3 soil sample has a uniform skeleton structure (Fig. 9c). The content of gravel grain in the soil is small, but the content of sand is high. The coarse grain bite aggregate forms an obvious soil skeleton. Due to the small gravel grain content, the coarse grain bite aggregate is mainly sand-sand contact, with shallow occlusion, and its skeleton size is relatively uniform. The content of fine grain aggregate is less, and the direct contact between coarse grains is more. It is difficult for fine grains to completely fill the soil skeleton, and there are many macropores.

Fig. 9d) shows that the soil sample of No. 4-6 sandy cohesive soil has an uneven skeleton structure. The content of gravel grains in the soil increases, and the existence of gravel grains makes gravel-gravel contact and gravel-sand contact appear in the coarse grain bite aggregate. The occlusal degree was deepened, and the skeleton size of coarse grain bite aggregate was uneven. Fine grains are filled in the skeleton, with less macropores and more micropores. Gravelly cohesive soil is mainly divided into skeleton dense structure, skeleton virtual filling structure and skeleton pore structure. No. 7 soil sample is of skeleton dense structure (Fig. 9e), the content of gravel grains in the soil continues to increase, and there are obvious gravel-gravel contact and gravel-sand contact in the coarse grain bite aggregate. The fine grains can be well filled between the soil skeleton, forming fewer macropores and micropores, and the soil sample structure is relatively dense. No. 8 soil sample is of skeleton virtual filling structure (Fig. 9f). The content of gravel grain and sand in the soil is high, and the gravel-sand contact is obvious, forming a complete soil skeleton. The content of fine grains is low, which is virtually filled in the skeleton, and macropores and micropores are relatively developed. No. 9 soil sample is of skeleton pore structure (Fig. 9g). The soil contains a large number of gravel grains, and the direct contact between coarse grains is more obvious. Due to the large content of gravel grains, the engagement between gravel grains is deep, forming a large soil skeleton. However, the content of fine grains is small, and the soil skeleton that can be filled is limited, resulting in large and more pores in the soil. It is precisely due to the seven different structural characteristics of micro models formed by soil with different grain size composition that differences in soil engineering properties (compaction characteristics and strength characteristics) occur.

When the gravel grain content is low, the soil structure is mainly uneven skeleton structure (No. 4-6 soil samples), with many macropores, loose structure and poor compactness. At this time, with the increase of gravel grain content, the soil sample structure gradually transformed into a relatively dense skeleton dense structure (No. 7 soil sample), which improved the compactness of the soil. At this time, the maximum dry density of soil sample increases significantly with the increase of gravel grain content. In addition, gravel grains are mainly composed of quartz minerals, and the particle proportion is relatively large, which is also of positive significance for the improvement of the maximum dry density of soil. As a result, the maximum dry density of soil sample did not decrease immediately during the process of soil structure from skeleton dense structure (No. 7 soil sample) to skeleton virtual filling structure (No. 8 soil sample). When the gravel grain content exceeds a certain value, the content of fine grains is relatively low, and it is difficult to completely fill the soil skeleton formed by the sand and gravel grain group. The soil sample structure is gradually transformed into a relatively loose skeleton pore structure (No. 9 soil sample), leading to the weakening of the compactness of granite residual soil. At this time, the maximum dry density of the soil sample decreases with the increase of gravel grain content.

When the soil structure is flocculation structure and flocculation skeleton structure (No. 1 and No. 2 soil samples), the coarse grains are wrapped by free oxides or clay minerals to play a cementing role, which will enhance its cohesion. At the same time, it also makes it difficult for soil particles to directly contact with each other, resulting in small bite force between coarse grains. On the other hand, at this time, there are many fine grains with strong hydrophilicity. These fine grains are filled between the coarse grains under the wrapping of water, which plays a role in lubrication and reduces the surface friction between the coarse grains. For the No. 8 and No. 9 soil samples with more gravel grains, their internal structures are distributed as skeleton virtual filling structure and skeleton pore structure, forming many macropores. This provides more space for the position change of large particles, and makes them easier to slide or rotate. The ability to resist shear deformation is reduced, which means that the friction is reduced. Therefore, when the gravel grain content exceeds a certain value, the internal friction angle of granite residual soil will decrease.

Conclusions

Based on the different gravel grain content, a series of soil samples with different grain size composition were prepared to conduct a comprehensive study on their compaction and strength. Finally, the relationship between the grain size composition of granite residual soil and engineering properties is established, and the mechanism is explained from the microscopic perspective. The main conclusions are as follows:

(1) The optimal moisture content of granite residual soil is mainly controlled by the fine grain content, and

the maximum dry density is mainly controlled by gravel grain content. The optimal moisture content is positively correlated with the fine grain content, and the maximum dry density first increases and then decreases with the increase of gravel grain content. The changing process of its compaction characteristics is determined by the grain size composition and soil structure. For each 1% increase in the fine grain content of the soil, the optimal moisture content of the soil will approximately increase by 0.11%.

(2) The peak strength of granite residual soil first increases and then decreases with the increase of gravel grain content. The cohesion of granite residual soil is mainly controlled by the fine grain content, and the internal friction angle is mainly controlled by gravel grain content. The cohesion of granite residual soil is positively correlated with the fine grain content, and the internal friction angle first increases and then decreases with the increase of gravel grain content. The changing process of its strength characteristics is determined by the grain size composition and soil structure. For each 1% increase in the fine grain content of the soil, the cohesion of the soil will approximately increase by 0.27 kPa.

(3) The microstructure of granite residual soil is composed of fine grain aggregate, fine grain wrapped coarse grain aggregate and coarse grain bite aggregate. The cohesive soil is mainly divided into flocculation structure, flocculation skeleton structure and uniform skeleton structure. The sandy cohesive soil has an uneven skeleton structure. Gravelly cohesive soil is mainly divided into skeleton dense structure, skeleton virtual filling structure and skeleton pore structure. Soils with different grain size composition have different microstructure models, leading to differences in soil engineering properties.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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