Micro-Structures and the Basic Engineering Properties of Beach

Calcarenites in South China Sea

Zhu Chang-qi *, Liu Hai-feng , Zhou Bin

State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics,
Chinese Academy of Sciences, Wuhan, China, 430071;

Abstract: Beach calcarenite is a sedimentary rock deposited on tidal beaches of coral reefs in the South China Sea. This study investigated beach calcarenite samples collected from different locations in the South China Sea and coastal areas by using both micro- and macro-structure study techniques. The objective of this study was to establish the major parameters that control the strength. The results indicated that the beach calcarenite is characterized by low unit weight, high porosity, and large permeability. The degree of cementation of the beach calcarenites was between weak and medium. The saturation of the samples reduced their uniaxial compressive strengths. The correlation analyses of parameters indicated that the unit weight and the cementation are major parameters affecting the compressive strength of beach calcarenite samples. Both porosity and grain size are secondary parameters with an insignificant effect on the compressive strength of the beach calcarenite.

Keywords: Beach Calcarenite; microstructure; strength; naturally cemented carbonite sediment; parameters control strength ;South China Sea

1. Introduction

Beach calcarenite is a sedimentary rock that is deposited on tidal beaches of coral reefs in the

South China Sea. From the point view of petrology, carbonate-cemented rocks that satisfy the above description are collectively referred to as beach calcarenite (Zhang, 1985; Sun and Xun, 2009). On a global scale, beach calcarenite is distributed between 0° and 60°N. In China, beach calcarenite is distributed between 14° and 36°N, from the Spratly Islands to the temperate Shandong coastal zone (northern China). Within this zone, 73.85% of beach calcarenite is located in tropical and subtropical zones (Li, 1948; Wu and Wang, 1995). These sediments could include various size fractions of sand, gravel, and bio-detritus in addition to ancient coins, cola bottles, and fragments of early formed beach calcarenite. As cementation of beach calcarenite takes place in seawater, the cement in the initial stages is usually composed of aragonite or high magnesium calcite, while low magnesium calcite is relatively rare. The mineral composition of the cement material is highly dependent on the concentration of Mg^{2+} in pore water. When the ratio of Mg/Ca is low, the cement is usually low magnesium calcite. In contrast, when the ratio of Mg/Ca is high, the cement is mainly high magnesium calcite or aragonite (Rubbert, 1974; Given and Wilkinson, 1985).

Beach calcarenite is widely distributed on coral reefs in the South China Sea. Its granular component consists almost exclusively of organic material, its fabric is supported by grains, and its cement is composed of carbonate minerals. The size difference between grains can be significant, while the arrangement of the grains is almost random, and the degree of sorting is medium to poor. Surveys revealed that beach calcarenite almost unanimously tilts to sea (as shown in Fig.1, the occurrence of beach calcarenite on Guangjin Island). The dip angle varies generally from 6° to 10°, with a maximum of 15°. Dip angles are generally consistent with the slope angle of the beach. However, some dip angles are greater or less than the slope angle of beach.

[Insert Fig.1 here]

In China, beach calcarenite is mainly studied by researchers in the context of marine geology and geography, and their work focuses on the morphology, texture, structure, cement characteristics, and the origins of beach calcarenite from the South China Sea. Thus far, there have been few investigations on the engineering properties of beach calcarenite.

With the rapid development of offshore engineering in the 1970s, and particularly with the construction of the offshore oil platform in the Persian Gulf, a large quantity of carbonate sediments were uncovered in the seabed foundation. Due to the lack of sufficient practical experience in engineering, it is difficult for conventional geotechnical analytical methods to predict the engineering behaviors and performance of marine structures. As a result, engineering instability accidents often occur with offshore structures built on a foundation of carbonate sediments. Therefore, a set of specific methods is urgently needed to analyze the engineering characteristics of carbonate sediments in offshore environments. Previous investigations determined the following properties in terms of the main geotechnical parameters of carbonate sediments: (1) There is great variability in grain sizes and shapes of sediments, leading to great spatial variability in the distribution of void ratios in sediments; (2) The void ratio of carbonate sediments is much larger than that of terrigenous sediments; (3) The grain strength of the carbonate sediments is much lower than that of quartz grain, there are inner pore grains, and carbonate sediments are easy to break; (4) Recently, sediments have easily changed as a result of processes such as cementation. The cementation degree and texture could significantly affect the engineering properties of cemented sediments (Given and Wilkinson , 1985). Cementation occurred at points of intergranular contact, and the distribution of the cementation occurring region is irregularly lamellar or lens-shaped; the occurrence of this cementation is unordered, and its strength

does not increase with depth. In the strongly cemented layer, there is a segment in which no cementation occurring. The spatial distribution of cementation degree is completely random. Previous investigations have also found that organic matter could significantly affect the cementation strength. The engineering properties of calcarenite are greatly affected when the content of organic matter reaches 1% to 2%. Fookes and Higginbottom (1975) believed that cementation occurred as long as there were tiny variations in temperature, content of CO₂, and other parameters. Actually, these kinds of environmental variations accompanied the whole sedimentation process for carbonate sediments. Cementation can effectively reduce the void ratio of sediment and "weld" the grains together, increasing the overall stiffness of carbonate sediments. In order to investigate the engineering properties of calcarenite at a specific location, it is necessary to classify the rock samples properly. However, this classification method could be useful only for foundation design at this specific location, because there is great variation in the properties of calcarenite. It is very difficult to get a comprehensive understanding of the engineering properties of calcarenite (Cater et al., 1988).

Many researchers have studied the calcarenite from the north-west shelf of Western Australia. They found that the slope λ of the isotropic compression line varied from 0.18 to 0.24, and the variation of calcarenite specific volume is minor under certain pressure, which is determined by the grain composition and cementation characteristics (Cater et al., 1988; Airey, 1993; Coop and Atkinson, 1993). In terms of strength and cementation features, previous investigation found that there is a threshold value for consolidation pressure. A consolidation pressure greater than this threshold value will result in a dramatic increase in the amount of compression (about 3 times). In addition, there is a well-correlated relationship between the threshold value and the dry unit weight.

At the same time, calcarenite has a relatively high permeability, and its permeability coefficient is usually between 10^{-8} and 10^{-6} m/s (Zhu ,et al., 2014a, b).

In their investigations on calcarenite, Leroueil and Vaughan (1990) and Lagioia and Nova (1995) found that density and cementation degree were the dominant factors controlling the mechanical behavior of calcarenite. However, due to the significant variation in fabric, it is very difficult to get a large number of samples whose properties are homogeneous. As a result, the experimental data of beach calcarenite is greatly scattered.

In order to fully understand the geotechnical engineering properties of beach calcarenite, it is necessary to carry out the single index study. Under the precondition that natural samples cannot satisfy the requirement of homogeneous samples, the artificial preparation of cementation samples in laboratory is necessary. However, there are always some differences in cementing agents, pore structure, and other parameters between the samples made by conventional methods and natural beach calcarenite. To solve this problem, researchers began to explore developing an artificial sample preparation method, which could simulate the natural cementation structure. In this way, cementation samples with high void ratio, high stiffness, and good homogeneity can be prepared for laboratory testing.

Kucharski et al. (1996) in Australia developed a technique to precipitate calcite between soil particles and termed it the Calcite In-situ Precipitation System (CIPS). This technique simulates the geological sedimentation process. Fortunately, the sample preparation can be completed in just a few

minutes or several hours.

In this study, using four types of beach calcarenite samples from different coral reefs and coastal zone in the South China Sea as representative samples, the relationship between the macro mechanical parameters and structural parameters, as well as basic physical parameters, were established adopting a combination technique with both macroscopic and microscopic means(Xu, 2002). We attempted to determine the dominant factors controlling the strength of beach calcarenite to provide a theoretical foundation for the single index study of artificially prepared samples. This investigation could be beneficial for engineering construction on coral reef in the South China Sea.

2. Samples

Samples were taken from Luhuitou Park in Sanya (Hainan Province), Shidao Island, Guangjin Island, and Yongxing Island, all of which belong to the Xisha Islands. Shidao Island and Yongxing Island are located in the Xuande Atoll; Guangjin Island is located at the southeast end of the Yongle Atoll; Luhuitou Park is located at the geomorphic unit of a coastal coral reef. For the sake of convenience, beach calcarenites from the above islands are labeled with SD, GJ, YX, and LH, respectively. The weathered samples varied in color, with gray black to greyish-green surfaces, while the fresh samples varied from grey white to yellowish-white. These samples showed grain-supported fabric. The particle size distribution curve for the samples after being dissociated using artificial physical methods is shown in Figure 2. In this way, investigation on calcareous deposits and siliceous soils are different. For siliceous soils , it can be dissociated when drying in a 105 degree oven. From the particle size distribution curve, the mean particle sizes (D_{50}) were 0.32 mm, 1.2 mm, 6.3 mm, and 6.0 mm, respectively. However, the mean particle size of the loose sediment on

Guangjin Island was 2.5 mm, while it was 16 mm for the beach calcarenite on ChenHang Island, which are only a few hundred meters away from Guangjin Island. It is apparent that the difference in particle size between the beach calcarenites found on different locations is large, which is mainly controlled by the hydrodynamic condition. It is indicated that the recent turbulence of the water in which the sediment deposited is stronger than the early. Particle size distribution curves also show that the grain sizes of the first two types of samples are relatively uniform, and the last two types of samples are well graded. According to the engineering classification method proposed by Clark and Walker (1977), the above four types of beach calcarenites are named respectively as biological (sandy) calcarenite (SD), biological gravel calcarenite (GJ), coral calcirudite (YX), and siliceous coral calcirudite (LH). The surface structural characteristics of the 4 types of fresh samples are shown in Figure 3.

[insert Fig.2 here]

[insert Fig.3 here]

Benthic foraminifera fossil grains were picked out (foraminifera shown in Figure 4 were picked from GJ samples) in the clastic fragments first. Then, the radioactive ^{14}C of benthic foraminifer grains were tested using the Accelerator Mass Spectrometry (AMS) dating method. The test results are shown in Table 1. Results show that the formation time of SD sample was earliest, during the late wurm. The samples GJ and YX formed during the Sub-Atlantic period. The sample LH formed during the Sub boreal and was the youngest. Among the four types of beach calcarenites, the SD sample represents the aeolian sediments on the coral island in the late wurm with low sea level. In addition, this sample is the residue of the Laohuisha Island (Zhao et al., 1994). Other samples are the

products of the coastal zone sedimentation.

[insert Fig.4 here]

[insert Tab.1 here]

3. Basic physical properties

3.1 Mineral composition

The mineral compositions of the beach calcarenite analyzed by the X-ray diffraction (XRD) method are shown in Table 2. As can be seen, the minerals in sample GJ and YX are mainly aragonite. The main biological sources of clastic particles were found to be hermatypic corals, gastropods, lamellibranchia, immortal palms, and millepores. Sample SD and LH mainly consisted of rich magnesium calcite, and their biological sources were primarily coralline algae and benthic foraminifera. The LH category of samples was taken from a geomorphic unit of the coastal zone of coral reef and included terrigenous minerals such as quartz. Because aragonite and rich magnesium calcite are extremely unstable minerals in the natural environment, they can gradually change into calcite over time. Thus, it can be inferred that the formation time of samples GJ and YX was later than that of samples SD and LH. This conclusion is consistent with the results of the ^{14}C dating method shown in Table 1.

[insert Tab.2 here]

3.2 Density and specific gravity

Tests were conducted based on the Chinese *Code for Tests of Hydroelectric and Water Conservancy Engineering* (DL/T5368-2007). Because beach calcarenite has a high porosity, the holes on the surface of the samples were filled by paraffin wax. When the volume of samples is relatively small, the density values measured through the wax sealing method could be in excess of 27% - 52.4% of the real value. Moreover, the higher the porosity, the larger the deviation. For this reason, in this investigation, the volumetric method was applied for the density measurement. In this method, the larger the volume of the sample, the more accurate the measured value is. Therefore, large volume samples were used in tests as often as possible.

For specific gravity measurements, distilled water was used as the test solution when test on siliceous soils. But, for calcarenite, the measured value is slightly greater when distilled water is used as the test solution rather than kerosene ; the difference in the measurements is approximately 0.04 to 0.08, accounting for 1.4% to 2.9%. There are two explanations for this test result. First, water can dissolve soluble salts contained in the beach calcarenite. As a result, the measured volume of beach calcarenite decreases. Second, water has an infiltrative effect on the bioclastic grains, which also causes the measured volume of the rock powder to decrease. These two effects ultimately lead to a measured specific gravity value that is greater than its real value when water is used as the test solution. Therefore, we propose that kerosene should be used as the test solution for the measurement of the specific gravity of carbonate sediments. The average measured values of density and specific gravity for beach calcarenite are listed in Table 3.

[insert Tab.3 here]

3.3 Water absorption and permeability

Tests were conducted based on the Chinese *Standard for Test Methods of Engineering Rock Mass* (GB/T 50266-2013). The size of cylindrical samples was 50 mm in diameter and 70 mm in height. The measured values of water absorption and saturated water absorption for the four types of beach calcarenites are shown in Table 4. There was only a small difference between the water absorption and saturated water absorption (0.7% - 3.4%).

[insert Tab.4 here]

Permeability tests were carried out on the “Rock Temperature-Stress-Seepage Coupling Triaxial Rheological Instrument”, which is located at the State Key Laboratory of Geomechanics and Geotechnical Engineering in China. This equipment was manufactured by the French Top Industrie company, and it consists of six parts, including the control system, the oil source system, the axial compression system, the confining compression system, the seepage system, the temperature system, as well as various types of sensors. This instrument is mainly used for conducting rheological tests on rock-like materials under the coupling conditions of stress, temperature, seepage, and chemical etching. The size of cylindrical test samples was 50 mm diameter and 100 mm height. Due to the large sample grain size the sample roughness, plasticine was used to fill the cavities and cracks on the surfaces of samples and to remove sharp grains in order to minimize the gap between sample surface and test tubes to improve test accuracy. Before testing, the samples were wrapped using a rubber membrane. Because of the limited amount of sample GJ, permeability tests were not

performed on it. The confining pressure was below 4 MPa for tests. The permeation rate was controlled by adopting discharge, and test results are shown in Table 5. The test results indicate that beach calcarenite is very permeable; the discharge became stable very rapidly during tests. The permeability of samples SD and LH was slightly higher than that of sample YX, indicating that the cementation degree of sample YX was higher, and the connectivity of inter-particle pores was not good. The test results of this study is about 50 to 5,000 times greater than reported in previous foreign investigations (10^{-6} - 10^{-4} cm/s) (Airey, 1993).

[insert Tab.5 here]

4. Microstructure features of beach calcarenites

Figure 5 is a photomicrograph of a thin-section of the beach calcarenites. From the microscopic observation, we find that the carbonate skeletal grains and clastic grains typically form a very loosely packed self-supporting framework so that open pore spaces between the grains constitute a large proportion of the material volume. Grains were bioclastics mainly composed of red algae and foraminifera, and there was a small amount of acanthosis. Samples had mainly inter-granular pores, with a small amount of moldic pores, and pore connectivity was relatively good. Sample GJ was also in grain-supporting texture. Its main bioclastics were corals, red algae, green algae, and a small amount of Brachiopoda and foraminifera. The main pore type was inter-granular pore, and pore connectivity was relatively good. Sample YX ,its main bioclastics were corals, red algae, green algae, and a small amount of foraminifera. The main pore types were dissolution pore, inter-granular pore, biological cavity pore, and a small amount of intragranular dissolution pore and moldic hole. Biological cavity pores were filled with needle sparry or micritic,

and the pore connectivity was poor. Sample LH , its main bioclastics were coralline algae, pleopods, red algae, foraminifera, and a small amount of peduncles and acanthosis. The main pore types were dissolution pore, cavity pore, intragranular dissolution pore, and a small amount of intergranular pore. The pore connectivity was relatively good. Quartz grains in samples were visible obviously, as shown in Figure 6.

[insert Fig.5 here]

[insert Fig.6 here]

From the observation of cement under a microscope, it was apparent that there are three kinds of cement in samples SD and GJ: biomicrite, acicular aragonite, and granular calcite. The cementation process can be divided into four stages. The first stage is the growth of the caniniform aragonite crystals in micrite envelopes. The second stage is the cementation of granular calcite crystals during a buried period. The third stage is dissolution, and the fourth stage is the growth of acicular aragonites on the walls of dissolution pores.

There were also three kinds of cementation matter in sample XY: biomicrite, acicular aragonite, and red algae. Through observation, it was found that there was obvious compaction in sample YX; meanwhile, biological cementation was also obvious. The crusty red algae grew in crustal pores and played a role in cementation between grains. The main cement of Sample LH was biomicrite. Cementation was good in the early stage, while dissolution was particularly strong in the later stage. A typical polarization crossed microphotograph of cements is shown in Figure 7.

[insert Fig.7 here]

5. Pore size distribution and porosity of beach calcarenites

A high pressure pore structure instrument (Poremaster33) was used for pore size distribution and porosity measurements. These tests were conducted in the State Key Laboratory of Geomechanics and Geotechnical Engineering. The samples were cubes with a size of 7 mm x 7 mm. The mass of each sample was about 1 gram.

[insert Fig.8 here]

Figure 8 shows the distribution curve of pore size and cumulative press-in mercury. It is apparent that the range in the measured pore size of beach calcarenite is 8×10^{-6} to 0.2 mm. According to the percentages, the pore size interval can be divided into 2 to 3 segments, as shown in Table 6. Correspondingly, the porosity value of beach calcarenite can be determined.

[insert Tab.6 here]

As shown in Table 6, the porosity values of beach calcarenites correspond with the above measured values of permeability coefficient. However, because the method adopted to measure the porosity of beach calcarenites is not applicable for large size pores, individual data in Table 8 is questionable.

6. Strength characteristics of beach calcarenite

The strength tests were conducted on a digital electro-hydraulic servo-controlled testing machine

for rock materials (RMT-150C), which was developed by the Institute of Rock and Soil Mechanics associated with the Chinese Academy of Sciences. Uniaxial compression, uniaxial indirect tensile, triaxial compression, and shear test of rock materials can be tested with this system. The size of cylindrical samples for uniaxial compressive strength tests was 50 mm diameter and 100 mm height. The tensile strength of beach calcarenite was tested by the Brazilian disc splitting method. The corresponding samples were cylindrical with a 50 mm diameter and a 50 mm height. Samples were divided into two groups. One set was dried for at least two weeks in the natural environment. The average water content of these dried samples was 2.2% for SD, 2.3% for GJ, 1.6% for YX, and 0.5% for LH. Another set was saturated with water using the vacuum method. The average water content of these saturated samples was 31.6% for SD, 24.2% for GJ, 8.9% for YX, and 29.0% for LH. The loading rate was controlled by applying the displacement controlling method; the loading rate in tests was 0.0002 mm/s.

6.1 Uniaxial compressive strength

At least three parallel samples in each group of uniaxial compressive strength tests were tested. Due to the significant anisotropy of the structure of beach calcarenite, the uniaxial compressive strength can differ greatly with differing density, porosity, or cementation, even though they are sampled from the same block. Correspondingly, it is reasonable to use the range value or the average value (Leroueil and Vaughan, 1990) to represent the strength characteristics of beach calcarenite. Taking the sample SD as a representative, Figure 9 shows the uniaxial stress - strain curves of the dried and saturated samples. All strength test results are listed in Table 7.

[insert Fig.9 here]

[insert Tab.7 here]

In Table 7, it can be seen that the strength of the saturated samples decreases to some extent due to the water softening effect. The softening coefficient K_d is about 0.92. It is also observed that the deformation related to peak strength increases significantly for saturated samples. The ratio between the deformations related to peak strength for dried samples and saturated samples could reach up to 376.3%. Additionally, saturation makes the initial elasticity modulus decrease compared to dried samples. The ratio between the initial elasticity modulus under dried and saturated status is about 0.4. However, it is interesting to notice that the residual strength is basically the same for dried and saturated samples.

Furthermore, compared to dried samples, two obvious differences were observed for the uniaxial compressive stress-strain curve of saturated samples. Firstly, the stress-strain curve presented a bimodal pattern. High porosity and low cementation strength could be the reason for this phenomenon. After the first peak appeared, the end of samples would present a trend of gradual compression with the increase of deformation in the test. As a result, the sample presents the properties of granular material, and the strength will increase with density until the appearance of the second peak strength. The second peak strength is about 1.47 times that of the first one. Secondly, the strain corresponding to the peak strength increases. The strain for saturated samples is nearly equal to that of dried samples at its first peak strength. However, the strain corresponding to the second peak strength for saturated samples is nearly 10 times that of the strain of dried samples at their second peak strength.

[insert Tab.8 here]

Table 8 summarizes the results of the uniaxial compressive tests for the four types of beach calcarenites. From Table 8, we can see that the peak strength of samples SD, GJ, and LH were between 2.02 and 5.81 MPa, and all were less than 12.5 MPa. According to the engineering classification method proposed by Clark and Walker (1977), samples SD, GJ, and LH should be classified as belonging to the weak cementation category. Sample YX can be classified as medium cementation. Saturation causes the uniaxial compressive strength of beach calcarenites to decrease. The softening coefficient (K_d) varies from 0.45 to 0.96. Generally, the lower the degree of cementation, the smaller the softening coefficient. Figure 10 shows the pattern of fracture surface of the dried samples. Due to the features of high porosity and low strength, tension failure occurs in the naturally dried sample SD. Shear failure occurs in the other samples.

[insert Fig.10 here]

6.2 Tensile strength

Generally, the Brazilian disc splitting method or direct tension method can be used to determine the tensile strength of rock materials. As the tensile strength of beach calcarenite is low, the mass and stiffness of fixture are great in direct tensile test. These factors could significantly affect the accuracy of the measurement. In this study, the Brazilian disc splitting method was adopted to determine the tensile strength of beach calcarenite indirectly. Samples were cylinders with a 50 mm diameter and a 50 mm height. Samples were divided into two groups. One group was naturally dried samples; the

other group was samples saturated with water by the vacuum method. Three sets of parallel tests were carried out for each group of sample. Test equipment and loading method were the same with the uniaxial compressive strength test. Table 9 shows a summary of the results of tensile strength for four types of beach calcarenites. In Table 9, it can be seen that the tensile strength of beach calcarenite varies from 0.64 to 2.52 MPa. Saturation makes the tensile strength decrease. The water softening coefficient for the tensile strength of beach calcarenite varied from 0.47 to 0.81. The ratio of compressive strength to tensile strength for dried samples was about 3.08 to 9.14, which is less than the statistical value of 8 to 12 in conventional terrigenous rock. This may be due to the different mechanical performance for the sedimentary rock formed by cementation under conventional temperature and pressure compared to the sedimentary rock formed under high pressure.

[insert Tab.9 here]

[insert Fig.11 here]

Observation of the characteristics of tensile failure sections of beach calcarenite are shown in Figure 11. It is apparent that there is no particle tension failure (particle breaking) in the weakly cemented samples, except for in the sample YX, which was well cemented. The tensile failure section basically develops along the inter-granular bonding area. This is to say, the degree of cementation basically governs the tensile strength of beach calcarenite. Therefore, the phenomenon of particle tension failure (breaking) becomes more and more significant in the tensile failure of beach calcarenite and with the increase of the cementation strength of beach calcarenite. It is reasonable to present the cementation degree of beach calcarenites using tensile strength, when the cementation degree of beach calcarenite is under medium.

7. Control parameters of strength

In order to determine the contribution of various parameters to the strength of beach calcarenite and to provide theoretical support for further research on the single index of artificial cemented samples, it is necessary to establish the correlation between the parameters and strength for beach calcarenite. Figure 12 shows the relationship between cementation degree and the density of beach calcarenite. In Figure 12, it can be seen that there is a positive correlation between density and cementation. Meanwhile, it also can be seen that the tensile strength values of most samples are close; data points in Figure 12 are relatively concentrated. This phenomenon could be attributed to the large variability in the spatial distribution of beach calcarenite, as well as physical and mechanical properties. It is very difficult to collect samples with full range strength at a field site. Therefore, the relationship between cementation degree and the density of beach calcarenites requires further verification in the future.

[insert Fig.12 here]

Figure 13 shows the relationship between the density and uniaxial compressive strength. In Figure 13, it can be seen that there is a good linear relationship between the density and uniaxial compressive strength for beach calcarenites, indicating that the uniaxial compressive strength of beach calcarenite increases linearly with the density. In addition, the sensitivity is quite strong when the cementation structure stays the same, even though beach calcarenite contains a certain amount (LH sample contains 8.3%) of terrigenous clastic grains. Therefore, density is obviously a controlling index for the uniaxial compressive strength of beach calcarenite.

[insert Fig.13 here]

Figure 14 shows the relationship between cementation degree and uniaxial compressive strength of beach calcarenite, with the cementation degree represented by uniaxial tensile strength. In Figure 14, it can be seen that because it is very difficult to collect samples with a large range of strength from a field site, test data points are mainly distributed in two regions. Basically, a positive correlation and a high sensitivity between cementation degree and uniaxial compressive strength of beach calcarenite are apparent, indicating that the degree of cementation is also a key parameter controlling the strength of naturally cemented calcarenite. However, in order to understand this relationship more comprehensively, it is necessary to carry out research on samples with a larger strength range.

[insert Fig.14 here]

Figure 15 is the relationship curve between porosity and the uniaxial compressive strength of beach calcarenite. In Figure 15, it can be seen that there is a good linear relationship between porosity and uniaxial compressive strength for samples GJ, SD, and LH, with the exception of sample YX. This relationship reveals that uniaxial compressive strength decreases linearly with porosity with a relatively small slope, indicating that porosity could reflect the strength of beach calcarenite to a certain extent. However, it is easily influenced by other parameters, making the data points in Figure 15 scattered. This test result may also be influenced by the test method. As was previously known, the structure of beach calcarenite is extremely uneven, and the distribution of its internal porosity displays high randomness. In addition, the connectivity between the pores is uneven due to the existence of internal cementation. As a result, the pore size distribution measured by the

pore size test is mainly due to the pore structure of rock surfaces. It cannot represent the characteristics of the whole sample. Additionally, the number of samples for tests should be increased to reveal the essential relationship more comprehensively and accurately.

[insert Fig.15 here]

In order to investigate the influence of the grain composition of beach calcarenite on its uniaxial compressive strength, the grain with the greatest content was taken as the characteristic grain size for this type of beach calcarenite. Figure 16 shows the relationship between characteristic grain size and the uniaxial compressive strength of beach calcarenites. In Figure 16, it can be seen that the discreteness of the test data is significant, indicating that the impact of the grain size on the strength of beach calcarenite is much less than that of other controlling parameters, such as density and cementation degree. Therefore, a large number of uniform samples should be collected in the field to carry out single index studies in order to establish the relationship between grain composition and strength of beach calcarenites. In reality, this is almost impossible for natural beach calcarenite samples. The only possibility is to make artificial cemented samples in a laboratory under the precondition of effective parameter control.

[insert Fig.16 here]

8. Discussions and Conclusions

In this study, a series of laboratory tests on physical and mechanical properties were conducted on beach calcarenites from the Xisha Islands in the South China Sea. Adopting a combination of

macroscopic and microscopic research means, the following main discussions and conclusions were drawn:

- a) According to the engineering classification method proposed by Clark and Walker (1977), the four types of beach calcarenite should be named biological (medium sand) calcarenite (SD), biological gravel calcarenite (GJ), coral calcirudite (YX), and siliceous coral calcirudite (LH). Beach calcarenite is a type of beach rock cemented under conditions of low temperature and pressure. Their diagenetic age is 1,660 to 15,980 BP. Grain composition was bioclastic, and mineral composition was aragonite and rich magnesium calcite, which accounted for more than 90% in beach calcarenites. Their typical characteristics were a relatively large porosity (18.36 to 53.78 %) and a lower density (1.33 to 2.17 g/cm³). Beach calcarenites have a high permeability, and the permeability coefficient was between 4.62×10^{-3} and 5.41×10^{-3} cm/s.
- b) There were three cementation categories for the beach calcarenite: biomicrite , acicular aragonite and granular calcite . In addition, red algae also to cementation in sample YX. Cementation process can be divided into two stages. In the first stage, the diagenesis in early synsedimentary allowed micrite envelopes grow. Consequently, micritic envelopes of aragonites grew further. In the second stage, the cementation of granular calcite occurred.
- c) The peak compressive strength of samples SD, GJ, and LH was between 2.02 and 5.81 MPa. These samples were in a weakly cemented state. The peak compressive strength of sample YX was 19.39 MPa, which was in the medium cementation state. Water saturation makes the uniaxial

compressive strength of beach calcarenite decrease, and the water softening coefficient (K_d) was 0.45 to 0.96. Generally, the lower the degree of cementation, the smaller the softening coefficient. The tensile strength of beach calcarenite was between 0.64 and 2.52 MPa. Water saturation also makes the tensile strength decrease. The water softening coefficient for the tensile strength of beach calcarenite was 0.47 to 0.81. Test results also indicate that the ratio of compressive strength to tensile strength of beach calcarenite was 3.08 to 9.14, which is less than statistical values of 8 to 12 in conventional terrigenous rocks. This may be due to the different diagenesis mechanism for sedimentary rock formed under conventional temperature and pressure and sedimentary rock formed under high pressure.

- d) The analysis of the correlation between each parameter shows that density and cementation degree are the main parameters that control the strength of beach calcarenite. The uniaxial compressive strength of beach calcarenite significantly increases with density and cementation degree. The effects of porosity and particle diameter on the uniaxial compressive strength of beach calcarenite were not obvious, making them secondary parameters controlling the strength of beach calcarenite.
- e) Comparison with other test result on calcarenite of NRA(Nyland,1988), calcarenite and calcareous sand stone of Abu Dhabi (Cook,1999) and coralline rock of Suakin Harbor (Medani et al.,1999) shows that the strength of calcareous deposits have a strong discreteness. Physical properties and uniaxial compressive strength on calcarenite of Abu Dhabi and South China Sea are similar. In this article, the result of strength tests presents some special characteristics of the

calcarenite of South China Sea. High porosity and low cementation strength could contribute saturated samples a bimodal pattern in uniaxial stress-strain curves. This presents that the uniaxial compressive strength on calcarenite of South China Sea was increased when compacted before the first peak occur. For weak cemented calcarenite sample of South China Sea, direct tension tests present that tensile failure sections is located in inter-granular bonding area. Therefore, we should take the possible of brittle failure occurred in the pile and the beach rock interface into account. Meanwhile, if the end of pile was located in this kind of deposit, we should take the compressibility into account.

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SD

GJ

YX

LH

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Sample SD

Sample GJ

Sample YX

Sample LH

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GJ

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Table 1 ¹⁴C-AMS dating results of the samples

Number of samples	Sample	¹⁴ C age / BP	Calibration age / BP
SD	foraminifera	15570±60	15980±60
GJ	foraminifera	1850±30	2270±30
LH	foraminifera	3160±30	3570±30
YX	foraminifera	1250±30	1660±30

Table 2 Mineral composition of the samples by X-ray diffraction analysis

Samples	Mineral composition / %			
	High magnesian calcite	Aragonite	Quartz	NaCl
SD	71.7	28.3	—	—
GJ	13.3	83.6	—	3.1
YX	35.0	65.0	—	—
LH	67.2	24.5	8.3	—

Table 3 Average bulk density and specific gravity of the samples tested

Samples	average density / g/cm ³	specific gravity
SD	1.33	2.71
GJ	1.60	2.73
YX	2.17	2.74
LH	1.45	2.75

Table 4 Results of water absorption test

Samples	water absorption/%	saturated water absorption/%
SD	30.5	31.6
GJ	23.7	24.2
LH	25.6	29.0
YX	8.2	8.9

Table 5 Permeability coefficient of beach calcaretines

Samples	seepage pressure/bar	permeability coefficient/ cm.s^{-1}
SD	2.245	5.22×10^{-3}
LH	2.072	5.41×10^{-3}
YX	2.314	4.62×10^{-3}

Table 6 Summary of the pore size distribution and porosity

Samples	segment 1		segment 2		segment 3	
	pore size/mm	/%	pore size/mm	/%	pore size/mm	/%
SD	$4 \times 10^{-5} \sim 0.07$	30	—	—	0.07~0.2	70
LH	$3 \times 10^{-5} \sim 10^{-4}$	10	$7 \times 10^{-4} \sim 0.05$	37	0.05~0.2	52
YX	$8 \times 10^{-6} \sim 0.1$	27.8	—	—	0.1~0.2	72.2
GJ	$10^{-5} \sim 8 \times 10^{-3}$	13	$8 \times 10^{-3} \sim 0.1$	40	0.1~0.2	47

Table 7 Summary results of uniaxial compressive test of SD sample

States	Peak strength σ_c /MPa	Residual strength σ_s /MPa	σ_s/σ_c	Axial strain for peak strength /10 ⁻³	Elasticity modulus /GPa
Naturally dried	2.06	1.52	0.74	1.2	2.05
	2.22	1.50	0.68	2.6	1.02
	2.72	1.40	0.52	1.6	2.33
	1.34	0.49	0.37	1.6	1.42
	1.78	1.26	0.71	2.3	0.85
Saturated	1.69	1.21	0.72	9.4	0.17
	2.27	1.48	0.65	6.1	1.70
	2.03	1.15	0.57	6.0	0.37
	1.47	1.23	0.84	13.2	0.19

Table 8 Summary results of the uniaxial compressive test for beach calcarenites

Samples	Dried samples				Saturated samples				K_d
	σ_c	σ_s	σ_s/σ_c	E	σ_c	σ_s	σ_s/σ_c	E	
SD	2.02	1.23	0.61	1.53	1.87	1.27	0.68	0.61	0.92
GJ	5.81	1.55	0.27	4.63	2.59	1.65	0.64	2.22	0.45
LH	3.47	1.35	0.39	7.22	1.55	0.88	0.56	2.83	0.45
YX	19.39	6.43	0.33	14.89	18.57	8.41	0.45	14.08	0.96

* σ_c --average of peak strength, MPa; σ_s --average of residual strength, MPa;

E--elasticity modulus, GPa; K_d -- softening coefficient

Table 9 Average values of tensile strength for beach calcarenites

Samples	σ_t /MPa		K_d
	Dried	Saturated	
SD	0.66	0.49	0.74
GJ	0.64	0.46	0.72
LH	0.81	0.38	0.47
YX	2.52	2.06	0.81

* σ_t -- the average value of tensile strength; K_d -- softening coefficient for tensile strength.