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Study on the microscopic characteristics of three-dimensional pores in coral sand

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Abstract: The pore is the place where the seepage occurs in the porous medium, which is inevitably related to the permeability of the medium. Due to the special material source and formation process, coral sand has completely different pore characteristics compared with terrestrial sand. Through a series of microscopic studies, the reason for the special pore properties of coral sand in essence was revealed. It is found that it is reasonable to describe the properties of pores from the aspect of pore shape, pore throat size and global connectivity. Among them, pore shape is measured by the shape factor. Pore throat size includes pore radius and throat radius. Global connectivity in the porous media is described by coordination numbers. Particle shape and particle surface roughness are the main factors affecting pore shape, pore throat size and global connectivity. Particle shape mainly affects pore shape, throat size, pore throat size dispersion and the uniform distribution of connectivity in the medium. Particle surface roughness mainly affects pore shape, pore shape dispersion, pore size and global connectivity in the porous medium.

Keyword: coral sand; quartz sand; microscopic angle; particle morphology; pore properties

1 Introduction

Coral sand is a special type of marine soil [1−2]. Due to its special material source, the particles of coral sand are irregular in shape and prone to breakage, and the pores on the surface and inside of the particles develop[3]. Coral sand is also known as calcareous sand or calcareous soil because it contains more than 90% calcium carbonate. The particularity of particle shape results in the special pore properties of coral sand in the medium. Therefore, it is very important to study the pore characteristics of coral sand from the microscopic perspective to reveal the special hydrology-physical properties of coral sand as the porous medium. This work will focus on this problem.

At present, many scholars have made some achievements in the study of the pore property of coral sand. In 2002, Sun et al. [4] conducted the study on the liquefaction characteristics of coral sand and proposed that coral sand had internal pores because of its biogenesis. When the particles were intact, the internal pores had little influence on the medium porosity; while when the particles were broken, the internal pores were released and transformed into the external pores, which would affect the mechanical properties of coral sand. In 2014, Zhu et al.[5] employed laser femtosecond cutting technology to cut coral sand particles. The images of the pores in the particles were obtained by using the optical microscope, and then the image processing function of Matlab was used to carry out statistical and quantitative analysis of the pores in the coral sand particles. In 2017, Jiang et al.[6] obtained two-dimensional plane images of the pores of coral sand through scanning electron microscope (SEM) tests, and examined the surface porosity distribution of coral sand with different particle sizes with the help of Matlab image processing program for binarization processing. In 2019, Zhou et al.[7] conducted secondary processing of the three-dimensional images of coral sand particles by using the three-dimensional closure operation algorithm, and optimized and reconstructed the three-dimensional pore structure of coral sand. Cao et al.[8] studied the distribution of micro-pores on the surface of coral sand particles through mercury intrusion tests and CT scanning tests, and proposed that the internal porosity of coral sands was about 1%, far less than the connected porosity.

The above research results have made outstanding contributions to the study of the pore properties of coral sand, and also laid a foundation and pointed out the direction for the later research. Pores can be divided into three categories: the pores inside the particle, the micro-pores on the particle surface and the interconnected pores [9−11]. However, the existing microscopic studies on the pores of coral sand mainly focus on the pores inside the particle and the pores on the particle surface, and there are few studies on the interconnected pores in coral sand. At present, the main method to study the microstructure of sand particles is to obtain the parameters of the two-dimensional size of particles by processing the SEM images, and then calculate the particle morphology parameters. However, due to technical limitations, this research method is limited to two-dimensional surface pores and cannot describe a large number of particles quantitatively. In contrast, the PartAn 3D particle morphology analyzer used in this work can quickly obtain the three-dimensional morphology

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parameters of a large number of particles, and the data obtained by this instrument are more real and representative. It should be noted that in porous media, the influence of interconnected pores on hydrology-physical properties of coral sand is much greater than that of the pores in the particle and the micro-pores on the particle surface. Therefore, based on CT scanning technology and three-dimensional reconstruction method, this work aims to reveal the fundamental factors affecting different pore properties of coral sand from the perspective of particle morphology, that is, how particle morphology affects the pore properties of porous media. Based on the results in this paper, the hydrology-physical properties of coral sand, such as permeability, dispersion, and water supply mechanism, can be further studied, or other macroscopic mechanical properties of coral sand affected by pores can also be analyzed. According to the idea in this paper, the microscopic pore properties of other soil media can also be studied.

2 Test principles and methods

2.1 Test principles

Through the comparative study of coral sand and quartz sand, this work firstly studied the particle morphology, and then explained the formation reasons of pore characteristics based on the research results of particle morphology

2.1.1 Particle morphology

In this work, PartAn 3D particle morphology analyzer produced by Microtrac Company (Florida, USA) was used to capture the particle morphology. The specific working principle of this instrument can refer to the quantitative research on the particle morphology of coral sand presented by Wang et al. [12]. Table 1 provides the selected particle morphology parameters according to the requirements of the study. The circularity values range from 0 to 1, and 1 represents that the particle shape is regular; the skewness value is greater than or equal to 1, and 1 represents that the particle shape is regular; the concave value ranges from 0 to 1, and 0 represents the particle has a smooth surface; the convex value ranges from 0 to 1, and 1 represents the particle has a smooth surface.

Table 1 Particle morphology parameters

Parameter	Symbol	Explanation
Circularity	Cir	$Cir = 4\pi A / P^2$
Skewness)	Ske	$Ske = FL^2 / (FW \times FT)$
Concavity	Cc	$Cc = (CA - A) / CA$
Convexity	Cv	$Cv = CP / P$

Note: A is the particle area (mm^2); P is the particle circumference (mm); FL is the maximal particle length (mm); FW is the maximal particle width (mm); FT is the minimal particle width; CA is the minimal convex boundary area (mm^2) around the particle; CP is the minimal convex boundary circumference (mm) around the particle.

2.1.2 Three-dimensional pores

In this paper, CT scanning technology and three-dimensional reconstruction method were used to examine the pore characteristics. The nanoVoxel-4000 series of high-resolution industrial CT scanner, produced by Tianjin Sanying Precision Instrument Co., LTD, was used for the CT scanning test, as shown in Fig. 1.

Fig. 1 High resolution industrial CT scanner

In the CT scanning test, conical X-rays emitted from microfocal X-ray sources penetrated the object and then were projected onto detectors forming images. Meanwhile, the sample was rotated 360° at a fixed angular velocity, and thousands of X-ray attenuation images were continuously collected from the three directions of *X*-*Y*-*Z*. After each sample was scanned by the CT scanner, a data package named “raw” was generated. Voxel Studio Recon software was used to connect the sample slices in the data packet with similar pixels to realize three-dimensional model reconstruction. Since the slices were densely distributed during CT scanning tests, the reconstructed model can basically reflect the real situation of the tested sample. After obtaining the 3D reconstructed model, software, such as Volume Graphics Studio Max, Fei Avizo and Sypi-Sore, were used to perform the image display, measurement, pore data extraction and digital core analysis of reconstructed model. The pore data extraction was based on the maximal balls algorithm. The principle of maximal balls algorithm is that at any point in the pore pixels of 3D digital core, the sphere radius is extended to the periphery with an increase in radius until the sphere surface touches the nearest rock skeleton, and the collection of all pixels in the formed region is called the largest sphere. A large ball can overlap an adjacent largest ball with a radius less than it, thus forming the largest cluster of balls. All the pores in the digital core are filled with the largest cluster of balls, and the sphere with the largest radius in the largest cluster of balls is defined as the ancestor of this largest cluster. If a certain ball in a largest cluster of balls has two ancestors, the location of this common largest ball is the throat. The length of throat is illustrated as shown in Fig. 2.

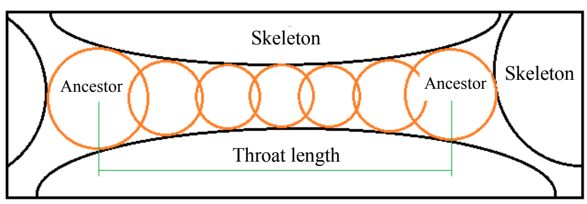


Fig. 2 Schematic diagram of the principle of maximal balls algorithm

Based on the maximal balls algorithm, the occupied space and connectivity of pores and throat in the three-dimensional image of digital core can be distinguished, and the corresponding structural network model of pores and throat can be extracted as well, as shown in Fig.3. At the same time, the quantitative extraction of pore structure, such as pore throat size, pore throat volume, pore-throat ratio, coordination number and shape factor, can be realized by using mathematical statistics method, and then the parameters characterizing the microscopic pore properties can be obtained.

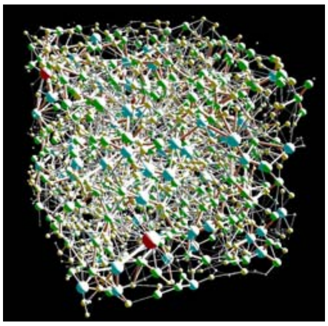


Fig. 3 Pore network model

In this work, a comparative study on coral sand and quartz sand was carried out from the three aspects of pore shape, pore size and pore connectivity. The pore shape was described by the shape factor. The calculation formula of shape factor is as follows:

$$F = S / L^2 \quad (1)$$

where F is the shape factor (dimensionless); S is the polygon area (mm^2); and L is the perimeter of the polygon (mm).

According to Eq. (1), the shape factor F of a circle is 0.079 6, the F of a square is 0.062 5, and the F of a triangle is between 0 and 0.048 1. Therefore, the larger the value of F , the more regular its shape.

The size properties of pores were described by pore radius and throat radius. The throat is a long and narrow channel connecting the two pores.

The overall pore connectivity of porous media was described by the coordination number. Coordination number refers to the number of pore throat connected to a single pore. The larger the coordination number, the more paired larynxes, indicating better connectivity.

2.2 Test plan

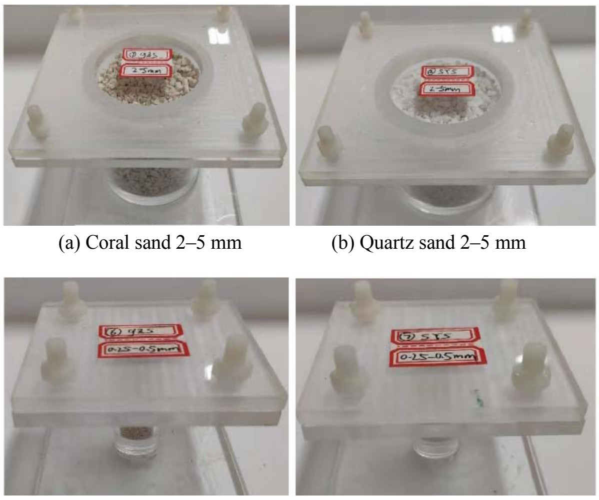
The coral sand used in the test was taken from an artificial reef in the Spratly Islands in the South China Sea. Through the vibrating sieve test [13], six groups of coral sand with single particle size were obtained: ≤0.1, 0.10–0.25, 0.25–0.50, 0.5–1.0, 1–2, 2–5 mm. By conducting the permeability tests on the six groups of coral sand and quartz sand with single particle size, it was found that when the particle size was smaller than 0.46 mm, the permeability coefficient of coral sand was greater than that of quartz, while when the particle size was greater than 0.46 mm, the permeability coefficient of coral sand was smaller than quartz, that is, the permeability of coral sand and quartz sand was reversed at the particle size between 0.25 and 0.50 mm. Therefore, two groups of coral sand with single particle size between 0.25 and 0.50 mm and between 2 and 5 mm were selected for study, and two groups of quartz sand with corresponding single particle size was set as the control group. The test scheme is shown in Table 2.

Table 2 Scheme of microscopic tests

Test name	Particle size/mm
PartAn morphology scanning	0.25–0.50，2–5
CT scanning	0.25–0.50，2–5

Note: The test materials are coral sand and quartz sand.

The purpose of CT scanning tests is to quantitatively study the pore characteristics of coral sand. Therefore, a mould was needed to fix the coral sand. Figure 4 shows the self-made mould and test samples for CT scanning tests. The material of the mould was acrylic board with a thickness of 3 mm, and the screws and nuts were made of nylon. The whole mould did not contain metal materials; thus it did not interfere with the CT scanning tests.



(a) Coral sand 2–5 mm (b) Quartz sand 2–5 mm

(c) Coral sand 0.25–0.50 mm (d) Quartz sand 0.25–0.50 mm

Fig. 4 CT scan samples

Table 3 gives the specific parameters of CT scanning test. Since the particle diameter determined the diameter of test sample, in the test, the sample diameter should be larger than 10 times the particle diameter in order to ensure that the interconnected open pores in the sample have research significance. The compaction is uniformly selected from the common values in nature to achieve the purpose of controlling variables. The optimum values of resolution, exposure time, scanning time and acquisition frequency were selected based on test experience.

3 Test results and analysis

3.1 Particle shape

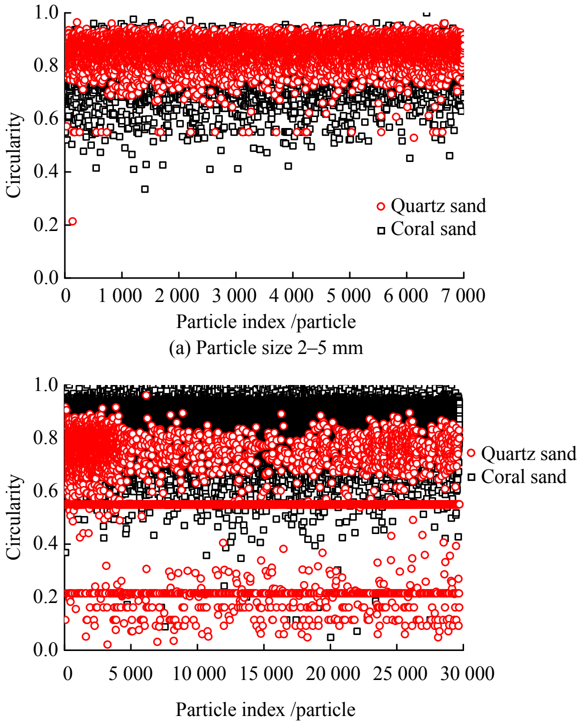
In the test, through the function of particle tracking and multi-particle parallel processing in PartAn particle morphology scanning system, 7,000 – 60,000 particles were scanned for each particle size group,

Table 3 Experimental parameters of CT scan test

Test group	Diameter / mm	Height / mm	Relative density D_r / (g • cm^{-3})	Resolution / µm	Exposure time / s	Scanning time / h
Coral sand 0.25–0.50 mm	10	15	1.19	8.96	0.8	1.5
Coral sand 2–5 mm	50	50	1.19	29.64	0.5	1.2
Quartz sand 0.25–0.50 mm	10	15	1.19	8.96	0.8	1.5
Quartz sand 2–5 mm	50	50	1.19	29.64	0.5	1.2

Note: The acquisition frequency is 0.25°/ frame.

which fully met the requirement of statistical analysis on data volume. Then, the arithmetic mean value of the morphology parameters of all the particles at each particle size group was taken as the comprehensive parameter to describe the morphology of each particle size group. Scatter plots of circularity, skewness, convexity and concavity are shown respectively in Figs 5–8.



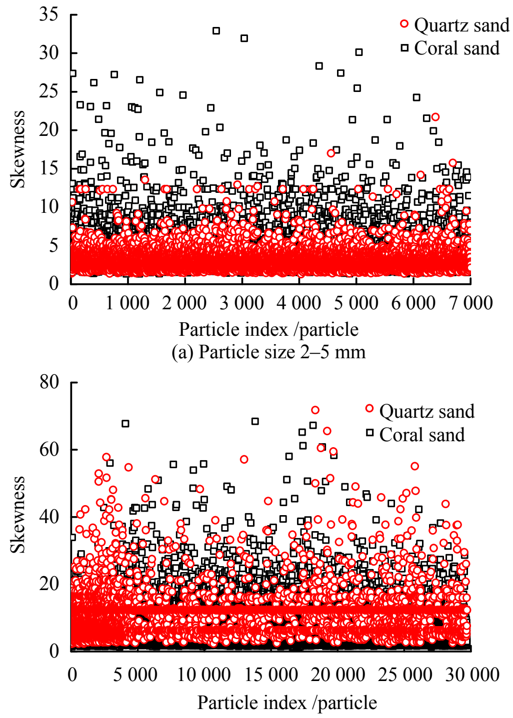
(a) Particle size 2–5 mm

(b) Particle size 0.25–0.50 mm

Fig. 5 Circularity scatter diagrams

Figure 5 shows that the circularity of coral sand with single particle size between 2 and 5 mm is smaller than that of quartz sand, therefore, the particle shape of coral sand at this particle size group is relatively irregular compared with quartz sand. The circularity of coral sand with single particle size between 0.25 and 0.50 mm is greater than that of quartz sand, therefore, the particle shape of coral sand at this particle size group is relatively regular compared with quartz sand. This is because the material sources of coral sand are come the fragmentation of sea creatures such as shells and corals and other marine organisms. The coral sand particles in the larger particle size group retain the shape characteristics of the obvious constituent materials. For example, the coral limbs severed are rod-shaped, the shell fragments are pieces, and the coral fragments are lumpy. Hence, the overall particle shape of coral sand is more irregular than that of quartz sand in the larger particle size group. In the smaller particle size group, the shape characteristics of the constituent materials of coral sand particles are no longer obvious, while quartz sand is formed by the crushing of quartz stone, and its crystal growth property leads to obvious edges and corners of the particles when the crushing occurs. Therefore, the particle shape of coral sand is more regular than that of quartz sand in the fine particle size group.

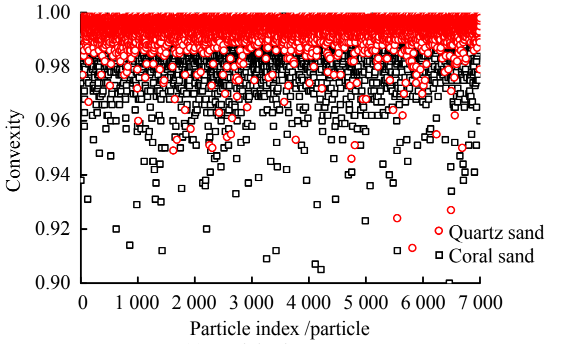
Figure 6 shows that the skewness of coral sand with single particle size between 2 and 5 mm is greater than that of quartz sand, therefore, the particle shape of coral sand at this particle size group is relatively irregular compared with quartz sand. The skewness of coral sand with single particle size between 0.25 and 0.50 mm is smaller than that of quartz sand, therefore, the particle shape of coral sand at this particle size group is relatively regular compared with quartz sand. Both skewness and circularity are used to evaluate the regularity of particle shape, so the skewness mechanism can be analyzed in the same way as the circularity mechanism.



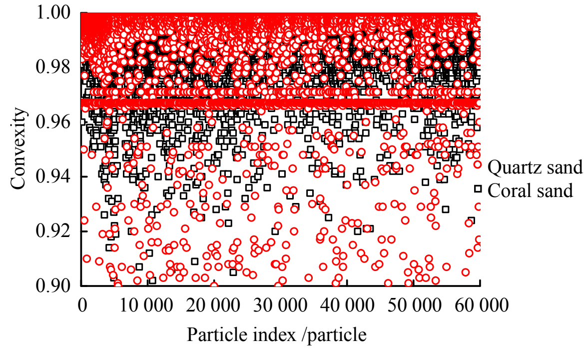
(a) Particle size 2–5 mm

(b) Particle size 0.25–0.50 mm

Fig. 6 Skewness scatter diagrams

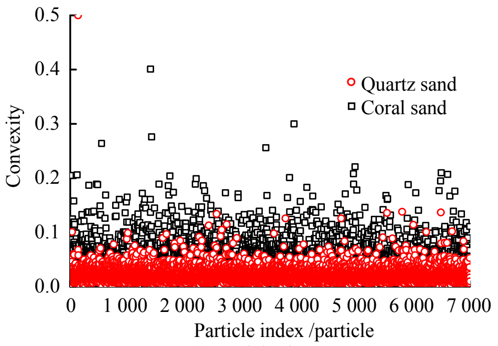


(a) Particle size 2–5 mm

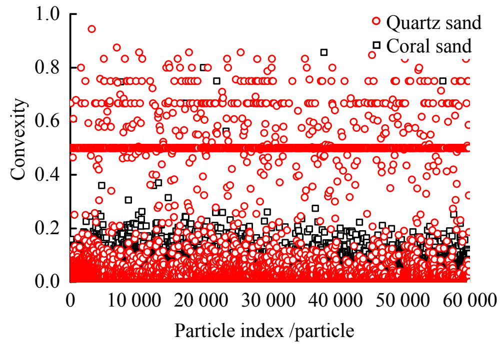


(b) Particle size 0.25–0.50 mm

Fig. 7 Convexity scatter diagram



(a) Particle size 2–5 mm



(b) Particle size 0.25–0.50 mm

Fig. 8 Concavity scatter diagram

It can be seen from Fig. 7 that the convexity of coral sand with single particle size both between 2 and 5 mm and between 0.25 and 0.50 mm is smaller than that of quartz sand, therefore, the particle surface of coral sand is relatively rougher than that of quartz sand at both particle size groups. This finding can be still explained by the material source and formation process of coral sand and quartz sand. As mentioned above, coral sand is formed by the fragmentation of marine creatures such as corals and shells, and there are biological characteristics of the marine creatures consisting of coral sand on the particle surface of coral sand. For example, there will be coral texture or actinozoan cavity structure on the surface of particles formed by coral breakage, and there will be shell texture on the surface of particles formed by shell breakage. While quartz sand is made of broken quartz stone formed by the crystallization of minerals. Although the edges of the particles are obvious, the surface of the particles is smooth. Therefore, regardless of the particle size group, the particle surface of coral sand is rougher than that of quartz sand.

It can be seen from Fig. 8 that the concavity of coral sand with single particle size both between 2 and 5 mm and between 0.25 and 0.50 mm is greater than that of quartz sand, therefore, the particle surface of coral sand is relatively rougher than that of quartz sand at both particle size groups. Both concavity and convexity are the characteristic parameters of particle surface roughness, so the concavity mechanism can be analyzed in the same way as the convexity mechanism.

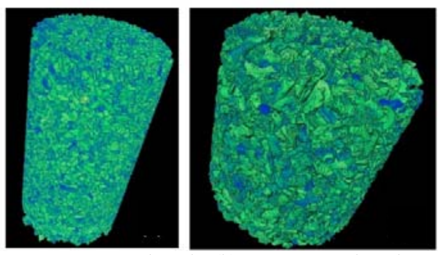
The morphology features of coral sand and quartz sand particles are concluded in Table 4.

Table 4 Morphologic features of particles

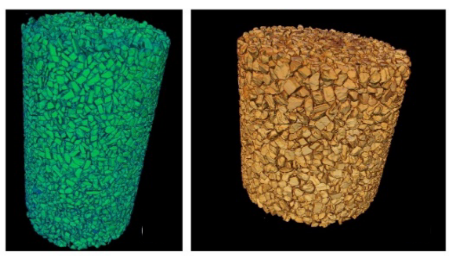
Particle size/mm	Features
0.25–0.50	Coral sand particles are more regular than quartz sand, and its surface is rough
2–5	Coral sand is more irregular than quartz sand and its surface is rough.

3.2 Analysis of medium pore properties

Figure 9 shows the data model generated by three-dimensional reconstruction of slice data obtained from CT scanning tests, and Figure 10 shows the results of pore extraction inside the sample. A comparative study was conducted on the pores of coral sand and quartz sand from three aspects of pore shape, pore size and connectivity.

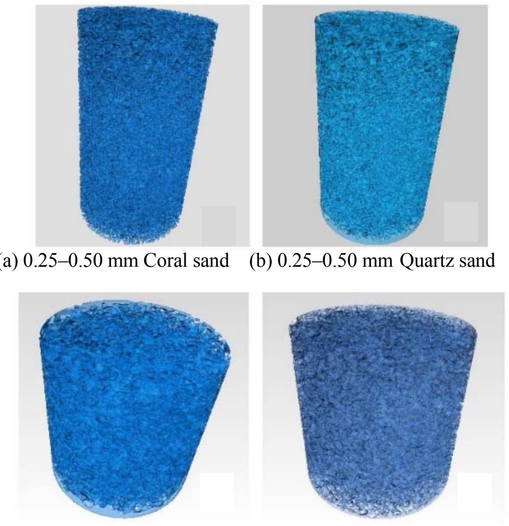


(a) 0.25–0.50 mm Coral sand (b) 2–5 mm Coral sand



(c) 0.25–0.50 mm Quartz sand (d) 2–5 mm Quartz sand

Fig. 9 Sample 3D reconstruction model



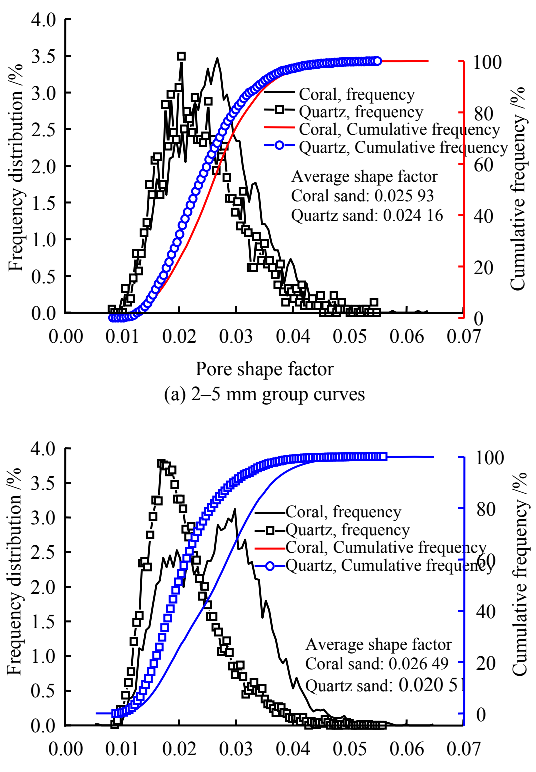
(a) 0.25–0.50 mm Coral sand (b) 0.25–0.50 mm Quartz sand

(c) 2–5 mm Coral sand (d) 2–5 mm Quartz sand

Fig. 10 Three-dimensional pore models of samples

3.2.1 Pore shape

The frequency distribution curves of pore shape factor is shown in Fig. 11 where the curves showing the change trend of first increasing and then decreasing are the frequency distribution curve, while the curves showing the trend of gradually increasing and tending to be stable are the cumulative frequency curves, the same case in Fig. 12–14.



(a) 2–5 mm group curves

(b) 0.25–0.50 mm group curves

Fig. 11 Frequency distribution curves of pore shape factor

It can be seen from Fig. 11 that at the particle size group from 0.25 mm to 0.50 mm, the shape factor of coral sand presents a bimodal distribution, which is mainly distributed in the range between 0.15 mm and 0.35 mm, while the shape factor of quartz sand is mainly distributed in the range between 0.15 mm and 0.25 mm. The average shape factor of coral sand is larger than that of quartz sand, indicating that the pore shape of coral sand is more regular than that quartz sand within this particle size group. Similarly, the pore shape of coral sand is also more regular than that of quartz sand in the particle size group from 2 mm to 5 mm. Combined with the above conclusions about the particle shape and particle surface roughness of coral sand and quartz sand, the influence of both on the pore shape can be analyzed. Based on the findings of Ye et al.[14], sand particles with the regular shape would form the irregular pore shape. However, CT scanning tests showed the opposite results because the particle surface roughness also had an impact on the pore shape in addition to the effect of particle shape on the pore shape. Generally, the rougher the particle surface is, the more regular the pore shape is. It can be seen from Table 4 that the particle surface of coral sand with single particle size between 0.25 mm and 0.50 mm is rougher than that quartz sand. Therefore, the particle surface roughness of coral sand at the particle size group from 0.25 mm to 0.50 mm is the main factor affecting the pore shape, while the particle shape is the secondary factor. Similarly, at the particle size group from from 2 mm to 5 mm, the particle shape of coral sand is more irregular than that of quartz sand, and the particle surface of coral sand particles is rougher than that of quartz sand. Hence, both influence factors make the pore shape of coral sand be more regular than that of quartz sand. According to the results of CT scanning test, the pore shape of coral sand at the particle size group from 2 mm to 5 mm is indeed more regular than that of quartz sand. Therefore, the particle shape and the particle surface roughness at this particle size group are the main factors affecting the pore shape. The standard deviations of the pore shape of coral sand and quartz sand at two particle size groups were calculated, as shown in Table 5. At the groups of particle size both between 0.25 mm and 0.50 mm and between 2 mm and 5 mm, the dispersion degree of pore shape distribution of coral sand is greater than that of quartz sand. Based on Table 4, the common property of coral sand at the groups of particle size both between 0.25 mm and 0.50 mm and between 2 mm and 5 mm is that the particle surface is rougher compared to that of quartz sand, so particle surface roughness is the decisive factor for the dispersion degree of pore shape distribution. However, at these two particle size groups, the property of particle shape of coral sand is opposite. Therefore, the particle shape is a secondary factor affecting the dispersion degree of pore shape distribution, that is, the pore shape formed by the particles with rougher surface is more dispersed.

Table 5 Dispersion degree of pore shape distribution

Sample	Standard deviation	Dispersion degree
Coral sand 0.25–0.50 mm	0.007 94	Large
Quartz sand 0.25–0.50 mm	0.006 30	Small
Coral sand 2–5 mm	0.007 29	Large
Quartz sand 2–5 mm	0.007 15	Small

3.2.2 Pore throat size

(1) Pore radius

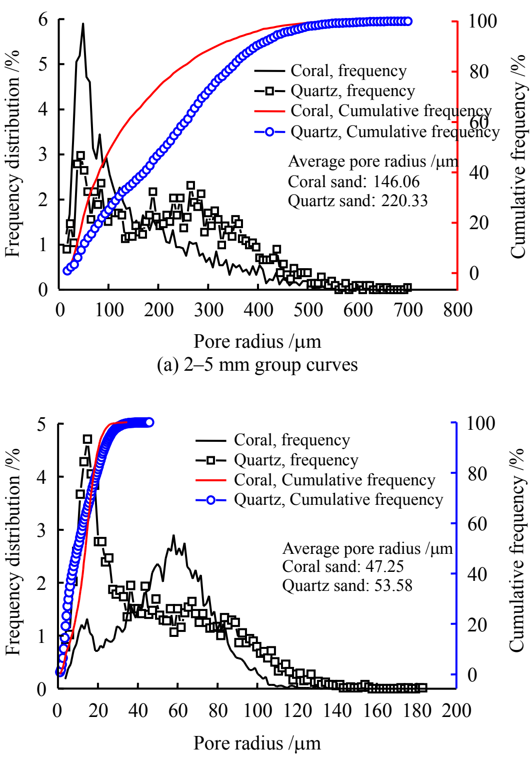
The frequency distribution curves of pore radius are shown in Fig. 12. It can be seen from Fig. 12 that at the particle size group from 0.25 mm to 0.50 mm, the pore radius of coral sand is mainly distributed in the range of 15 μm to 25 μm, and the pore radius of quartz sand is mainly distributed in the range of 45 μm to 80 μm, so the average pore radius of coral sand is smaller than that of quartz sand. Similarly, at the particle size group from 2 mm to 5 mm, the average pore radius of coral sand is smaller than that of quartz sand as well. Following the above analysis of pore shape, combined with the information in Table 4, it can be found that the particle surface roughness is the dominant factor affecting the pore size. The rougher the particle surface, the smaller the pore size formed. The standard deviations of the pore radius of coral sand and quartz sand at two particle size groups were calculated, as shown in Table 6. It can be seen that the dispersion degree of the pore radius distribution of coral sand is greater than that of quartz sand at the particle size group from 0.25 mm to 0.50 mm, while the dispersion degree of the pore radius distribution of coral sand is smaller than that of quartz sand at the particle size group from 2 mm to 0.50 mm. Following the above analysis of the dispersion degree of pore shape distribution, combined with the information in Table 4, it can be found that the particle shape is the decisive factor for the dispersion degree of pore radius distribution, and the pore size formed by the particles with more regular shape is more dispersed.

Table 6 Dispersion degree of pore radius distribution

Sample	Standard deviation	Dispersion degree
Coral sand 0.25–0.50 mm	32.461 5	Large
Quartz sand 0.25–0.50 mm	22.777 4	Small
Coral sand 2–5 mm	113.732 8	Small
Quartz sand 2–5 mm	133.010 8	Large

(2) Throat radius

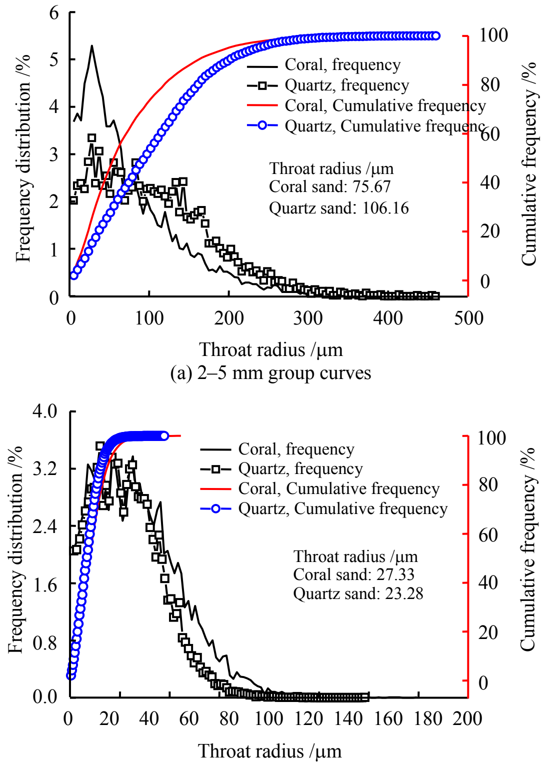
The frequency distribution curves of throat radius are shown in Figure 13. It can be seen from Fig. 13 that at the particle size group from 0.25 mm to 0.50 mm, the average throat radius of coral sand is larger than that of quartz sand, while at the particle size group from 2 mm to 5 mm, the average throat radius of coral sand is smaller than that of quartz sand. At these two particle size groups, the average throat radius of coral sand is opposite. Based on Table 4, at both particle size groups, the property of the particle shape of coral sand is opposite, while the property of the particle surface roughness of coral sand is the same. Therefore, the overall particle shape is the dominant factor for the throat radius of coral sand. At the particle size group from 0.25 mm to 0.50 mm, the particle shape of coral sand is more regular than that of quartz sand, so the irregular particles are more likely to form a relatively small throat radius. Standard deviations of the throat radii of coral sand and quartz sand at two particle size groups were calculated, as shown in Table 7. It can be found that the dispersion degree of the throat radius distribution of coral sand is greater than that of quartz sand with single particle size between 0.25 mm and 0.50 mm; while the dispersion degree of the throat radius distribution of coral sand is smaller than that of quartz sand with single



(a) 2–5 mm group curves

(b) 0.25–0.50 mm group curves

Fig. 12 Frequency distribution curves of pore radius



(a) 2–5 mm group curves

(b) 0.25–0.50 mm group curves

Fig. 13 Frequency distribution curves of throat radius

Table 7 Dispersion degree of throat radius distribution

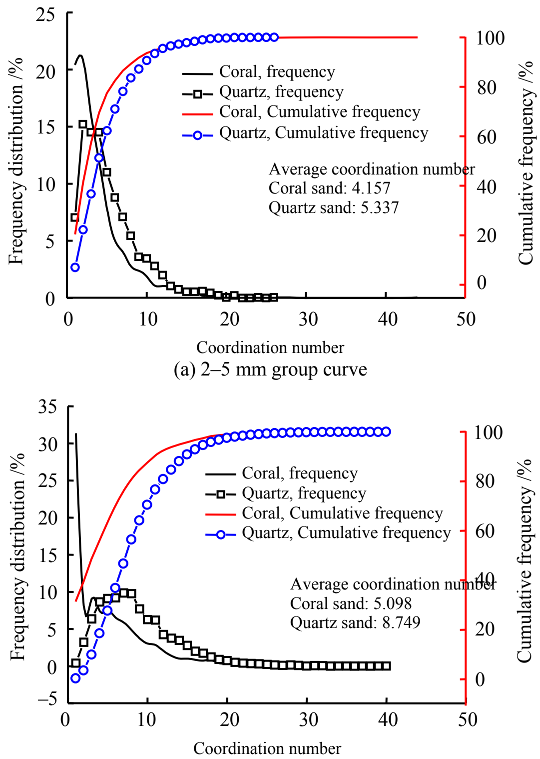
Sample	Standard deviation	Dispersion degree
Coral sand 0.25–0.50 mm	17.575 8	Large
Quartz sand 0.25–0.50 mm	13.974 4	Small
Coral sand 2–5 mm	61.874 5	Small
Quartz sand 2–5 mm	72.407 3	Large

particle size between 2 mm and 5 mm. Following the above analysis of the dispersion degree of pore shape distribution, combined with the information in Table 4, it can be found that the particle shape is the decisive factor for the dispersion degree of throat radius distribution, and the throat size formed by the particles with more regular shape is more dispersed.

3.2.3 Global connectivity

The frequency distribution curve of coordination number is shown in Fig. 14. It can be observed from Fig. 14 that at the groups of particle size both between 0.25 mm and 0.50 mm and between 2 mm and 5 mm, the average coordination number of coral sand is smaller than that of quartz sand, that is, the property of the pore connectivity of coral sand is the same at these two particle size group. Based on Table 4, at both particle size groups, the property of the particle shape of coral sand is opposite, while the property of the particle surface roughness of coral sand is the same. Therefore, the particle surface roughness of coral sand was the dominant factor for coordination number. At the particle size group from 0.25 mm to 0.50 mm, the particle surface of coral sand is rougher than that of quartz sand, so the rougher particle surface is more likely to form the smaller coordination number, that is, the rougher the particle surface, the less connectivity within the medium. Standard deviations of the coordination numbers of coral sand and quartz sand at two particle size groups were calculated, as shown in Table 8. It can be found that the dispersion degree of the coordination number distribution of coral sand is smaller than that of quartz sand with single particle size between 0.25 mm and 0.50 mm; while the dispersion degree of the coordination number distribution of coral sand is greater than that of quartz sand with single particle size between 2 mm and 5 mm. Following the above analysis of the dispersion degree of pore shape distribution, combined with the information in Table 4, it can be found that the particle shape is the decisive factor for the dispersion degree of coordination number distribution. The coordination number formed by the particles with more regular shape is more concentrated, that is, when the particle shape is relatively regular, the permeability distribution within the medium is relatively uniform.

In this work, the microscopic characteristics of the three-dimensional pores of coral sand were studied systematically, and the key parameters to describe three dimensional pores were revealed. However, in practical engineering, the pores of coral sand, as a porous medium, will change under the condition of overlying load. This is because the particle breakage or the particle rearrangement probably occurs in a state of stress [15–16]. So, in the future research work, the research methods and results in this work can be used to deeply interpret the pore changes of porous media under the state of stress, and then explore the change in the mechanical and hydraulic properties resulting from the pore changes of porous media under the state of stress.



(a) 2–5 mm group curve

(b) 0.25–0.50 mm group curve

Fig. 14 Frequency distribution curves of coordination number

Table 8 Dispersion degree of coordination number distribution

Sample	Standard deviation	Dispersion degree
Coral sand 0.25–0.50 mm	13.938 6	Small
Quartz sand 0.25–0.50 mm	15.305 0	Large
Coral sand 2–5 mm	14.867 0	Large
Quartz sand 2–5 mm	9.821 5	Small

3.3 Coupling analysis between particle shape and medium properties

To facilitate the comparison between the microscopic properties of the particles and pores of coral sand and quartz sand, the particle morphologies and the pore characteristics of these two porous media are summarized in Table 9. For example, at the particle size group from 0.25 mm to 0.50 mm, the particle shape of quartz sand is more irregular compared with that coral sand; at the particle size group from 2 mm to 5 mm, the particle shape of coral sand is more irregular compared with that quartz sand. The shape of the particle with a size smaller than 0.5 mm is the same as the shape of the particle with a size between 0.25 mm to 0.50 mm. The property of the particle with a size greater than 0.5 mm is the same as the particle with a size between 2 mm to 5 mm.

Based on the above studies, the dominant factors that determine the pore properties of coral sand and how the dominant factors affect the pore properties of coral sand are summarized in Table 10. For example, the dominant factors that affect the property of pore shape include the particle shape and the particle surface roughness. Irregular particle shape can easily form regular pore shape. Rough particle surface is easy to form regular pore shape.

Table 9 Comparison of particle and pore properties between coral sand and quartz sand

Features		Comparison 0.25–0.50 mm	2–5 mm
Particle morphology	Particle shape	Quartz: irregular	Coral sand: irregular
	Surface roughness	Coral sand: rough	Coral sand: rough
Pore shape	Regularity	Coral sand: regular	Coral sand: regular
	Dispersion degree	Coral sand: large	Coral sand: large
Pore/throat size	Pore size	Coral sand: small	Coral sand: small
	Dispersion degree	Coral sand: large	Quartz sand: large
	Throat size	Quartz sand: small	Coral sand: small
	Dispersion degree	Coral sand: large	Quartz sand: large
Connectivity	Global connectivity	Coral sand: poor	Coral sand: poor
	Distribution	Quartz sand: nonuniform	Coral sand: nonuniform

Table 10 Mechanism of the difference in pore properties between coral sand and quartz sand

Features		Leading factors and rules
Pore shape	Pore shape	①Irregular particle shape makes the pore shape regular ②The rough surface of the particles makes the pore shape regular
	Dispersion degree	Rough particle surface leads to discrete distribution of pore shapes
Pore/throat size	Pore size	The rough surface of the particles makes the pore size small
	Dispersion degree	The regular particle shape makes the pore size discretely distributed
	Throat size	Irregular particle shape results in small throat size
	Dispersion degree	The regular particle shape causes the throat size to be discrete
Connectivity	Global connectivity	Rough particle surface causes poor pore connectivity
	Distribution	Regular particle shape makes pore distribution uniform

4 Conclusion

(1) There are obvious differences in the microscopic particle morphology of coral sand and quartz sand, mainly including the overall particle shape and the particle surface roughness. The microscopic particle morphology of the two porous media at the different particle size groups are also different, as shown in Table 9.

(2) There are differences between coral sand and quartz sand in the three-dimensional microscopic pore properties, mainly including the pore shape, the pore throat size, and the connectivity of media. When the particle size is different, the characteristics of three-dimensional pores are also different, as summarized in Table 9.

(3) The property of the three-dimensional microscopic pores of porous medium is determined by the microscopic morphology of particles within the medium. The overall particle shape and the particle surface roughness have different effects on pore shape, pore throat size, and medium connectivity. The irregular particle shape leads to the regular pore shape. The rough particle surface results in the small pore size. The irregular particle shape results in the small throat radius. The rough particle surface leads to the poor connectivity. The regular particle shape results in the uniform pore distribution.

Reference

[1] ZHU Chang-qi, CUI Xiang, HU Ming-jian, et al. Studies on the conductivity and permeability of calcareous soils[J]. Rock and Soil Mechanics, 2018, 39(Suppl.2): 142–148.

[2] HU Ming-jian, CUI Xiang, WANG Xin-zhi, et al. Experimental study on the influence of fine particles on the permeability of calcareous sand[J]. Rock and Soil Mechanics, 2019, 40(8): 2925–2930.

[3] CHEN Hai-yang, WANG Ren, LI Jian-guo, et al. Shape analysis of calcareous sand particles[J]. Rock and Soil Mechanics, 2005, 26(9): 1389–1392.

[4] SUN Ji-zhu, HUANG Ming-li, WANG Ren. Effects of internal porosity and anisotropy on liquefaction characteristics of calcareous sand[J]. Rock and Soil Mechanics, 2002, 23(2): 166–169.

[5] ZHU Chang-qi, CHEN Hai-yang, MENG Qing-shan, et al. Structural characteristics of pores in calcareous sand grains[J]. Rock and Soil Mechanics, 2014, 35(7): 1831–1836.

[6] JIANG Ming-jing, WU Di, CAO Pei, et al. Analysis of the connected pores of calcareous sand based on SEM [J]. Chinese Journal of Geotechnical Engineering, 2017, 39(Suppl.1): 1–5.

[7] ZHOU Bou, KU Quan, LÜ Ke-zhen, et al. Three-dimensional characterization of internal pores in calcareous sand grains[J]. Journal of Tianjin University (Science and Technology), 2019, 52(Suppl.1): 41–48.

[8] CAO Pei, DING Zhi-jun. Pore distribution characteristics of calcareous sand based on MIP and CT tests[J]. Journal of Water Resources and Architectural Engineering, 2019, 17(3): 55–59.

[9] CHEN Hai-yang. Internal porosity of calcareous sand[D]. Wuhan: Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, 2005.

[10] REN Yu-bin, WANG Yin, YANG Qing. Effects of particle size and shape on the permeability of calcareous sand[J]. Rock and Soil Mechanics, 2018, 39(2): 491–497.

[11] HU Ming-jian, ZHANG Chen-yang, CUI Xiang, et al. Experimental study on capillary water height and influencing factors in calcareous sand[J]. Rock and Soil Mechanics, 2019, 40(11): 4157–4164.

[12] WANG Bu-xue-yan, MENG Qing-shan, WEI Chang-fu, et al. Quantitative experimental study on the morphology of coral sand and gravel grains under multiple projective surfaces[J]. Rock and Soil Mechanics, 2019, 40(10): 3871–3878.

[13] Ministry of Water Resources of the People's Republic of China. GB/T 50123－1999 Standard for geotechnical test methods[S]. Beijing: China planning Press, 1999.

[14] YE Jia-bing, ZHANG Jia-fa, ZOU Wei-lie. Study on the influence of particle shape on pore characteristics of crushed stone[J]. Rock and Soil Mechanics, 2018, 39(12): 4457–4467.

[15] ZHANG Xiao-yan, CAI Yan-yan, WANG Zhen-bo, et al. Fractal crushing and particle shape analysis of one-dimensional creep under high pressure of coral sand[J]. Rock and Soil Mechanics, 2018, 39(5): 1573–1580.

[16] WU Yang, CUI Jie, LI Neng, et al. Coral reef reclaimed sand mechanical behavior and particle breakage characteristic test research[J]. Rock and Soil Mechanics, 2020, 41(10): 3181–3191.