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A digital image analysis of gravel aggregate using CT scanning technique

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Abstract

Particle shape was one of the most important factors which affects the gravel aggregate's properties. It was also one of the important factors that directly affects the performance of asphalt pavements. In this paper, the gravel aggregate of quartzite was studied by using the industrial CT instrument. MATLAB was used to capture the aggregate slice properties including reverse color, median filtering, noise reduction, binarization and so on. The 3D aggregate model was reconstructed by using the software of MIMICS. The three-dimensional model of the aggregate was further optimized. The best fitting cuboid, cylinder, cone and sphere information of the aggregate were obtained by using the characteristics analysis function.

Keywords: CT scanning; 3D reconstruction; Watershed transform; Particle shape; Gravel aggregate

1. Introduction

The morphological characteristics of coarse aggregate played a key role in the mechanical properties of asphalt mixture. It was therefore necessary to study the aggregate properties and its morphological characteristics through appropriate approaches. With the development of computer technology, computed tomography (CT) scanning technology had been widely used as an advanced non-destructive testing method. The different characteristics of aggregate samples could be characterized by the change of grey-scale value. The information of aggregates could be then transformed into digital images for further analysis.

There have been many research in applying the scanning technology for aggregates. Kwan (1999) adopted digital image processing technology to analyze the 3D quantitative parameters of the aggregate particles through the 2D image information [1]. Buchanan (2000) studied the correlation between the particle and the properties of the mixture, and found that the more the content of the needle, the worse the performance of the road [2]. Thomas Fletcher et al. (2003) designed and developed a unified computer-automated system which could analyze the shape (angularity, texture and form) of fine and coarse aggregates by using different methods [3]. Herrin and Goetz (2005) studied the influence of the shape of the crushed stone particles on the hot mix asphalt mixture and found the higher the aggregate crushing rate, the greater the tensile strength of the mixture [4]. Sun et al. (2012) measured external edge

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characteristics of seven kinds aggregates by Fourier Transform Interferometry (FTI) system and got the sphericity, flatness ratio, elongation ratio, angularity, and texture for each individual aggregate particle by developing a program in MATLAB to quantify morphologic characteristics of aggregates from a variety of sources [5]. Chen et al. (2003) found that the shape of the crushed stone particles had significant influence on the rutting resistance and deformation rate of asphalt mixture [6]. Xiao et al. (2006) defined five basic shape parameters of coarse aggregate by using the image processing technology [7], and studied the influence of the shape characteristics of coarse aggregate on the shear resistance of asphalt mixture. Chen et al. (2006) studied the effect of the content of angular particle in aggregate [8]. The aggregate shape has great influence on the fracture performance of asphalt mixture [9–13], which can be analyzed using the CT technique. The 3D reconstruction of the continuous CT image was also carried out and the visualization of the crack distribution at the crack initiation stage in the rock loading test was realized. Su (2013) selected roundness as characterization index of the shape of crushed stone particles [14]. Thus, the geometry of the aggregate has an important influence on its service performance including shear resistance, rutting resistance and tensile strength of the asphalt mixture. There have been many studies on the aggregate shape. However, the current study mainly uses 2D image to analyze the shape information of aggregates rather than a 3D model of a single aggregate. Analysis results of 2D image are easily influenced by observation angle, aggregate location and other factors. It could overcome the shortcomings of traditional measurement and evaluation methods by using 3D digital image processing technology to evaluate the shape of aggregate particles [15].

In this paper, the three-dimensional shape characteristics of aggregates were analyzed. The industrial CT scanning technology was used to get the aggregate digital slice images, and the MATLAB software was used to capture the aggregate slice properties. The aggregate 3D model was reconstructed and analyzed by using the software of MIMICS and GEOMAGIC STUDIO. Six evaluation indexes were proposed to evaluate the 3D shape characteristics of aggregates. The purpose of the study was to characterize the three-dimensional shape of aggregate better, and provided an accurate aggregate model for finite element numerical simulation.

2. CT scanning test material preparation

Quartzite gravel aggregates, which were from Lincheng County in Hebei Province, were used in the research. The aggregates were crushed by Jaw Crusher. All qualified aggregate particles had been screened out as the test materials of CT scanning. According to ASTM D6928-10, gravels had been sieved by rock standard sieve [16] and measured by WT50001KF (5000 g/0.1 g). Three different gravels (375 g, 375 g, 750 g) were obtained, whose sizes were 19–16 mm, 16–12.5 mm and 12.5–9.5 mm with the error ranging from −1 g to 1 g. The quartzite gravels had been dried in the convection oven at a constant temperature 105 ± 5 °C for 2 h. The weight of all samples had been tested twice and recorded, and the difference between two measured values was less than 1‰, which meant quartzite gravels had been completely dried since the mass of sample didn't change any more. Some gravels selected in this research were shown in Table 1. The selected sample with different sizes had been swept by CT scanning to measure and collect 3D shape information. The aggregate container was a hollow cylinder with 150 mm height and 100 mm diameter which was built by using a 3D printer.

3. Industrial CT scanning test

3.1. CT scanning test equipment

The BIR320 industrial CT scanner produced by Varian Company (United States) was adopted in the research, as shown in Fig. 1. It could detect the internal composition and structure distribution of gravel aggregate through the high voltage current excitation X-ray radiation exposure combined with computed tomography imaging technology. Based on the test data, the 2D slices were obtained which could be used for the aggregate 3D reconstruction. The equipment mainly consists of X-ray generator, collimator, bearing turntable and full digital X-ray array detector with 1024 × 1024 pixels, 200 microns pixel pitch and 65,536 grayscale level.

The transverse section of 2D images from top to bottom was obtained by CT scanning experiment. Each sample obtained 904 two-dimensional slice images whose actual height was 0.15 mm as a basis for gravel aggregate 3D model reconstruction.

3.2. Optimized processing of CT slice images of gravel aggregate

3.2.1. Slice images preprocessing of gravel aggregate

The images were preprocessed to minimize the system error under the premise without breaking aggregate information. The optimization functions in the MATLAB software were used for the CT slice images. Fig. 2 shows the capturing of the aggregates by using the color processing. The phenomenon of aggregate "adhesion" was decreased significantly through the reverse color processing as shown in Fig. 2(b).

Due to the huge number of scanned images, MATLAB was used to calculate these images to improve the efficiency, as shown in Fig. 3. After the optimization processing, the aggregate images in the section were clearer. There was little information loss caused by image optimization processing, as shown in Fig. 3(b). The small particles of aggregate in the lower left corner were removed during the optimization process. The phenomenon of aggregate adhesion still existed in the contact area, as shown in Fig. 3(d).

Table 1
Sample selection of the quartz gravel aggregate.

Sample number	Particle size (mm)	Number	Total number	Selection ratio (%)	Mass (g)	Total mass (g)	Mass ratio (%)
1	19–16	26	61	42.623	158.2	374.3	42.266
2	16–12.5	35	71	49.296	188.8	374.7	50.387
3	12.5–9.5	87	310	28.065	214.9	749.0	28.692
Total		148	442	33.484	561.9	1498.0	37.510

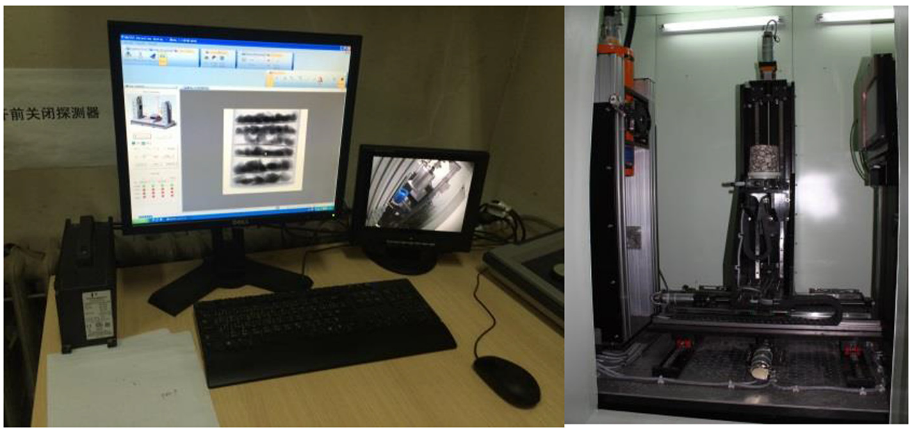


Fig. 1. Main components of CT scanning system.

a. No reverse color processing b. Reverse color before optimized processing

Fig. 2. Comparison of different optimization process of gravel aggregate.

3.2.2. Segmentation of gravel aggregate slice images

The image segmentation was one of the most difficult tasks during image processing [17]. The accuracy of image segmentation determined the accuracy of image analysis results. During the scanning process, the aggregates were densely placed, which caused the phenomenon of aggregate adhesion. Thus, it was needed to segment the images of the different aggregates. In this paper, the method of watershed transform was used to segment the images by data processing tools in MATLAB software [18].

The watershed area and lines of aggregate gray images were found by the method of watershed transform. The watershed lines of these images were the boundaries of the aggregate which were needed to be identified. Using the watershed transform, each aggregate was corresponding to a small watershed area, where the tag matrix formed in this method contained the positive integer of each watershed area location. Taking a value of 1 of the elements, they were located just as the boundary line of the aggregate in the watershed line, which was used to segment the rock in the original image. Using the “bwareaopen” function in MATLAB to take noise reduction processing of the image, removing the smaller clutter of the image, and obtaining the distance transform by using the distance transform function of “bwdist”. The binary image was transformed to the image where pixel distance was the nearest [19]. The template was added to the original image by using the “imshowpair” command, and thus the superposition of images was achieved. The “imextendedmin” function was also used to filter out some of the local minimum value. And the excessive subdivision of the local area and the error were both reduced, where the whole process was shown in Fig. 4.

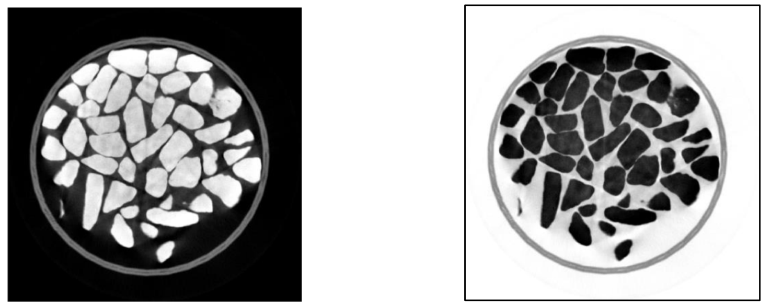
The MIMICS software could only identify the white area of gravel aggregate slice images. Therefore, the color of images needed to be inverted twice in order to reconstruct the aggregate 3D model. The aggregate binary images were obtained by using MATLAB software. The aggregate images were clearly visible, which provided the foundation for the reconstruction of the 3D aggregate model.

4. Gravel aggregate 3D model reconstruction

4.1. 3D reconstruction of single gravel aggregate

MIMICS was a Materialise’s interactive medical image control system. It was a software for 3D model generating, editing and processing with highly integrated function and it was easy to be used.

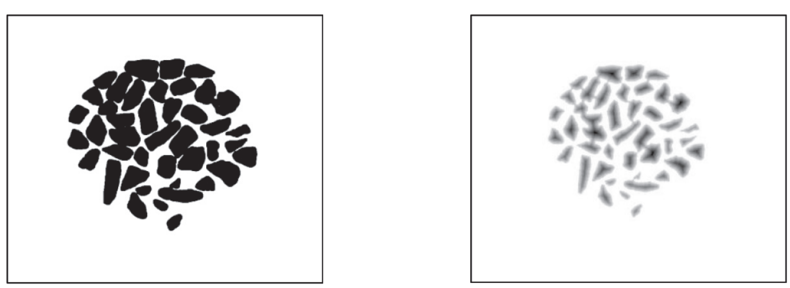
In this study, the slices of 19–16 mm aggregate were used as examples, which were imported into the



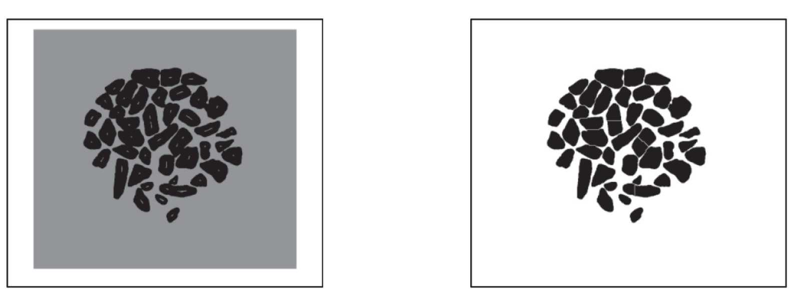
a. Original CT slice of gravel aggregate b. CT slice after reverse color

c. CT slice after optimization process d. Phenomenon of aggregate adhesion

Fig. 3. CT scanning slice optimization process of gravel aggregate.



a. Optimized slice image b. Slice image after pixel distance transform



c. Slice image after graphic overlay d. Segmentation of gravel aggregate

Fig. 4. Watershed segmentation of gravel aggregate slices.

Mimic10.0.1 software. One hundred and nineteen aggregate slices were used to form different sections of the 14 aggregates. The slice distance was 0.15 mm with 1024×1024 pixel. The contour of each aggregate was extracted in slice and the surface model was reconstructed by using regional growth function. It transformed 2D image into 3D model of single aggregate using different colors as shown in Fig. 5. There was a sticking phenomenon between aggregates such as red and blue rocks.

Based on the gravel aggregate 3D model, the aggregate morphology characteristics could be observed and analyzed through arbitrary rotation and scaling. Its STL format 3D model files could be read and edited by combining the 3D reconstruction and post-processing software. It could directly measure diameter in 3D model by using the line measurement tools in MIMICS software, but it could only measure the distance from point to point and could not measure the distance of the whole 3D model. Therefore, GEOMAGIC STUDIO software was adopted to do the data analysis and measurement.

4.2. Measurement and analysis of gravel aggregate 3D model

The aggregate 3D model was built by superimposing the 2D images and dividing the model boundaries. The aggregate model was obtained with higher accuracy and better quality triangular surface grid by using GEOMAGIC STUDIO software [20]. It could provide reference in irregular aggregate model construction with discrete element method and finite element method [21]. The aggregate 3D information was obtained through the feature analysis of GEOMAGIC STUDIO software.

The aggregate 3D model obtained by MIMICS software was imported into GEOMAGIC STUDIO software, and then the grid doctor was used to do the model grid detection, and meshes defect repair, as shown in Fig. 6(a). The red area was the detection area that had grid problem and needed to be repaired. By removing the nail function, the model was smoothed, as shown in Fig. 6(c).

Regarding the adhesion phenomenon in gravel aggregates, the curve cutting function was adopted to separate aggregates along the connection region, and analyze the data of a single aggregate. By analyzing the distance between two points in aggregate, the most external rectangle of the 3D model of aggregate include length, width and height information could be obtained. According to the feature analysis function, the best fitting sphere, cylinder and cone, of gravel aggregate particles were achieved as shown in Fig. 7. Different fitting methods obtained different length information for calculating the 3D evaluation indexes include roundness, squareness, flat rate and so on. Table 2 showed the statistical data on the 3D information of the aggregate such as sphere of radius, the cylinder diameter and height, cone base diameter, top diameter and height information.

Among them, h_c and D_c, respectively, indicated the cylinder height and radius, h_{co}, D_{co_1} and D_{co_2} respectively indicated the cone height, base diameter, top diameter, and D_l, D_m, D_S respectively indicated the longest side, long edge and the short edge of the most external rectangle along the 3D coordinate system.

There were four commonly used indexes to evaluate shape of gravel particles namely flatness ratio, sphericity, squareness, and shape factor. Aspect ratio was the ratio between height and radius. Flatness ratio was the ratio of the maximum size to the minimum size of aggregate, or the ratio of the minimum size to the median size. Sphericity referred to the edge of aggregate particles and each corner of the relatively sharp degree [14]. Squareness was the ratio between maximum projected area and external rectangle area of aggregate. According to the best fitting information obtained by GEOMAGIC STUDIO software in Table 2, Six evaluation indexes were proposed to characterize the 3D shape of the gravel aggregate in reference to the domestic and foreign references [5]. Aggregate shape was described by aspect ratio, flatness ratio, sphericity, and squareness as defined by the following Eq. (1), the gravel aggregate 3D index data were showed in Table 3 and Fig. 8.

$$\begin{aligned}
&\text{aspect ratio}: \ A_1 = \frac{h_c}{D_c};\ A_2 = \frac{2h_{co}}{D_{co1}+D_{co2}};\\
&\text{flatness ratio}: \ A_3 = \frac{D_l}{D_s};\ A_5 = \frac{D_s}{D_m}\\
&\text{sphericity}: \ A_4 = \sqrt[3]{\frac{D_s \cdot D_m}{D_l^2}};\\
&\text{elongation ratio}: \ A_6 = \frac{D_m}{D_l};
\end{aligned} \tag{1}$$

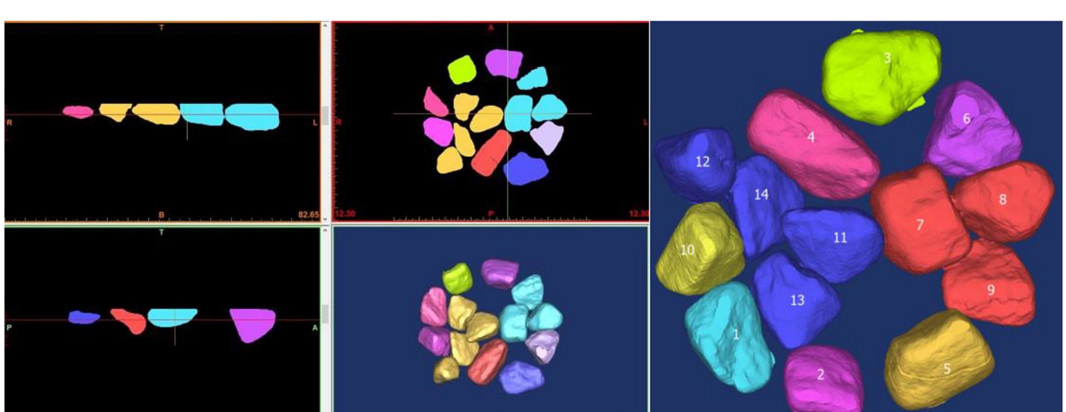
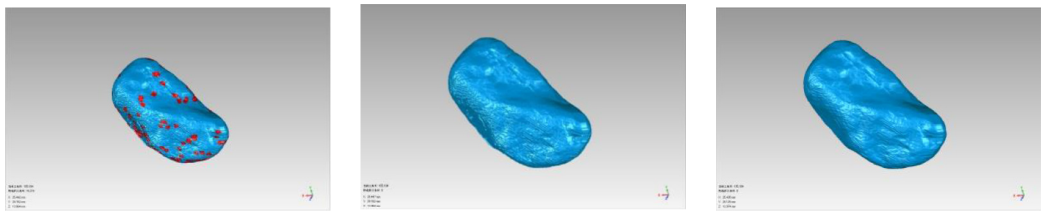
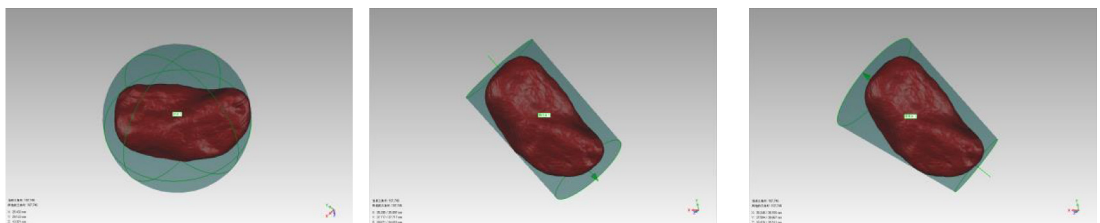


Fig. 5. Three-dimensional model of gravel aggregate.



a. Grid defect detection b. Model before removing nail c. Model after removing nail

Fig. 6. Grid defect detection and optimization of 3D model of rock.



a. Sphere best fitting b. Cylinder best fitting c. Cone best fitting

Fig. 7. Best fitting of gravel aggregate.

Table 2
3D statistical information of gravel aggregate.

Number	Cylinder		Sphere	Cone			Axial external rectangle		
	h_c	D_c	D_{sp}	D_{co1}	D_{co2}	h_{co}	D_l	D_m	D_s
1	24.27	18.91	28.30	14.96	21.10	24.20	29.39	29.07	27.73
2	19.82	20.18	23.70	18.01	22.71	20.19	24.52	16.93	9.17
3	28.80	24.38	32.01	13.60	48.35	19.62	19.71	18.96	17.12
4	31.73	20.51	34.62	15.87	26.71	31.14	28.80	21.16	10.11
5	23.71	22.78	28.23	21.28	23.37	23.77	29.12	25.43	13.97
6	23.66	26.16	26.10	17.78	27.22	22.77	23.78	18.86	17.87
7	24.48	22.61	26.75	19.38	24.49	24.25	23.04	21.85	14.12
8	23.33	20.17	25.59	19.44	20.09	23.13	23.77	19.22	11.88
9	21.87	21.59	25.12	14.48	27.33	18.88	22.78	17.64	14.14
10	19.68	23.42	24.10	19.43	21.66	19.22	22.03	19.92	9.05
11	23.44	21.61	27.14	20.58	23.23	24.07	19.95	18.61	18.47
12	19.40	20.32	23.55	15.22	25.72	19.66	21.02	18.68	13.07
13	21.37	20.29	25.12	17.13	24.55	20.23	18.92	17.33	16.32
14	22.59	22.83	26.02	19.10	25.30	20.20	22.31	17.91	10.08

According to the obtained 3D model and index of gravel aggregates, A_1, A_2, A_3 were a kind of index system, which were calculated from best fitting results of the cylinder, cone, external rectangular; A_4, A_5, A_6 were calculated from external rectangular, as another kind of index system. Through the analysis of the 3D index of aggregate, the aggregate was classified, and the influence of pavement performance could be studied.

Through the analysis of Table 3 and Fig. 8, A_1, A_2, A_3 index could be in accordance with the 0.4 for a dividing line to carry out the classification of gravel aggregate. Except for the aggregate No.1, 3, 4, A_1 and A_2 index of other aggregates were all located in the range of 0.8–1.2. It indicated that A_1 and A_2 index needed to be further refined the evaluation criteria. A_4, A_5, A_6 indexes could be divided by the range of 0.1. According to different indexes, the distribution of aggregate particles was statistically calculated in Table 1. The aggregates were divided into different types (Table 4).

Through the above analysis, it could be found that the two sets of evaluation index system named A_1, A_2, A_3 and A_4, A_5, A_6 had some differences, but the basic rock classification was consistent. The aggregates could be divided into four categories at least: First of all, No. 10, 12 belong to a class with more round shape; Second, No. 13, 14 belong to a class with flat shape; Third, No. 5 and 8; Fourth, No. 1, 3. Although there were many research on other pavement materials, the evaluation index suggested in this paper to classify the aggregate 3D shape was still meaningful. The 3D evaluation index needed to

Table 3
3D index statistical information of gravel aggregates.

Aggregate number	Aggregate color	Gravel aggregate 3D indexes					
		A_1	A_2	A_3	A_4	A_5	A_6
1	Cyan	1.284	1.342	2.675	0.977	0.691	0.637
2	Fuchsia	0.982	0.992	1.151	0.637	0.962	0.942
3	GreenYellow	1.181	0.634	2.849	0.942	0.735	0.637
4	Magenta	1.547	1.463	2.084	0.637	0.873	0.748
5	Orange	1.041	1.065	1.331	0.748	0.793	0.842
6	Purple	0.905	1.012	1.632	0.842	0.948	0.834
7	Red-01	1.083	1.106	2.000	0.835	0.809	0.739
8	Red-02	1.157	1.170	1.611	0.739	0.774	0.783
9	Red-03	1.013	0.903	2.436	0.783	0.904	0.719
10	Yellow	0.840	0.935	1.080	0.719	0.933	0.953
11	Blue-01	1.085	1.099	1.608	0.952	0.889	0.821
12	Blue-02	0.955	0.960	1.159	0.821	0.916	0.925
13	Blue-03	1.053	0.971	2.214	0.924	0.803	0.713
14	Blue-04	0.990	0.910	2.022	0.713	0.838	0.746

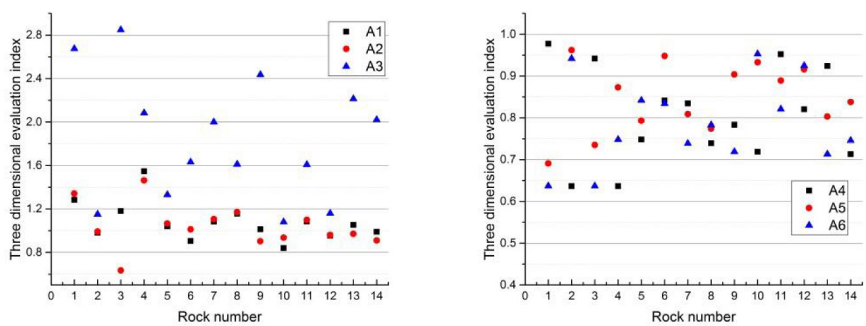


Fig. 8. 3D index system of gravel aggregates.

Table 4
Distribution of aggregate particles.

No.	3D index		Aggregate No.	No.	3D index		Aggregate
1	A_1	0.8–1.2	2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14	5	A_4	0.6–0.7	2, 4
		1.2–1.6	1, 4			0.7–0.8	5, 8, 9, 10, 14
2	A_2	0.4–0.8	3			0.8–0.9	6, 7, 12
		0.8–1.2	2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14			0.9–1.0	1, 3, 11, 13
		1.2–1.6	1, 4	6	A_6	0.6–0.7	1, 3
3	A_3	0.8–1.2	2, 10, 12			0.7–0.8	4,7,8,9,13, 14
		1.6–2.0	6, 8, 11			0.8–0.9	5, 6, 11
		2.0–2.4	7, 9, 13, 14			0.9–1.0	2, 10, 12
4	A_5	0.7–0.8	1, 3, 5, 8				
		0.8–0.9	4, 7, 11, 13, 14				
		0.9–1.0	2, 6, 9, 10, 12				

be optimized, so as to evaluate the aggregate model, and establish the correlation between 3D model and the road performance.

5. Conclusions

Particle shape was one of the most important factors which affected the gravel aggregate's properties include density, mechanics, seepage characteristics, etc. It was also one of the important factors that directly affected the service performance of asphalt mixture. This paper introduced a new study on the gravel aggregate of quartzite by constructing the real 3D model. Follows are the conclusions:

1) By using the industrial CT instrument, a series of aggregate grayscale slice images were obtained. On this basis, a series of optimization for the aggregate slices was achieved using MATLAB. By using the watershed transform function, automatic segmentation of aggregate particles was achieved.

2) The software of MIMICS was used to reconstruct aggregates 3D model and obtain the true model of single gravel aggregate. It provided the foundation for the aggregate discrete or finite element analysis.
3) Combined with GEOMAGIC STUDIO software, the three-dimensional model of the aggregate was optimized. The best fitting information of the aggregate according to the characteristics analysis function was obtained. Six indexes were proposed to evaluate the 3D shape of the aggregates, which could be more accurate and comprehensive.
4) For the 3D indexes of aggregates, the study is still in the preliminary stage and cannot be directly used for actual engineering applications. In our future studies, we will focus on the application of these indexes and try to establish the relationship between the engineering properties and the shape characteristics of aggregates.

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