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Fractal analysis of granular ore media based on computed tomography image processing

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Abstract: The cross-sectional images of nine groups of ore samples were obtained by X-ray computed tomography(CT) scanner. Based on CT image analysis, the fractal dimensions of solid matrix, pore space and matrix/pore interface of each sample were measured by using box counting method. The correlation of the three fractal dimensions with particle size, porosity, and seepage coefficient was investigated. The results show that for all images of these samples, the matrix phase has the highest dimension, followed by the pore phase, and the dimension of matrix-pore interface has the smallest value; the dimensions of matrix phase and matrix-pore interface are negatively and linearly correlated with porosity while the dimension of pore phase relates positively and linearly with porosity; the fractal dimension of matrix-pore interface relates negatively and linearly with seepage coefficient. Larger fractal dimension of matrix/pore interface indicates more irregular complicated channels for solution flow, resulting in low permeability.

Key words: granular ore media; CT image; fractal dimension; box counting method

1 Introduction

The granular ore medium used for heap or dump leaching is a kind of unconsolidated porous body, which is packed by ore particles with different sizes and shapes. The pores in the medium provide the pathway for air and solution flow, so their shape and size distribution directly influence the permeability and leaching performance. Since the ore particles are randomly produced by blasting and crushing, they are very irregular. As a result, the pores between them are also greatly irregular. All of them are unable to be described with Euclidean geometry, so it is necessary to adopt fractal geometry here[1], viz, describing the characteristics of the structure of a granular medium quantitatively by fractal dimensions. Fractal geometry has been used widely to analyze the pore structure of some porous media, such as soil[2−3], particle aggregates[4], rock[5−6], and oil reservoir[7]. The fractal dimensions of various features of a porous medium can be determined experimentally, such as mercury intrusion curves[8−9] and water retention curves[10]. However, the most popular method is image analysis, which can directly obtain the structure of a porous medium and quantify the self-similarity or the fractal dimension of the structure[11−13]. Presently, the methods for getting pore images of porous media include optical microscopy, scanning electron microscopy(SEM), X-ray CT, and nuclear magnetic resonance(NMR), etc [14]. Granular medium is different from soil and rock. It is an unconsolidated dynamic body[15], so the slicing method used traditionally is not suitable for obtaining the sectional images. Therefore, the nondestructive detecting technique, X-ray CT, was used.

In this work, the fractal dimensions of solid matrix, pore space and pore/matrix interface of granular media

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were calculated. Moreover, the correlations between them and particle size, porosity, and permeability were analyzed. The method of synthetically applying X-ray CT, image analysis and fractal geometry to quantitatively describe the characteristics of granular ore media is new and feasible.

2 Experimental

2.1 Principle of X-ray CT

X-ray CT can penetrate nonmetal materials and the penetrating ability of X-rays with different wavelength is different. The ability of absorbing the same X-ray for different materials is also different. The higher the density of the material is, the stronger the absorbing ability is. During X-ray penetrating the material, its intensity attenuates exponentially. The density of material is represented by the attenuation coefficient of material to X-ray. When X-ray penetrates the detected object, its intensity is given by[16]

$$I=I_0\exp(-\mu_\mathrm{m}\rho x) \tag{1}$$

where I_0 is the intensity of X-ray before penetrating object; I is the intensity of X-ray after penetrating object; μ_m is the absorbing coefficient per unit mass of detected object; ρ is the density of material; and x is the penetrating length of incident X-ray.

CT can make the information of materials with different density at certain section display as high resolution digital images by computer image reconstruction. In this study, the spiral CT scanner of SOMATOM Sensation 16 was used for measurement of the column packed with ore particles. It integrates multi-section images collecting technology, reconstruction technology and high speed of rotating as well. The images of 32 sections can be collected per second and can be displayed with resolution of 0.5 mm, so it can meet the requirement of image collection in this experiment. The CT scanning apparatus is shown in Fig.1.

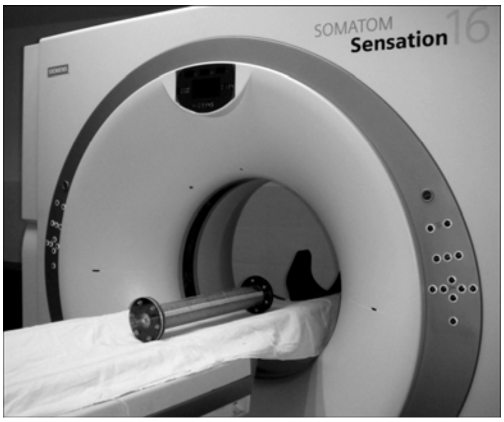

Fig.1 CT scanning apparatus

2.2 Calculation method of fractal dimension

Dimension is one of the most important concepts in fractal geometry. At present, there are several definitions, including Hausdorff dimension, box counting dimension, modified box counting dimension and packing dimension, etc. Since the mathematic calculation and estimation of box counting dimension are relatively easy, it has become one of the most popular dimensions. Assuming F is a nonempty set bounded in R^n, $N_\delta(F)$ is the smallest number of set with diameter of δ to cover F, then box counting dimension is defined as [17]

$$D_\mathrm{b}=\lim_{\delta\to 0}\frac{\ln N_\delta(F)}{\ln(1/\delta)} \tag{2}$$

In this study, the dimensions of matrix phase, pore phase and their interface were estimated by programming with MATLAB 6.5. Taking the calculation of the pore phase dimension as an example, and supposing there are several pores (the white closed areas) in the image of $L\times L$ shown in Fig.2, if the image is partitioned by a square with side length of δ into an orthogonal grid with mesh size of $(L/\delta)\times(L/\delta)$, then the total number of lattices containing pores in the grid is $N(\delta)$. Changing δ in a certain range, a serial of lattice number will be obtained accordingly, namely, $N(\delta_1)$, $N(\delta_2)$, $\cdots$, $N(\delta_n)$. As these data are plotted in logarithmic coordinate system, the corresponded relationship between $\ln N(\delta)$ and $\ln\delta$ can be easily determined. If the correlation is linear in the plot, which indicates that the pores have fractal characteristic, then we have

$$D_\mathrm{p}=-\lim\frac{\ln N(\delta)}{\ln(\delta)} \tag{3}$$

where D_p is the fractal dimension of pore phase.

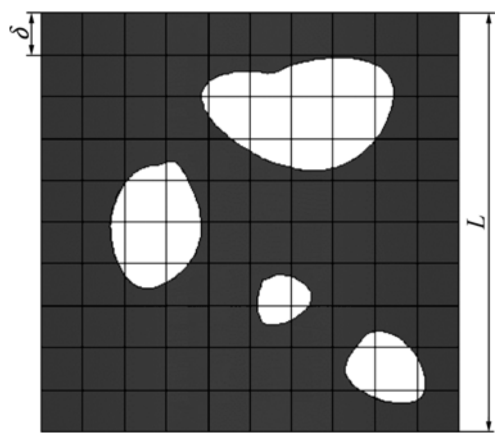

Fig.2 Schematic illustration of fractal dimension algorithm for pore phase

Similarly, the fractal dimensions of matrix phase and matrix/pore interface can be estimated.

2.3 Materials and experiment

The organic glass column used in the experiment was 540 mm in height and 60 mm in inner diameter, as shown in Fig.1. The ore particles were copper sulfide ores. The particle size of each sample is listed in Table 1. The diameter of the column was 6 times that of the largest ore particles, so the wall effect can be avoided. The ore samples were packed in the column orderly according to their particle size. During scanning, the CT scanner was operated at 120 kV and 330 mA and the scan interval was set at 0.75 mm/scan. The three-dimensional reconstructed image of granular ore media in the column and its longitudinal profile are shown in Fig.3. The two-dimensional CT image of each granular ore sample is shown in Fig.4.

Table 1 Ore particle size of granular samples

Sample No.	Particle size/mm
G1	1−2
G2	2−3
G3	3−4
G4	4−5
G5	5−6
G6	6−7
G7	7−8
G8	8−9
G9	9−10

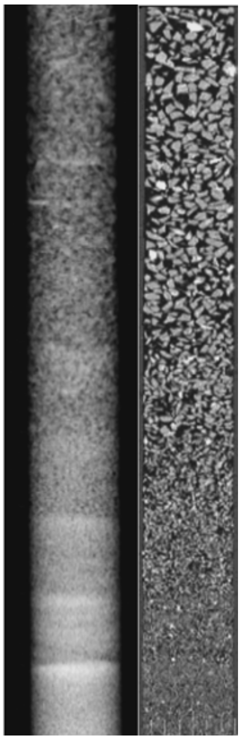

Fig.3 Three-dimensional reconstructed image of granular ore samples and its longitudinal profile

2.4 Image analysis

In order to calculate fractal dimension, the obtained CT images must be preprocessed firstly, including cropping, thresholding and edging. All of these were finished by programming with MATLAB 6.5. The preprocessing procedure is shown in Fig.5. The steps are as follows: 1) select a rectangle zone from original CT image by cropping and create a new image with size of 236×236; 2) transform the new grey image to binary particle image with a suitable threshold value; 3) invert the particle image to binary pore image; and 4) extract the spatial boundary of particles and pores. Since the diameters of ore particles packed in the column are larger than 1 mm and the density difference between particles and pores is very large, it is very easy to distinguish them and achieve the boundary of their interface by thresholding. Furthermore, by assuring that the calculation results are comparable, all of images were processed with same crop size and threshold value.

3 Results and discussion

3.1 Calculation of fractal dimension and porosity

The fractal dimensions of all images were calculated by programming with MATLAB 6.5. The program aimed at the background of an image, so the images obtained at different stage of preprocessing, shown in Figs.5(b), (c) and (d), could be used to calculate the fractal dimension of pore phase, D_p, the fractal dimension of matrix phase, D_s, and the fractal dimension of the interface, D_i, respectively. Moreover, from Fig.5(c), the porosity can be calculated. It is the ratio of pixel number of white area to the total pixel number of the image, commonly called as surface porosity. Since the scanning interval was 0.75 mm, the image number of each sample was about 80. In order to assure the accuracy of the results, the images of the interface of any adjacent samples were excluded. 50 images of each sample were selected for calculating fractal dimensions and porosity. Their average values were used for further analysis, which are listed in Table 2. Furthermore, for analyzing the relationship between fractal dimensions and permeability, the seepage coefficient of each sample was measured by constant head permeability test based on Darcy’s law. The results are also listed in Table 2.

3.2 Correlation between fractal dimensions and particle size

According to Table 2, the correlation of the fractal dimensions of matrix phase, pore phase and interface with particle size was plotted and the relevant regression analysis was performed, as shown in Fig.6. It can be known that, for the two-dimensional images of granular

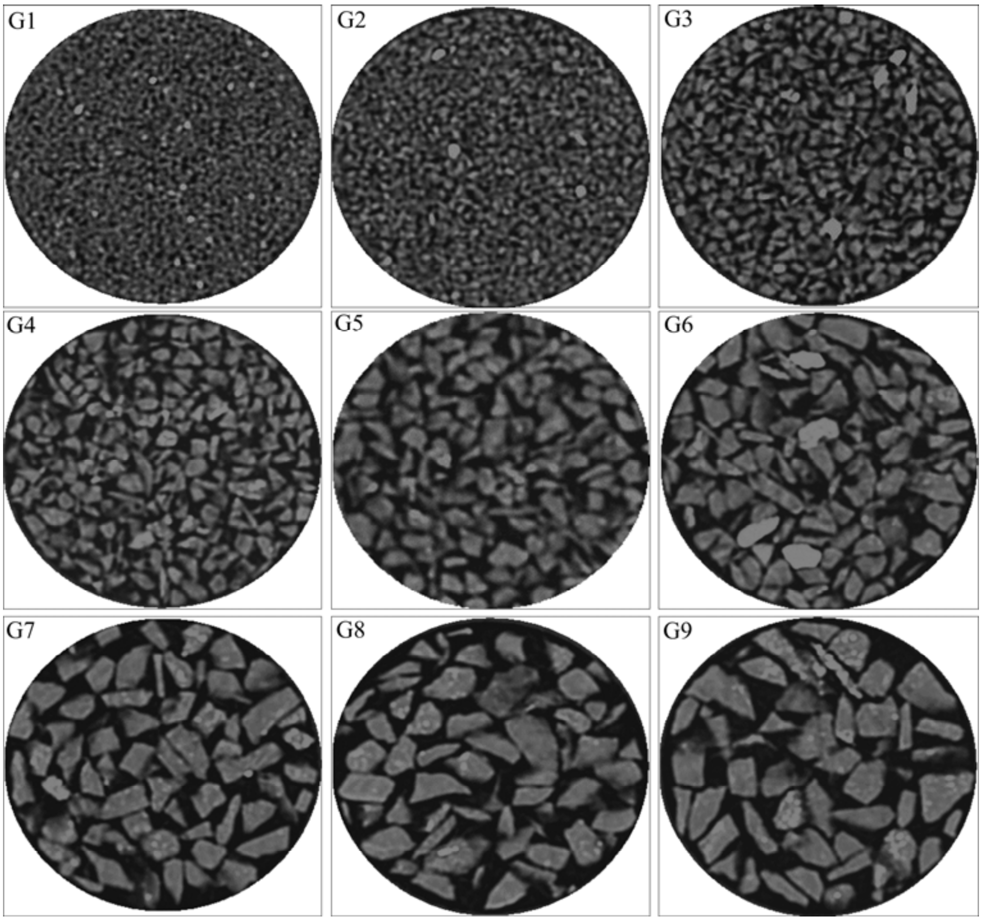

Fig.4 Two-dimensional CT images of granular ore samples

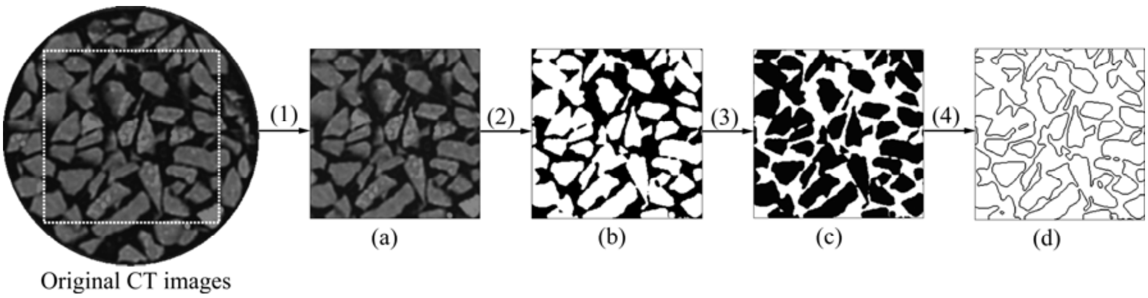

Fig.5 Preprocessing procedure of CT images: (a) Grey image of selected zone; (b) Binary ore particle image (pore black); (c) Binary pore image (pore is white); (d) Boundary line of pores and ore particles

Table 2 Fractal dimensions, porosities and seepage coefficients of nine granular ore samples

Sample No.	D_p	D_s	D_i	Porosity	Seepage coefficient/(cm·s^{-1})
G1	1.783 5	1.890 8	1.636 9	0.368 5	1.04
G2	1.786 5	1.892 5	1.621 9	0.382 1	1.40
G3	1.800 9	1.881 1	1.600 7	0.401 7	1.62
G4	1.806 5	1.875 2	1.573 2	0.408 5	1.75
G5	1.806 2	1.876 7	1.542 5	0.410 5	2.25
G6	1.811 1	1.876 7	1.517 8	0.417 9	2.65
G7	1.814 3	1.872 0	1.497 7	0.428 4	3.25
G8	1.818 1	1.869 1	1.479 4	0.437 4	3.61
G9	1.819 5	1.868 1	1.469 0	0.440 3	4.15

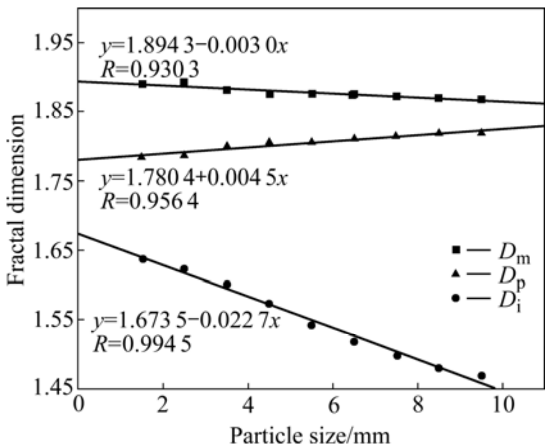

Fig.6 Correlation of fractal dimension and particle size of ore granular samples

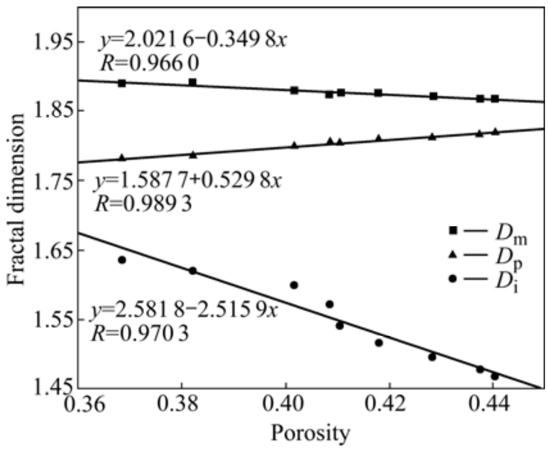

Fig.7 Correlation of fractal dimensions and porosity of ore granular samples

media, the fractal dimensions of matrix phase, pore phase and their interface range in 1−2. The matrix phase has the highest dimension, followed by the pore phase, and the interface has the smallest dimension. With the increasing of particle size, the fractal dimensions of matrix phase and interface decrease while the fractal dimension of pore phase increases. These three fractal dimensions are correlated linearly with particle size and the correlation coefficients are 0.930 3, 0.956 4 and 0.994 5, respectively, which exhibits good fitting. In addition, we can know that with the increasing of particle size, the change rate of the fractal dimensions of matrix phase and pore phase is low while that of the interface is larger.

3.3 Correlation between fractal dimensions and porosity

According to Table 2, the correlation of the fractal dimensions of matrix phase, pore phase and interface with porosity was plotted and the relevant regression analysis was performed, as shown in Fig.7. With the increasing of porosity, the fractal dimensions of matrix phase and interface decrease while the fractal dimension of pore phase increases. These three fractal dimensions are correlated linearly with porosity and the correlation coefficients are 0.966 0, 0.989 3 and 0.970 3, respectively, exhibiting good fitting effects. Furthermore, it can be known that the difference between the fractal dimensions of matrix phase and pore phase gradually decrease as porosity closes to 50% and they almost equal to each other when the porosity is 50%. This indicates that fractal dimension relates to mass fraction of each phase. For the granular media with porosity less than 50%, the fractal dimension of matrix phase is larger than that of pore phase; for those with porosity more than 50%, the fractal dimension of matrix phase is smaller than that of pore phase. The porosities of the ore samples shown in Table 2 are all less than 50%, so their fractal dimensions of matrix phase are all larger than those of pore phase.

3.4 Correlation between fractal dimensions and permeability

According to Table 2, the correlation of the fractal dimensions of matrix phase, pore phase and interface with seepage coefficient was plotted and the relevant regression analysis was performed, as shown in Fig.8. With the increasing of seepage coefficient, the fractal dimensions of matrix phase and interface decrease while the fractal dimension of pore phase increases. The correlation coefficients of linear regression are 0.879 5, 0.907 1 and 0.975 9, respectively. So we can know that the linear relations of the fractal dimensions of matrix phase and pore phase with seepage coefficient are not obvious. However, the fractal dimension of interface is linearly correlated with seepage coefficient obviously. The permeability of granular media relates to not only the porosity, but also the matrix/pore interface. If the

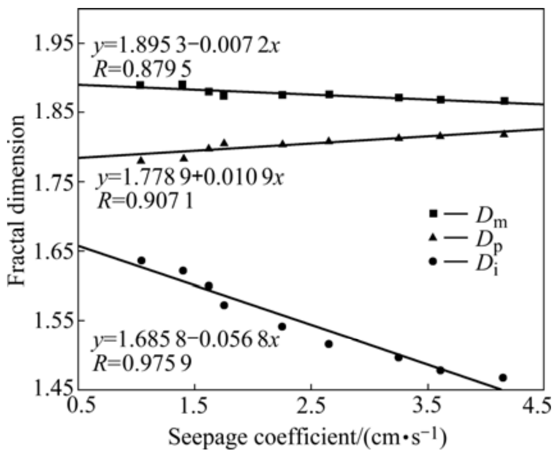

Fig.8 Correlation of fractal dimensions with permeability of ore granular samples

interface is rough and irregular, the length of fluid flow pathway and resistance will increase. So the fractal dimension of the interface is very applicable for evaluating the permeability of granular media. The larger the fractal dimension of interface is, the more the complicated fluid flow pathway is and the lower the permeability is.

4 Conclusions

1) For the two-dimensional images of granular media, the fractal dimensions of matrix phase, pore phase and their interface range in 1−2. The matrix phase has the highest dimension, followed by the pore phase, and the interface has the smallest dimension.

2) The fractal dimensions of matrix phase and interface are negatively correlated with porosity while the fractal dimension of pore phase is positively correlated with it. Fractal dimension relates to the mass fraction of each phase. For the granular media with porosity less than 50%, the fractal dimension of matrix phase is larger than that of pore phase and vise verse.

3) The fractal dimension of interface is linearly correlated with the seepage coefficient of granular medium obviously. The larger the fractal dimension of interface is, the more irregular it is, which results in more complicated fluid flow pathway and lower permeability.

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