Pore Structure Identification of GMZ Bentonite with Different Water Content Based on Digital Image

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Abstract: Bentonite contains many pore structures with irregular geometric shapes, with a strong adsorption to various fluids. It swells in the presence of water and could cause a significant change in its microscopic pore structures. This would lead to significant changes in its permeability, which will impact its engineering applications. This study analyses and compares the pore structure of bentonite cured under different humidity based on their microscopic images. The threshold segmentation algorithm is used to identify the pore structure in the microscopic image. Then the porosity and pore size distributions are measured, and the Hagen Poiseuille formula is used to calculate its permeability. After comparing bentonite treated with humidity of 91% and 98%, the porosity of bentonite decreased in the presence of water, while the proportion of small-sized pores increased, and the average permeability of bentonite of 98% humidity was half of that of 11%. Thus, the pore structure and permeability of bentonite changed significantly when subjected to different humidity.

1. Introduction
Bentonite is a common geotechnical material used in engineering applications and scientific research. Its adsorption and swelling properties have a marked impact on all aspects of it. For example, the swelling ability makes it easier for water molecules to enter the internal pore structure as the crystal layer spacing increases in the presence of water. This can have a significant impact on its engineering applications, for example, as a barrier material for nuclear waste disposal or a landfill cover, that can provide an opportunity for the infiltration of nuclear waste or leachate, which in turn can cause pollution to the surrounding soil and water environment[1]. Therefore, the quantitative characterization of the microscopic pores of bentonite in the presence of water and the study of permeability is essential and helpful for engineering-related problems’ solving[2].

This study considered two bentonite specimens stored at different relative humidities. First, images of their microstructures were obtained using scanning electron microscopy. Then, we selected a high magnification image and segmented its matrix section using image processing tools, leading to pore fraction extraction and porosity evaluation based on binary image[3]. After that, the pores’ distribution in different sizes was calculated using Continuous Pore Size Distribution[4]. Finally, the permeability...
of bentonites with varying water contents was predicted based on Hagen’s Poiseuille equation and combined above pore size distribution results.

2. Pre-preparation
The bentonite powder was placed in a mold and compressed at a constant speed using a compressor to obtain 2 bentonite specimens: the compaction was carried out by an MTS universal testing machine, and the bentonite powder was pressed into a sample having height \( h = 10 \) mm and diameter \( d = 50 \) mm and an initial dry density of \( 1.70 \pm 0.02 \) g/cm\(^3\). After preparing the samples, they were dried in an oven to measure their dry mass and density. If the dry density were within \( 1.70 \pm 0.02 \) g/cm\(^3\), the samples would be stored and the subsequent ones prepared. Secondly, four bentonite samples were maintained in environments where the relative humidities were 11% and 98%, obtained from saturated salt solutions. Their masses and volumes were periodically measured. The measurement intervals were 0.5 h, 1 h, 2 h, 4 h, 8 h, and then once a week. When the change in three consecutive measurement results differed by less than 0.01 g, the sample was considered to have reached equilibrium at the target relative humidity. Thirdly, specimens were cut with a tool into four small cubes with a side length of 10 mm. Finally, the specimens were imaged using a scanning electron microscope at a magnification of 8000 to characterize their microstructure\[5\].

![Figure 1. SEM image of compacted GMZ bentonite](image1)

**Figure 1.** SEM image of compacted GMZ bentonite

![Figure 2. Flow chart of this paper](image2)

**Figure 2.** Flow chart of this paper

2.1 Image pre-process and image binarization
We employed a median filtering tool on the acquired SEM greyscale image during the denoizing operation to denoise the image for subsequent image segmentation. The principle is as follows: by choosing a \( 3 \times 3 \) template and moving it to sweep the region, the median value of the pro-domain of a pixel point is obtained and used as the greyscale value of that pixel point in Figure 3.
Figure 3. Demonstration of median filtering

A threshold segmentation method is selected to binarize the image to obtain the part representing the pore image [5]. The principle of image binarization is straightforward: by comparing the grey value of each pixel in the image with the selected threshold, the pixel is determined to belong to the pore or matrix based on the comparison result.

\[ g(x,y) = \begin{cases} 
1 & f(x,y) > T \\
0 & f(x,y) < T 
\end{cases} \]  

(1)

T is the image segmentation threshold, \( f(x,y) \) is the grey value of the pixel located at the position of \( (x,y) \) in the grey scale image.

2.2 Pore size distribution calculation

There are two popular pore size distribution methods: Discrete Pore Size Distribution (DPSD) and Continuous Pore Size Distribution (CPSD). DPSD transit pores in an image to a circle based on the principle of area equivalence. At the same time, CPSD assumes that the pores inside the specimen are a continuum, and pores vary in size continuously. The process of mercury indentation is simulated by continuously filling the pores with circles in different radii, and the area filled is calculated and counted to obtain the percentage of pores of various sizes in the overall pore interval. In this study, we show a schematic diagram of CPSD in Figure 6.

Figure 4. CPSD calculation process

2.3 Permeability prediction based on Hagen Poiseuille equation

The permeability calculation is based on the pore size distributions obtained and combined with the Hagen-Poiseuille law [6, 7].

\[ Q = \frac{\pi R^4 \Delta p}{8 \eta l} \]  

(2)
\[ \Delta P \] is the pressure loss, \( l \) is the length of the fine tube, \( \mu \) is the kinetic viscosity, \( Q \) is the volumetric flow rate, and \( R \) is the radius of the fine tube. For porous media, the total flow of fluid through the specimen and the sum of the flow-through each tiny pore are seen as equal, as shown in Figure 5

\[ Q = \sum Q_i \] (3)

\( Q \) is the total flow rate through the specimen’s microstructure, and \( Q_i \) is the flow rate through each pore. Also, the flow of the fluid follows Darcy’s law, with the expression

\[ Q = \frac{kA}{\mu l} \Delta P \] (4)

where \( k \) is the permeability, and \( A \) is the cross-sectional area of the fluid. Rectifying equation (3) and equation (4) yield

\[ k = \frac{\pi}{8A} \sum R_i^4 = \frac{\pi}{8A} \sum A_i R_i^2 \] (5)

where \( R_i \) is the pore radius, and \( A_i \) is the area of the pore in radius \( R_i \).

**Figure 5.** Permeability prediction model

3. **Data calculation and analysis**

In this study, four bentonite clays at 11\% (2 samples) and 98\% (2 samples) relative humidities were selected for SEM microscopic imaging at a magnification of 8000, pre-processed with denoise filtering, and then binarized for segmentation, and the results are shown below. The white part is the skeleton, and the black is the pore. Then we analyzed and compared these binary images based on the aforementioned quantitative study to investigate the effect of the relative humidity on its pore structure[1, 3].
3.1 Porosity of bentonite and pore size distributions with different water content

The magnification chosen for SEM acquisition is 8000, so the larger magnification detects more small-sized pores than physical testing methods such as MIP. The PSD results measured in this study include some small-sized pores. Comparing Figure 6 and Figure 7(a), the porosity decreases significantly from 26.890% and 12.094% to 7.786% and 0.739% in an environment where the relative humidity changes from 11% to 98%, with the average pore size being only 1/5 of the previous state. As a result, the two 11% RH samples had a larger pore size, with a maximum value of approximately 2.509 μm and 2.036 μm, while the 98% RH recorded just 1.054 μm and 0.581 μm. This confirms that the internal skeleton of the bentonite expanded when it adsorbed water, resulting in compressed pore volumes and smaller pore sizes. The shrinkage of the internal bentonite space is noticeable when used as a shielding material. For example, when a less contaminating fluid enters its pores, the radioactive material’s radiation can be reduced, and thus reducing the contamination of the surrounding soil environment to some extent.

3.2 Permeability prediction based on PSD

We can observe significant changes in permeability due to the substantial reduction in pore space and existing pore sizes’ decreasing trend, which present obstacles to fluid flow. When placed in an environment of 11% RH, bentonite permeability can be as high as $4.440 \times 10^{-14} \text{ m}^2$ and $1.671 \times 10^{-14} \text{ m}^2$. 
but the figures of 98% are only $3.715 \times 10^{-15}$ m$^2$ and $1.397 \times 10^{-16}$ m$^2$. The internal microscopic pore structure changes significantly, resulting in a blockage of fluid percolation, which can improve its sealing properties to some extent, using as a shielding material. This reduces the risk of spillage when materials are susceptible to stored environmental contamination, thereby enhancing the safety and reliability of the project.

![Figure 8. Comparison of permeability prediction results](image)

4. Conclusion

Four bentonite specimens were stored at 11% and 98% relative humidities, then imaged using SEM to obtain microscopic images at a magnification of 8000, and then binarized for pore extraction using the images. CPSD was used to calculate the distribution of different pore sizes and predict their permeability based on Hagen’s Poiseuille equation. After comparison and analysis, this study showed that when the relative humidity of the environment is high, the tight pore space of the bentonite swells by adsorbing water, with subsequent reduction in porosity and pore sizes. As a result, fluid percolation channels are blocked, and the value of permeability decreases. Therefore, in engineering practice, we can see a decrease in the internal pore space of these materials when exposed to water, such that their fluidity and permeability reduced substantially.

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