Image Analysis Approach to Determine the Porosity of Rocks

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Abstract

Accurate characterisation of rock porosity is essential for assessing its strength and durability. This study explores both conventional and image analysis methods for determining rock porosity of two types of rocks, Bibai sandstone, a hard clastic rock and limestone, a soft rock. Conventional methods for determining rock porosity involve physical measurements and laboratory analysis, while image analysis methods utilise advanced imaging techniques such as CT scans or SEM to assess porosity based on visual information extracted from rock images. While various image analysis approaches exist to determine rock porosity, questions arise as to which approach is applicable and whether the results are comparable to current conventional methods. Hence, this study focuses on comparing the accuracy of alternative image analysis approaches. Representative rock chips from each core sample were examined using SEM, and 2D porosity was evaluated through image processing with ImageJ software. The Avizo visualisation software was employed to assess Bibai sandstone samples' porosity from CT images. The research offers insights into the pros and cons of each approach, contributing to the enhancement of accuracy and efficiency in rock porosity evaluation, particularly in geology, mining, and civil engineering applications.

Keywords: Avizo, CT-mage, Limestone, Porosity, Sandstone, SEM image, Conventional

1 Introduction

Porosity is a petrophysical parameter in geomechanics and the petroleum industry as it affects the mechanical properties of rocks, including their strength, deformation behaviour and permeability. It refers to the amount of open space or voids within a material and represents the rock's storage capacity for petroleum fluids in reservoir rocks [1]. A higher porosity means that a material has more voids, which can make it weaker and more susceptible to deformation, whereas a lower porosity means that a material has fewer voids, which can make it stronger and more resistant to deformation [2]. Understanding porosity is crucial for various engineering applications, including oil and gas extraction, foundation design, underground, radioactive waste disposal repositories, and slope stability analysis [3].

The geomechanics and petroleum industry recognises several different types of porosities, including total porosity, connected porosity, effective porosity, primary porosity, and secondary porosity. Primary porosity is the initial pore space present in rocks during their formation, while secondary porosity is formed or enhanced by subsequent geological processes that occur after the rock has been lithified. Both primary and secondary porosities play crucial roles in the evaluation of reservoir rocks, especially in the context of hydrocarbon exploration and production, where they affect the storage and flow of fluids within subsurface formations. [3]. The primary porosity of a rock is primarily influenced by factors such as grain distribution, packing, sorting, roundness, sphericity, and contact area, whereas the secondary porosity is influenced by weathering and fracturing [4]. In this study, we focus mainly on the total and effective porosities of rock.

Rock porosity is a crucial parameter in oil and gas exploration, providing valuable insights into the capacity of rocks to store and transmit hydrocarbons [5]. It is used in reservoir evaluation, rock-physics analysis, fluid substitution modelling, petrophysical analysis, geomechanics, and real-time prediction of rock porosity during well drilling [6]. Rock porosity is essential for estimating reservoir properties, such as rock strength, deformation behaviour, and failure mechanisms [7]. Geo-mechanical engineers can make informed decisions regarding excavation design, stability analysis, and support system design [8]. Porosity information is also linked to the failure mode and fracture intensity of sedimentary rocks, making porosity information crucial for geo-mechanical studies and engineering applications [9]. Real-time prediction of rock porosity during well drilling is another valuable application, as it can be time-consuming and expensive. Additionally, porosity can serve as a geo-mechanical index for estimating various rock mechanics material properties, providing valuable insights for material properties estimation in geomechanics [10].

Two main approaches for analysing rock porosity include conventional methods and image analysis techniques. Conventional methods include water absorption, helium pycnometer and mercury porosimetry methods. Image analysis methods involve imaging the rock using electronic apparatus, such as scanning electron microscope (SEM), X-ray Computed Tomography (CT), and Optical microscope [11], and then separating and identifying the pores from the medium by using a grey level difference on the image capturing of the rock. Numerous image analysis approaches have already been studied using open-source software and self-written codes. Compared to other methods of determining porosity, image analysis methods have the advantage of providing quantitative data on the pore system, such as pore size and shape [12]. Traditional approaches for assessing porosity frequently entail time-consuming, that have a limited ability to capture the spatial heterogeneity and intricate pore patterns inside rock samples. As a result, a quick and effective method that can analyse rock porosity in its entirety without causing damage is required.

While various image analysis approaches exist to determine rock porosity, questions arise as to which approach is applicable and whether the results are comparable to current conventional methods. Hence, this study focuses on comparing the accuracy of alternative image analysis approaches to determine the porosity of rock based on their CT images and SEM images.

2 Material and methodology

2.1 Rock types and study areas

Bibai sandstone was used as a hard clastic rock which was sampled just above a coal seam at an open pit in Sambi Coal Mine in Bibai, Hokkaido, Japan.

Bibai sandstone was classified into arenite sandstone with little matrix. It was mainly formed of coarse sand particles consists of quartz particles (< 1 mm) from granite, slate fragments, mudstone fragments, and siliceous mudstone and chert fragments (< 1.4 mm) which include a few illite and chlorite. Matrix is less than 1% and mainly consists of illite. The rock also has thin seams of coal [14]. No expansive clay mineral could be found.

Table 1: The physical properties of the Bibai sandstone

V_p (km/s)	V_s (km/s)	Dry density (g/cm³)	Effective porosity (%)	UCS (sat) (MPa)
2.941± 0.028	1.245± 0.026	2467± 12	5.79 ± 0.22	101.9 ± 2.3

High grade and low-grade limestone samples (Fig.1) were collected from Aruwakkalu limestone mine. The laboratory study carried out by Jayawardena, (2017) on Miocene limestones of Sri Lanka revealed the properties of the limestone deposit as shown in table 2, in the Northwestern belt from Puttalam to Jaffna.

Figure 1: High-grade and Low-grade limestone

Table 2: Properties of the Miocene Limestone in Sri Lanka

Property	Property range	Average value
Bulk density (kg/m³)	2213–2643	2452
Porosity (%)	1–15	0.065
Specific gravity	2.58–2.68	2.62
Uniaxial compressive strength (MPa)	11–92	35

2.2 Sample Preparation

The samples were prepared to perform water absorption method and SEM analysis. Irregular shape representative limestone, both high grade and low-grade rock samples that accurately reflect the characteristics of the rock formations under investigation were taken for water absorption test. Selected rock samples were cleaned to remove any contaminants such as dirt or loose particles. For SEM analysis, approximately 1cm*1cm samples were prepared. Before mounting the sample on the stub for SEM analysis, the specimen was kept in a dust free environment to avoid contamination. [4].

2.3 Water absorption method

The water absorption method serves as an established laboratory technique for assessing the porosity of rock samples. This method is based on saturation and water immerse methods. In the study, three distinct tests were conducted to ascertain the effective and total porosity of the limestone samples. The water saturation method was employed to identify and quantify the interconnected pore volume within the samples, while the water immerse method was utilised to determine the bulk volume of the specimens. To estimate the total porosity of the limestone, it was imperative to calculate both the interconnected and isolated pore spaces. This involved using a pycnometer to ascertain the matrix density of the limestone rock. Subsequently, following the completion of all tests, the pore, bulk, and matrix volumes of both high grade and low-grade samples were determined.

$$\text{Pore Volume } (V_p) = \frac{W(Saturated) - w_{(Dry)}}{density\ of\ water} \quad (1)$$

$$\text{Bulk Volume } (V_{b}) = V_{(displaced)} - V_{(saturated)} \quad (2)$$

$$\text{Grain Volume } (V_g) = \frac{Average\ W(dry)}{Specific\ gravity} \quad (3)$$

2.4 SEM Imaging and Image processing

High-resolution imaging was performed using a scanning electron microscope (SEM) at two distinct magnifications: 100X and 500X. For one of the samples, a total of five images were captured by adjusting the magnification settings, resulting in a cumulative collection of fifteen images, each elucidating surface details of the rock specimen. The initial step of the analysis involves importing the SEM images of the rock samples into the ImageJ software. This software offers a diverse array of tools and functionalities to enhance images, modulate contrast, and eliminate noise, thereby enhancing the precision of subsequent porosity estimations.

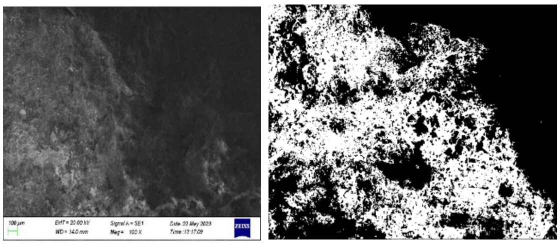


Figure 2: SEM image using 100X magnifications of a sample 1

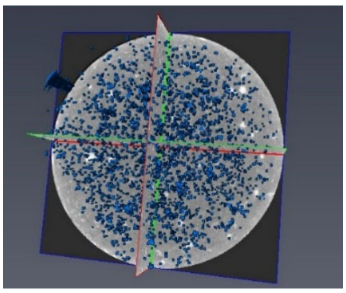
Through the application of ImageJ software, the area fraction of each image, corresponding to the surface porosity of the rock sample, can be accurately determined. Subsequent to this, leveraging Python, the porosity data is extrapolated in conjunction with the sample's volume. This method aims to establish a robust methodology for calculating the total porosity encompassing the entire rock sample. A comprehensive understanding of the porosity distribution within the sample can be derived by leveraging the relationship between porosity and volume. This analytical process facilitates the quantification of void space and enables an accurate assessment of the overall porosity characteristics of the rock specimen.

2.5 CT image analysis

CT images of Bibai sandstone, obtained from the micro-focus X-ray computed tomography (CT) scanner, installed at Hokkaido University, Japan, was used in this study. Those CT images were obtained in three perpendicular planes with a resolution of 37 μm.

The systematic methodology employed for the analysis of CT scan images via Avizo software encompasses the extraction of meaningful insights from volumetric data. Initial processing involves the conversion of all CT images into DICOM files or other compatible formats, accomplished through the utilisation of ImageJ software. Subsequently, the imported images, initially in a Raw format, undergo pixel adjustments and window level modifications to facilitate compatibility with Avizo software.

In the investigation of porosity within a core sample utilising CT image data, a series of methodical steps was undertaken. Commencing with the loading and visualisation of data from the designated folder through volume rendering, ortho views are then employed to elucidate pore spaces and generate a three-dimensional rendering of the sample. A global thresholding approach, informed by the dataset's histogram, is applied to discern dark regions. To ensure judicious application, the thresholding is conservatively adjusted. The resultant binarisation image is seamlessly integrated with the original data through a transparent slice overlay.



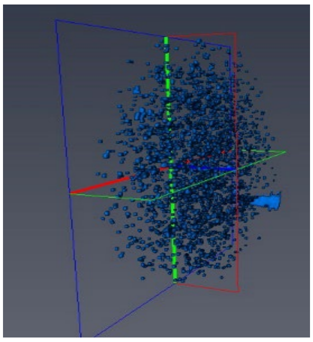


Figure 3: Pore spaces of the Bibai sandstonanalysed by Avizo.

This facilitated the visualisation of pore spaces within the dataset (Fig. 3). However, it is essential to highlight the potential presence of additional pores outside the sample, indicative of the surrounding air. To mitigate this concern, the selected data underwent voxelised rendering. The elimination of the surrounding area was achieved by employing a dilation module from the feature selection group, specifically designed to remove all connected voxels touching the bounding box border. The resulting dataset was subsequently linked to both the voxel rendering and slice overlay modules. Upon meticulous examination, the outline of the voxelised rendering revealed numerous small and larger detections within the sample.

The procedural steps encompassed loading and visualising the data, applying binarisation through thresholding, executing voxelised rendering, conducting porosity computation, and visualising both connected and unconnected pore spaces.

3 Results

3.1 Water absorption method

Table 3: Results for limestone sample

Sample 1- High grade limestone	
Total porosity	14.75 %
Effective porosity	14.30 %
Sample 2- Low grade limestone	
Total porosity	16.15%
Effective porosity	14.13 %

3.2 Image analysis method

3.2.1 Scanning electron microscope

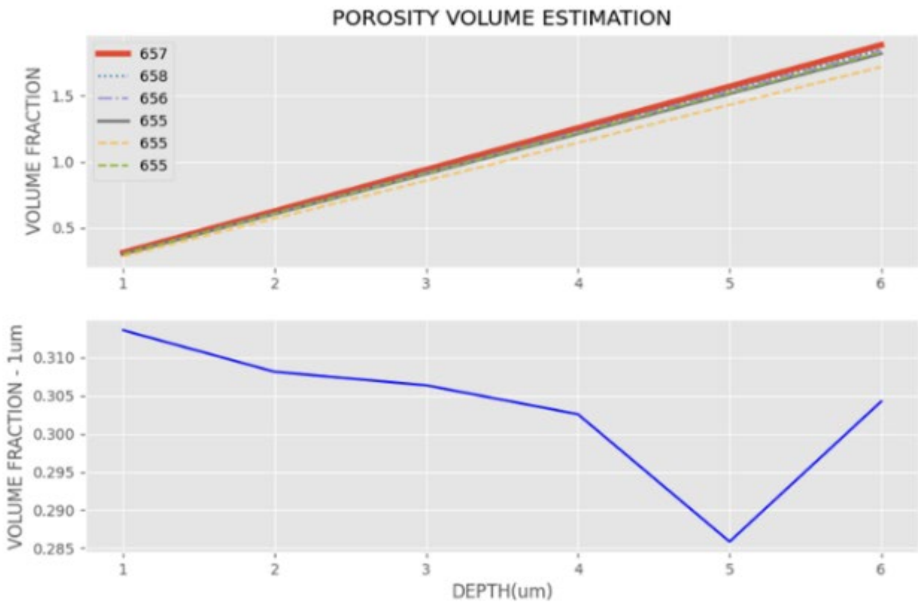


Figure 4: SEM results after extract the volume fraction

3.2.2 CT image

Table 4: Results from Avizo 3D

	Volume fraction	Label volume	Total volume
Mean	0.088	1.64389e+08	1.96602e+08
Max	0.088	1.64389e+08	1.96602e+08

4 Discussion

The porocity of limestone was determined using two methods: water absorption and SEM image analysis, yielding notably different results (Table 3 and Fig. 4). The water absorption method, globally recognised for its accuracy, determined the total and effective porosity within the expected nominal range. However, SEM image analysis through Image J software provided information solely on surface porosity, posing a challenge in achieving congruent results between the two methods. Analysed SEM images, particularly for volume calculation, proved challenging. Despite implementing a Python code with assumptions to extrapolate total porosity, effective results remained elusive. Despite these challenges, the research underscores the critical importance of carefully considering porosity analysis methods and enhancing their compatibility and accuracy. Exploring methods like Python, MATLAB, or machine learning may reconcile surface porosity with other sample data, optimising total porosity calculation.

For CT image analysis, Image J, Slicer 3D, and Avizo software were employed. Initial challenges with Slicer 3D prompted a shift to Avizo after investing considerable time. Using diverse techniques, analysed CT images revealed 8.36% porosity for the Bibai sandstone (Table 4).

5 Conclusion

In conclusion, the results suggest that the water absorption method used for porosity estimation proved more accurate than the SEM image analysis process for limestone. The mathematical extrapolation employed in the latter process exhibited limited effectiveness, indicating the need for improvement, possibly through the utilisation of MATLAB or machine learning. Additionally, the study emphasises the importance of refining assumptions for analysis. The findings also indicate the potential of Avizo in identifying sandstone porosity, with varying results obtainable through different Avizo recipes for CT image analysis. As a result, further testing on a variety of soft and hard rocks is recommended to enable comparative analysis and enhance the robustness of outcomes.

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