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PERMEABILITY OF PHU PHAN AND SAO KHUA SANDSTONES UNDER HIGH CONFINING PRESSURES (10-50 MPa)

Sawarin Champanoi [1], Supattra Khamrat[2], Thanittha Thongprapha[3*] and Kittitep Fuenkajorn[4]
[1]Student, Geomechanics Research Unit, Suranaree University of Technology, Thailand
[2]Researcher, Geomechanics Research Unit, Suranaree University of Technology, Thailand
[3]Lecturer, Geomechanics Research Unit, Suranaree University of Technology, Thailand
[4]Professor, Geomechanics Research Unit, Suranaree University of Technology, Thailand
*Corresponding author: thanittha@sut.ac.th

ABSTRACT

Constant head flow test has been performed on twenty-four cylindrical rock specimens obtained from Phu Phan and Sao Khua formations, representing ones of the aquifers in northeast of Thailand. The specimens are prepared with nominal diameters of 54 mm and length-to-diameter ratio of 1.5. The flow direction is normal and parallel to bedding planes. The test procedure is in accordance with the ASTM standard practice. The permeability of Sao Khua sandstone is lower than that of Phu Phan sandstone. It decreases with increasing confining pressures. The flow rates in the direction normal to the bedding planes are lower than those parallel to the bedding planes. The permeability anisotropy tends to be independent of the confining pressure. It is about 10 for Phu Phan sandstone, and 12 for Sao Khua sandstone. The effective porosity of Phu Phan sandstone is higher than that of Sao Khua sandstone, particularly under high confining pressures. They range from 4.5% to 7.3% for Phu Phan sandstone and 1.9% to 4.3% for Sao Khua sandstone.

KEYWORDS: Flow Test, Permeability Anisotropy, Porosity, Bedding Plane

บทคัดย่อ

การทดสอบการอัดน้ำภายใต้แรงดันแบบคงที่ได้ดำเนินการในตัวอย่างหินรูปทรงกระบอกทั้งหมด 24 ตัวอย่าง จากหินทรายชุดภูพานและเสาขัว ซึ่งเป็นตัวแทนของชั้นหินอุ้มน้ำในภาคตะวันออกเฉียงเหนือ โดยตัวอย่างได้ถูกจัดเตรียมให้มีขนาดเส้นผ่าศูนย์กลาง 54 มิลลิเมตร และมีอัตราส่วนความยาวต่อเส้นผ่าศูนย์กลาง 1.5 มีแนวการวางตัวของชั้นหินขนานและตั้งฉากกับทิศทางการอัดน้ำ การทดสอบดำเนินตามมาตรฐานของ ASTM โดยความซึมผ่านของตัวอย่างหินทรายเสาขัวมีค่าน้อยกว่าตัวอย่างหินทรายภูพาน ซึ่งความซึมผ่านมีค่าลดลงเมื่อความเค้นล้อมรอบสูงขึ้น ผลระบุว่าอัตราการไหลของน้ำในทิศทางตั้งฉากกับแนวการวางตัวของชั้นหินมีค่าน้อยกว่าในทิศทางขนานกับแนวการวางตัวของชั้นหิน แอนไอโซทรอปิกของค่าความซึมผ่าน ไม่ขึ้นต่อความเค้นล้อมรอบ โดยมีค่าเท่ากับ 10 สำหรับหินทรายชุดภูพานและ 12 สำหรับหินทรายชุดเสาขัว และความพรุนของหินทรายชุดภูพานสูงกว่าหินทรายชุดเสาขัวโดยเฉพาะอย่างยิ่งในสภาวะความเค้นล้อมรอบสูง ซึ่งผันแปรจาก 4.5 ถึง 7.3 เปอร์เซ็นต์ สำหรับหินทรายชุดภูพานและ 1.9 ถึง 4.3 เปอร์เซ็นต์ สำหรับหินทรายชุดเสาขัว

1. Introduction

For intact rock without any fractures, the fluid will flow through the small pores, which are randomly distributed in its matrix. The hydraulic and mechanical behaviors for the intact rock can be described by continuum mechanics like soil, which are relatively straightforward. Permeability is a measurement of the ability of a porous media to transmit fluids. It is an important controlling parameter of fluid flow systems in the rocks. This parameter is particularly important in sandstones since they generally are either groundwater or petroleum reservoirs. At greater depths, the permeability of the rocks tends to reduce due to higher stresses [1]. The mechanical behavior and structural expression of deformation in a porous sandstone may be influenced by many competing factors, including porosity, mineralogy, pore fluid and confining pressure [2,3]. It has been commonly found that the confining pressure can notably reduce the effective porosity of rocks, and subsequently decreases their permeability [4-6]. This finding has been concluded from many flow tests conducted in the laboratory under controlled hydrostatic pressures.

Most of the previous researchers have been concentrated on the effects of confining pressure and pore pressure on the permeability of rock. Wannakao et al. [7] estimate the coefficient of permeability of Phra Wihan, Phu Phan and Nam Phong formations under confining pressures by using flowing water with different pressures at inlet and outlet positions. The results indicate that the permeability reduces as the confining pressure increases. The equation used to estimate permeability based on porosity is proposed as $k = 9.68n^{1.899}$, where k is permeability (mD) and n is fractional porosity. The significant variables affecting the permeability of rock are porosity, mineral compositions and thickness of cross bedding [8]. The permeability increases with effective grain size and porosity increase. Sukplum et al. [9] study the permeability by flowing gas and water under confining pressures from 4 to 16 MPa, using specimens from the Nam Phong formation. The anisotropy of rock permeability is measured in two directions (parallel and perpendicular with lamination or cross bedding of specimens). The results indicate that the permeabilities of rocks sample are very low. The water permeability ranges from less than 1 to 340 μDarcy, while the gas permeability ranges from less than 1 to 59.25 μDarcy. The anisotropic water permeability $(k_{1//}/k_{1\perp})$ range from 0.30-18.54, and anisotropy infinite permeability $(k_{\infty//}/k_{\perp})$ ranges from 0.19-2.26 (Table 1). Several models used to describe the relation between confining pressure and permeability have been proposed by several previous researchers, including exponential, power and polynomial relations [10-12].

The objective of this study is to assess experimentally the permeability and effective porosity of Phu Phan and Sao Khua sandstone formations under different depths. The work involves constant head flow test under various confining pressures with flow direction normal and parallel to the bedding planes. Anisotropic permeability is determined. Since the fracture permeability is not considered here, the findings can be useful for a conservative prediction the yield pumping rate of the two sandstone formations.

2. Sample Preparation

The rock specimens belong to Phu Phan and Sao Khao formations. The Phu Phan sandstone is fine-grained comprising 80% quartz, 2.5% fledspar, 5.5% rock fragment, 1.5% mica and 10.5% other. Sao Khua sandstone is very fine-grained comprising 58% quartz, 5.5% fledspar, 7.5% rock fragment, 3% mica and 26% other [13].

The specimen density of Phu Phan sandstone is averaged as 2.4 ± 0.1 g/cc and 2.37± 0.1 g/cc for Sao Khua sandstone. The sample preparation follows the ASTM standard practice [14] with nominal dimensions of 54 mm in diameter and 81 mm in length. A total of 12 specimens are prepared for each rock type.

3. Test Apparatus and Method

Figure 1 shows the test arrangement. Before testing, the specimens are dried at 100 °C in an oven, and saturated in a vacuum-chamber at a negative pressure of 0.1 MPa for 48 hours. The specimen is then placed in a triaxial cell which is used to inject water pressure under constant confining pressures. The confining pressures are from 10 to 50 MPa. The injected water pressure is about 0.69 MPa which is controlled by a regulating valve connected on the nitrogen gas tank. The outlet pressure is taken as the atmospheric pressure, and is assumed to be 1 atm. Pipette with precision of 0.1 cc and 0.01 cc is used to collect the outflow of water. The flow rates under each confining pressure are measured to calculate the rock permeability and porosity. Testing durations are up to 19 to 46 days.

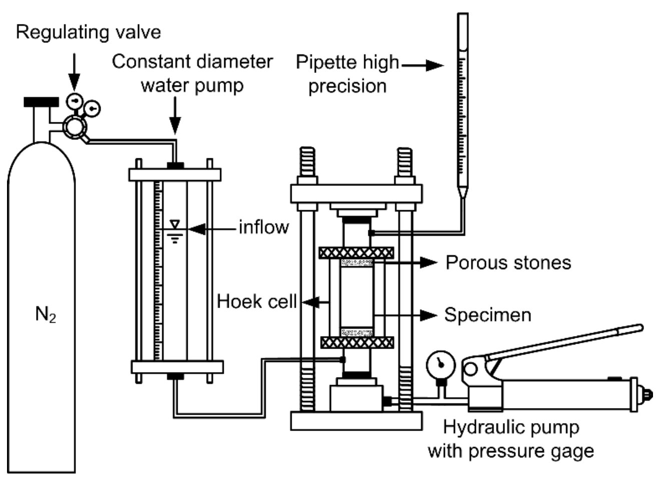

Figure 1 Laboratory arrangement for constant head flow test under high confining pressures

Table 1 Permeability of associated rock formations obtained elsewhere [1, 7-9]

Rock Formations	Confining Pressures (MPa)	Flow Directions	Permeability (m^2)	Porosity (%)	Permeability Anisotropy (k_p/k_n)
Namphong Formation (Khon Kaen Province)	4	Parallel	3.41×10^{-16}	4.38	19.73
		Normal	1.73×10^{-17}	4.48	
	8	Parallel	2.74×10^{-16}	3.94	18.82
		Normal	1.45×10^{-17}	4.06	
	12	Parallel	2.37×10^{-16}	3.55	17.74
		Normal	1.33×10^{-17}	3.55	
	16	Parallel	2.02×10^{-16}	3.69	16.07
		Normal	1.26×10^{-17}	3.34	
Namphong Formation (Loei Province)	4	Parallel	3.55×10^{-18}	2.66	1.29
		Normal	2.75×10^{-18}	2.71	
	8	Parallel	2.30×10^{-18}	2.15	1.15
		Normal	2.00×10^{-18}	2.24	
	12	Parallel	1.81×10^{-18}	1.74	1.23
		Normal	1.47×10^{-18}	1.86	
	16	Parallel	1.13×10^{-18}	1.33	1.25
		Normal	8.98×10^{-19}	1.47	
Namphong Formation (Chaiyaphum Province)	4	Parallel	1.02×10^{-17}	2.82	4.39
		Normal	2.33×10^{-18}	3.59	
	8	Parallel	6.72×10^{-18}	2.41	4.93
		Normal	1.36×10^{-18}	3.15	
	12	Parallel	5.13×10^{-18}	2.07	5.15
		Normal	9.97×10^{-19}	2.81	
	16	Parallel	4.02×10^{-18}	1.71	4.33
		Normal	9.28×10^{-19}	2.46	

4. Test Results

The flow rates as a function of times for Phu Phan and Sao Khua sandstones are shown in Figure 2 and Table 2. The curves show inflow and outflow with the flow directions parallel and normal to bedding planes. The flow rates are measured as a function of time until the inflow and outflow rates are equal. This is to ensure that the specimens are under saturated condition. The results indicate that the outflow rate increases with times, and decreases with increasing confining pressures. The time at which the inflow and outflow rates are balanced increases with increasing confining pressures. The flow rates normal to the bedding plane are lower than those parallel to the bedding plane. The Phu Phan sandstone gives the flow rate higher than that of Sao Khua sandstone for both normal and parallel to the bedding planes. This is probably controlled by the porosity and pore space arrangement of the specimens.

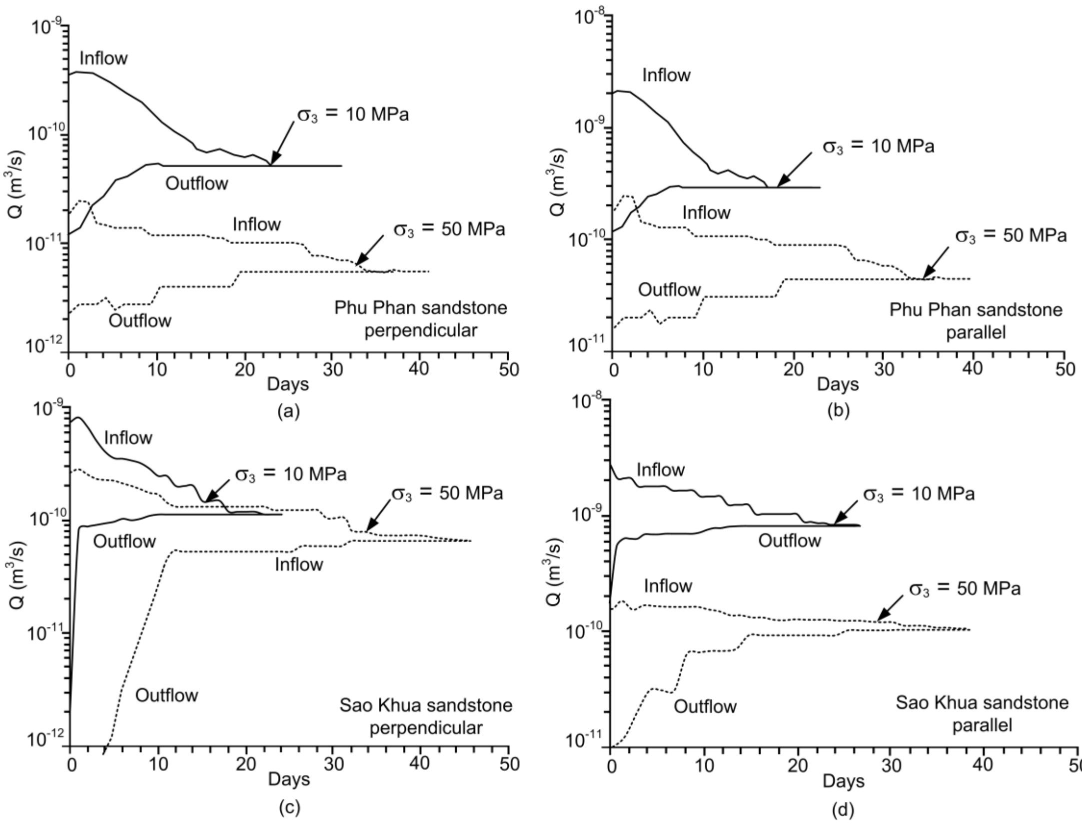

Figure 2 Examples of flow rates as a function of time for Phu Phan and Sao Khua sandstone specimens in directions normal (a),(c) and parallel (b),(d) to bedding planes for various confining pressures (σ_3)

Table 2 Summary of test results

Rock types	Flow Directions	Confining pressures (MPa)	Testing time (Days)	Flow rates (cc/s)
Phu Phan sandstone	Parallel (//)	10	19	0.00807
		20	24	0.00272
		30	26	0.00160
		40	30	0.00128
		50	35	0.00078
	Perpendicular (⊥)	10	24	0.00096
		20	27	0.00046
		30	30	0.00016
		40	34	0.00012
		50	37	0.00006
Sao Khua sandstone	Parallel (//)	10	22	0.00400
		20	27	0.00139
		30	30	0.00078
		40	34	0.00044
		50	37	0.00018
	Perpendicular (⊥)	10	24	0.00019
		20	26	0.00011
		30	29	0.00004
		40	35	0.00002
		50	46	0.00001

5. Permeability Calculation

The hydraulic conductivity *(K)* can be calculated from the test results. Based on the Darcy's law [15] the conductivity can be calculated from:

$$K = Q / A(\Delta h/L) \tag{1}$$

where K is hydraulic conductivity (m/s), Q is flow rate (m^3/s), A is a cross-section area of flow (m^2), γ_w is unit weight of water (9,789 N/m^3), and $\Delta h/L$ is hydraulic head gradient. The hydraulic conductivity can be used to calculate the intrinsic permeability (k) as:

$$k = (K\mu/\gamma_w) \tag{2}$$

where μ is dynamic viscosity of water (1.005×10^{-3} N•s/m^2). The intrinsic permeability values parallel and normal to the bedding planes are plotted as a function of confining pressure in Figure 3. The results show that the intrinsic permeability decreases when confining pressures increase from 10 to 50 MPa. The permeability of Phu Phan sandstone is higher than that of Sao Khua sandstone for all test conditions. The permeability of rock specimens with flow direction parallel to the bedding planes are always greater than those normal to the bedding planes. Table 3 shows the empirical equation and parameters used to fit the curve in Figure 3. The parameter k_0 represents the rock permeability under zero confinement.

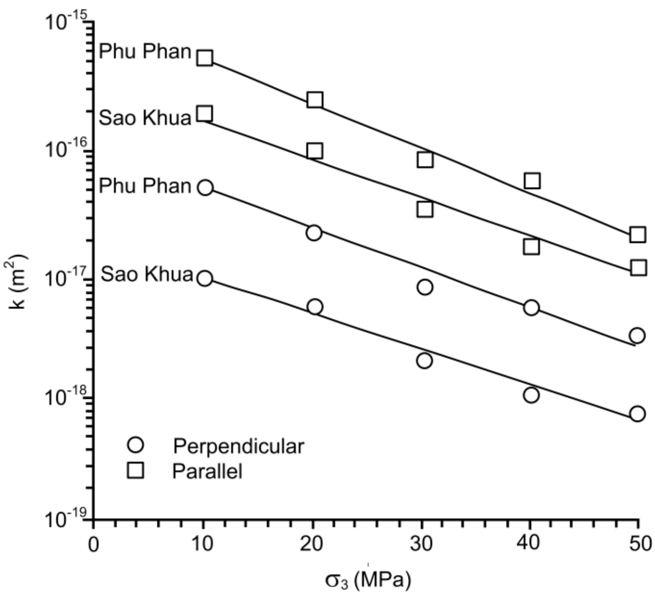

Figure 3 Intrinsic permeability as function of confining pressures

Table 3 Summary of empirical constants

Rock types	**Flow directions**	$k = k_0 \exp^{\eta\sigma_3}$		
		k_0	η	R^2
Sao Khua sandstone	Parallel	4×10^{-16}	-0.078	0.988
	Perpendicular	2×10^{-17}	-0.064	0.967
Phu Phan sandstone	Parallel	1×10^{-15}	-0.089	0.989
	Perpendicular	9×10^{-17}	-0.078	0.988

The effective porosity of the two sandstones can also be determined from the specimens tested under each confining pressure. This can be done by weighting the specimens before and after placing in an oven for 24 hours after flow testing. The weight differences represent the weight of water. The effective porosity can then be calculated by [16]:

$$n_e = [(W- d)/\rho_w]/V) \times 100 \quad (3)$$

where W is saturated weight of specimen (g), d is dry weight of specimen (g), ρ_w is density of water (g/cm^3) and V is total bulk volume of specimen (cm^3). The results indicate that the effective porosity of sandstones in the flow direction normal and parallel to the bedding plane are equal, and decrease with increasing confining pressures (Figure 4). The porosity of Phu Phan sandstone is higher than that of Sao Khua sandstone, particularly under high confining pressures. They are ranging from 4.5% to 7.3% for Phu Phan sandstone and 1.9% to 4.3% for Sao Khua sandstone.

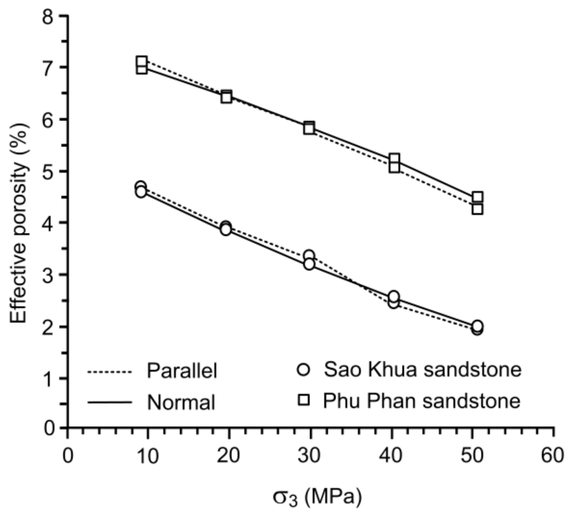

Figure 4 Effective porosity in directions normal and parallel to bedding plane as a function of confining pressures

The volumetric changes or reductions of the sandstone specimens have been measured after they are removed from the confining chamber. It is found that the specimen volume reduces as increasing the confining pressure. The volumetric changes are calculated by dividing the volumetric changes by the original volume of the specimen. The results are shown in Table 4, and are plotted as a function of confining pressure in Figure 5. This suggests that permanent closure of the pore spaces has occurred after the specimens have been subjected to the confining pressures. The greater confinement is applied, the more permanent pores closure is obtained.

Table 4 Volumetric change of specimens under each confinement

Confining pressures (σ_3) (MPa)	Dry density (g/cc)		Volumetric change (%)	
	Sao Khua sandstone	Phu Phan sandstone	Sao Khua sandstone	Phu Phan sandstone
0	2.365	2.409	0	0
10	2.387	2.421	0.950	0.520
20	2.394	2.437	1.220	1.170
30	2.406	2.446	1.730	1.530
40	2.417	2.461	2.220	2.160
50	2.423	2.468	2.470	2.470

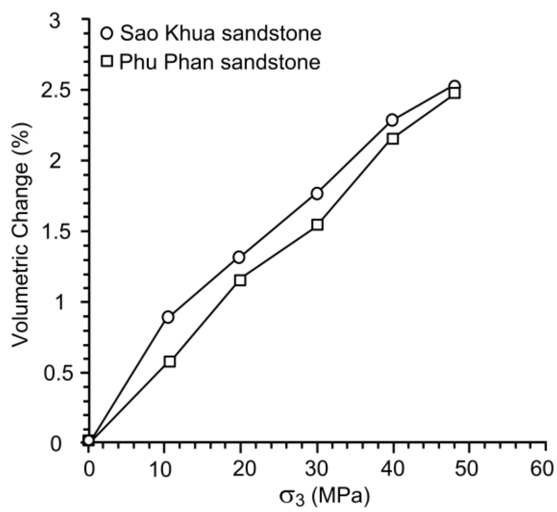

Figure 5 Volumetric change as a function of confining pressure

6. Discussions and Conclusions

Permeability and porosity of sandstones are measured under different confining pressures ranging from 10 to 50 MPa. The results clearly indicate that the permeability of Phu Phan sandstone is higher than that of Sao Khua sandstone. Both sandstones show the anisotropic permeability. The permeability parallel to the bedding planes is about 10 times higher than that normal to the bedding planes. This permeability anisotropy tends to be independent of the confining pressure. The confining pressures within the range used here affect equally on the permeability in both flow directions. Increasing the confining pressure from 10 to 50 MPa can reduce the sandstone permeability by about one order of magnitude. The results suggest that the closure of the pore space after subjecting to high confining pressures tends to be permanent. This is evidenced from the measurements of the specimen diameters before and after testing.

Acknowledgements

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