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MECHANICAL PROPERTIES OF PHRA WIHAN SANDSTONE UNDER SUBZERO TEMPERATURE

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ABSTRACT

The objective of this study is to examine the mechanical properties of sandstone under subzero temperature. This sandstone belongs to the Phra Wihan formation which is commonly found in the northeast of Thailand. The cylindrical shaped specimens with diameter of 54 mm are prepared by cutting machine to obtain the specified length and ratios (L/D = 0.5 for Brazilian tension test, L/D = 2.5 for uniaxial compression test and L/D = 2.0 for triaxial compression test). The tests are performed on dry and saturated rock samples under the temperature varying from 25 to -40°C. The cubical rock samples with nominal dimensions of 26×26×26 mm^3 are also prepared to be investigated the effect of water expansion in pore spaces during freezing-thawing cycle. The results indicated that the tensile and compressive strength under dry and saturated conditions slightly increased (ranging from 60.9 to 184.1 MPa for compressive strength and 5.3 to 9.0 MPa for tensile strength) with decreasing of temperatures (between 25 and -40°C). This is due to the fact that the specimens under low temperature have a lower thermal energy than those under high temperature. This allows the rock sample to absorb more mechanical energy and to develop higher stresses before the failure occurs. The effect of temperature on strength under saturated conditions is considerably greater than that under dry condition. After the temperature below -5°C, the increasing rate of tensile and compressive strength tend to get high as temperature decreases. This is because the strength of ice in pore space becomes high. The strength parameters, cohesion (c) and internal friction angle (ϕ) based on Coulomb criterion, slightly increase with decreased temperatures. The "m" constant based on Hoek and Brown criterion decreases with decreasing temperature. Under saturated condition, the adhesive force between ice and grain of sandstone can strengthen the rock strength. The temperature has a significantly effect on elasticity of saturated rock specimens when it was below freezing temperature. The strength parameters determined from the test results of dry and saturated rock samples under subzero temperatures can be applied to determine the mechanical stability of the rock mass during the excavation with ground freezing techniques.

KEYWORDS: Strength, Deformation, Frozen Sandstone, Subzero Temperature, Freezing-Thawing Cycle

บทคัดย่อ

วัตถุประสงค์ของการศึกษาครั้งนี้เพื่อศึกษาคุณสมบัติเชิงกลศาสตร์ของหินทรายภายใต้อุณหภูมิต่ำกว่าศูนย์องศา หินทรายชนิดนี้จัดอยู่ในชุดหมวดหินพระวิหารซึ่งมักพบได้ในภาคตะวันออกเฉียงเหนือของประเทศไทย ตัวอย่างหินรูปทรงกระบอกที่มีขนาดเส้น

ผ่านศูนย์กลาง 54 มิลลิเมตร ได้จัดเตรียมโดยการตัดด้วยเครื่องตัดเพื่อให้ได้ความยาวตามที่กำหนด (L/D = 0.5 สำหรับการทดสอบแรงดึงแบบบราซิล L/D = 2.5 สำหรับการทดสอบแรงกดในแกนเดียว และ L/D = 2.0 สำหรับการทดสอบแรงกดในสามแกน) การทดสอบได้ดำเนินการกับตัวอย่างในสภาวะที่แห้งและอิ่มตัวด้วยน้ำภายใต้อุณหภูมิตั้งแต่ 25 ถึง -40 องศาเซลเซียส นอกจากนี้ตัวอย่างหินรูปทรงลูกบาศก์ที่มีขนาด 26×26×26 ตารางมิลลิเมตร ถูกจัดเตรียมขึ้นเพื่อตรวจวัดผลกระทบของการขยายตัวของน้ำในช่องว่างระหว่างวัฏจักรการแข็งตัวและการละลายตัว ผลการทดลองชี้ให้เห็นว่าแรงดึงและแรงกดภายใต้สภาวะแห้งและอิ่มตัวด้วยน้ำเพิ่มขึ้นเล็กน้อยเมื่ออุณหภูมิลดลงเนื่องจากตัวอย่างภายใต้อุณหภูมิต่ำมีพลังงานเชิงความร้อนสะสมในตัวอย่างระดับต่ำกว่าตัวอย่างหินภายใต้อุณหภูมิสูง ด้วยเหตุนี้จึงทำให้ตัวอย่างหินดังกล่าวสามารถรับพลังงานเชิงกลได้มากขึ้นและสามารถพัฒนาความเค้นให้สูงขึ้นก่อนเกิดการวิบัติ ผลกระทบของอุณหภูมิต่อความแข็งของหินในสภาวะอิ่มตัวด้วยน้ำมีแนวโน้มสูงกว่าตัวอย่างหินในสภาวะแห้ง หลังจากอุณหภูมิลดต่ำกว่า -5 องศาเซลเซียส กำลังรับแรงดึงและแรงกดมีแนวโน้มเพิ่มเมื่ออุณหภูมิลดลง เนื่องจากความแข็งของน้ำแข็งในช่องว่างมีค่าสูงขึ้น ค่าพารามิเตอร์ความแข็งอันได้แก่ค่าความเค้นยึดติด (c) และมุมเสียดทานภายใน (ϕ) ตามเกณฑ์การวิบัติของคูลอมบ์มีค่าเพิ่มขึ้นเล็กน้อยเมื่ออุณหภูมิลดลง ค่าคงที่ "m" ตามเกณฑ์การวิบัติของฮุกและบราวน์มีค่าลดลงตามการลดลงของอุณหภูมิ ในสภาวะที่อิ่มตัวด้วยน้ำนั้นแรงยึดระหว่างน้ำแข็งและเม็ดหินทรายสามารถเพิ่มความแข็งของหินได้ อุณหภูมิจะมีผลกระทบอย่างมีนัยสำคัญต่อสัมประสิทธิ์ความยืดหยุ่นของหินที่อิ่มตัวด้วยน้ำเมื่อตัวอย่างหินอยู่ภายใต้อุณหภูมิต่ำกว่าศูนย์องศา พารามิเตอร์ความแข็งที่คำนวณได้จากผลการทดสอบของตัวอย่างหินในสภาวะแห้งและอิ่มตัวด้วยน้ำภายใต้อุณหภูมิต่ำกว่าศูนย์องศาสามารถนำมาประยุกต์ใช้ในการประเมินเสถียรภาพเชิงกลศาสตร์ของมวลหินระหว่างการขุดเจาะ โดยการใช้เทคนิคการกราวด์ฟรีซซิ่ง

คำสำคัญ: กำลัง, การเปลี่ยนแปลงรูปร่าง, หินทรายที่แช่แข็ง, อุณภูมิที่ต่ำกว่าจุดเยือกแข็ง, วัฏจักรการเยือกแข็งและการละลาย

1. Introduction

Rock salt and potash in the Khorat and Sakon Nakhon basins in the northern Thailand have become important mineral resources for industry. The deposits in the Maha Sarakham formation which consisted upper salt, middle classtic, middle salt, lower clastic and lower salt member. Potash has been found only in the lower salt member [1]. For mining process of underground mine, the mining access (shaft and declined) is excavated through the deep of rock strata with the operational problems created by adverse groundwater conditions. Artificial ground freezing is one of the effective methods to control or to mitigate the potential of groundwater inflow into the excavation area [2]. Ground freezing is a process of making water-bearing soil or rock decrease the temperature below 0°C. This process can create temporary impermeability and increased the compressive and shear strength by transforming water to ice. However, uncertainties still remain in terms of understanding and predicting the behaviour of rocks under subzero temperature.

2. Research Objective

The objective of this study is to assess of the mechanical properties of sandstone under subzero temperature condition in the laboratory. The tests are performed on dry and saturated samples under the temperatures below as -40°C. The mechanical properties including the uniaxial compressive strength, the Brazilian tensile strength and the triaxial compressive strength are employed. The strength and stiffness modulus under underlined particular temperature can be used to assess the predictive capability of some failure criteria by which can be readily applied in the design and stability of excavations.

3. Sample Preparation

Rock samples used in this experiment are the sandstone from Phra Wihan formation which is commonly found in the northeast of Thailand. They have fine grained, brownish white color with scattered black, quartz and feldspar dominated with less mica, well sorted and angular [3]. The rock blocks are drilled into the cylindrical shaped specimens with diameter of 54 mm with then later are cut by cutting machine to obtain the specified length. Length to diameter ratio (L/D) are equal to 2.0 for the compressive strength tests and equal to 0.5 for the Brazilian tensile strength tests. The preparations of these samples follow as much as practical the American Society for Testing and Materials [4,5]. Two test conditions of rock samples are performed: dry and saturated conditions. Performing in the, the samples were kept for one day in an oven at 60°C. Then they were removed from the oven and stored for one other day at the room temperature before testing. For the saturated condition, the samples were prepared by submerge in pure water and kept them in a vacuum desiccator for more than three weeks. All rock samples were wrapped with low density polyethylene (LDPE) to keep them from any change of moisture content. The mechanical properties tests are performed to examine the influence of temperature by varying the temperate ranging from 25, -5, -20 and -40°C. The rock samples were kept in refrigeration before cooling down by coolant (liquid nitrogen, LN_2) for protecting the specimens from thermal shock. Moreover the cubical blocks of sandstone with nominal size of 26×26×26 mm^3 are prepared for the examination of the influencing of temperature on the initial inducing of micro-crack in rock samples during cooling down process. Figure 1 shows some of rock samples prepared for the laboratory testing.

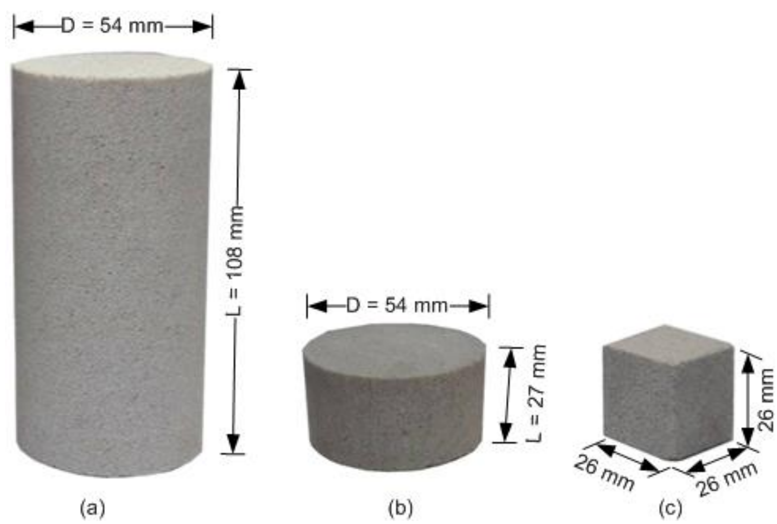

Figure 1 Examples of rock specimen prepared for compressive strength test (a), Brazilian tensile strength test (b) and freezing and thawing cyclic test (c).

4. Test Methods

4.1 Compressive and Tensile Strength Test

The uniaxial and triaxial compression tests were performed to determine the compressive strength and deformation of sandstone specimens under various confining pressure as influencing of temperature. The test temperatures ranging from 25, -5, -20 and -40°C. The test procedure was following the test procedures specified in the ASTM standard [4, 5]. A compression load frame was used to apply the axial stresses and the conventional triaxial (Hoek) cell was used to apply the confining pressure on the specimens. The confining pressure were maintained constant at 0, 3, 7 to 12 MPa while the axial stresses were increased with constant rate of 0.1 MPa/second until failure occurs. The conventional triaxial cell was frozen by using the refrigerator before testing to prevent the heat loss out of rock specimen during the tests. The specimen installation and testing were completed within 5 minutes. The Brazilian tensile strength test was conducted to determine the indirect tensile strength of the speci mens. The test was performed in accordance with the ASTM standard [6]. Ten specimens of the sandstone were tested under temperatures ranging from 25, -5, -20 and -40°C. The diametrical load was applied to the specimen until the failure occurs. The constant stress rate was maintained about 0.1 MPa/second. The axial load was applied until failure occurs. The changes of specimen's temperatures ware measured before and after testing.

4.2 Freezing and Thawing Cyclic Test

The freeze-thaw cycle on the cubical rock specimens were conducted to examine microstructure changes in rock specimens by measure the inducing of the porosity. Three cycles were conducted here. For each cycle the saturated specimens were frozen under subzero temperatures (-20°C) in a thermostatic chamber for a week. Then they were thawed under ambient temperatures and dry in oven at 100 ± 5°C for two days. The specimens under dry and saturated surface dry were weighted for each cycle used to determine the changing of their apparent porosity [7]. The porosity increments were plotted as a function of freeze-thaw cycle.

4.3 Test Results

Table 1 gives the compressive strength results in terms of the major and minor principal stresses at failure for dry and saturated conditions. Some post-test specimens show shear failure mode (Figures 2). The effects of the confining pressure on the compressive strength of the specimens can be observed from the σ_1-σ_3 diagrams as shown in Figures 3. The compressive strength tends to increase with increasing of confining pressure for all test temperatures. The specimens under low temperature give a higher strength than those under high temperature. Because of specimens under low temperature contained low thermal energy those under high temperature. This allows the rock samples to absorb more mechanical energy and to develop higher stresses. The effect of temperature on strength under saturated condition is considerably greater than that under dry condition.

The Brazilian tensile strength of the sandstone has been determined from disk specimens under the temperatures ranging from 25 °C freeze up to -40°C (Table 2). The tensile strengths increase with decreasing temperatures (Figure 4). Tensile strengths of the saturated specimens are lower than the dry specimens. This is true only in the case of temperature higher than -20°C. When the temperatures are lower than -20°C, the tensile strength of saturated specimens are greater than that dry specimens. The strength of saturated rock samples under low temperature (< 20°C) are increased with temperature decreased. This is due to the fact that the pore-water are changed to an ice which its strength is increased with decreasing of temperature.

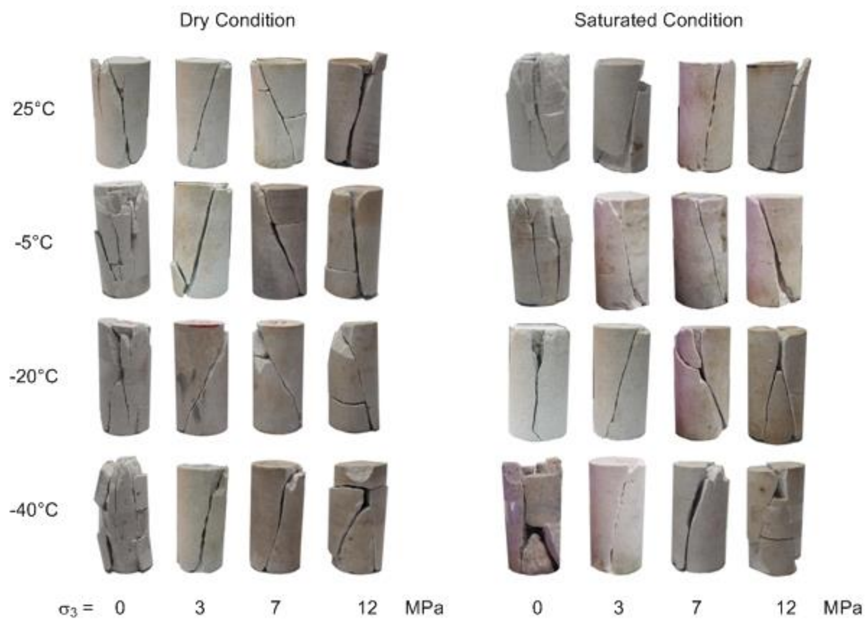

Figure 2 Post-test specimens obtained from compressive strength testing under different confining pressures and temperatures.

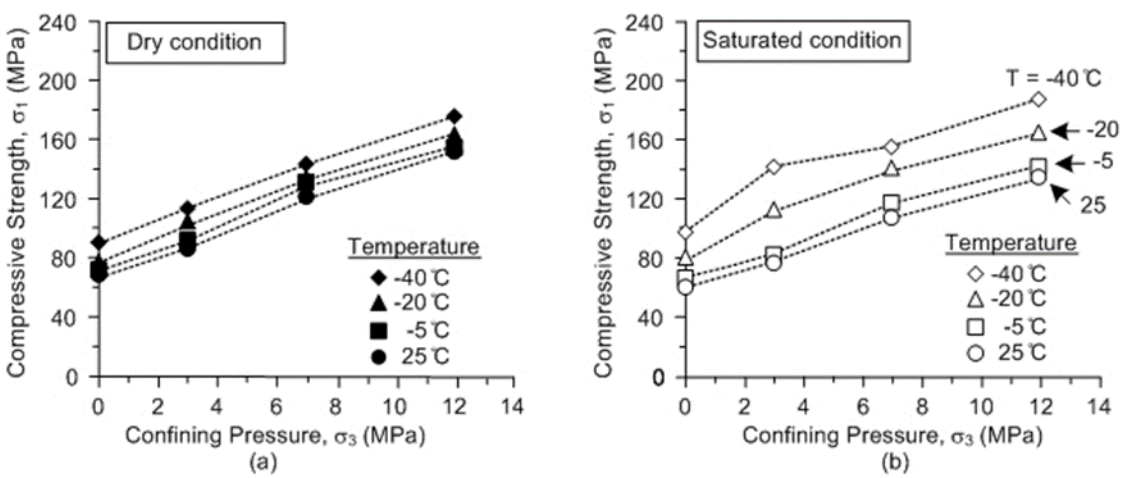

Figure 3 Principal stresses at failure as a function of confining pressure for dry (a) and saturated (b) conditions.

Table 1 Compressive strength and deformability of sandstone specimens.

Temperature (°C)	σ_3 (MPa)	σ_1 (MPa)		Young's modulus, E (GPa)		Poisson's ratio, ν	
		Dry	Saturated	Dry	Saturated	Dry	Saturated
25	0	68.75	60.93	10.38	10.00	0.28	0.29
	3	86.28	77.48	10.69	9.80	0.29	0.28
	7	121.58	108.68	10.41	10.17	0.28	0.29
	12	152.13	136.39	11.50	11.84	0.28	0.30
-5	0	72.02	65.59	10.77	9.27	0.28	0.27
	3	92.04	83.19	10.13	11.53	0.30	0.29
	7	131.23	118.79	10.86	10.42	0.30	0.29
	12	159.94	146.71	11.10	10.66	0.30	0.29
-20	0	77.71	81.45	10.51	10.01	0.28	0.29
	3	104.91	114.36	11.03	11.59	0.30	0.29
	7	134.24	142.85	10.48	11.14	0.30	0.28
	12	163.19	170.23	10.19	11.15	0.30	0.29
-40	0	90.53	101.99	10.33	11.29	0.28	0.30
	3	113.58	137.81	10.30	10.95	0.30	0.27
	7	143.62	157.03	10.13	11.14	0.29	0.28
	12	170.01	184.11	11.56	11.84	0.29	0.28

Table 2 Tensile strength of sandstone specimens.

Temperatures (°C)	σ_B (MPa)	
	Dry	Saturated
25	6.48±0.52	5.32±0.55
-5	6.55±0.77	5.18±0.39
-20	6.94±0.74	7.08±0.54
-40	7.80±0.81	9.00±1.29

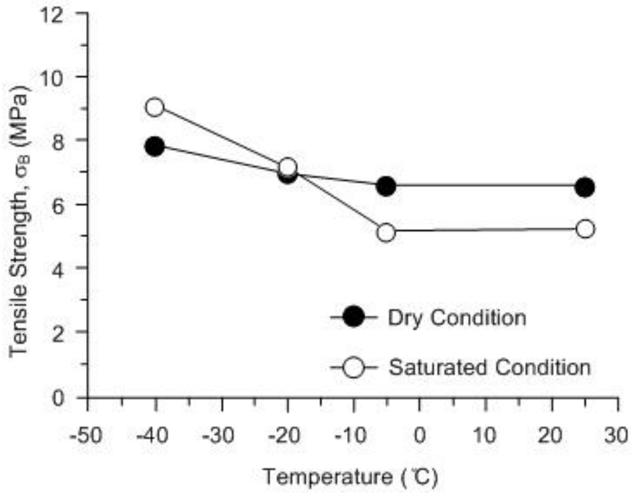

Figure 4 Brazilian tensile strength as function of temperatures for dry and saturated conditions.

The elastic modulus and Poisson's ratio have been calculated from measured stress-strain curves obtained from compressive strength test. Figure 5a plotted the elastic modulus and as a function of temperatures. The elastic modulus determined for saturated condition slightly increased with the temperature decreases whereas the elastic modulus are same values at dry condition. The influence of temperature on the rock deformability is reflected as elastic modulus under saturated condition. The relationship between Poisson's ratio and temperatures is shown in Figure 5b. In the both conditions of the specimens there is no apparent difference of Poisson's ratio with temperature.

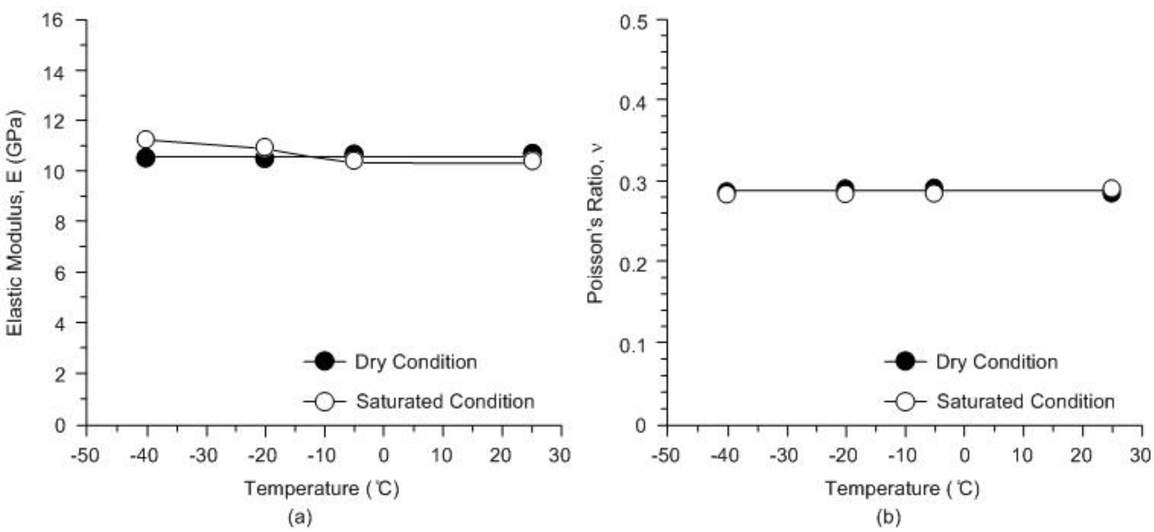

Figure 5 Elastic modulus (a) and Poisson's ratio (b) as function of temperatures for dry and saturated conditions.

5. Strength Criteria

Two strength criteria were commonly used to compare against the test results. These include Hoek-Brown criterion [7] and Coulomb criteria [8]. They have been widely used to study the strengths of rock.

Based on the Coulomb criterion the cohesion (c) and internal friction angle (ϕ) can be determined from the strength results for each temperature using the following relations:

$$\sigma_1 = 2c \tan\beta + \sigma_3 \tan2\beta = 2c \tan(45 + \phi/2) + \sigma_3 \tan^2(45 + \phi/2) \quad (1)$$

Both the cohesion and internal friction angle of the sandstone can be represented by Figure 6. The cohesions for both dry and saturated conditions were increase with decreasing temperatures. The internal friction angle under saturated condition was slightly increase with decreasing temperatures. The decreases of temperatures were no apparent influence the internal friction angle under dry condition. At the subzero temperature, the ice filled in pore space of rock can be cement matrix of rock under saturated condition. This agrees reasonably well with the increased strength as the temperature decreases.

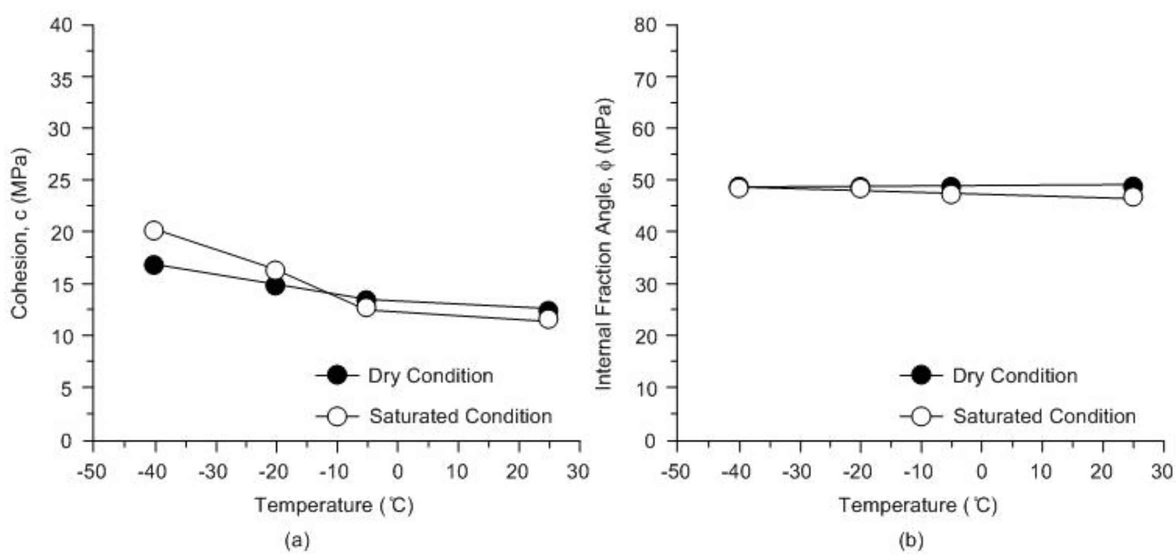

Figure 6 Cohesion and internal friction angle obtained from Coulomb criterion as a function of temperatures.

The Hoek-Brown criterion defines the relationship between the principal stresses associated with the failure of rock as:

$$\sigma_1 = \sigma_3 + (m\sigma_c\sigma_3 + s\sigma_c^2)^{1/2} \quad (2)$$

where *m* and *s* are material constants and σ_c is the uniaxial compressive strength of the intact rock. For intact rock specimens the "*s*" constants equal to 1. The results show that the "*m*" constants decrease with decreasing temperature and uniaxial compressive strength (σ_c) increase with decreasing temperature (Figure 7).

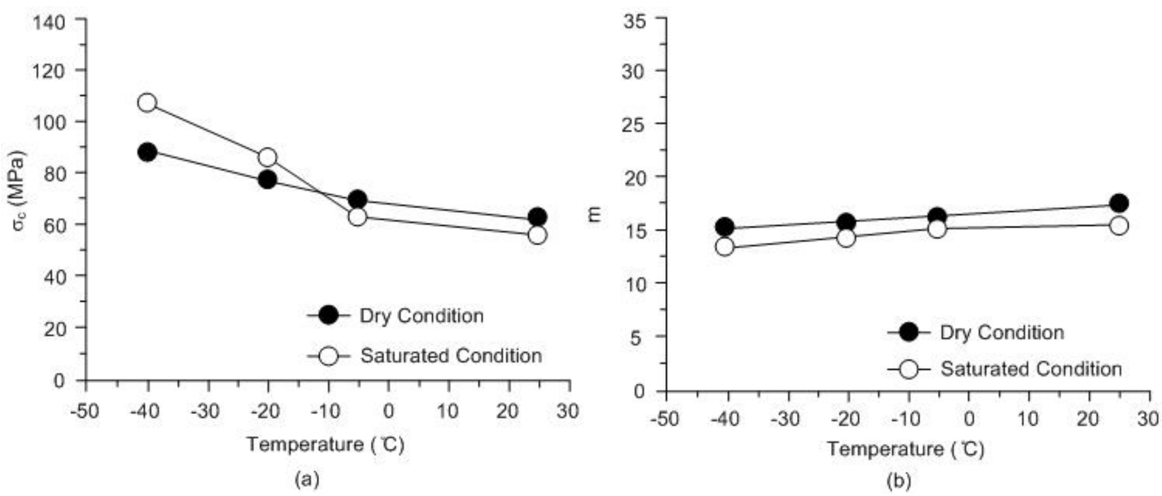

Figure 7 Uniaxial compressive strength (σ_c) and parameter "*m*" based on Hoek-Brown criterion plotted as a function of temperatures.

The regression analysis was performed to determine the strength parameters based on the Coulomb criterion and the Hoek-Brown criterion. The results used to assess their predictive capability in dry and saturated conditions. The predictive capability of these criteria was determined and compared using the coefficient of correlation (R^2) as an indicator. The calculated property parameters of each failure criterion are given in Table 3 and 4. Figure 8 compares the test results with curve fit by each strength criterion in the terms of σ_1 as a function of σ_3 at failure.

Table 3 Strength parameters based on Coulomb failure criterion calibrated form the test results.

Temperatures (°C)	*c* (MPa)		ϕ (degree)		R^2	
	Dry	Saturated	Dry	Saturated	Dry	Saturated
25	12.73	11.93	48.93	46.95	0.994	0.995
-5	13.77	13.06	48.86	47.41	0.978	0.985
-20	15.18	16.63	48.90	48.57	0.991	0.968
-40	17.17	20.49	48.93	48.64	0.998	0.931

Table 4 Strength parameters based on Hoek and Brown failure criterion calibrated form the test results.

Temperatures (°C)	σ_c (MPa)		m		s		R^2	
	Dry	Saturated	Dry	Saturated	Dry	Saturated	Dry	Saturated
25	63.60	56.69	20.18	17.81	1.00	1.00	0.989	0.991
-5	70.41	63.75	18.74	17.80			0.980	0.984
-20	78.18	86.66	18.15	16.54			0.999	0.987
-40	88.68	107.79	17.69	15.63			0.998	0.944

6. Deformation Modulus

The variation elastic modulus and the Poisson's ratio of the Phra Wihan sandstone with different confining pressures and temperatures under dry and saturated conditions have been presented in test results. There was just a little bit change in the shape of the curves with temperature for the saturated condition. In case of the dry conditions of sandstone specimens there was not difference in the elastic modulus at each temperature. The elastic modulus is increased with decreasing the temperature under saturated condition. At -5°C the elastic modulus of saturated specimens was lower than dry specimens suggest that in porous rock is almost ice filled have thin films of unfrozen water forming between ice and grain of rock. This process is occurring at temperatures in range -4 to -15°C [9]. Therefore, the pore pressure is affected on deformability of rocks is reflected as a reduction of elastic modulus. Poisson’s ratio obtained from this study ranged from 0.27 to 0.30 for the sandstone specimens under dry and saturated conditions. This indicates that Poisson’s ratio is independent of temperatures.

7. Influencing of Temperature on Effective Porosity

The freeze-thaw cycle was conducted to examine microstructure changes in rock specimens by measuring the inducing of the porosity. The change of the effective porosity after each set of cycles of freezing and thawing are represented in Figure 9. The water content of the specimen gives some influence to the porosity change. The reason of the increase in porosity may be mineral grains occurred shrinkage lead to expansion of pore water. This shrinkage of rock matrix accompanied by dilation of pore spaces results in micro crack formation and the material is not return to original state after thermal unloading [10].

8. Discussions and Conclusions

Series of compression tests were performed to determine the strength and deformability of Phra Wihan sandstone specimens using difference confining pressure and subzero temperatures under dry and saturated conditions. The testing was assumed to be under isothermal conditions (constant temperature with time during loading). It was found that the compressive strength increase with increasing confining pressure and inversely with temperatures. At -5 and 25°C, the strength for saturated sandstone samples is lower than that of the strength for dry samples. However, at subzero temperatures (-20 and -40°C) the strength of saturated samples is greater than that of the dry ones due to the conversion of the water in the pores to ice. This agree with the experimental

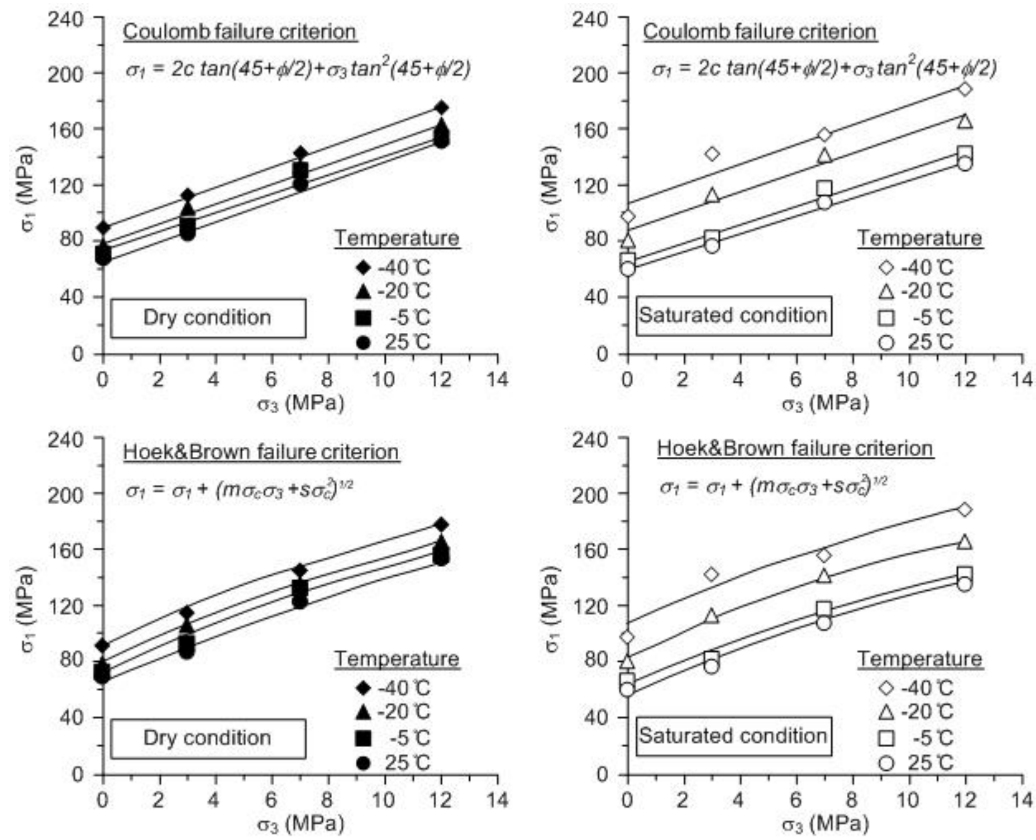

Figure 8 Test results (point) with cure fit (solid line) for each strength criteria.

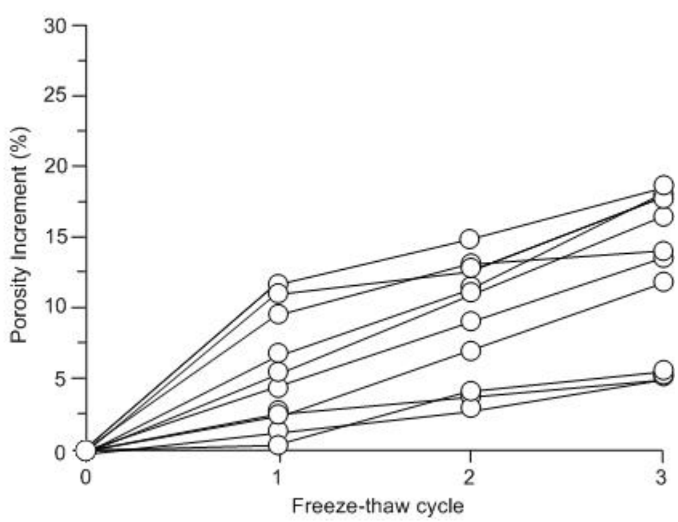

Figure 9 Porosity increment caused by freezing and thawing.

results obtained by Inada and Kinoshita [11] and Hara [12]. This indicated that the influence of temperature on the saturated samples was greater than the dry ones. The tensile strength increased with decreasing temperature. At the temperature below -20 °C, the tensile strength of saturated specimen is greater than that of the dry specimen. The reason of this phenomenon is that pore-water changes into ice when the temperature dropped to subzero. Therefore, it can be said that ice is also acted an adhesive material with contributed to increase the strength of sandstone. The two strength criteria used here give a good estimation of the specimen compressive strength. The Coulomb criterion can describe the cohesion and internal friction angle from the strength results for each temperature. At the subzero temperature, the effect of temperature is more evidently affect the cohesion than the internal friction angle for both dry and saturated conditions. Cohesion parameter of the saturated specimens are greater than the dry specimens. It can be describing from this study that the ice content is an adhesive material in rock. The Hock-Brown criterion can sufficiently predict the strength of sandstone specimen as well. The Hoek and Brown criterion uses only two material constants (m and s), the parameter "s" for intact sandstone specimens is equal 1.00. The parameters "m" for specimens decrease with subzero temperature. The calculated uniaxial compressive strengths of the rock specimens (σ_c) increase with decreasing temperature. For the deformation modulus of rock specimens are determined from the stress-strain curves at about 50% of the failure stress. The elastic modulus of saturated specimen was higher than that of dry specimens at subzero temperature. The saturated specimens have been subjected to the influence of ice in porous media of rock. The Poisson's ratios of saturated specimens and dry specimens show no significant difference. This result suggested that the temperatures will not effected on Poisson's ratio. The specimens subjected to the number of freezing-throwing cycle (-20°C to +100°C) lead to increases of the porosity. It is observed that the damage of the specimen is due to the repeat of expansion and shrinkage of its mineral component under difference thermal condition. The number of cycles of temperature changes (freezing and thawing cycle) increase with increment of the effective porosity. The different thermal conditions not only created the micro-cracks inside the rock but also changed its mechanical properties.

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References

[1] Suwanich, P., Geology and Geological Structure of Potash and Rock Salt Deposits in Chalerm Phrakiat District, Nakhon Ratchasima Province in Northeastern Thailand, *Kasetsart Journal (Natural Science)*, 2010, 44 (6), pp. 1058 – 1068.

[2] Farazi, A. H. and Quamruzzaman, C., Structural Design of Frozen Ground Works for Shaft Sinking by Practicing Artificial Ground Freezing (AGF) Method in Khalashpir Coal Field, *The International Journal of Engineering and Science (IJES),* 2013, 2 (3), pp. 69-74.

[3] Phueakphum, D. *Experimental assessment of solar thermal energy storage in basaltic rock fill.* PhD Thesis, Suranaree University of Technology. Nakhon Ratchasima, 2008.

[4] ASTM International, ASTM D7012: 2014, *Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures.* West Conshohocken: ASTM International, 2014.

[5] ASTM International, ASTM D2664: 2004, *Standard Test Method for Triaxial Compressive Strength of Undrained Rock Core Specimens without Pore Pressure Measurements.* West Conshohocken: ASTM International, 2004.

[6] ASTM International, ASTM D3967: 2016, *Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens*. West Conshohocken: ASTM International, 2016.

[7] Hoek, E. and Brown, E. T. (ed.) *Underground excavations in rock,* London: Institution of Mining and Metallurgy, 1990.

[8] Jaeger, J. C.*et al.* (ed.) *Fundamentals of Rock Mechanics,* 4th ed. Oxford: Blackwell Publishing, 2007.

[9] Vlahou, I. and Worster, M. G. Freeze fracturing of elastic porous media: a mathematical model. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 2015, 471 (2175), pp. 1-20.

[10] Yamabe, T. and Neupane, K. Determination of some thermo-mechanical properties of Shirahama sandstone under subzero temperature condition. *International Journal of Rock Mechanic and Mining Sciences,* 2001, 38 (7), pp. 1029-1034.

[11] Inada, Y. and Kinoshita, N. A few remarks on storage of low temperature materials in rock caverns. In: *Proc. of 10th International Society for Rock Mechanics Congress (ISRM): Technology Roadmap for Rock mechanics,* South African Inst. of Min. and Metall., 8-12 September 2003, pp. 211–220.

[12] Hara, S. *et al.* Uniaxial compressive strength of Shikotsu Welded Tuff and Bibai Sandstone at sub-zero temperature. In: *ISRM International Symposium - 8th Asian Rock Mechanics Symposium,* Sapporo, 14-16 October 2014, pp. 21–28.