



WEATHERING SIMULATION OF FOUR THAI SANDSTONES UNDER DRY, WET AND ACIDIC CONDITIONS

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บทคัดย่อ

การจำลองการกัดกร่อนของหินทราย 4 ชนิด ได้ถูกดำเนินการโดยนำตัวอย่างหินมาเผชิญกับวัฏจักรร้อน-เย็น เป็นจำนวน 300 รอบ สภาวะเย็น 3 ลักษณะ ได้ถูกออกแบบขึ้นสำหรับตัวอย่างหิน 3 ชุด ที่เตรียมจากหินทรายแต่ละชนิด ได้แก่ การปล่อยให้เย็นที่ อุณหภูมิห้อง การจุ่มลงในน้ำกลั่น และการจุ่มลงในกรดซัลฟิวริก (มีค่าความเป็นกรดเท่ากับ 5.6) ผลที่ได้ระบุว่าหินทรายทุกชนิดไม่ อ่อนไหวต่อสภาวะร้อน-เย็นแบบแห้ง อย่างไรก็ตาม หินทรายเหล่านี้อ่อนไหวอย่างมากต่อน้ำและกรด การทำให้ตัวอย่างหินเย็นโดย ฉับพลันในของเหลวจะทำให้เกิดรอยแตกเล็ก ๆ ในวัสดุเชื่อมประสานของหิน ซึ่งต่อมากจะทำหน้าที่เป็นช่องเปิดให้ของเหลวซึมลึก ลงไปในตัวอย่างหิน เมื่อวัสดุเชื่อมประสานของหินทรายถูกละลายด้วยของเหลว ส่งผลให้ความหนาแน่น ความแข็ง และความ เหนียวของหินทรายมีค่าลดลงเมื่อจำนวนรอบของวัฏจักรการจำลองเพิ่มขึ้น ผลที่ได้จากการศึกษานี้จะเป็นประโยชน์ในการคัดสรร และการนำไปประยุกต์ใช้ของหินทรายเหล่านี้ในอุตสาหกรรมหินก่อสร้างและหินประดับ

ABSTRACT

Weathering simulations have been performed on four sandstone types by subjecting them up to 300 heating-cooling cycles. Three cooling conditions are imposed on three separate sets of specimens prepared from each sandstone type: air-cooling, submerging in distilled water and in sulfuric acid (pH = 5.6). Results indicate that all sandstones are insensitive to heating-dry cooling cycles. They are however highly sensitive to water and particularly to acid. Such rapid cooling in liquid induces micro-cracks in the cementing materials, which become preferential paths allowing liquid to penetrate deeper into the specimens. As the cementing materials are dissolved by the liquids, the sandstone density, strength and stiffness decrease as the simulation cycles increase. The findings can be useful for the selection criteria and application of these sandstones in the construction and decoration industry.

KEYWORDS: Weathering; Sandstone; Strength; Elastic Modulus; Density

1. Introduction

Sandstone is used in heritage buildings due to the high degree of cementation and its local availability [1]. Seasonal changes in groundwater level and humidity can lead to cyclic actions of wetting and drying and accelerate the weathering process of the rocks, which over the years would eventually result in deterioration and even damage [2]. Even though the influence of weathering

processes on the physical and mechanical properties of rocks has been studied by many researchers [3-6], an attempt at investigating their long-term durability has rarely been addressed. Such relatively short-term testing above may not be sufficient to distinguish some rocks with similar strengths and compositions, and in particularly to determine their long-term durability under different environmental conditions.

The objective of this study is to simulate the effect of weathering on the physical, mechanical and mineralogical properties of four sandstones commonly used in construction and decorating industry in southeast Asia. The simulation is made under 300 heating and cooling cycles. Three separate sets of specimens are cooled under three different conditions: dry, wet and acidic conditions. For every 100 cycles, the physical, mechanical and mineralogical properties of the specimens are determined.

2. Sample preparation and test methods

Rock samples belong to Phu Kradung, Phra Wihan, Sao Khua and Phu Phan sandstone formations. The collected sandstone blocks are cut and ground to obtain prismatic specimens with nominal dimensions of $35 \times 35 \times 152 \text{ mm}^3$. Ten specimens are prepared for each sandstone type.

Figure 1 shows the heating-cooling cycles to simulate the weathering environment for the sandstones. The specimens for each sandstone type are separated into three sets. Nine specimens are used for each set. They are subjected to oven-heating at $105 \pm 5 \text{ }^\circ\text{C}$ for 12 hrs. Then, three specimens are air-cooled at $25 \pm 2 \text{ }^\circ\text{C}$ for 12 hrs. Three specimens are cooled by submerging in distilled water for 12 hrs. And the last three are submerged in sulfuric acid (with pH = 5.6) for 12 hrs. This acidic condition follows the annual precipitation in southeast Asia monitored by EANET [7] from 2010 to 2014. The entire process is repeated for 300 cycles (300 days). Every 100 cycles, one specimen of each set is taken out of the test cycles. The rest of the specimens continues to subject to test cycles.

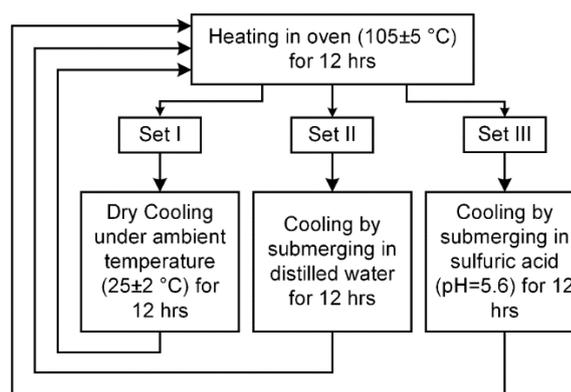


Figure 1 Heating-cooling cycles for three sets of specimens under 300 cycles

The specimens that have been taken out every 100 cycles are subjected to physical, mechanical and mineralogical testing and compared with those of the initial condition (without subjecting to test cycle), of which test methods can be summarized below.

The density of the prismatic sandstone specimens is first determined based on the ASTM C127-15 [8] standard practice. The method involves weighting the specimen in the air and in distilled water.

Then, the specimens are subjected to three-point-bending test (ASTM C293-16 [9]) to determine their bending tensile strength. A strain gage is installed at the incipient crack initiation point. Its readings can provide tensile strains which can be later used to determine tensile deformation (elastic) modulus before failure occurs.

After the specimens are spitted into 2 pieces, one is cut to obtain flat ends with nominal dimensions of $35 \times 35 \times 70$ mm³. They are subjected to uniaxial loading to obtain their unconfined compressive strength and elastic modulus. The test procedure and calculation are in accordance with the ASTM D7012-14 [10] standard practice. High-precision dial gages are used to measure axial and lateral deformations, and hence the Poisson's ratios can also be determined.

The other half of the prismatic specimens after subjecting to the three-point bending test, is ground to obtain powder with particle sizes of less than 0.25 mm (mesh #60). The powder specimen is used to determine mineral compositions by X-ray diffraction (XRD) analysis.

3. Test results

Figure 2 shows the rock densities for all cooling conditions up to 300 test cycles. All sandstone types tend to be durable under heating-air cooling cycles. Water and acid can notably reduce the rock density. This may be due to that these liquids can dissolve the cementing materials of the sandstones, and hence increases their pore spaces (porosity). Rock specimens that are cooled by submerging in acid show lower densities than those in distilled water. All sandstone types pose similar reduction of the density as the number of test cycles (N) increases.

The effects of water and acid clearly show on the compressive and tensile strengths of the four sandstones, as shown in Figure 3. After 300 test cycles, the strength reduction is about 30-50% of the initial values. Under air-cooled (dry) conditions, the compressive and tensile strengths for the four sandstones tend to be unchanged.

Submerging in acid can reduce the rock strengths more than submerging in water. Sao Khua sandstone is highly sensitive to water and acid. After 100 cycles under acid cooling and 200 cycles under water cooling the specimens disintegrated along the bedding planes, and hence the compression testing can not be performed.

Similar to the strength reduction above, the effects of cooling by water and acid on the compressive and tensile elastic moduli of the sandstones can be clearly seen (Figure 4). The reduction of rock elastic moduli as the number of test cycles increase is more significant for the specimens that are cooled in acid than those in water. No significant change of the compressive and tensile elastic moduli has been observed for the specimens that subject to air-cooled (dry) condition.

Submerging in liquids to cool the specimens also increases their Poisson's ratios, as indicated in Figure 5. The Poisson's ratio is determined by the ratio of lateral expansion-to-axial contraction during axial loading of the uniaxial compression test. For all sandstone types, the Poisson's ratio increases with the test cycles. Slight increase is observed when the specimens are air-cooled (dry condition). Specimens that are submerged in acid laterally dilate more than those in water.

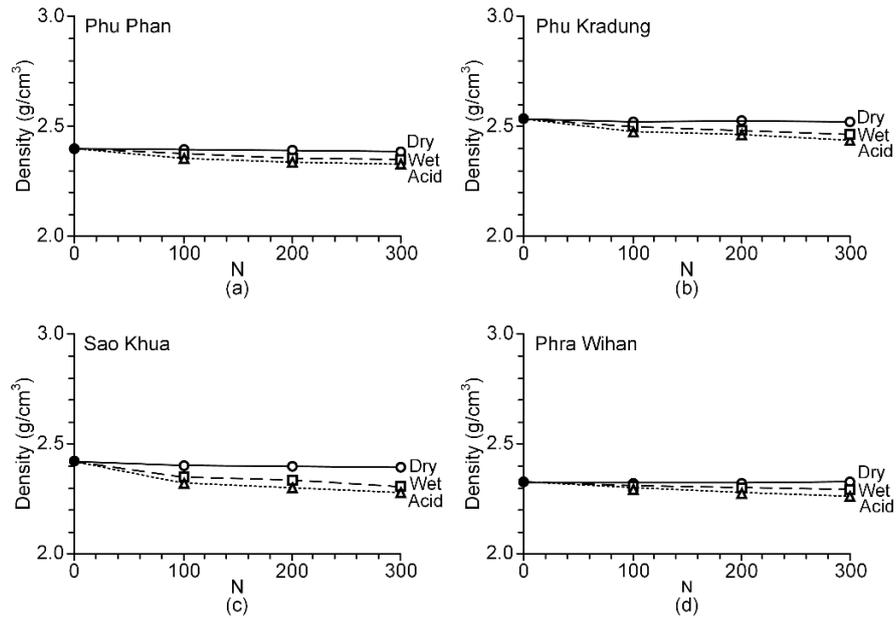


Figure 2 Density as a function of number of cycles (N) for Phu Phan (a), Phu Kradung (b), Sao Khua (c), and Phra Wihan (d) sandstones

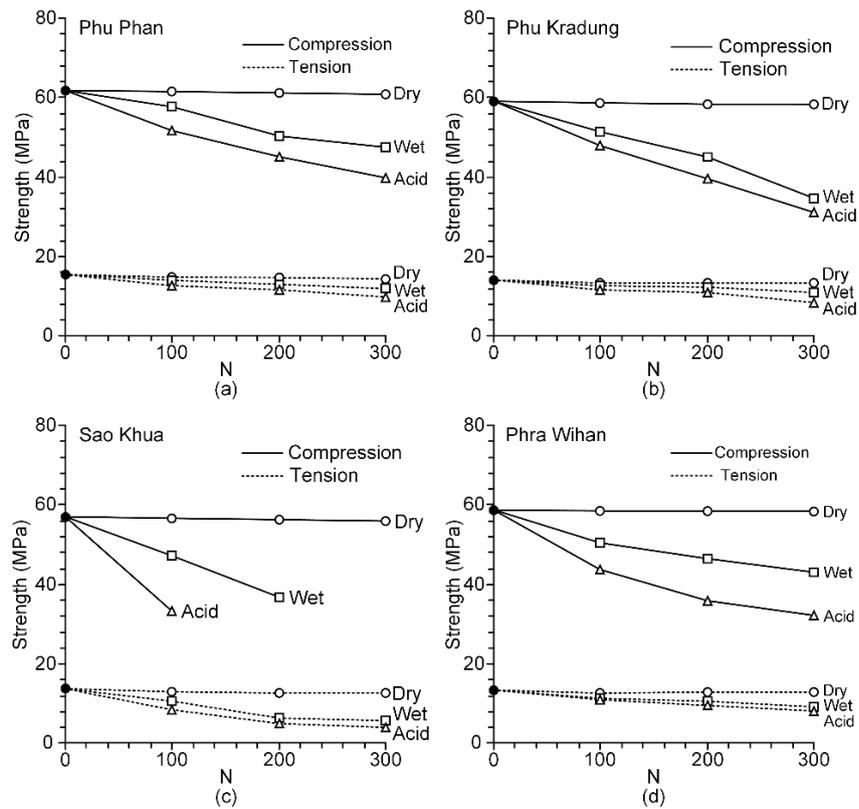


Figure 3 Compressive and tensile strengths as a function of number of cycles (N) for Phu Phan (a), Phu Kradung (b), Sao Khua (c), and Phra Wihan (d) sandstones

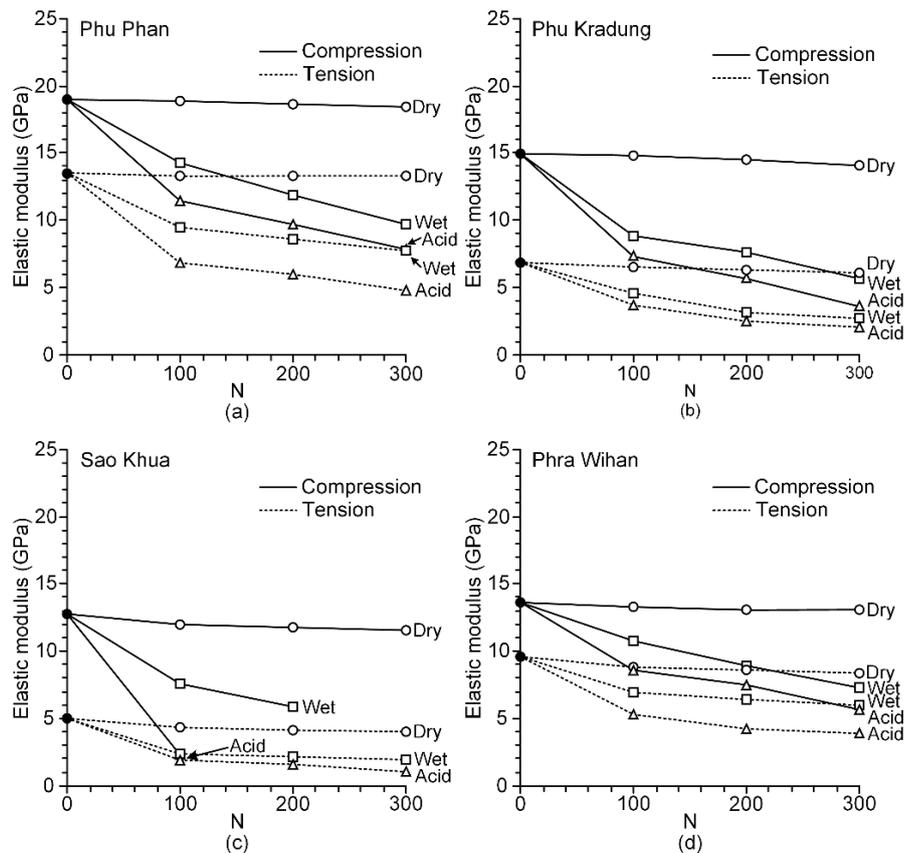


Figure 4 Elastic moduli as a function of number of cycles (N) for Phu Phan (a), Phu Kradung (b), Sao Khua (c), and Phra Wihan (d) sandstones

Forty specimens have been prepared and analyzed by XRD to determine their mineral compositions in weight percent. Table 1 gives the results. Quartz represents the largest percentages for all sandstone types under all test cycles and conditions. The rest of the minerals represent cementing materials of the rocks. Direct comparison of the mineral contents among different test conditions and cycles is difficult. The ratios of quartz-to-cementing material (called here as equivalent quartz content) are, therefore, proposed. They are plotted as a function of test cycles in Figure 6. For all sandstone types, the equivalent quartz content (Q_e) increases with the test cycles, particularly those that are submerged in acid. Slight increase has been observed for those that are cooled under dry condition. This supports the previous postulation that cooling the sandstone specimens in liquid can dissolve their cementing materials which results in an increase of their porosity (density decrease).

4. Discussions and conclusions

Admittedly the number of test specimens used here tend to be limited: one for each sandstone type and cooling condition. This is primarily due to the limited oven space and project duration (10 months). The test results, nevertheless, tend to show clear trends of rock deterioration in the forms of the reduction of physical and mechanical properties. The designed test cycles

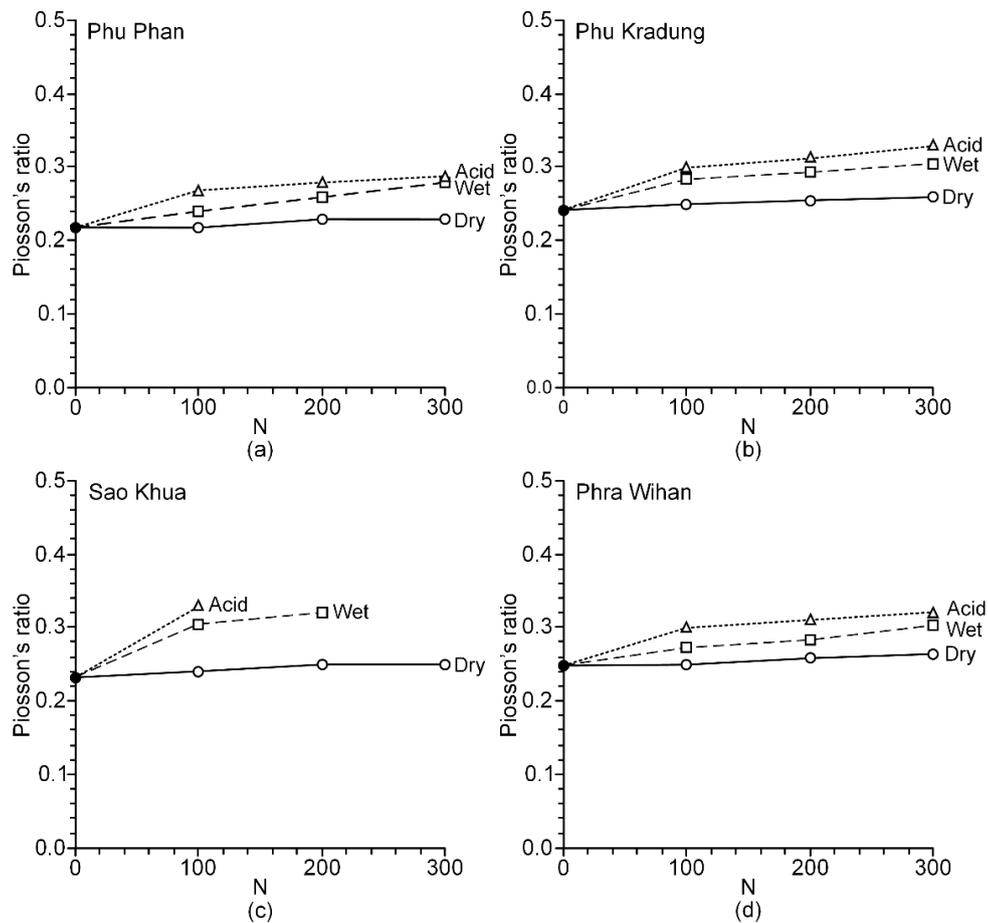


Figure 5 Poisson's ratio as a function of number of test cycles (N) for Phu Phan (a), Phu Kradung (b), Sao Khua (c), and Phra Wihan (d) sandstones

are aimed at accelerating and enhancing the weathering process, and hence reveals the long-term responses of the test sandstones in terms of density, strength, elastic modulus and mineral compositions.

Correlation between the test duration (300 days) with those of the actual duration under in-situ condition may not be possible at this point. This is due to the fact that the sandstone specimens are subjected to the temperature up to 105 °C (during 12 hrs. of heating) and immediately (2-3 minutes) cooled by submerging in the water or acid. This temperature is significantly higher than those occur naturally in southeast Asia. It is postulated that the rapid cooling by submerging in liquid may induce micro-cracks in the rock matrix. These cracks can propagate deeper and eventually becomes preferential flow paths allowing the liquid, particularly acid, to further dissolve the cementing materials. This could explain why the rock density becomes lower as the test cycles increase. The increase of the sandstone porosity and micro-cracks with the test cycles cause the decrease of strength and stiffness of the sandstones. Under dry condition, all sandstones tend to be insensitive to heating (up to 105 °C) and slow cooling under ambient temperature. The results obtained here agree reasonably with those of Sun and Zhang [1] and Zhou et al. [2] who investigate the physical and mechanical properties of sandstones under wetting and drying cycles.

Table 1 Mineral compositions of sandstone specimens

Rock type	Conditions	Number of cycles	Mineral compositions (%)								
			Quartz	Kaolinite	Muscovite	Albite	Anorthite	Microcline	Calcite	Oligoclase	Chlorite
Phu Phan	Initial	0	84.94	2.94	3.89	1.55	0.00	1.20	0.03	0.00	5.45
	Dry	100	85.18	1.68	3.37	0.25	1.27	0.62	0.04	0.89	6.70
		200	85.66	8.94	1.89	0.21	0.72	1.46	0.04	0.00	1.08
		300	85.75	6.45	0.92	2.23	0.04	0.00	0.07	0.00	4.16
	Wet	100	86.75	6.02	1.37	0.40	0.82	1.91	0.00	0.00	2.66
		200	86.93	2.56	4.12	0.09	0.10	1.24	0.41	0.00	4.96
		300	87.32	5.12	2.27	1.47	0.23	0.76	0.07	0.00	2.42
	Acid	100	88.32	3.41	2.66	0.02	1.92	0.09	0.00	0.00	1.37
		200	88.77	4.34	2.35	1.21	0.13	0.55	0.05	0.06	2.12
		300	88.95	1.11	3.74	0.65	0.11	0.07	0.16	0.00	4.34
Phu Kradung	Initial	0	35.15	2.94	9.36	22.17	2.89	4.69	0.26	13.03	9.51
	Dry	100	35.34	1.00	6.59	5.46	5.70	2.50	1.60	27.35	14.46
		200	36.20	5.50	2.13	20.63	10.43	6.05	1.30	3.33	14.43
		300	37.23	3.92	7.45	23.52	5.56	10.51	0.00	2.61	9.20
	Wet	100	37.65	3.82	6.33	25.20	6.81	7.21	0.76	1.33	10.89
		200	40.16	1.11	4.47	29.10	2.65	4.58	0.87	1.05	16.01
		300	40.37	6.69	2.45	21.11	1.03	8.75	0.15	4.82	14.63
	Acid	100	40.95	1.25	1.25	33.80	1.07	5.70	0.32	2.60	1.77
		200	40.97	7.11	7.11	23.08	0.92	10.59	0.06	2.46	13.73
		300	45.71	3.03	3.03	18.67	7.46	10.14	0.71	0.78	12.77
Sao Khua	Initial	0	34.17	3.07	11.01	33.26	3.52	4.56	0.17	2.66	7.58
	Dry	100	37.23	3.92	7.45	23.52	5.56	10.51	0.00	2.62	9.19
		200	37.29	0.45	7.84	30.52	3.65	9.60	0.10	5.26	5.29
		300	37.63	0.48	8.43	30.43	4.72	11.42	0.49	2.21	4.19
	Wet	100	38.34	0.26	10.84	25.05	8.84	8.13	0.00	2.73	5.81
		200	38.47	0.52	11.64	26.74	4.23	8.72	0.00	4.09	5.59
		300	38.69	0.70	10.57	29.91	1.86	9.25	0.03	4.32	4.67
	Acid	100	38.76	0.58	10.17	30.89	2.08	6.88	0.30	4.56	5.78
		200	42.19	2.06	5.77	35.80	1.62	3.56	0.00	3.53	5.47
		300	42.40	2.59	8.94	27.06	3.43	9.39	0.20	2.04	3.95
Phra Wihan	Initial	0	82.84	3.41	3.44	0.79	1.07	3.31	0.31	0.00	4.83
	Dry	100	84.48	11.32	0.24	2.25	0.28	0.73	0.05	0.00	0.65
		200	84.93	3.19	1.54	0.00	2.47	2.81	0.10	0.00	4.96
		300	85.30	2.62	3.94	0.40	0.94	1.53	0.05	0.00	5.22
	Wet	100	86.88	2.97	2.84	0.02	2.02	1.51	0.04	0.00	3.72
		200	87.34	2.77	1.92	0.85	2.30	1.66	0.54	0.00	2.62
		300	88.98	2.20	2.81	0.68	1.78	0.69	0.06	0.00	2.80
	Acid	100	89.01	8.74	0.20	1.28	0.15	0.18	0.05	0.04	0.35
		200	90.57	1.45	1.60	0.00	3.38	1.08	0.11	0.00	1.81
		300	91.49	1.86	2.49	0.36	1.24	0.32	0.06	0.02	2.16

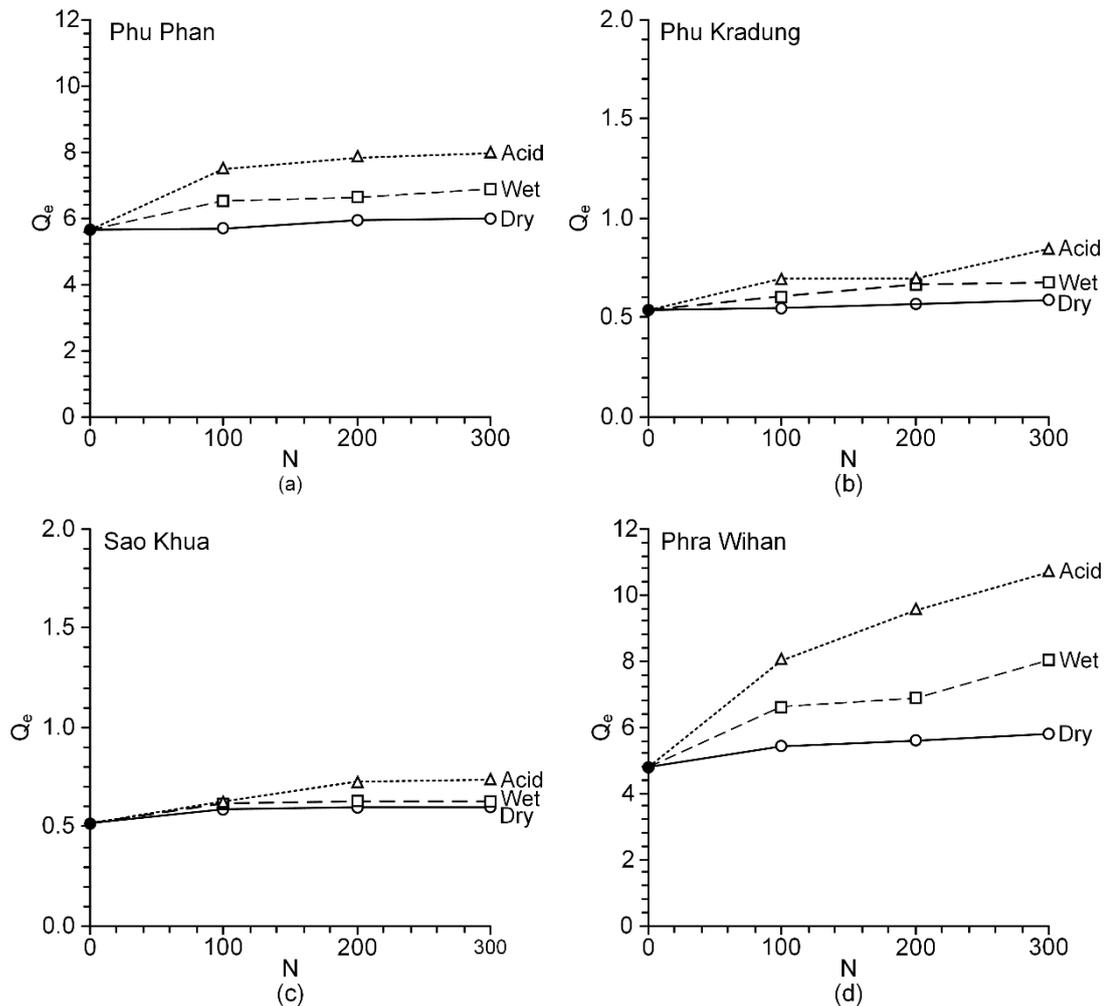


Figure 6 Equivalent quartz content (Q_e) as a function of number of test cycles (N) for Phu Phan (a), Phu Kradung (b), Sao Khua. (c), and Phra Wihan (d) sandstones

It is recognized that the sandstone formations from which the specimens are obtained show significant variations in terms of their mineral compositions from varying locations (DMR [11]). The mineral compositions of the test specimens determined here however can be useful to understand or compare the sandstone properties and durability under different environments.

Results from this study can be used for the selection criteria of sandstone type and the application of these sandstones under appropriate environments and locations. The conclusions from our study can be drawn as follows:

- All sandstones tend to be durable under dry condition even they are cyclically subjected to heating up to 105 °C for 300 cycles.
- Water and particularly acid can cause significant increase of sandstone porosity, and hence reduces their density. Sao Khua sandstone is highly sensitive to liquids, compared to the other three sandstones.

- Micro-cracks induced by heating and relatively rapid cooling can propagate deeper in to the rock matrix as the test cycles increase. They become preferential paths allowing the liquid to penetrate farther.
- As evidenced by the increase of equivalent quartz content (Figure 6), the sandstones lose more cementing materials than quartz gains as the test cycles increase. The cementing materials can be dissolved more easily than quartz grains.
- The loss of cementing materials means that the sandstones lose cohesive bonding which leads to the reductions of compressive and tensile strengths and of the compressive and tensile elastic moduli. When the rocks become more porous, they can laterally dilate more under axial loading, and hence their Poisson's ratio increases with the test cycles.

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References

- [1] Sun, Q. and Zhang, Y. Combined effects of salt, cyclic wetting and drying cycles on the physical and mechanical properties of sandstone. *Engineering geology*, 2019, 248, pp. 70-79.
- [2] Zhou, Z. *et al.* Influence of cyclic wetting and drying on physical and dynamic compressive properties of sandstone. *Engineering geology*, 2017, 220, pp. 1-12.
- [3] Pardini, G. *et al.* Structure and porosity of smectitic mudrocks as affected by experimental wetting-drying cycles and freezing-thawing cycles. *Catena*, 1996, 27(3-4), pp. 149-165.
- [4] Sumner, P. D. and Loubser, M. J. Experimental sandstone weathering using different wetting and drying moisture amplitudes. *Earth Surface Processes and Landforms: Journal of the British Geomorphological Research Group*, 2008, 33(6), pp. 985-990.
- [5] Özbek, A. Investigation of the effects of wetting-drying and freezing-thawing cycles on some physical and mechanical properties of selected ignimbrites. *Bulletin of Engineering Geology and the Environment*, 2014, 73(2), pp. 595-609.
- [6] Khanlari, G. and Abdilor, Y. Influence of wet-dry, freeze-thaw, and heat-cool cycles on the physical and mechanical properties of Upper Red sandstones in central Iran. *Bulletin of Engineering Geology and the Environment*, 2015, 74(4), pp. 1287-1300.
- [7] Lee, S. *The third periodic report on the state of acid deposition in east Asia, Part II National Assessments. Acid deposition monitoring network in east Asia*, Niigata-shi, Japan, 2016.
- [8] American Society for Testing and Materials. ASTM C127-15. *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*. ASTM International, West Conshohocken, PA, 2015.
- [9] American Society for Testing and Materials. ASTM C293 / C293M-16. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading)*. ASTM International, West Conshohocken, PA, 2016.
- [10] American Society for Testing and Materials. ASTM D7012-14e1. *Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures*. ASTM International, West Conshohocken, PA, 2014.
- [11] Department of Mineral Resources. *Geology of Thailand*. Department of Mineral Resources, Ministry of Industry, Bangkok, Thailand (in Thai), 2001.

