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EFFECTS OF TRANSVERSE ISOTROPY ON COMPRESSIVE STRENGTH AND ELASTIC PROPERTIES OF ROCK SALT

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บทคัดย่อ

การทดสอบแรงกดแบบแกนเดียวและแบบสามแกนได้ถูกดำเนินการเพื่อหาผลกระทบของทรานเวอร์สลีไอโซโทรปิกต่อกำลังกดและการเปลี่ยนแปลงรูปร่างของตัวอย่างเกลือหินที่มีการวางตัวของระนาบชั้นหินแตกต่างกันภายใต้ความดันล้อมรอบมากถึง 15 เมกะปาสคาล ผลที่ได้ระบุว่า กำลังรับแรงกดมีค่าสูงสุดเมื่อแรงกดมีทิศทางตั้งฉากกับระนาบของชั้นหิน และจะมีกำลังรับแรงต่ำสุดเมื่อแรงกดมีทำมุม 60 องศา กับทิศทางของแรงที่ตั้งฉากกับระนาบของชั้นหิน โดยเฉพาะอย่างยิ่งภายใต้แรงดันล้อมรอบต่ำ ผลกระทบของทรานเวอร์สลีไอโซโทรปิกจะลดลงเมื่อตัวอย่างเกลือหินอยู่ภายใต้แรงดันล้อมรอบที่สูงขึ้น ตัวอย่างเกลือหินมีแนวโน้มที่จะกลายเป็นวัสดุไอโซโทรปิก เนื่องจากเกลือหินมีคุณสมบัติในการเชื่อมประสานตัวเองภายใต้ความดันล้อมรอบ สูง ส่งผลให้มีพฤติกรรมแบบแอนิโซทรอปิกลดลง

ABSTRACT

Uniaxial and triaxial compression tests have been performed to determine the transversely isotropic effect on strength and deformation of rock salt specimens with different bedding plane orientations under confining pressures up to 15 MPa. The results indicate that the compressive strength is maximum when loading is perpendicular to the bedding (anisotropic) planes. The minimum strength occurs when normal to the bedding planes makes an angle of 60 degrees with the loading direction, especially under lower confining pressures. The effect of transversely isotropy decreases when salt is subjected to higher confining pressures where the salt tends to behave as an isotropic material. This is probably because the salt specimens have ability of self-healing under confinement, and hence decreases their anisotropic behavior.

KEYWORDS: Anisotropy; Bedding plane; Elastic modulus; Compressive strength

1. Introduction

The deformation and strength properties are important parameters for design and stability analysis of support pillars in salt mines [1]. Rock salt exhibits anisotropic characteristics [2] in terms of strength and deformational properties and are generally considered to be transversely isotropic materials due to the existence of bedding planes. The true understanding of the transversely isotropic behavior of rock salt is therefore needed for the salt mine design and operation, particularly where excavation intersect flanks of salt folds. The objective of this study is to determine the effects of transverse isotropy on the compressive strength and elastic properties of Maha Sarakham salt. The tasks involve preforming uniaxial and triaxial compression tests on rock salt, developing a strength criterion that can incorporate the transversely isotropic effect, and determining the elastic properties of salt as affected by bedding plane orientations.

2. Sample preparation and test procedure

Salt blocks (0.5×0.5×1.0 m3) are collected from an underground mine opening of Thai Kali Co., Ltd. They belong to the Lower Salt member of the Maha Sarakham formation. The specimens are virtually pure halite with slight amount of clay and anhydrite inclusions (less than 1%). The average density is 2.16 ± 0.09 g/cm3. The salt blocks are dry-cut to obtain rectangular specimens with nominal dimensions of 54×54×108 mm^3. Twenty-six specimens have been prepared. They contain different bedding plane orientations. The angles between the major axis and the normal to bedding planes (β) vary from 0, 25, 45, 60 to 90 degrees (Figure 1). Sample preparation is made such that, the bedding plane strike is parallel to one of the specimen sides.

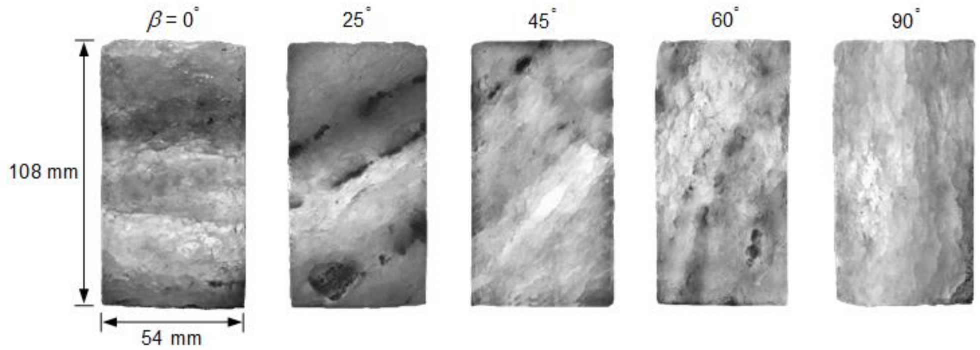

Figure 1 Examples of specimens prepared for uniaxial compression test

A polyaxial load frame [3] has been used to apply lateral and axial stresses to the salt specimens. Except for the specimen geometry, the test procedure and calculation follow the ASTM D7012-14e1 [4] standard practice. The constant and uniform lateral stresses ($\sigma_2 = \sigma_3$) range from 0 to 15 MPa. Neoprene sheets are used to minimize the friction at all interfaces between the loading platens and the rock surfaces. The axial stress is increased at the rate of 0.1 MPa/s until failure occurs. The specimen deformations are monitored along the three loading directions and are used to calculate the principal strains during loading.

The elastic moduli along the major principal (axial) direction (E_1) and along the two minor principal axes that are normal (E_{3O}) and parallel (E_{3P}) to bedding planes can be calculated using an elastic solution modified from those of Jaeger et al. [5] as follows:

$$\varepsilon_1 = \sigma_1/E_1 - (\nu_{1,3P}\,\sigma_{3P})/E_{3P} - (\nu_{1,3O}\,\sigma_{3O})/E_{3O} \quad (1)$$

$$\varepsilon_{3P} = -(\nu_{1,3P}\,\sigma_1)/E_1 + \sigma_{3P}/E_{3P} - (\nu_{3P,3O}\,\sigma_{3O})/E_{3O} \quad (2)$$

$$\varepsilon_{3O} = -(\nu_{1,3O}\,\sigma_1)/E_1 - (\nu_{3P,3O}\,\sigma_{3P})/E_{3P} + \sigma_{3O}/E_{3O} \quad (3)$$

where σ_1 is the major principal stress, σ_{3P} and σ_{3O} are the minor principal stress that are parallel and normal to the strike of the bedding planes, ε_1 is the major principal strain, ε_{3P} and ε_{3O} are the minor principal strains measured parallel and normal to the strike of bedding planes, $\nu_{1,3P}$ and $\nu_{1,3O}$ are Poisson's ratios between major principal axis and the directions that are parallel and normal to the strike of bedding plane, and $\nu_{3P,3O}$ is Poisson's ratio between the directions that are parallel and normal to strike of bedding planes. The transverse elastic moduli and Poisson's ratios under triaxial stress can be calculated only for the conditions where β = 0 and 90 degrees, primarily because beyond these conditions the unknows are more than the number of equations, and hence the equations above are indeterminate.

3. Test results

Figure 2 shows examples of some post-test specimens. The failure stresses and the calculated elastic properties are summarized in Table 1. Figure 3 shows the stress–strain curves monitored from the test specimens under various confining pressures and bedding plane orientations. The effect of transverse isotropy on lateral strain can be clearly observed, particularly when β approaches 90°. Figure 4 presents the failure stresses as a function of angle β. The variation of strengths with angle β shows U-shaped anisotropic curve where the strength is maximum when loading is perpendicular to the bedding (anisotropic) plane and minimum when β equals to 60 degrees.

To incorporate the effect of angle β into the failure stresses, the Hoek–Brown criterion [6] is used to describe the relationship between the major (σ_1) and minor (σ_3) principal stresses at failure as:

$$\sigma_1 = \sigma_3 + (\mathrm{m}\sigma_c\sigma_3 + \mathrm{s}\sigma_c^2)^{1/2} \tag{4}$$

where σ_c is the uniaxial compressive strength, and m and s are material constants. The constant m depends on the strength of rock, and s = 1 for intact rock. Figure 5 shows the Hoek-Brown failure envelopes for different bedding plane orientations. The results indicate that salt strengths increase with increasing confining pressure. The minimum compressive strength is obtained for β = 60 degrees. The greatest strength is obtained under β = 0. The constant m varies with the bedding plane orientations. The transversely isotropic effect decreases when the salt specimens are subjected to higher confining pressures. Extrapolation of the failure envelopes suggests that under about 30 MPa the salt property approaches isotropic condition.

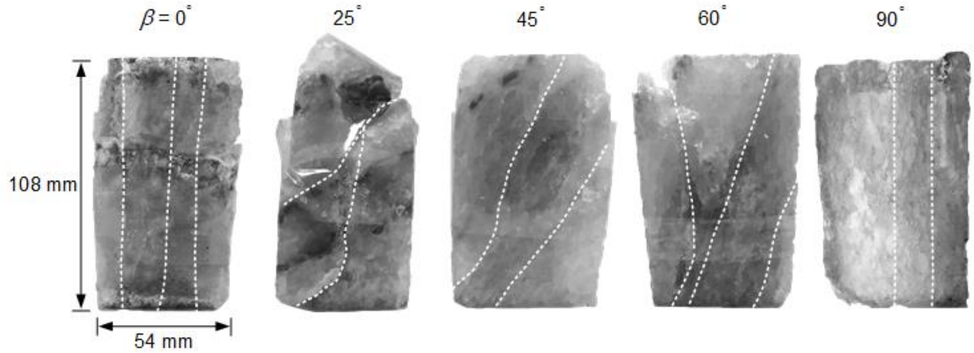

Figure 2 Some post-test specimens of uniaxial compression test. White lines indicate induced fractures

Table 1 Compression test results

Orientation	$\sigma_{3P} = \sigma_{3O}$ (MPa)	$\sigma_{1,f}$ (MPa)	E_1 (GPa)	E_{3P} (GPa)	E_{3O} (GPa)	$\nu_{1,3P}$	$\nu_{1,3O}$	$\nu_{3P,3O}$
$\beta = 0°$	0	25.1	1.35	2.40	2.40	0.35	0.35	0.32
	2	43.1	1.46	2.42	2.42	0.35	0.35	0.32
	3	51.2	1.60	2.42	2.42	0.34	0.34	0.31
	5	60.3	1.72	2.43	2.43	0.34	0.34	0.32
	8	70.3	2.01	2.45	2.45	0.33	0.33	0.31
	12	80.5	2.16	2.45	2.45	0.33	0.33	0.32
	15	87.2	2.37	2.46	2.46	0.31	0.32	0.32
$\beta = 25°$	0	19.3	1.46	1.51	1.46	0.33	0.34	0.32
	5	56.6	-	-	-	-	-	-
	8	68.0	-	-	-	-	-	-
	15	86.3	-	-	-	-	-	-
$\beta = 45°$	0	13.6	1.61	1.71	1.61	0.33	0.36	0.34
	5	50.2	-	-	-	-	-	-
	8	62.9	-	-	-	-	-	-
	15	82.9	-	-	-	-	-	-
$\beta = 60°$	0	11.4	1.92	2.04	1.92	0.32	0.36	0.33
	5	46.9	-	-	-	-	-	-
	8	60.7	-	-	-	-	-	-
	15	81.3	-	-	-	-	-	-
$\beta = 90°$	0	16.3	2.40	2.40	1.35	0.31	0.36	0.36
	2	32.1	2.42	2.42	1.45	0.31	0.36	0.36
	3	43.5	2.42	2.42	1.60	0.32	0.35	0.35
	5	53.9	2.43	2.43	1.72	0.31	0.34	0.34
	8	65.4	2.45	2.45	2.02	0.31	0.33	0.33
	12	77.8	2.45	2.45	2.15	0.32	0.33	0.33
	15	85.4	2.46	2.46	2.37	0.32	0.32	0.32

Note: Since specimens are not isotropic, their elastic parameter for $0° < \beta < 90°$ under $\sigma_3 > 0$ can not be determined from measurements.

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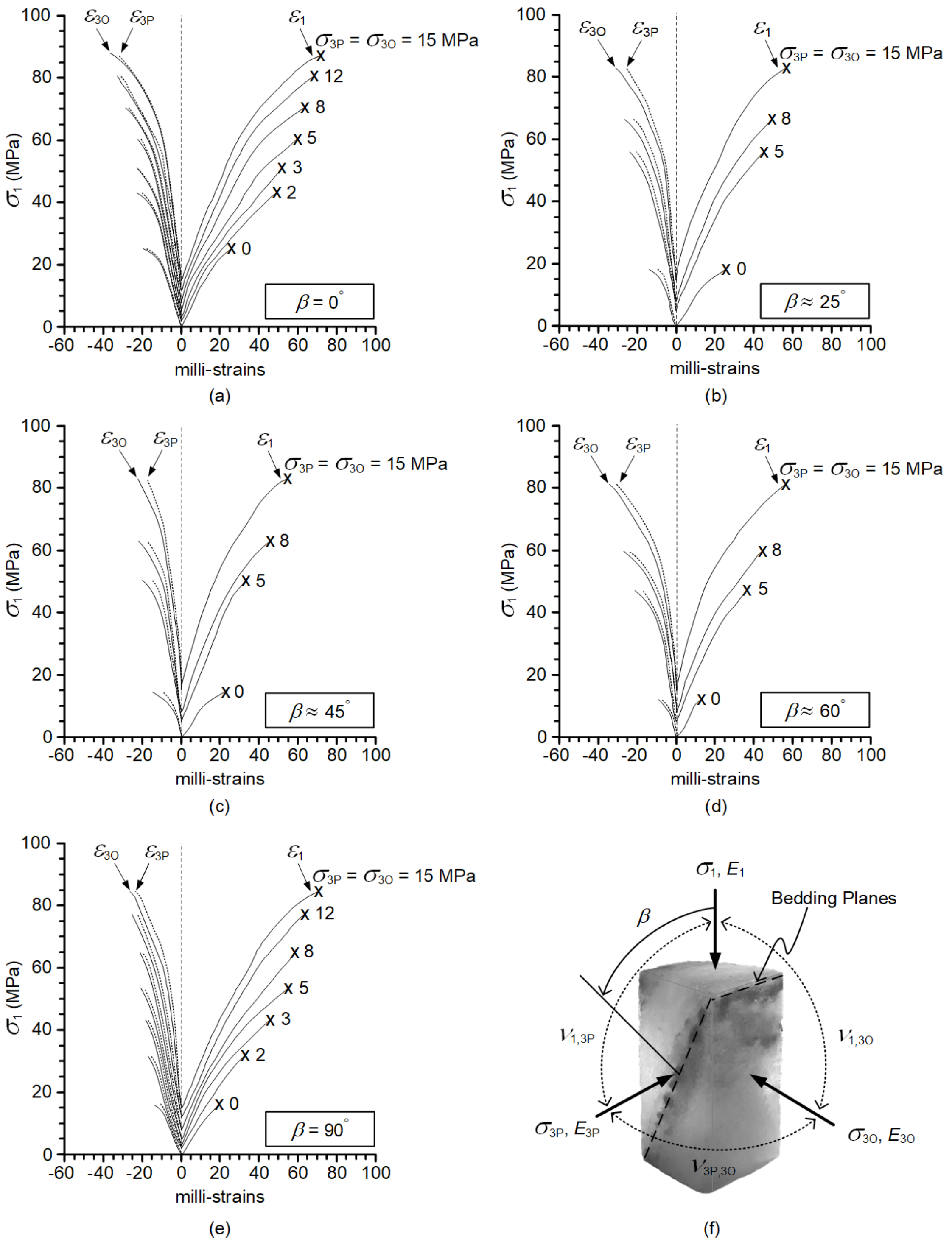

Figure 3 Stress-strain curves from compression strength tests on salt specimens with $\beta = 0^{\circ}$ (a), 25° (b), 45° (c), 60° (d) and 90° (e), (f) shows notations used in stress-strain diagrams

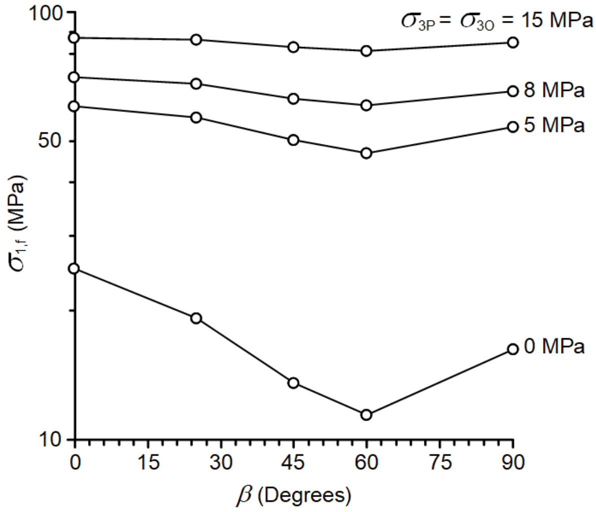

Figure 4 Compressive strengths as a function of angle β for different confining pressures (σ_3)

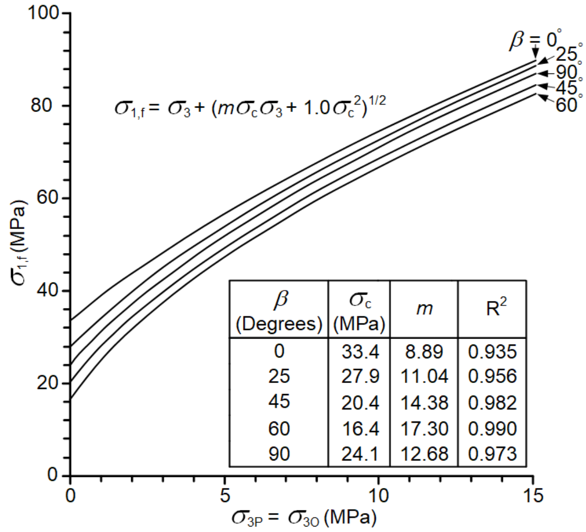

Figure 5 Mohr's failure envelopes based on Hoek-Brown criterion of salt specimens with different bedding plane angles (β)

Figure 6 plots the constant m and uniaxial compressive strength as a function of β varying from 0 to 90 degrees. Via regression analysis, their relationships can be expressed as follows:

$$m = (-7.00\times10^{-5})\cdot\beta^3 + (7.20\times10^{-3})\cdot\beta^2 + (-4.65\times10^{-2})\cdot\beta + m_{(0)} \qquad (5)$$

$$\sigma_c = (8.00\times10^{-5})\cdot\beta^3 + (-5.90\times10^{-3})\cdot\beta^2 + (-1.92\times10^{-1})\cdot\beta + \sigma_{c(0)} \quad \text{(MPa)} \qquad (6)$$

The polynomial equations fit well to the parameter m and strength results ($R^2 > 0.9$).

Figure 7 shows the elastic moduli as a function of β for different confining pressures (σ_3). The elastic modulus increases with increasing β, especially under uniaxial condition. Under high confining pressures, the transversely isotropic effect of the salt

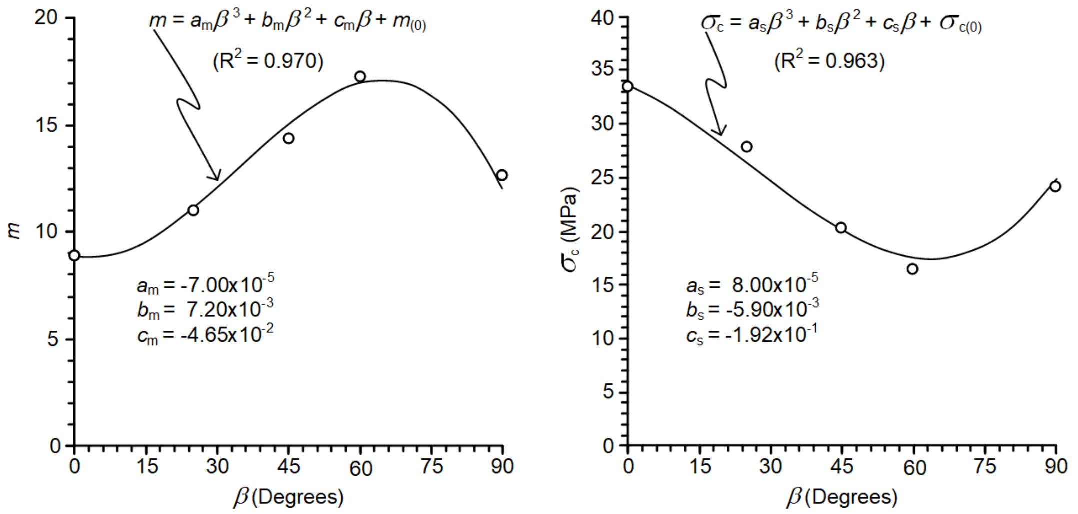

Figure 6 Hoek-Brown parameter m (a) and calculated uniaxial compressive strength (b) as a function of angle β.

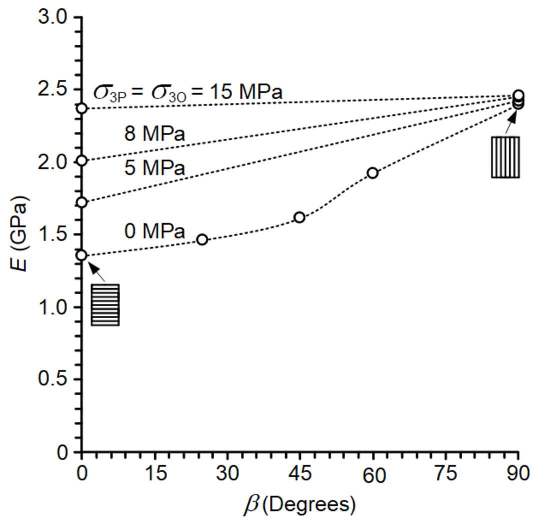

Figure 7 Elastic moduli as a function of angle β for different confining pressures (σ_3)

specimens tends to decrease. This is probably because salt is capable of self-healing, and hence they tend to restore to the isotropic condition.

4. Discussions and conclusions

Uniaxial and triaxial compression tests have been performed to determine strength and deformation of rectangular rock salt specimens with different bedding plane orientations under confining pressures varying from 0 to 15 MPa. The results indicate that the strength is maximum when loading is perpendicular to the bedding (anisotropic) planes. The minimum strength occurs when normal to bedding planes makes an angle (β) of 60 degrees with the loading direction, especially under lower confining pressures. This agrees with the test results obtained by McLamore and Gray [7] on slate and shale, Al-Harthi [8] and Colak and Unlu [9] on sandstones, siltstone and claystone, and Omid et al. [10] on sandstone, limestone, shale, slate, gneiss and schist. The effect of transverse isotropy decreases when salt is subjected to higher confining pressures and could reach the isotropic behavior, which is different from the strength envelopes obtained by Jaeger et al. [5] and Colak and Unlu [9] who show that the transversely isotropic effect of most sedimentary rocks remains unchanged even under high confining pressures. The decrease of transversely isotropic effect on salt is probably due to that rock salt specimens are capable of self-healing under high confining pressure [11-12].

The Hoek and Brown criterion can well describe the salt strength where the constant m is defined as polynomial function of angle β. The criterion can be useful for the design and stability analysis of support pillars in salt mines where the excavations intersect salt beds that are not in horizontal.

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