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MECHANICAL INTEGRITY OF CEMENT SEALS IN EXPLORATORY BOREHOLES AND ITS STABILITY DUE TO MINE SUBSIDENCE

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บทคัดย่อ

คุณสมบัติเชิงกลศาสตร์ของส่วนผสมซีเมนต์เพื่อใช้อุดในหลุมเจาะสำรวจในเหมืองเกลือและเหมืองโพแทชได้นำมาทดสอบในห้องปฏิบัติการ ส่วนผสมซีเมนต์ที่ใช้ในการทดสอบเตรียมมาจากปูนซีเมนต์ปอร์ตแลนด์ประเภทที่ 5 ผสมกับสารละลายโซเดียมคลอไรด์อิ่มตัว ผลการทดสอบระบุว่าความเค้นกดในแกนเดียวและสัมประสิทธิ์ความยืดหยุ่นมีค่าลดลงและอัตราส่วนปัวซองมีค่าเพิ่มขึ้นเมื่ออัตราส่วนของสารละลายโซเดียมคลอไรด์อิ่มตัวต่อซีเมนต์เพิ่มขึ้น ความเค้นกดในแกนเดียวและสัมประสิทธิ์ความยืดหยุ่นมีค่าสูงสุดเมื่อส่วนผสมของซีเมนต์ผสมกับทราย ค่าความเค้นดึงของส่วนผสมซีเมนต์มีค่าผันแปรจาก 2.36 ถึง 3.61 เมกะปาสคาล พลังงานความเครียดทั้งหมดที่จุดแตกถูกนำมาสร้างความสัมพันธ์กับอัตราส่วนสารละลายโซเดียมคลอไรด์อิ่มตัวต่อซีเมนต์ เกณฑ์การเฉือนของคูลอมบ์และพลังงานความเครียดถูกนำมาประยุกต์ใช้เพื่อหาค่าปัจจัยความปลอดภัยของวัสดุอุดในหลุมเจาะในบริเวณที่มีการทรุดตัวของผิวดิน โดยใช้ค่าความเค้นเฉือนและค่าความเค้นดึงสูงสุดที่เกิดขึ้นกับหลุมเจาะ ผลการคำนวณระบุว่าค่าปัจจัยความปลอดภัยมีค่าเพิ่มขึ้นเมื่อความลึกเพิ่มขึ้นและเมื่อค่าการทรุดตัวของผิวดินลดลง ผลที่ได้สามารถนำไปใช้ประเมินเสถียรภาพของส่วนผสมซีเมนต์ในหลุมเจาะที่อยู่ในพื้นที่ที่มีการทรุดตัวของผิวดิน

ABSTRACT

The mechanical properties of cement mixtures for use as sealing in exploration boreholes in salt and potash mines have been experimentally determined. The mixtures are prepared from commercial grade Portland cement type V mixed with saturated brine. The results indicate that the uniaxial compressive strength and elastic modulus decrease and Poisson's ratio increases with increasing brine-to-cement ratio. The highest compressive strengths and elastic modulus are obtained from cement-sand mixture. The bending tensile strengths of the mixtures range from 2.36 to 3.61 MPa. The total strain energy at failure has been calculated and derived as a function of brine-to-cement ratio. The Coulomb and strain energy criteria are applied to determine the factors of safety of the materials in boreholes during subsidence in terms of shear strength and bending tensile strength. The *factors of safety increase when the depths increase and surface subsidence decreases. The findings can be used to assess the stability of the cement seals in boreholes drilled in the subsidence areas.*

KEYWORDS: Sludge, Sand, Cement, Strain Energy

1. Introduction

The penetrations of geological formations for the purpose of salt and potash exploration in the Maha Sarakham formation can have a detrimental impact on the environment. Boreholes that penetrate aquitards may allow migration and mixing of groundwater of different qualities, and may contaminate aquifers. Open boreholes may allow premature and unnecessary depressurization of formations, and may result in wasting of natural resources. The sealing method can be used to prevent or minimize the detrimental effects that may result from leaving geological penetrations open. Sealing abandoned exploratory drill hole is a partial important. The seals will ensure that the water protection layer (Middle Salt member) will remain impervious, and that the portions of the drill hole penetration the Lower Salt member will not become flow path of water or brine from the Lower Clastic member into the mine openings. More important the borehole seal must be specifically designed to suite the site-specific for conditions where formation subsidence, may occur due to the underground excavations. The seals should be able to sustain the deformation and movement of the subsiding overburden formations due to the underground excavation.

The objective of this study is to assess the mechanical performance of the commercial grade cement mixtures used as sealing in boreholes. The mixtures include cement, cement-sand and cement-sludge. Their results are compared in terms of compressive and tensile strengths, elastic modulus and Poisson's ratio. The strain energy criterion is used to fit with the test results. Potential applications of the proposed criterion are presented for sealing material in borehole drilled in salt and potash mines. The sealing materials should be able to sustain the deformation and movement of the subsiding overburden formations due to the underground excavations.

2. Cement Seal Preparation

The sealing material used in this study is the commercial grade Portland cement type V. The sand and sludge with average particle sizes of 1 mm and 75 μm are used as aggregate. The mixing weight ratio of cement-to-sand (C:S) is 1:1, and of cement-to-sludge (C:SL) is 1:0.5. The ratios of brine-to-cement (*B/C*) vary from 1, 0.8 to 0.6. The brine is prepared from pure halite mixed with distilled water in plastic tank and stirred continuously. The grout preparation follows the API American Petroleum Institute No.10 [1]. The cement slurry mixtures are poured and cured in 54 mm diameter PVC pipes for use in the mechanical testing. The specimens are cured in PVC pipe under saturated brine at room temperature for 28 days before testing. A total of 135 specimens have been prepared.

3. Test Method

3.1 Compression Test

The sample preparation and test procedure follow the applicable ASTM standard practice [2] and the ISRM suggested methods, as much as practical. The compressive strengths of the mixtures are measured from cylindrical specimens with a diameter of 54 mm. The L/D ratios of specimens are 2.5 for the uniaxial test and 2.0 for the triaxial test. The confining pressures are from 0.34, 0.68, 1.02, 1.36 to 1.70 MPa. The axial stress is applied at a constant rate of 0.1-0.5 MPa/second until failure. During the test, the axial and lateral deformations are monitored. The post-failure characteristics are observed. Based on the Coulomb's criterion the shear strength can be represented by Jaeger et al. [3]:

$$\tau = c + \sigma_n \tan\phi \quad (1)$$

where τ is shear strength (MPa), c is cohesion (MPa), σ_n is normal strength (MPa) and ϕ is internal friction angle (degrees).

3.2 Four Point Bending Test

The test method and calculation follow the ASTM standard practice [4]. A data logger (TC-32K) connected with the switching box (Type B-2760) is used to monitor the induced tensile strains while loading. The tensile strength can be calculated by ASTM D6272-10 [4]:

$$\sigma_T = 16PL / 3\pi d^3 \quad (2)$$

where σ_T is tensile stress (MPa), P is applied load (N), L is support span (220 mm), and d is specimen diameter (54 mm). The load is applied under constant magnitudes which are equivalent to the induced stress rate of 4×10^{-4} MPa/s at the center of the specimens. The specimen deformations are monitored and used to calculate the principal strains during loading. The readings are recorded every 50 N of load increment until failure.

4. Test Result

4.1 Compression Test Results

Some post-test specimens obtained from the compression test under various confining pressures (σ_3) are shown in Figure 1. Shearing failure is observed under high confining pressure while extension failure is found in low confining pressure specimens. Figure 2 shows the stress-strain curves under different confining pressures and *B/C* ratios. The diagrams show that higher confining pressures result in higher stresses and strains at failure. The compressive strength increases as *B/C* ratio decreases. Under the same *B/C* ratio, the cement-sand mixture shows higher strengths than those of the cement pure and cement-sludge mixtures. The elastic modulus and Poisson's ratio are determined from the tangent of the stress-strain curves at about 50% of the failure stress. The elastic moduli decrease and Poisson's ratios increase with increasing *B/C* ratio, as shown in Figure 3. The specimens mixed with sand tend to show higher elastic modulus and lower Poisson's ratio than those mixed with sludge. The cohesion and internal friction angle are summarized in Table 1. It suggests that increasing the *B/C* ratio slightly decreases the cohesions and friction angles of the mixtures. The average cohesion and friction angle of the mixtures range from 2.33 to 3.38 MPa and 44 to 55 degrees.

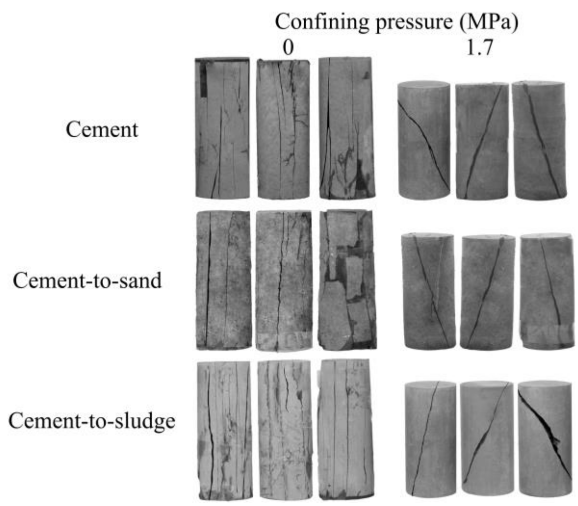

Figure 1 Examples of post-test specimens from uniaxial and triaxial compressive strength tests

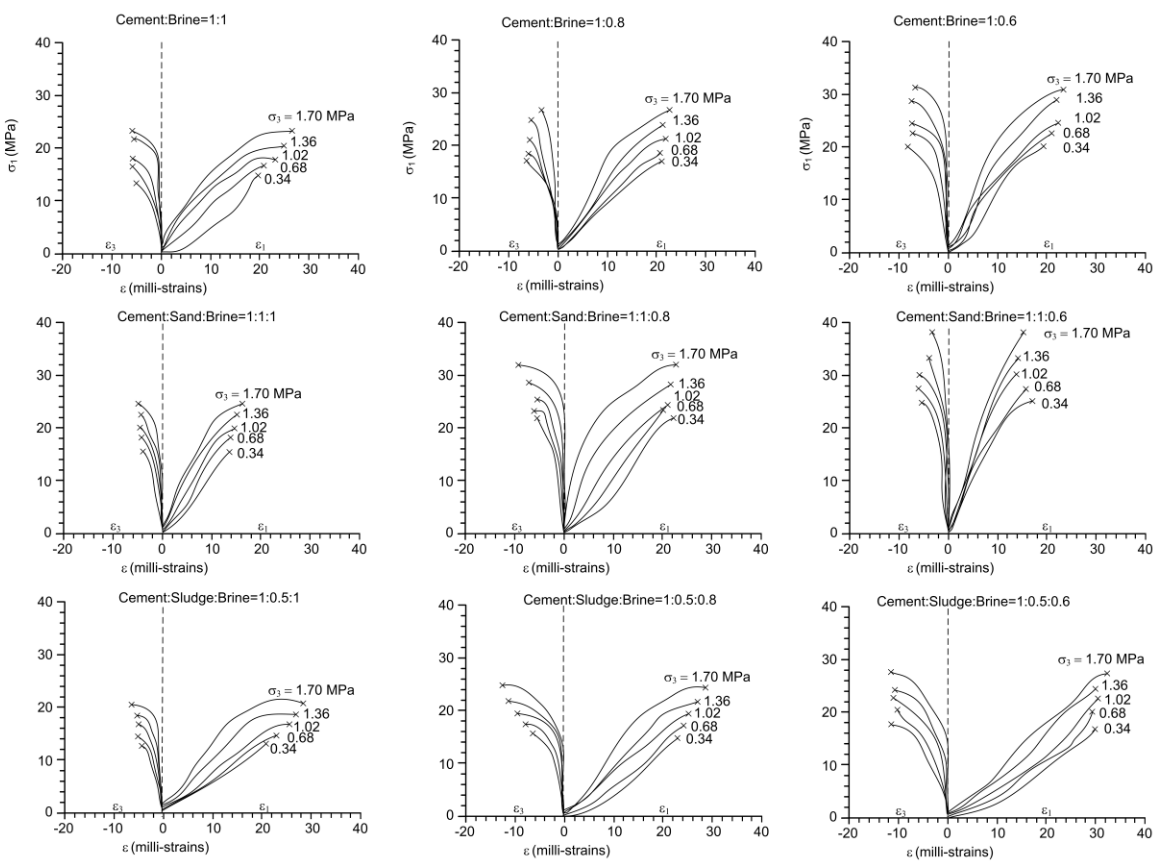

Figure 2 Stress-strain curves for compression tests

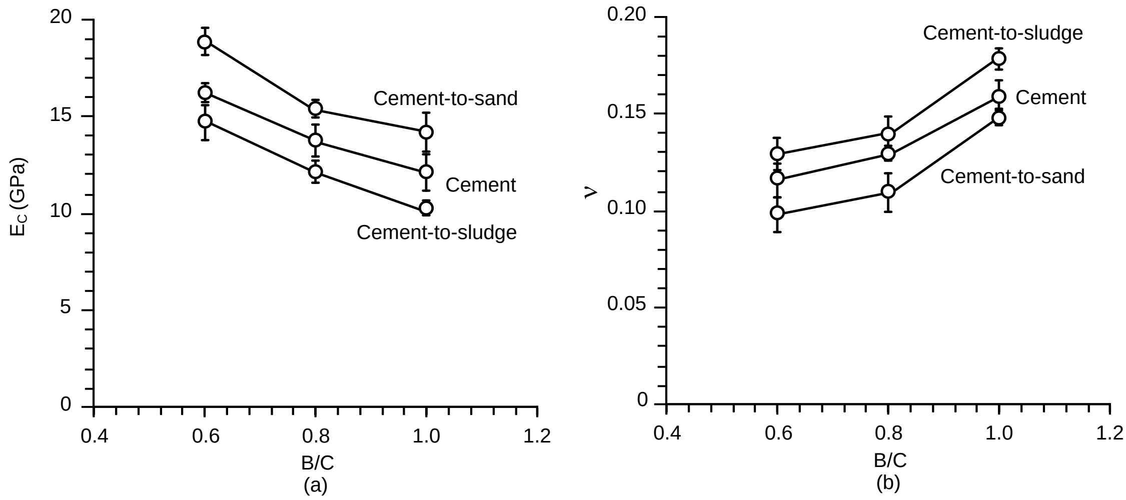

Figure 3 Elastic modulus (E_c) (a) and Poisson's ratio (ν) (b) as a function of brine-to-cement ratio (B/C)

Table 1 Cohesions and friction angles of cement mixtures

Mixtures	Brine-to-cement ratios	Friction angles (degrees)	Cohesions (MPa)
Cement	1	46	2.45
	0.8	49	2.69
	0.6	50	3.03
Cement-to-sand	1	47	2.67
	0.8	50	3.35
	0.6	55	3.38
Cement-to-sludge	1	44	2.33
	0.8	47	2.62
	0.6	50	2.85

4.2 Four Point Bending Test Results

Figure 4 shows some post-test specimens from the four point bending test under different ratios. The fractures are induced at the center of specimen for all testing. The compressive and tensile moduli (E_C and E_T) can be calculated from the linear portion of the stress-strain curves. Table 2 summarizes the tensile stresses and strains at failure and the elastic moduli obtained from the four point bending test. It is found that the tensile strengths, strains and deformation moduli decrease with ratios. This is probably due to that the increase of liquid can lower the bonding strength of the cement mixtures. The compressive modulus is slightly higher than tensile modulus. The compressive modulus obtained here is comparable to those obtained from the compression tests.

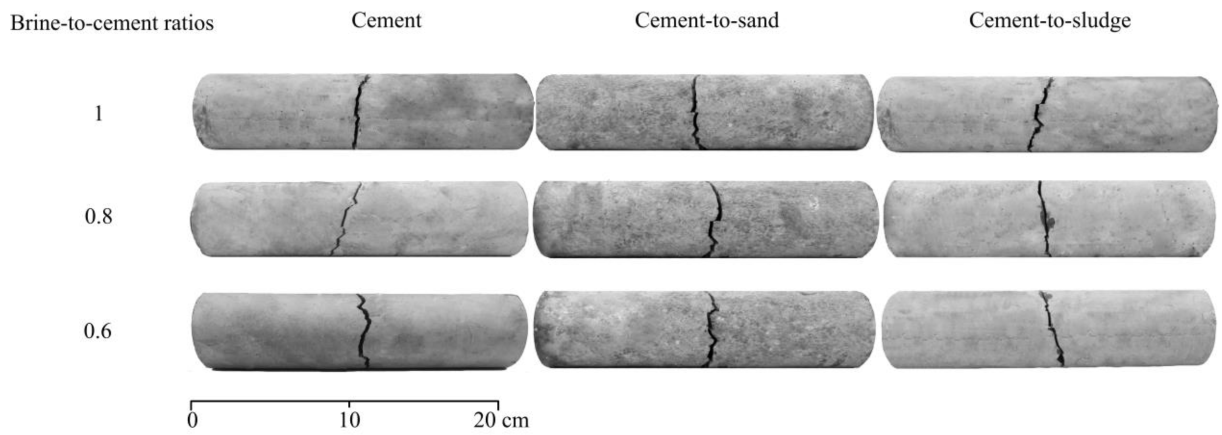

Figure 4 Examples of post-test specimens from four-point bending test

Table 2 Four-point bending test results of cement mixtures

Mixtures	brine to cement ratios	σ_T (MPa)	ε_T (milli-strains)	E_T (GPa)	E_C (GPa)	W_T (kPa)
Cement	1	2.53	0.234	8.8	11.0	0.30
	0.8	2.92	0.269	10.1	11.9	0.39
	0.6	3.36	0.348	12.5	14.2	0.58
Cement-to-sand	1	2.99	0.312	10.0	13.7	0.47
	0.8	3.35	0.336	11.7	14.7	0.56
	0.6	3.61	0.382	14.2	17.3	0.69
Cement-to-sludge	1	2.36	0.214	8.5	10.6	0.25
	0.8	2.73	0.247	10.0	11.4	0.34
	0.6	3.14	0.333	12.0	13.1	0.52

5. Strain Energy Density

The strain energy density principle is applied here to describe tensile strengths and deformability of the cement mixtures. Assuming that the crack initiation point is under tensile stress condition, the total strain energy density (W_T) can be calculated from the tensile stress and strain at failure using the relation [3]:

$$W_T = \frac{1}{2}(\sigma_T \cdot \varepsilon_T) \tag{3}$$

where σ_T and ε_T are the tensile stress and strain at failure.

To develop a strength criterion based on the energy density principle, the total strain energy that the specimen can sustain before tensile failure occurs can be presented as a function of brine-to-cement ratio (*B/C*). Figure 5 plots the W_T as a function of ratio. A linear trend is obtained which can be described by.

$$W_T = \alpha(B/C) + \beta \tag{4}$$

where α and β are empirical parameters. Their numerical values are given in Figure 5. Regression analyses are performed to determine the parameters in Equations (4). The proposed criterion fits well to the test data with the correlation coefficients (R^2) greater than 0.9. The results show that the strain energy densities of the mixtures decrease with increasing ratio. The cement-sand mixture shows higher strain energy than those of the pure cement and cement-sludge mixtures. This depends on the tensile strength of the mixtures (represented by σ_T). Higher tensile strengths lead to higher total strain energy.

6. Potential Applications

Borehole drilled in or nearby subsidence areas may be subjected to large strains under tension and shear forces. The stability of sealing material is necessary to prevent water inflows into the salt and potash mine openings underneath. The strain-energy equation proposed above and the Coulomb's criterion can be applied to determine the factors of safety of the cement seal in the borehole. The tensile strain energy ($W_{T,i}$) of the mixtures in borehole can be induced by the formation movement above the mine horizon, which can be determined as [3]:

$$W_{T,i} = \frac{1}{2}(\sigma_{T,i} \cdot \varepsilon_{T,i}) \tag{5}$$

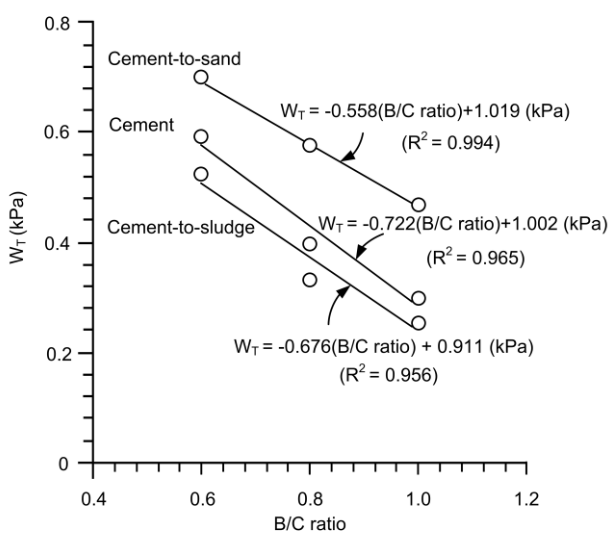

Figure 5 Total strain energy densities (W_T) as a function of brine to cement ratios (*B/C*)

where $\sigma_{T,\,i}$ is the maximum induced tensile stresses, and $\varepsilon_{T,\,i}$ is the induced tensile strains occurred in borehole which can be calculated from Pytel and Kiusalaas [5] as follows:

$$\sigma_{T,i} = \frac{MC}{I} \tag{6}$$

$$\varepsilon_{T,i} = \frac{\sigma_{T,i}}{E} \tag{7}$$

where M is bending moment (N•m), C is horizontal distance away from the borehole axis (m) and I is the moment of inertia (m^4):

$$M = \frac{\omega l^2}{2} \tag{8}$$

$$\omega = \frac{6\theta EI}{l^3} \tag{9}$$

$$I = \frac{\pi}{4} r^4 \tag{10}$$

where ω is uniform distributed load (N/m), l is borehole depth (m), θ is the slope angle induced at the top of borehole and r is borehole radius (m). The uniform distributed load is assumed here primarily to induce the bending of the cement column to obtain the maximum inclination angle of 0.172 degrees. In this study θ is taken as 0.172 degrees which is equivalent to the surface slope of 3×10^{-3} (Figure 6). This maximum value is suggested by Singh [6] to ensure that the subsidence slope will not impact the engineering structures and natural resources on the surface within mine area.

To determine the factor of safety based on the Coulomb's criterion, the maximum shear stress at fix end (bottom) of the borehole can be determined as:

$$\tau_i = \frac{4V}{3A} \tag{11}$$

where V is shear force: $V = \omega \cdot l$ (N) and A is cross section area of borehole (m^2). (12)

The factor of safety (FS) for cement seal in borehole considers the strain energy under tension and the Coulomb's criterion under shear stress.

Tensile strain energy criterion: $FS = \frac{W_T}{W_{T,i}}$ (13)

Coulomb's shear criterion: $FS = \frac{\tau}{\tau_i}$ (14)

where $W_{T,\,i}$ and τ_i are the induced tensile strain energy and shear stress. Figure 7(a) shows the factors of safety calculated from tensile energy as a function of depths for the surface slope of 3×10^{-3}. The factors of safety increase with depths. If the boreholes are over 250 m depth, their cement seal should be stable (no tensile failure occurs). For shallow boreholes (less than 250 m) it is possible that tensile failure may occur particularly for the subsidence slopes of 3×10^{-3} or greater. Figure 7(b) shows the factors of safety against the shear stress based on the Coulomb's criterion. They also increase with depth. All cement mixtures can sustain the shear stresses induced by the formation movement even at the point where the maximum surface slope is allowed (3×10^{-3}).

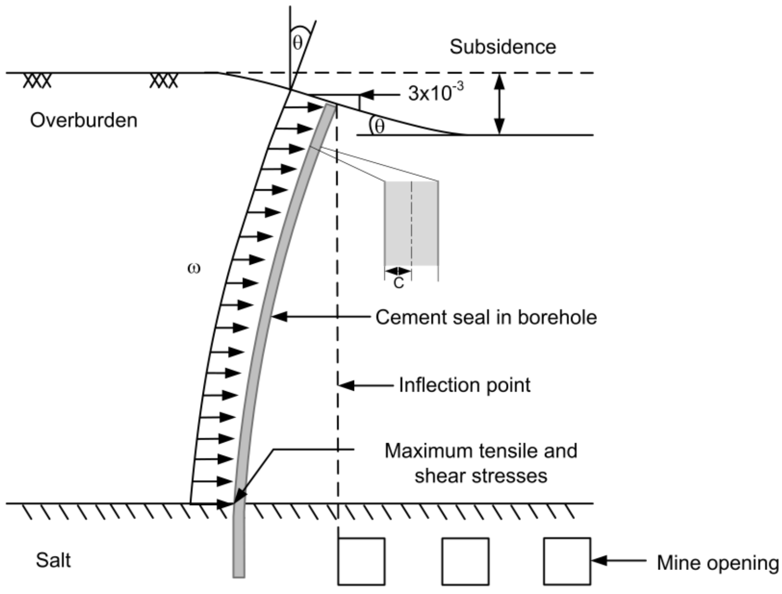

Figure 6 Cement seal in borehole under bending with maximum ground surface slope of 3×10^{-3}

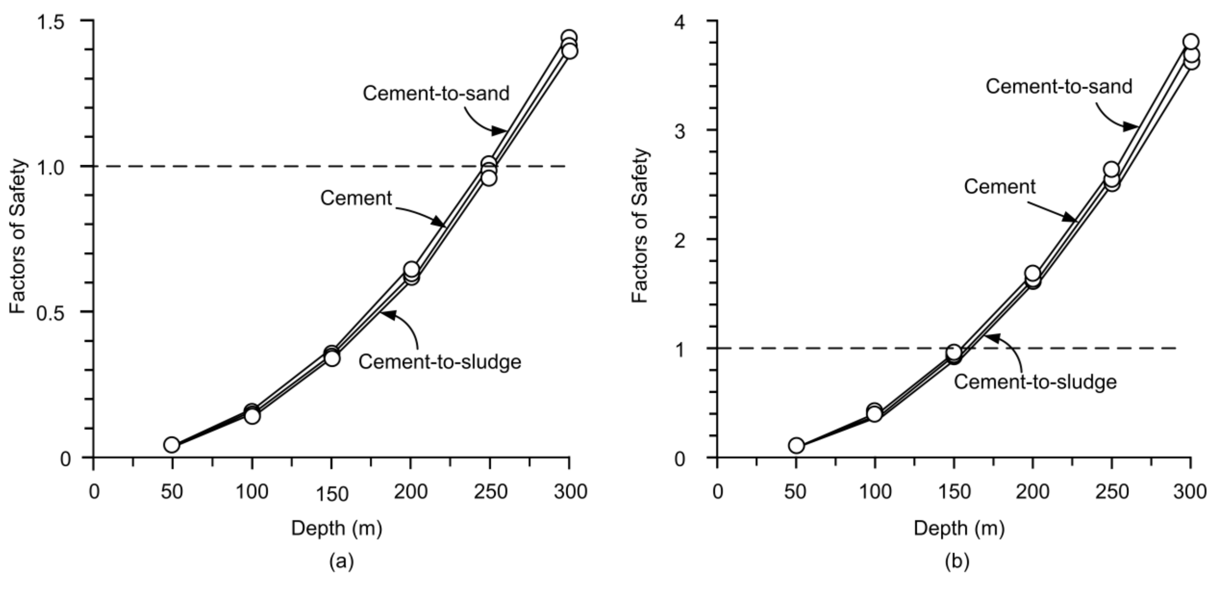

Figure 7 Factors of safety as a function of depth calculated by tensile strain energy (a) and the Coulomb's criterion (b)

7. Discussions and Conclusions

The triaxial compression and four point bending tests have been performed to obtain the mechanical properties of cement-aggregate mixtures for use as sealing materials in and nearby boreholes drilled in and nearby subsidence area. The results indicate that the cement mixed with sand shows higher strength and elastic modulus and lower Poisson's ratio than other materials do. This observation agrees well with the results obtained elsewhere [7-10]. The compressive and tensile strengths are used to develop criteria in the form of the Coulomb and the tensile strain energy. The two criteria are used to determine the factor of safety of sealing materials in boreholes under various depths. The results show that the factors of safety increase when the depths increase. All mixtures tested here show similar factors of safety against shearing and tensile bending. The tensile bending strength of the cement in borehole tends to be sensitive to the borehole depths. Tensile failure may occur at the bottom of the cement seals in the Lower salt, particularly in shallow boreholes that are subjected to the large subsidence magnitude (large surface and formation slopes).

Acknowledgements

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