วิศวกรรมสารฉบับวิจัยและพัฒนา
Engineering Journal of Research and Development
วิศวกรรมสถานแห่งประเทศไทย ในพระบรมราชูปถัมภ์
The Engineering Institute of Thailand under H.M. The King's Patronage

ปีที่ 28 ฉบับที่ 1 มกราคม-มีนาคม 2560
Volume 28 Issue 1 January-March 2017
Received 21 February 2017
Received in Revised from 25 March 2017
Accepted 31 March 2017

SEALING OF SALT AND POTASH MINE USING SUGARCANE BAGASSE ASH MIXTURE

Ei Ei San[1] and Decho Phueakphum[2]

[1]Student, Geomechanics Research Unit, Suranaree University of Technology, Thailand

[2]Lecturer, Geomechanics Research Unit, Suranaree University of Technology, Thailand

ABSTRACT

This research investigates the utilization of sugarcane bagasse ash (SCBA) mixed with Portland cement, bentonite and crushed salt as sealing materials to reduce the subsidence in salt and potash mine. The strength and toughness of the mixture are determined here. The ratio of SCBA-to-cement (cementitious materials) is 20:80 by weight and bentonite-to-crushed salt (bentonite crushed salt mixture) is 30:70 by weight. The mixture ratios of cementitious materials to bentonite-crushed salt are 1:2 (CPB-1) and 1:3 (CPB-2). The constant saturated brine-to-mixed materials ratio of 0.4 is used for blending. The uniaxial compressive strength (UCS) test, triaxial compression (TRI) test and Brazilian tensile strength (BZ) test are performed for each curing period of 3, 7, 14 and 28 days. The test results are used in FLAC program to simulate the time dependent behaviors of salt and potash mine with sealing materials. In this study, the UCS and BZ of CPB-1 mixture provides 7 MPa and 1.02 MPa while CPB-2 mixture gives 5 MPa and 0.86 MPa at a curing period of 28 days. The results clearly show that CPB-1 mixture can produce more strength than CPB-2 mixture. The cohesion (c) and internal friction angle (ϕ) are gradually increased at the first two weeks and then tend to remain constant after 28 days. The elastic moduli and Poisson's ratio are slightly increased. From the numerical analysis, the result obtained from the mine opening with the CPB-2 sealing can reduce the magnitude of subsidence about 46% as compared with that without backfills.

KEYWORDS: Sugarcane bagasse ash (SCBA), Cemented paste backfill (CPB), Strength development, Subsidence

บทคัดย่อ

งานวิจัยนี้ศึกษาการใช้เถ้าชานอ้อยเป็นวัสดุทดแทนซีเมนต์เพื่ออุดในช่องเหมืองเกลือและเหมืองโพแทช โดยส่วนผสมประกอบด้วยเถ้าชานอ้อย ปูนซีเมนต์ปอร์ตแลนด์ เบนโทไนท์และเกลือหินบด การทดสอบกำลังและความแกร่งของวัสดุผสมได้ถูกดำเนินการเพื่อนำมาใช้ในการประเมินประสิทธิภาพการลดขนาดการทรุดตัวของผิวดินในเหมืองเกลือและเหมืองโพแทช "วัสดุซีเมนต์" ผสมระหว่างเถ้าชานอ้อยกับปูนซีเมนต์ปอร์ตแลนด์ ในอัตราส่วนเท่ากับ 20:80 โดยน้ำหนัก และเบนโทไนท์ผสมเกลือหินบดในอัตราส่วนเท่ากับ 30:70 โดยน้ำหนัก โดยกำหนดให้ส่วนผสมของ "วัสดุซีเมนต์" ต่อ "เบนโทไนท์ผสมเกลือบด" มีอัตราส่วน 1:2 (CPB-1) และ 1:3 (CPB-2) ในการทดสอบใช้สัดส่วนของน้ำเกลือเข้มข้นต่อวัสดุผสมทั้งหมดมีค่าเท่ากับ 0.4 การทดสอบกำลังอัดแกนเดียว (UCS) และกำลังอัดแบบสามแกน (TRI) และการทดสอบกำลังรับแรงดึงแบบบราซิล (BZ) ถูกทดสอบกับตัวอย่างที่ผ่านการบ่มด้วยระยะเวลา 3, 7, 14 และ 28 วัน ผลที่ได้จากการทดสอบถูกนำมาใช้การคำนวณด้วยโปรแกรม FLAC เพื่อจำลองพฤติกรรมในเชิงเวลาของช่องเหมืองในชั้นเกลือและโพแทชที่ถูกอุดด้วยวัสดุผสมนี้ จากผลการทดสอบพบว่าค่ากำลังอัดในแกนเดียวและกำลังดึงแบบ

บราซิลหลังจากผ่านการบ่มด้วยระยะเวลา 28 วัน สำหรับตัวอย่างที่ผสม "วัสดุซีเมนต์" ต่อ "เบนโทไนท์ผสมเกลือบด" อัตราส่วน 1:2 (CPB-1) มีค่าเท่ากับ 7 MPa และ 1.02 MPa และสำหรับอัตราส่วน 1:3 (CPB-2) มีค่าเท่ากับ 7 MPa และ 1.02 MPa ตามลำดับ ผลระบุว่าส่วนผสม CPB-1 มีกำลังสูงกว่าส่วนผสม CPB-2 ค่าความเค้นยึดติดและมุมเสียดทานภายในของตัวอย่างมีค่าเพิ่มขึ้นในช่วงสองสัปดาห์แรกและมีแนวโน้มคงที่หลังจาก 28 วัน ค่าสัมประสิทธิ์ความยืดหยุ่นและอัตราส่วนปัวซองมีการเพิ่มขึ้นเพียงเล็กน้อย การวิเคราะห์ด้วยแบบจำลองทางคอมพิวเตอร์ที่ใช้ผลการทดสอบของตัวอย่างส่วนผสม CPB-2 พบว่าการทรุดตัวของผิวดินลดลงประมาณ 46% เมื่อเทียบกับกรณีที่ไม่มีการอุดช่องเหมือง

คำสำคัญ: เถ้าชานอ้อย, ซีเมนต์เพสต์, การพัฒนากำลัง, การทรุดตัวของผิวดิน

1. Introduction

The extraction of natural resources from the ground creates large underground voids that will lead not only the environmental problems such as subsidence, an undeniable consequence of underground mining, but also the foremost effect to engineering structures and, in the worst cases, injury or loss of life. The range of these underground voids depends on the magnitude of the in-situ stresses, mining induced stresses, immediate roof characteristics and presence of geological discontinuities. With time, the superjacent strata moves into the voids, resulting in instability of underground workings and forms a depression on the ground surface which is commonly referred to as subsidence [1].

Surface subsidence generally implicates both vertical and lateral ground movements. Although rock properties and geological structure greatly impact the surface subsidence, its intensity counts on a number of factors as diverse as extraction height, mining depth and method, panel dimensions, overlying strata properties, geological disturbances, surface topography and more [2]. At first, it may be small and confined but after many years, it extends gradually over large areas.

These underground voids in mine should therefore, be backfilled with the waste tailings in the form of mechanical fills, pneumatic fills, hydraulic fills, and paste fills to ensure regional stability, minimize ore dilution, control subsidence, facilitate subsequent excavation and provide a stable platform for the workers and ground support for the nearby regions [3]. Among the different types of backfill, the use of cemented paste backfill (CPB) becomes an increasingly important component and standard practice for use in underground mining operations [4, 5]. It ultimately improves the productivity because of ground support to the pillars and walls, and prevention of caving and roof falls to enhance pillar recovery [6].

In recent years, there have been notable efforts in utilizing a variety of industrial by-products as pozzolanic materials in formulating CPBs in the mining industry. This utilization can not only increase product performance and technical benefits but also reduce cement content resulting in reduced carbon emission and, therefore, supporting sustainable development. The materials incorporating supplementary cementing materials exhibit unique characteristics that often make them more durable than ordinary CPBs [7].

The utilization of pozzolanic materials as partial replacement of cement in concrete or mortar mixtures provides a satisfactory solution to some of the environmental and technical concerns and problems associated with waste management. Many researches had shown that industrial by-products and agricultural wastes have a significant amount of amorphous silica in their chemical composition which can be used as pozzolanic materials. When pozzolanic materials are added to the cement, the presented silica reacts with the free lime from the hydration of the cement and new silicate hydrate products are formed, that can improve the compressive strength, pore structure, and permeability of the mortars and concretes because the total porosity decreases with increasing the hydration time [8, 9].

Sugarcane bagasse ash (SCBA) is an agro-industrial by-product of the sugar mills and alcohol factories. It is mainly composed of silica and other high amounts of aluminum, iron and calcium oxides, enabling to use as a supplementary cementing material. The results obtained by different researchers indicate that SCBA is an effective mineral admixture with 20% as optimal cement replacement without any adverse effect on the desirable properties of concrete. The specific advantages of such replacement are the development of high early strength, reduction in water permeability, and appreciable resistance to chloride permeation and diffusion [8, 9].

The objective of this study is the suitability of the utilization of SCBA as 20% cement replacement material in the mixture of SCBA, cement, bentonite and crushed salt. Towards this, the uniaxial compressive strength (UCS) test, triaxial compression (TRI) test and Brazilian tensile strength (BZ) test are carried out for each curing period of 3, 7, 14 and 28 days to determine the strength and toughness development of that mixture to use as cemented paste backfill and its efficiency to reduce the subsidence in salt and potash mine. The test results are used in FLAC program to simulate the time dependent behaviors of salt and potash mine with sealing materials.

2. Materials and Methods

2.1 Materials

In this study, four materials were used. The cement (C) used in this study was sulphate resistant Portland cement (ASTM Type V) [10]. SCBA was collected from Mitr Phol Phu Luang mill in Leoi Province, Thailand. The chemical composition data for C and SCBA determined using X-ray fluorescence method are compared in Table 1. The data indicate that SCBA has three times higher silica content than C.

Bentonites, ideal grout materials for sealing or backfilling into the borehole or water-resistant barriers, were also applied into the mixture because it has low permeability, proper swelling capacity, sorptive and self-sealing behaviors [11]. Crushed salts (passed through a 40-mesh sieve), prepared from the Lower members of the Maha Sarakham Formation in the Khorat basin, northeastern Thailand, were used as coarse-grained materials.

Table 1 Chemical composition of C and SCBA (%).

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3
C	24.14	7.66	10.01	51.03	1.41	0.98	0.75	4.02
SCBA	76.82	6.25	6.28	2.78	1.99	1.91	3.25	0.72

2.2 Sample Preparation

The four materials were mixed according to their weight ratio. At first, cementitious materials were prepared by replacing C with 20% of SCBA in dry condition. And then the ratio of bentonite to crushed salt with 30:70 was used. These two mixtures were then mixed with 1:2 and 1:3 composition ratios of cementitious materials to bentonite-crushed salt to form the final mixture. The saturated brine was used with the W/materials ratio of 0.4. Figure 1 shows the summary of CPB mixtures preparation.

Figure 1 Summary of CPB mixtures preparation.

The CPB mixtures were prepared using the professional 600™series 6-Quart stand mixer for a total of three minutes. After thoroughly mixed, the CPB mixtures were poured into the 54mm diameter PVC mold. The molds were then sealed and cured for periods of 3, 7, 14 and 28 days. For UCS test, three specimens with length to diameter ratio (L/D) of 2.5 were prepared for both mixtures. Another three specimens with L/D ratio of 2 for TRI test and ten specimens with 0.5 L/D for BZ test were also prepared to determine the mechanical strengths of CPB mixtures after curing. Figure 2 shows some of the examples of sealing material after curing in PVC mold prepared for laboratory test.

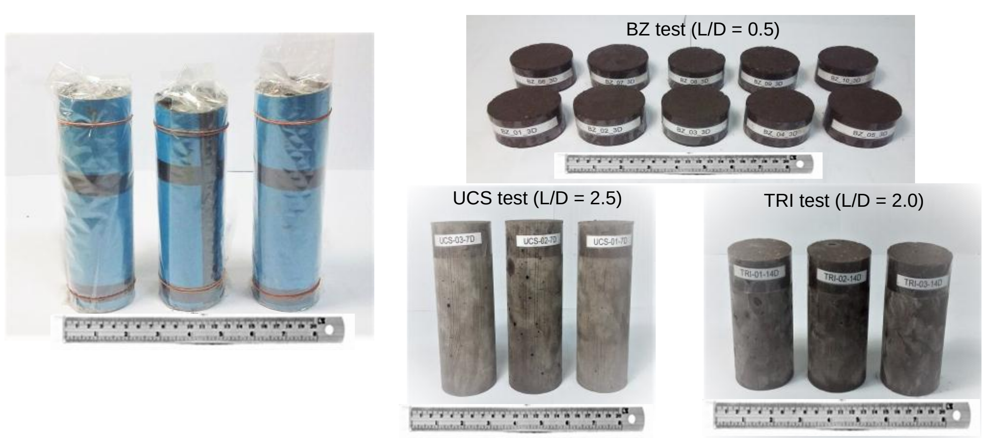

Figure 2 Examples of sealing material after curing in PVC mold prepared for laboratory test.

2.3 Laboratory Tests

At each curing stages, three tests were performed in accordance with the requirement of ASTM standards. The uniaxial compressive strength (UCS) tests were conducted on both CPB mixtures per ASTM D7012 [12]. The tensile strength was determined according to ASTM D3967 [13]. The confining pressures of 0.69, 1.28, and 2.07 MPa were used in the triaxial compression (TRI) test to find the cohesion and internal friction angle [10]. The mean values of each test were presented in the results. Figure 3 shows three tests set up used in this study.

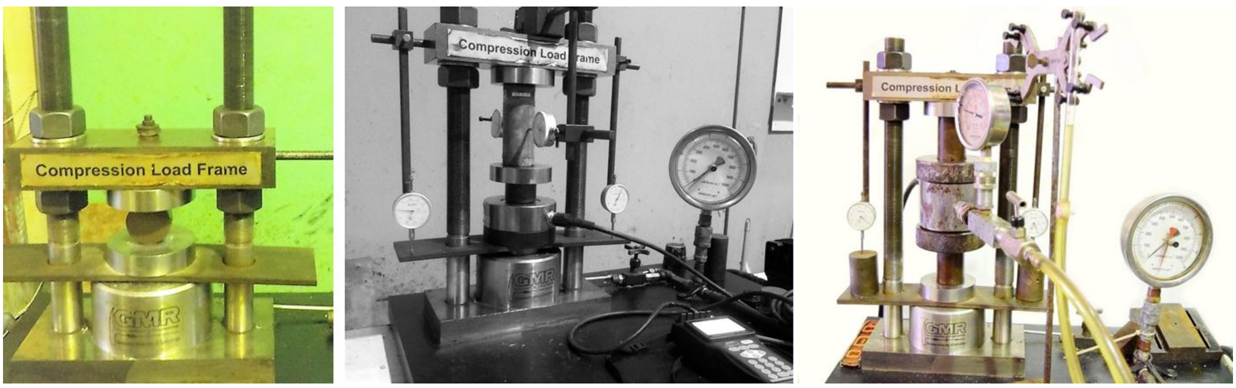

Figure 3 Test set up to obtained the mechanical properties.

3. Test Results

3.1 Uniaxial Compressive Strength (UCS) Test

The uniaxial compressive strength (UCS) values of CPB mixtures are shown in Table 2. The results clearly show that the UCSs of both mixtures are gradually increased with the curing periods and 28-day UCS values are over the minimum requirement of 5 MPa [4]. Three-day UCS values of CPB-1 is equivalent to the 7-day UCS values of CPB-2, whereas other values of CPB-1 are higher than CPB-2. When CPB-2 provides 5.12 MPa at 28 days, CPB-1 can supports 5.19 MPa at only 14 days. This confirms that CPB-1 can provide more strength than that of CPB-2.

Table 2 Uniaxial compressive strength of CPB-1 and CPB-2 mixtures.

Mixtures	Uniaxial compressive strength (MPa)			
	3 days	7 days	14 days	28 days
CPB-1	2.01	3.76	5.19	6.87
CPB-2	1.08	2.01	3.22	5.12

Figure 4 shows the behaviors of the elastic moduli and Poisson's ratio related with time. According to the figures, both the trends are slightly increased with the time. Although the elastic moduli of CPB-1 are lesser than CPB-2, the values of Poisson's ratio are greater. Therefore the use of CPB-1 is more effective than CPB-2.

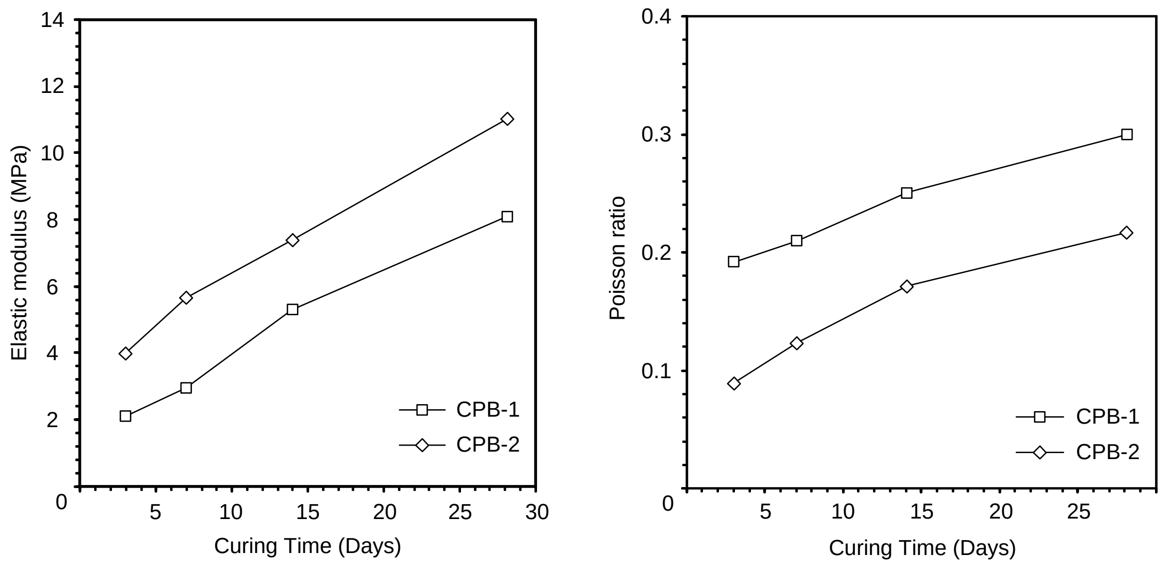

Figure 4 (a) Elastic modulus and (b) Poisson's ratio from UCS of CPB-1 and CPB-2.

3.2 Brazilian Tensile Strength (BZ) Test

Table 3 shows the increasing tensile strength values of CPB-1 and CPB-2 mixtures at each curing periods. The results show that the strength values of 14-day CPB-1 is similar with 28-day strength values of CPB-2. Obviously CPB-1 is also more useful than CPB-2 from the tensile strength point of view.

Table 3 Tensile strength of CPB-1 and CPB-2 mixtures.

Mixtures	Splitting tensile strength, □$_B$ (MPa)			
	3 days	7 days	14 days	28 days
CPB-1	0.519	0.663	0.838	1.115
CPB-2	0.238	0.351	0.547	0.859

3.3 Triaxial Compression (TRI) Test

The normal stress (σ_1) and confining pressure (σ_3) of 0.69, 1.28, 2.07, and 2.76 MPa for CPB-1 mixtures are shown in Table 4, and Table 5 for CPB-2 mixture. The relationship between these two stresses can also be clearly seen in Figure 5. The strength results of both mixtures are steadily increased with curing time. Although the trends of both mixtures' increasing strength are similar, the graphs show that the 28-day strength of CPB-2 mixture with confining pressures of 2.76 MPa is 70.78 MPa which is nearly equal to the CPB-1 mixture with only confining pressures of 0.69 MPa. When the 2.76 MPa confining pressure is applied, it can resist up to 90 MPa.

Table 4 Normal stress (σ_1) and confining pressure (σ_3) of CPB-1 mixture

Confining pressure, σ_3 (MPa)	Normal stress, σ_1 (MPa) at curing time			
	3 days	7 days	14 days	28 days
0.69	39.78	51.00	60.67	70.25
1.28	43.92	56.35	67.06	76.64
2.07	48.99	62.98	72.93	84.62
2.18	53.04	67.56	77.90	90.08

Table 5 Normal stress (σ_1) and confining pressure (σ_3) of CPB-2 mixture

Confining pressure, σ_3 (MPa)	Normal stress, σ_1 (MPa) at curing time			
	3 days	7 days	14 days	28 days
0.69	25.02	33.15	38.32	45.55
1.28	28.95	37.41	45.55	53.68
2.07	33.06	43.92	52.05	62.27
2.18	38.32	49.72	57.48	70.78

The cohesion, c and internal friction angle, ϕ are determined by the Coulomb failure criterion in terms of the principal stresses (σ_1, σ_3) as expressed in equation (1) [14].

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

The cohesion and internal friction angle of both mixtures at each curing periods are summarized in Table 6 and the relation are shown in Figure 6. The values are gradually increased in the first two weeks and then tend to remain constant after 28 days. In spite of not much difference in friction angle of both mixtures at each curing periods, cohesion results are obviously different. According to the Table 6, the CPB-1 mixtures can yield roughly twice of cohesion strength by CPB-2 mixtures.

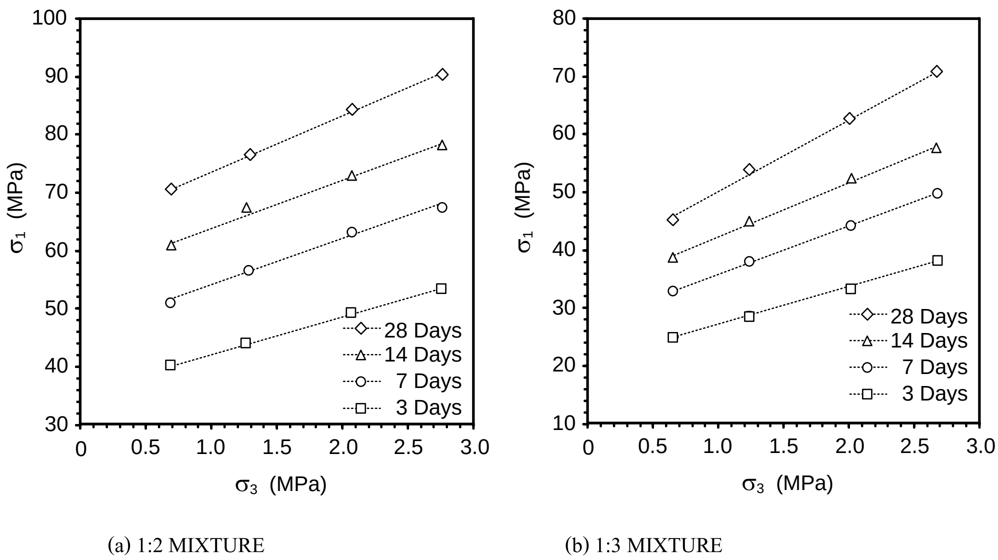

Figure 5 The strength development of CPB-1 and CPB-2 mixtures.

Table 6 Cohesion and internal friction angle of CPB-1 and CPB-2 mixture at each curing periods.

Curing time (Days)	Cohesion, c (MPa)		Internal friction angle, ϕ (Degrees)	
	CPB-1	CPB-2	CPB-1	CPB-2
3	4.79	4.41	60	45
4	5.54	4.94	62	51
14	6.68	5.10	63	55
28	7.11	5.42	65	58

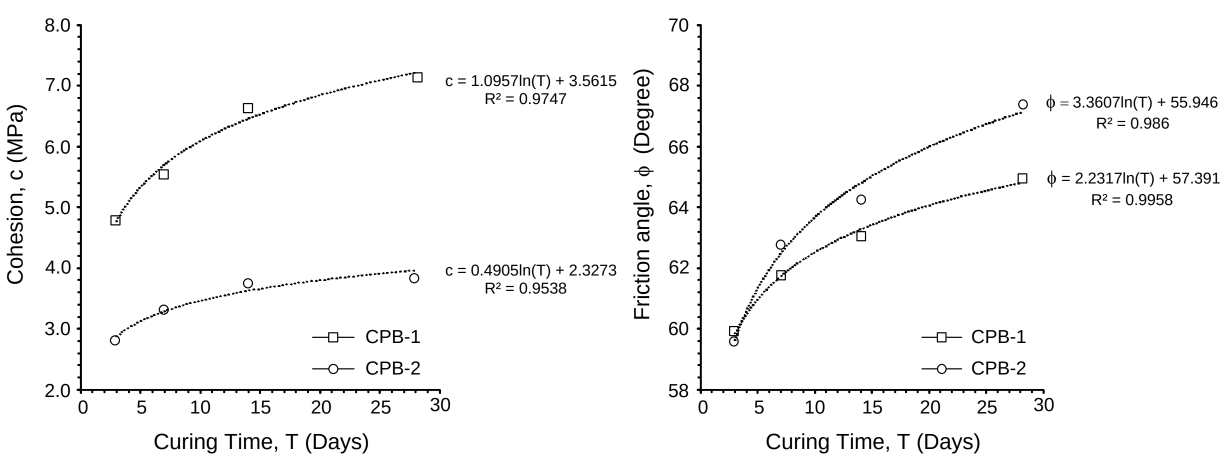

Figure 6 Cohesion and internal friction angle of CPB-1 and CPB-2 mixture with curing period.

The data used in this study are recorded manually so relevant standard deviation factors are used for all tests to obtain the precise results. The composition of four materials; SCBA, cement, bentonites and crushed salt should be changed and curing time should also be longer to accomplish the long-term effect on strength and toughness development.

4. Computer Simulations

In this study, the finite difference analysis using FLAC 4.0 with Burger model is used to determine the effectiveness of backfill materials in salt and potash mines after the mine excavation was completed. This simulation can predict the elastic, visco-elastic, visco-plastic, strain-softening and dilation behavior of geological materials [15]. The modular components of the Burgers model used in this computation are shown in Figure 7. Figure 8 expresses an example of the stratigraphic column of rock salt and clastic rock at Ban Hhao, Muang district, Udon Thani province (borehole no. K-089) [16]. The material property parameters used for the computer simulations are described in Tables 7 and 8.

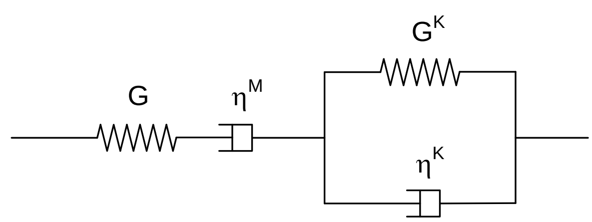

Figure 7 The modular components of the Burgers model [15].

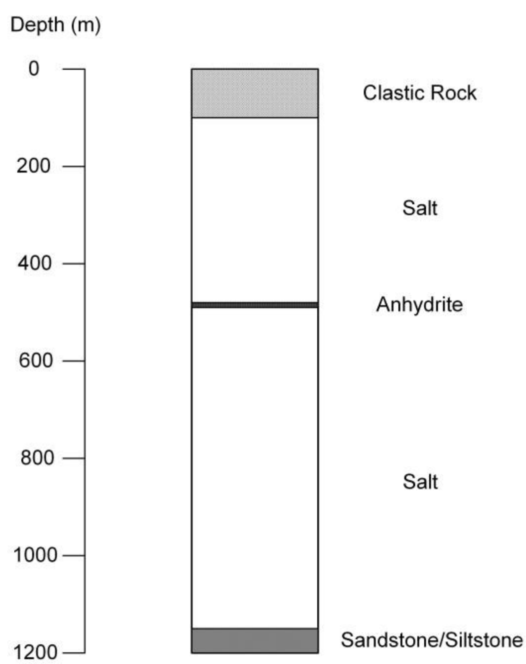

Figure 8 Stratigraphy of borehole no. K-089 at Ban Hhao, Muang district, Udon Thani province [16].

Table 7 Mechanical properties of clastic rock, rock salt and CPB-2 for FLAC 4.0 simulations.

Parameters	Rock types		
	Clastic rock[a]	Rock salt[b]	CPB-2[c]
Density, ρ (kg/m^3)	2,490	2,150	1,881
Bulk modulus, K (GPa)	1.70	2.22	2.203
Shear modulus, G (GPa)	0.30	1.67	2.961
Cohesion, c (MPa)	3.50	0.50	5.42
Internal friction angle, ϕ (Degrees)	25	50	58
Tension, T (MPa)	0.83	1.00	0.859

[a,b] Results obtained from previous study [17, 18]

[c] Presented laboratory test results

Table 8 Visco-elastic and visco-plastic properties of rock salt for FLAC 4.0 simulations [19].

Parameters	Values
Elastic modulus, E_1 (GPa)	1.90
Spring constant in visco-elastic phase, E_2 (GPa)	5.79
Visco-plastic coefficient in steady-state phase, η^K (GPa.day)	0.34
Visco-plastic coefficient in transient phase, η^M (GPa.day)	0.71
Density, ρ (kg/m^3)	2,150

Figure 9 shows the finite difference mesh constructed to represent vertical model with the mine depth of 280m and opening depth and width of 10m and 8m. Small elements are provided near the opening boundaries to obtain detailed behavior of the surrounding rocks and larger elements are used in the region far from the openings because of the lower stress and strain gradients. The simulation is carried out to predict the deformation behavior with or without sealing materials in mine ground under long-term interest of 50 years after mining. The time to seal in mine is also considered as CPB mixtures used in this study can be prepared and placed right away when mine process are finished. The magnitudes of surface subsidence with sealing time at 1, 3, 6, 9, and 12 months are considered in this calculation.

Sealing at different time after mining has different effect on the magnitude of surface subsidence. The calculated surface subsidence after 50 years of prediction in selected mine with overturn thickness of 250 m and opening height 10 m, and sealing time at 1, 3, 6, 9 and 12 months are shown in figure 10. According to this figure, if CPB mixtures are applied at 1 month after mining, the magnitude of surface subsidence is reduced as good as 46%, from about 54 cm to 29 cm, than without sealing. Sealing at other times can reduce the subsidence, but the amount of reduction is smaller when compared with 1 month result.

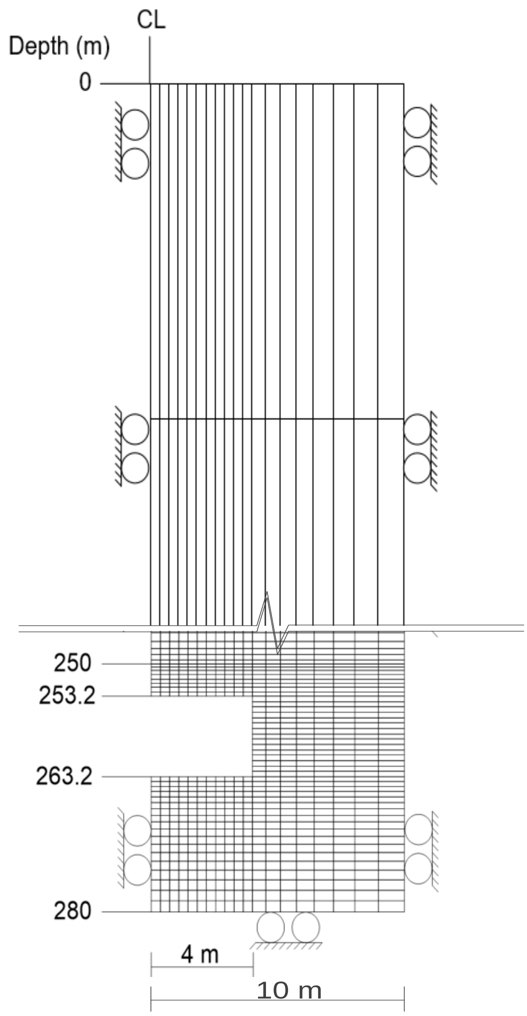

Figure 9 Finite difference mesh used in this study.

The sealing materials however cannot immediately perform after they are placed into the opening. They are functional after the roof deflected as a results of inducing the vertical stresses on sealing material then they are expanded around in the horizontal direction to support or strengthen the pillar. Then the deformations of roof deflection, pillar deformation and subsidence are reduced with time. For long-term periods, the opening will be falling under hydrostatic stresses conditions. This evidence can be confirmed by the numerical simulation results that the subsidence still increased at the first five years then it decreased with time (Figure 10). Table 9 clarifies the different resulted surface subsidence at each considered sealing time. It can obviously be described that the sealing time has the specific effect on the reduction of surface subsidence in mining. To acquire more relevant results, different mine and opening depths should also be suggested.

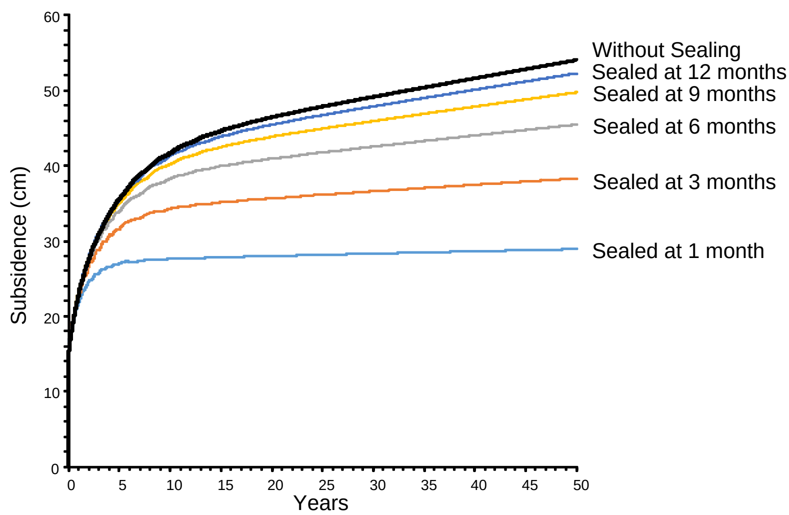

Figure 10 Surface subsidence as a function of time with overturn thickness = 250 m and opening height = 10 m.

Table 9 Subsidence reduction with the function of sealing time

Sealing Conditions	Subsidence (cm) at 50 Years	Reduction of Subsidence
Without sealing	54.04	-
Sealed at 1 month	28.92	46%
Sealed at 3 months	38.31	29%
Sealed at 6 months	45.46	16%
Sealed at 9 months	49.74	8%
Sealed at 12 months	52.27	3%

7. Discussions and Conclusions

In accordance with the present investigation, the use of sugarcane bagasse ash as cement replacement material has merits in the strength development of CPB mixtures and all the strength values are reasonable when compared with the previous findings. The remarkable content of reactive silica in sugarcane bagasse ash help the cement reaction with brine to apply more strength in the CPB mixture. The greater strength can be attained by increasing the amount of cement and SCBA as CPB-1 mixture supports approximately 75% more strength than CPB-2 mixture. The significant result is the use of CPB mixture as sealing material at early state after mining has more efficiency than after a long time because it can provide more strength to diminish the deterioration of pillar and prevent the extension of surface subsidence by supporting safer place in mine area. According to this study, sealing at 1 month after mining has excellent effect with virtual 46% reduction on the magnitude of surface subsidence while 29% reduction at 3 months and 16% at 6 months. After 6 months, sealing has insignificant effect on the subsidence reduction as the subsidence is already extend in the mine zone. To adopt the presented CPB mixture as one of sealing materials in practice, more relevant researches are suggested.

Acknowledgements

The work was supported by Suranaree University of Technology, the Higher Education Promotion and National Research University of Thailand and Thai International Cooperation Agency (TICA). Permission to publish this paper is gratefully acknowledged.

References

[1] Sahua P. & Lokhandeb R.D. (2015). An investigation of sinkhole subsidence and its preventive measures in underground coal mining. *Procedia Earth and Planetary Science* **11**, 63–75.

[2] Ju J. & Xu J. (2015). Surface stepped subsidence related to top-coal caving longwall mining of extremely thick coal seam under shallow cover. *International Journal of Rock Mechanics & Mining Sciences* **78**, 27–35.

[3] Sivakugan N., Veenstra R. & Naguleswaran, N. (2015). Underground mine backfilling in Australia using paste fills and hydraulic fills. *Int. J. of Geosynth. and Ground Eng* **1**, 18.

[4] Landriault, D.A., Verburg, R. & Cincilla, W. (1997). Welch D. Paste Technology for underground backfill and surface tailings disposal applications, Short Course Notes. In: CIM Technical Workshop – April 27, Vancouver, British Columbia, Canada.

[5] Naylor J., Famermery R.A. & Tenbergen R.A. (1997). Paste backfill at the macassa mine with flash paste production and storage mechanism. Proceedings of the 29th annual meeting of the Canadian Mineral Processors (Division of the CIM); 1997 Jan 21–23; Ottawa, Ontario.

[6] Belem T., Harvey A., Simon R. & Aubertin M. (2004). Measurement and prediction of internal stresses in an underground opening during its filling with cemented fill. Proceedings of the 5th Int. Symp. on Ground support in Mining and Underground Construction. Villaescusa & Potvin (eds.); 2004 Sep 28-30; Perth, Western Australia, Australia, Tayler & Francis Group, London. p. 619 – 630.

[7] Tariq A. & Yanful E.K. (2013). A review of binders used in cemented paste tailings for underground and surface disposal practices. *Journal of Environmental Management* **131**: 138–149.

[8] Boateng A.A. & Skeete D.A. (1990). Incineration of rice hull for use as a cementitious material: The Guyana experience. *Cem. Concr. Res* **20(5)**, 795–802.

[9] Ganesan K., Rajagopa K. & Thangavel K. (2007). Evaluation of bagasse ash as supplementary cementitious material. *Cement & Concrete Composites* 29, 515–524.

[10] ASTM C150/C150M. Standard specification for Portland cement. Annual Book of American Society for Testing and Materials Standard 2016.

[11] Domitrovic D. & Kovacevic Z.B. (2013). The relationship between swelling and shear strength properties of bentonites. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Technical Committee 101-Session I, pp. 219-222.

[12] ASTM D7012. Standard test methods for compressive strength and elastic moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures. Annual Book of American Society for Testing and Materials Standard 2014.

[13] ASTM D3967. Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens. Annual Book of American Society for Testing and Materials Standard 2008.

[14] Jaeger J.C., Cook N.G.W. & Zimmerman R.W. (2007). Fundamentals of rock mechanics. 4th ed. UK: Blackwell publishing; 2007.

[15] Itasca. (2002). FLAC-Fast Langrangian Analysis of Continua, Version 4.0, User' guide. Itasca Consulting Group Inc., Minnespolis, MN, USA.

[16] Suwanich P. & Ratanajaruraks P. (1986). Sequences of rock salt and potash in Thailand (Nonmetallic Minerals Bulletin No. 1). Bangkok: Economic Geology, Division. Department of Mineral Resources. Bangkok. 1986.

[17] *Crosby K. (2007). Integration of rock mechanics and geology when designing the Udon South sylvinite mine. In Proceedings of the First Thailand Symposium on Rock Mechanics (ThaiRock 2007), The Greenery Resort, Khao Yai, 13-14 September 2007, pp. 3-22.*

[18] *Samsri P., Sriapai T., Walsri C. & Fuenkajorn K. (2011). Polyaxial creep testing of rock salt. In Proceedings of the Third Thailand Symposium on Rock Mechanics (ThaiRock 2011), Springfield @ Sea and Resort Spa, Cha-am, 10-11 March 2011, pp. 79-87.*

[19] *Sriapai T., Walsri, C. & & Fuenkajorn K. (2012). Effects of temperature on compressive and tensile strengths of salt. ScienceAsia 2012; 38: 166-174.*