



CONSOLIDATION OF COMPACTED SLUDGE-CRUSHED SALT MIXTURES AS BACKFILL IN POTASH MINES

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บทคัดย่อ

งานวิจัยนี้ได้ทำการหาศักยภาพเชิงกลศาสตร์ของส่วนผสมดินตะกอนประปาและเกลือบดภายใต้การอัดตัวคายน้ำเพื่อใช้เป็นวัสดุถมกลับในเหมืองแร่โปแตช ตัวอย่างเกลือบดมีขนาดตั้งแต่ 0.075 ถึง 4.75 มิลลิเมตร จัดเตรียมจากเกลือชั้นล่างของหินชุดมหาสารคาม นำมาผสมกับดินตะกอนประปาจากการประปานครหลวงแห่งประเทศไทย อัตราส่วนผสมของดินตะกอนประปาต่อเกลือบด 30:70 ถึง 70:30 ได้ถูกบดอัดเพื่อหาปริมาณน้ำเกลือที่เหมาะสม จากนั้นตัวอย่างที่ถูกบดอัด ได้ถูกอัดตัวคายน้ำภายใต้ความเค้นคงที่จาก 2.5 ถึง 10 เมกะปาสคาล เป็นระยะเวลา 30 วัน ผลการศึกษาระบุว่ากำลังรับแรงกด สัมประสิทธิ์ความยืดหยุ่นและอัตราส่วนปัวซงของของส่วนผสมมีค่าลดลงเมื่อเพิ่มปริมาณดินตะกอนประปา และเพิ่มขึ้นตามความเค้นกดและระยะเวลาในการอัดตัวคายน้ำที่เพิ่มขึ้น การผสมเกลือบดกับดินตะกอนประปาสามารถลดอัตราการยุบตัวเชิงเวลาของส่วนผสม เนื่องจากดินตะกอนประปาประกอบด้วยอนุภาคละเอียดของควอตซ์เป็นส่วนใหญ่ ซึ่งสามารถแทรกในช่องว่างระหว่างเม็ดเกลือบด

ABSTRACT

Mechanical performance of consolidated sludge-crushed salt mixtures is determined for use as backfilling material in potash mines. Crushed salt with sizes ranging from 0.075 to 2.35 mm is prepared from Lower member of Maha Sarakham formation. Sludge has been obtained from the Metropolitan Waterworks Authority of Thailand. The sludge-to-crushed salt mixtures having weight ratios from 30:70 to 70:30 are compacted to determine their optimum brine contents. The compacted specimens are then consolidated under constant stresses from 2.5 to 10.0 MPa for up to 30 days. The results indicate that compressive strengths, elastic moduli and Poisson's ratios of the mixtures decrease with increasing sludge contents and increase with consolidation stress and period. Mixing crushed-salt with sludge can reduce long-term consolidation rate of the mixtures. This is primarily because sludge composes mainly of fine particles of quartz which can fill voids between crush salt grains.

KEYWORDS: Backfilling, Elastic modulus, Strength, Mine opening

1. Introduction

Underground potash mines can induce surface subsidence due to the creep deformation of support pillars and opening roof. The subsidence may impact engineering structures and natural resources on the surface. One of the remediation methods is to return the waste crushed salt to the mined out openings to reduce the roof and pillar deformations. Crushed salt has been widely recognized as the most suitable backfill material in salt and potash mines [1-3]. Its primary advantages are availability, low cost and compatibility with the host rock [4]. The volumetric strain and density of crushed salt can increase with consolidation periods and stresses [5]. Over long periods, crushed salt is expected to gradually reconsolidate into a material comparable to intact rock salt [6]. Backfilling with crushed salt may however lead to large time-dependent deformation of the openings because it can consolidate significantly under applied load induced by opening convergence [7]. Mixing of the crushed salt with a more rigid granular material can reduce its consolidation ability. In addition, the amount of crushed-salt obtained from processing plant is not adequate to backfill the mine openings. The crushed-salt backfill is commonly mixed with other geologic materials, e.g. sand and gravel. Sludge is being considered in the crushed-salt mixtures because it is a waste product obtained from water purification plant. It composes mainly of quartz [8] which tends to be chemically stable under underground environment.

The objective of this study is to assess the mechanical performance of sludge-crushed salt mixtures for use as backfill in potash mine openings. The task involves performing compaction and consolidation tests on various weight ratios of the sludge-to-crushed salt mixtures. The compaction test results can be used as initial installation parameters of the backfill.

2. Material Preparation

Sludge is collected from the purification plant of Metropolitan Waterworks Authority, Bangkok. It is oven-dried at 105°C for 24 hours or until its weight remained constant. The dried sludge is sieved to obtain particle sizes ranging from 0.001 to 0.475 mm (Figure 1). Based on Atterberg's limits testing it is classified as silt with over 80% silica. It has liquid limit = 59%, plastic limit = 31%, plastic index = 28%, and specific gravity = 2.56. Table 1 shows the chemical compositions of the sludge sample obtained from the X-Ray diffraction (XRD) analysis.

Crushed salt is prepared from Lower member of Maha Sarakham formation in the Korat basin, northeastern Thailand. It is virtually pure halite. Salt blocks are crushed by hammer mill to obtain grain sizes ranging from 0.075 to 2.35 mm (Figure 1). The specific gravity of salt is 2.160. This size range is equivalent to those expected to be obtained as waste product from the potash mine processing plant. Based on the Power [9] classification systems, the crushed salt is classified as angular to sub-angular with spherical shape.

Saturated brine is prepared by mixing pure rock salt with distilled water in plastic tank and stirred continuously. The salt is added until no further dissolution occurs. The concentration of salt in distilled water is measured as 39.1% by weight. The specific gravity of the saturated brine is measured as 1.211 at 21°C.

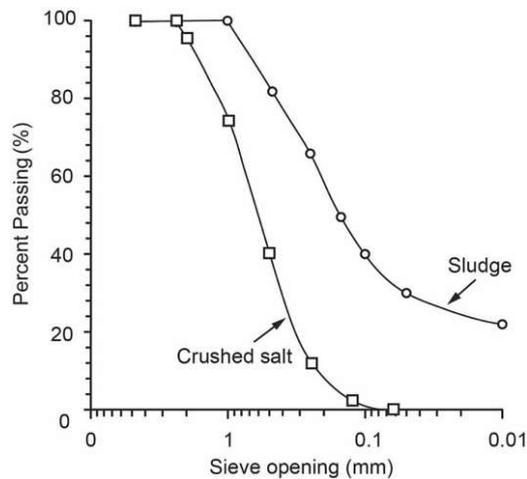


Figure 1 Grain size distributions of sludge and crushed salt.

Table 1 Chemical compositions of sludge.

Chemical compositions	weight (%)	Chemical compositions	weight (%)
SiO ₂	88.877	CuO	0.038
K ₂ O	4.932	ZnO	0.097
CaO	3.113	Ga ₂ O ₃	0.022
TiO ₂	0.993	Rb ₂ O	0.073
Cr ₂ O ₃	0.157	ZrO ₂	0.075
MnO ₂	1.547	PbO	0.076
Total		100	

3. Compaction Test

Three-ring mold [10] is used to perform compaction tests on the mixtures with sludge to crushed salt weight ratios (S:C) ranging from 30:70, 50:50 and 70:30 with brine content varied from 5%-45%. The mixtures are dynamically compacted with a release of weight steel hammer 10 pounds in three-ring mold of 27 times per layer for six layers, based on the ASTM (D1557-12e1) standard practice [11]. The moist density of the compacted sample is determined.

Figure 2 shows the relationship between dry densities and brine contents (by weight percent of dry mixture) for various sludge contents. The optimum brine contents (OW_b) range from 9.1% to 22.9%, and the maximum dry density ($\rho_{d,max}$) are from 1.51 to 1.73 g/cm³. The results show that the maximum dry density decreases, and optimum brine content increases with increasing sludge contents. These mixture ratios are used for the subsequent consolidation tests.

4. Consolidation Test

Consolidation tests are performed on the mixtures under their optimum brine content. The constant axial stresses range from 2.5, 5.0, 7.5 to 10.0 MPa, for periods of 0, 7, 15 and 30 days. The axial displacements are monitored using high precision dial gages ($\pm 0.001\text{mm}$). The axial displacements are used to calculate the axial (consolidation) strains (Figure 3).

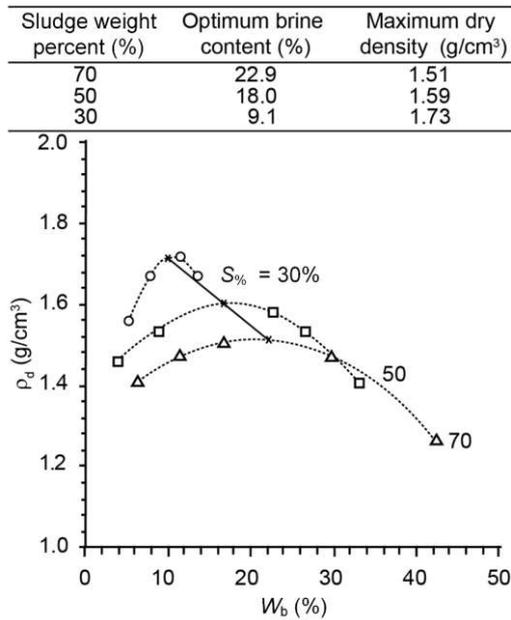


Figure 2 Dry density as a function of brine content $S\%$ = sludge weight percent, W_b = brine weight percent, and ρ_d = dry density.

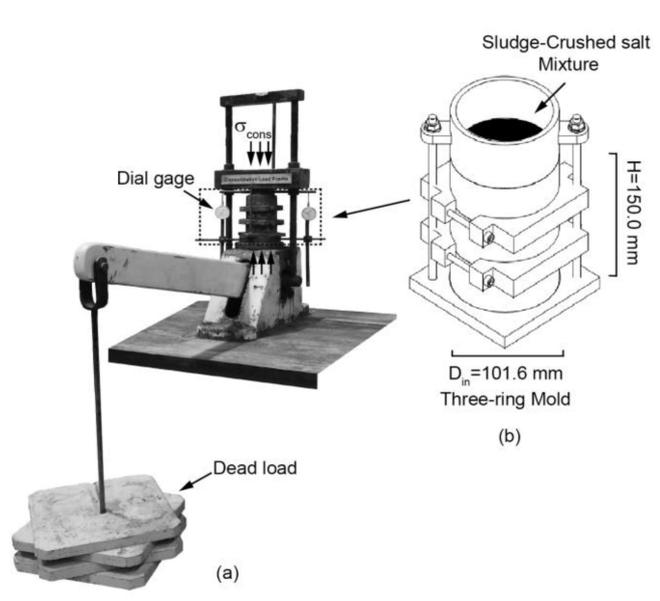


Figure 3 Consolidation frame (a) and three-ring compaction mold (b)

Figure 4 shows axial strains (ϵ_{cons}) as a function of time (t) up to 30 days. The results show that ϵ_{cons} increases with sludge contents, consolidation stresses (σ_{cons}) and duration. They increase rapidly after the axial stress is applied, and tend to increase at constant rates. The ϵ_{cons} of 30% and 50% sludge content specimens slowly decrease with time and tend to remain relatively constant after 15 days. The strain rates of 70% sludge mixtures tend to be independent of time. This may be because the sludge is an elastic silt and cohesionless material. Sludge particle sizes are smaller than 0.047 mm. They can fill and reduce void between crushed salt grains [12].

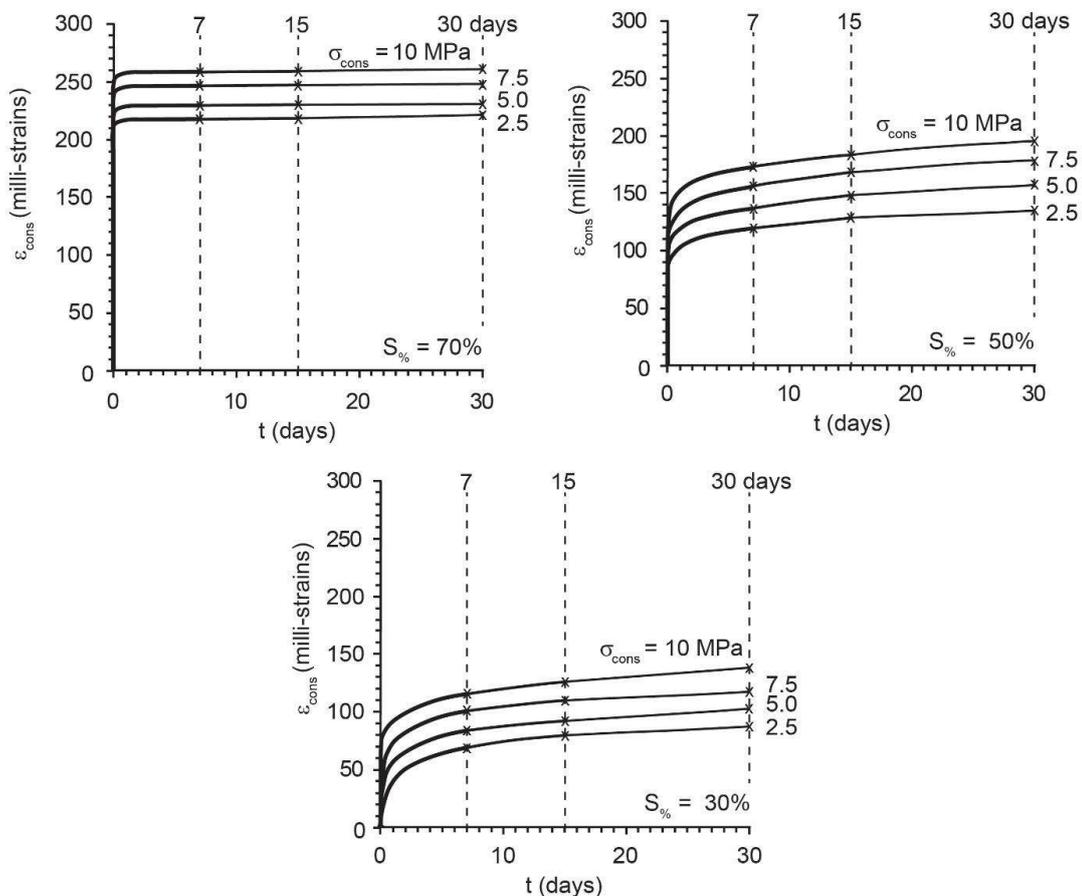


Figure 4 Axial (consolidation) strain (ϵ_{cons}) as a function of time (t) for different consolidation stresses (σ_{cons}). Dash lines indicate time at which each specimen is removed from three-ring mold.

5. Uniaxial Compressive Strength Test

After the specimen is consolidated according to the specified applied stress and period, it is removed from the mold for the compression strength testing. The sample preparation and test procedure follow the ASTM (D7012-14e1) standard practice [13]. The nominal diameters of the specimens are 101.6 mm with length-to-diameter ratios ranging from 2 to 3. The density of specimen is determined before compression testing. Neoprene sheets are used to minimize the friction at the interfaces between the loading

platen and the sample surface. The axial and lateral displacements are monitored to calculate the elastic properties (E and ν) of the specimen.

The results indicate that the density, strength and stiffness of the mixtures increase with increasing consolidation stresses and duration (Figure 5a). The uniaxial compressive strength, elastic modulus and Poisson's ratios decrease with increasing sludge contents (Figures 5b-5d). The results suggest that longer consolidation duration can make the specimen denser, stiffer, and stronger. This generally agrees with the results obtained from Wang et al. [1] and Miao et al. [7] who performed uniaxial compression test on compacted crushed salt specimens. Even though the increase of sludge content reduces the mechanical properties of the mixtures, it makes the mixtures less sensitive to consolidation period, i.e., the consolidation rate decreases with increasing sludge content.

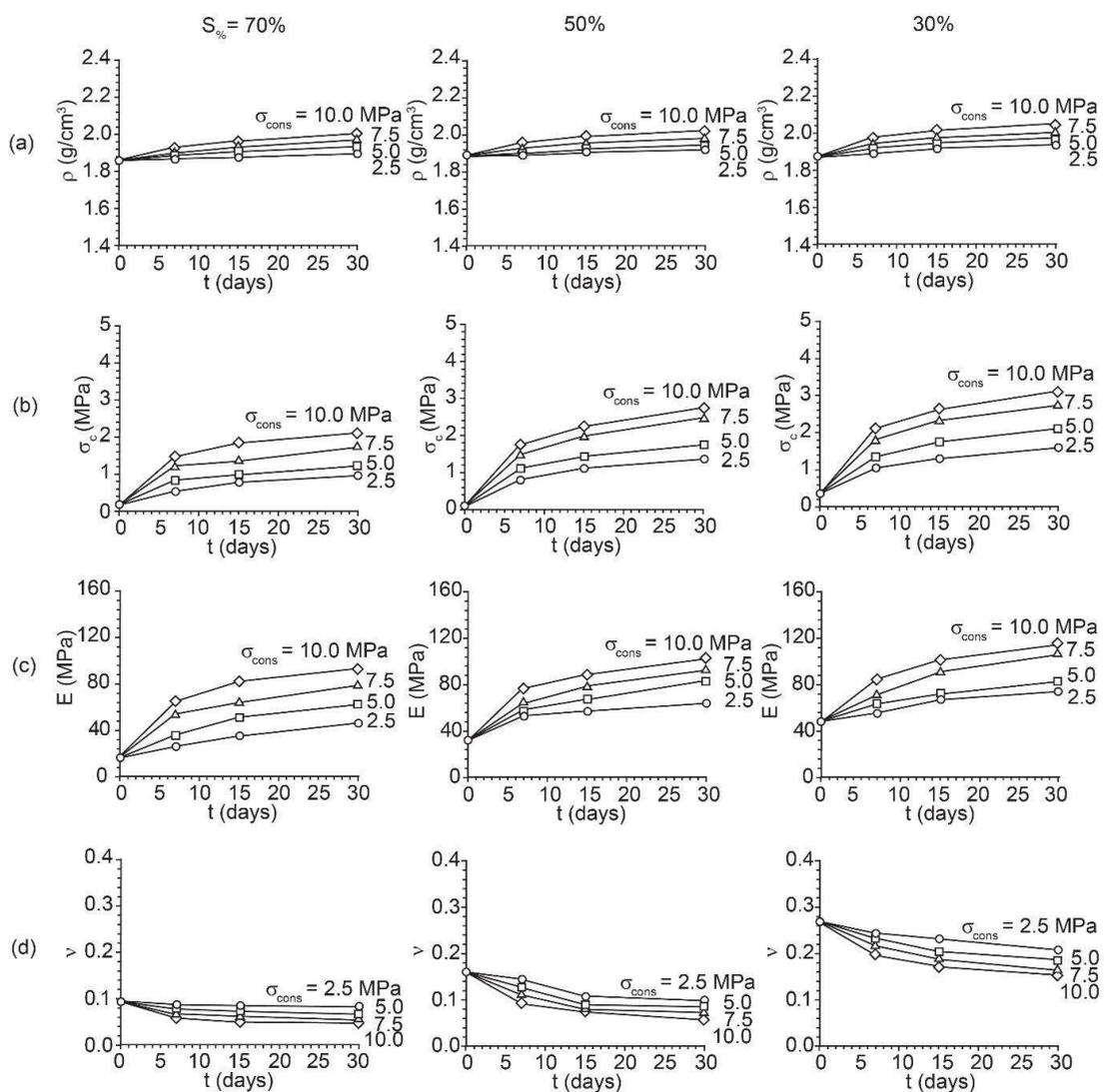


Figure 5 Density (ρ), uniaxial compressive strengths (σ_c), elastic modulus (E) and Poisson's ratio (ν) a function of consolidation period (t) for different consolidation stresses (σ_{cons}).

The results obtained here are compared with those obtained from Khamrat et al. [14] and Suwannabut et al. [15] in Table 2. They are consolidated under the same stress (5 MPa) and duration (15 days). The comparison suggests that the sludge content can significantly reduce the strength (σ_c) and stiffness (E) of the mixtures.

Table 2 Comparison of mechanical properties under $\sigma_{cons} = 5.0$ MPa for $t = 15$ days.

S:C (%)	Mixing fluid (% weight)	ρ (g/cm ³)	σ_c (MPa)	E (MPa)	K (MPa)	ν	Sources
0:100	5.0 (NaCl)	1.44	4.14	180.10	187.60	0.34	Khamrat et al. [13]
0:100	5.0 (MgCl ₂)	1.56	1.87	213.30	209.12	0.33	Suwannabut et al. [14]
30:70	9.1 (NaCl)	1.95	1.74	71.12	40.87	0.21	This study
50:50	18.0 (NaCl)	1.92	1.43	67.07	27.26	0.09	This study
70:30	22.9 (NaCl)	1.91	1.00	51.67	20.03	0.07	This study

6. Discussions and Conclusions

The compacted sludge-crushed salt specimens are consolidated under periods of 0–30 days. The results indicate that the optimum brine contents range from 9.1 to 22.9% by weight for the sludge-to-crushed salt mixture weight ratios of 30:70, 50:50 and 70:30. The maximum dry density decreases, and optimum brine content increases with increasing sludge contents which agree with the results obtained by Sattrra et al. [16]. The density increases with consolidation period. These findings agree well with those from other researchers [5,6,13,14]. The density, uniaxial compressive strength, elastic modulus and Poisson's ratio decrease with increasing sludge content. This is because sludge contains over 80% silica. It is cohesionless with grain size smaller than 0.047 mm. This makes the mixtures less rigid. Nevertheless, the sludge content can reduce the consolidation rate of the mixtures which makes them less sensitive to time. Selection of the appropriate mixing ratio for backfill depends largely on the availability of the materials and the site-specific location and depth of the openings. Mixtures with lower sludge content may be considered when or where the high strength backfill is required.

Acknowledgements

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