Consolidation of Crushed Salt Backfill for Salt and Potash Mines

S. Khamrat*, S. Somtong and K. Fuenkajorn

Geomechanics Research Unit, Suranaree University of Technology
111 University Avenue, NakhonRatchasima 30000, Thailand
* Supattra_khamrat@hotmail.com

Abstract

The objective of this study is to experimentally determine the mechanical and hydraulic performance of consolidated crushed salt as affected by applied stresses and consolidation period. The crushed salt has grain sizes ranging from 0.075 to 4.76 mm. The constant axial stresses are applied to the crushed salt samples installed in steel cylinders, varying from 2.5, 5, 7.5to 10 MPa. The nitrogen gas flow testing is performed to determine intrinsic permeability of crushed salt during consolidation up to 90 days. Higher axial stresses applied result in higher consolidation magnitude and density. The axial stresses and consolidation periodexponentially decreasethe void ratio and intrinsic permeability of the crushed salt. The uniaxial compressive strengths are measured after the samples have been consolidated for 3, 5, 7, 10, 15, 30, 90 days. The applied axial stresses and consolidation time increase the compressive strength and elastic modulus and decreases the Poisson's ratio.A set of empirical equation is developed to represent the strength (σ_c), elastic modulus (E), intrinsic permeability (k) and density (ρ) of the consolidated crushed salt as a function of mean stress (σ_m) and time (t) , as follows: $\sigma_c = \varphi \cdot \sigma_m^{\delta} \cdot t^{\eta}$, $E = \chi \cdot \sigma_m^{\upsilon} \cdot t^{\psi}$, $k = \alpha \cdot exp(\beta \cdot \sigma_m \cdot t)$, $\rho = \rho_0 + (\omega \cdot \sigma_m^{\kappa} \cdot t^{\lambda})$where ρ_0 = initial density, φ, δ, η, χ, υ, ψ, α, β, ω, κ and λ= empirical constants.The equations can be used to design the initial installation parameters in terms of the physical and mechanical properties of the crushed salt as backfill material in salt and potash mine openings.

Keywords: Crushed Salt, Backfill, Consolidation, Strength, Sealing

1. Introduction

The function of the crushed salt backfill is to act as a geotechnical long-term barrier against inflowing brine or water. Crushed salt has been widely recognized as the most suitable backfill material (Heemann et al., 1999; Case and Kelsall, 1987). Crushed salt can be compacted and its initial porosity and permeability will decrease. Over long periods, the crushed salt is expected to gradually reconsolidate into a material comparable to intact rock salt (Heemann et al., 1999). For crushed salt emplaced in an opening in a rock salt formation, the consolidation is driven by the creep closure of the adjacent rock. The primary advantages of crushed salt are availability, low cost and obvious compatibility with host rock (Stormont and Finley, 1996).

Miao et al. (1995) and Kelsall et al. (1984) suggest that the range of grain size for the consolidated crushed salt is 0.3 mm to 4.76 mm and 75 mm to about 0.05 mm, respectively. Wang et al. (1992) conducted several series of densification tests on crushed rock salt with water contents varying from 0.12% to 4.72%. The compaction of crushed salt increase with increasing brine content until the optimum brine content is reached, and decreases with further brine content increases. Brodsky et al. (1995) conducted hydrostatic and triaxial compression tests with brine content of 2.5% to 3% by weight. The results indicate that the permeability decreases approximately 2.1 orders of magnitude as fractional density increases from 0.9 to 1. The unconfined compressive strength and Young's modulus of crushed rock salt also increase with respect to densification time (Miao et al., 1995) and decreases with porosity (Kelsall et al., 1984). The relationship between void ratio and time are found to be exponential equations (Olivellaand Gens, 2002). The initial porosity and permeability decrease with increasing density (Case and Kelsall, 1987; Stührenberg, 2007; Lokenand Statham, 1997; Hansen and Mellegard, 2002; Salzer et al., 2007). Commonly employed theories on modeling creep of rock salt are rheological theories including empirical creep laws, viscoelasticity, elastic viscoplasticity theories, damage mechanics, hot-pressing theories and pressure solution theories (Miao et al., 1995; Olivella and Gens, 2002; Callahan and Hansen, 2002; Korthaus, 1999). The understanding of the consolidation behavior of crushed salt is an important precondition for repository design and for long-term safety assessment. Nevertheless, correlations between the physical (bulk density) and mechanical (strength and elasticity) properties of crushed salt after installation have rarely been established. Therefore, this study is conducted to establish a simple mathematical relationship. Only substituting time and consolidation stress values in the empirical equations, the physical and mechanical parameters can be obtained. Even though relatively extensive laboratory test results have been obtained for crushed salt behavior under consolidation, they can not readily be applied to the actual in-situ conditions. Most of the previous researchers have been concentrated on waste repository sealing. Their results may not be applicable to the salt and potash mine industry. The objectives of this study are to experimentally determine the mechanical properties of crushed salt as affected by consolidation pressure and period. Empirical relations have been derived to predict the mechanical properties of crushed salt as their density and porosity are reduced by consolidation. The results can also be used to define the initial installation parameters of the crushed salt to be used as backfill material in potash mine openings.

2. Crushed Salt Specimens

Crushed salt used in this study is prepared from the Middle member of the MahaSarakhamFormation (warren, 1999) in theKhorat basin, northeastern Thailand. The salts are crushed by hammer mill until has grain size ranging from 0.075 to 4.75 mm. This size range is equivalent to those expected to obtain as waste product from the potash mines. Saturated brine is prepared by mixing pure salt with distilled water in plastic tank. The proportion of salt to water is about 39% by weight. Specific gravity of the saturated brine ($S.G._B$) can be calculated by $S.G._B = \rho_{Brine}/\rho_{H_2O}$, where ρ_{Brine} is density of saturated brine (measured with a hydrometer, kg/m^3) and ρ_{H_2O} is density of water equal 1,000 kg/m^3. The specific gravity of the saturated brine in this study is 1.211 at 21°C. The optimum brine content are performed by applying axial stresses on loading steel piston to the crushed salt mixed with 0, 5 and 10% of saturated brine. The axial stresses are varied from 5, 10, 15 to 20 MPa. All tests are conducted under ambient temperature for 96 hours at the 5% and 10% of brine contents. The density of the consolidation specimens is similar. The proportion of saturated brine to crushed salt in this study is therefore determined as 5% by weight.

3. Consolidation Testing

The consolidation tests are performed by applying constant axial stresses on loading steel pistons to the crushed salt samples installed in the 54 mm diameter steel cylinders (Fig. 1). The constant axial stresses are 2.5, 5, 7.5 and 10 MPa. The axial displacements are continuously measured as a function of time by dial gages to calculate the changes of axial strain, density, and void ratio. The uniaxial compressive strength test procedure follows the ASTM standard practice (ASTM D2938-95). The nitrogen gas flow testing is performed to determine intrinsic permeability of crushed salt consolidation that changes over time. The flow rates under constant head are continuously monitored every 6 hours for 3, 5, 7, 10, 15, 30 and 90 days of each test conditions.The compressive strength of the consolidated crushed salts samples is determined by axially loading the crushed salt cylinder (after removing from the steel tube) with a nominal diameter of 54 mm and L/D ranging from 2 to 3. Uniaxial compressive strength measurements are made after 3, 5, 7, 10,15, 30 and 90 days of consolidation.

Results indicate that the consolidation magnitude and density of the crushed salt samples increase with applied axial stresses and consolidation time (Fig. 2). The permeability coefficient (K) can be calculated by ASTM (D2434-68): Δh=($\Delta P/\gamma_f$) where Δh is head difference (m); ΔP is difference pressure at the initial point and end point (kPa); and γ_f is unit weight of fluid (kN/m^3), the flow in longitudinal direction of a tested system is described by Darcy's law. The coefficient of permeability can be calculated from the equation (Indraratna and Ranjith, 2001)

$$Q = KA\,(\Delta h/L) \quad (1)$$

where$K$ is hydraulic conductivity (m/s); Q is flow rate (m^3/s); A is a cross-section area of flow (m^2); $\Delta h/L$ is hydraulic head gradient. The hydraulic conductivity used to calculate the intrinsic permeability (k) from equation:

$$k = (K\mu/\gamma_f) \quad (2)$$

where$k$ is intrinsic permeability (m^2); and μ is dynamic viscosity of N_2 (Pa·s).

The results indicate that when the consolidation increases the intrinsic permeability of crushed salt decreases, as shown in Fig. 3.The uniaxial compressive strengths are determined after removing from the steel tube. The results indicate that the uniaxial compressive strength and elastic modulus increase with the axial stress and consolidation duration. The Poisson's ratio decreases as the axial

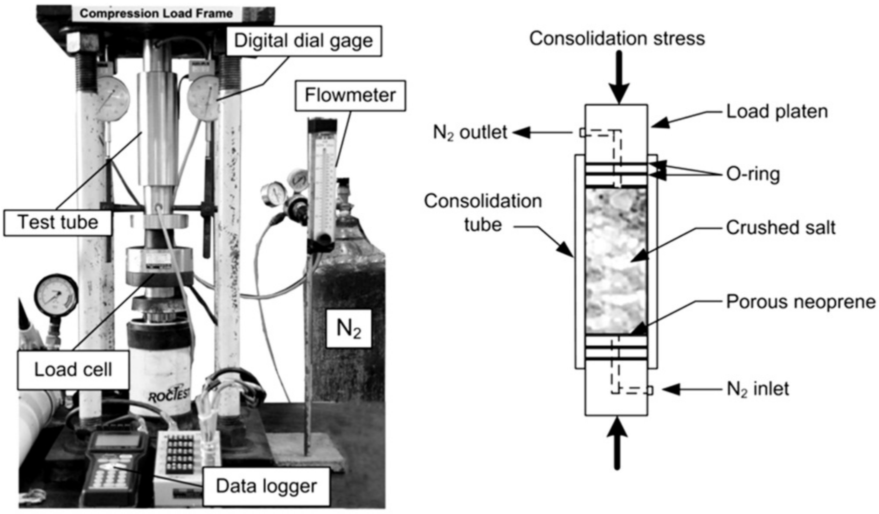

Fig. 1.Laboratory arrangement for consolidation testing.

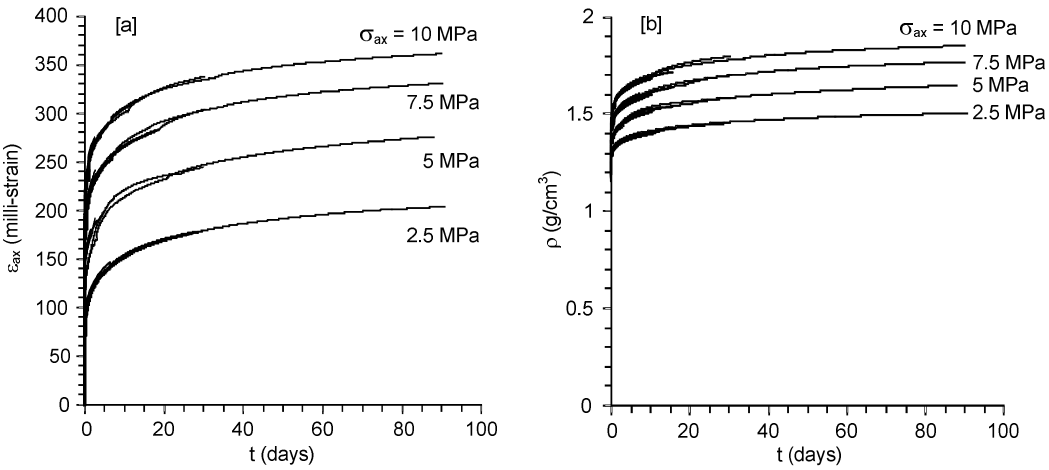

Fig. 2.Axial strain (ε_{ax}) [a] and density (ρ) [b] as a function of time (t) for different axial stresses (σ_{ax}).

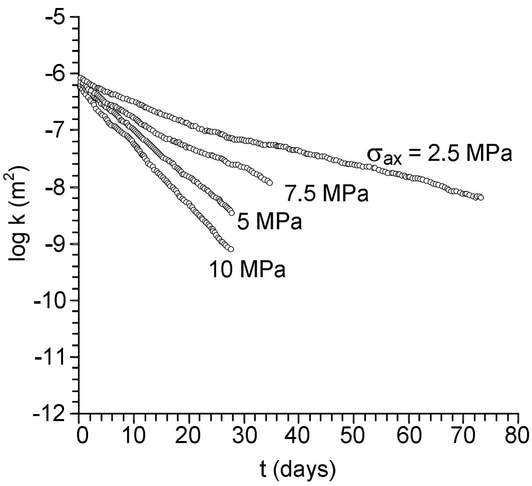

Fig. 3.Intrinsic permeability (k) as a function of time (t) and for different axial.

stresses and consolidation increases. The results are shown in Figs.4 and 5.The stresses of the sample are calculated as a function of time based on the uniaxial strain condition ($\varepsilon_1 \neq 0$, $\varepsilon_2 = \varepsilon_3 = 0$, $\sigma_2 = \sigma_3 \neq 0$). The axial strains from the measurement results represent the volumetric strain of crushed

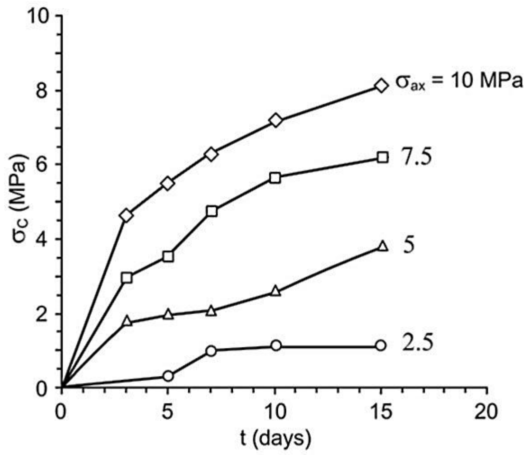

Fig.4. Uniaxial compressive strength (σ_c) as a function of consolidation time (t) for different consolidation stresses (σ_{ax}).

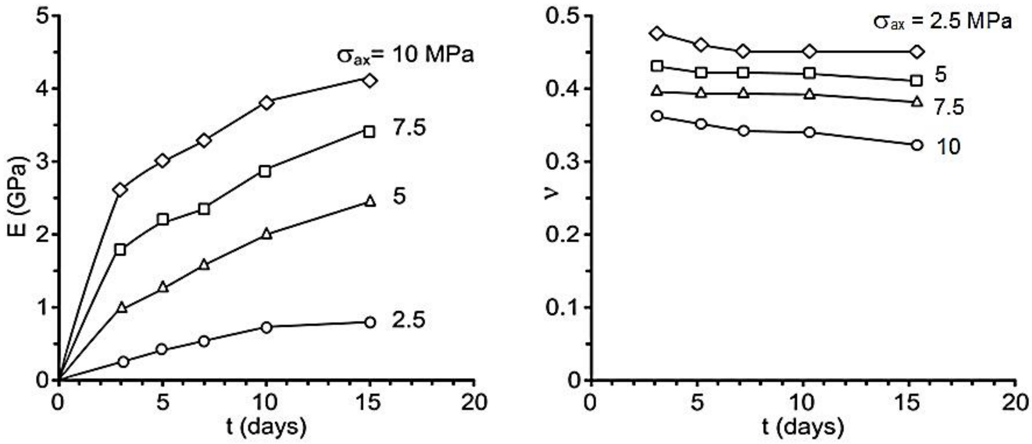

Fig.5. Elastic modulus (E) and Poisson's ratio (ν) as a function of time (t) for different consolidation stresses (σ_{ax}).

salt specimens. Poisson's ratio is calculated from the uniaxial strain and the lateral stresses (σ_3) as follows (Jaeger et al., 2007).

$$\sigma_2(t) = \sigma_3(t) = [\nu(t)/(1-\nu(t))]\sigma_1 \tag{3}$$

where σ_2(t) and σ_3(t) are lateral stresses exerted as a function of time, ν(t) is Poisson's ratio and σ_1 is constant consolidation stress (σ_{ax}). The mean stresses as a function of time [σ_m (t)] are also determined using the following relations (Jaeger et al., 2007)

$$\sigma_m(t) = (\sigma_{ax} + 2\sigma_3(t))/3 \tag{4}$$

where σ_{ax} is consolidation stress, and σ_3(t)is lateral stress, changing with time.Mean stresses are found to decrease with the increase of axial stresses and time (Fig. 6).

4. Predications

The results above are used to develop a set of empirical equation as a function of mean stress and time. The regression analysis on the test data using IBM SPSS Statistics 19 (Wendai, 2000) isperformed to determine the relevant parameters. The relationships between density,strength, elastic modulus, intrinsic permeabilityas a function of mean stress and time are non-linear which can be represented by a power equation:

$$\rho(t) = \rho_0 + (\omega\cdot\sigma_m{}^{\kappa}\cdot t^{\lambda}) \tag{5}$$

$$\sigma_c = \varphi\cdot\sigma_m{}^{\delta}\cdot t^{\eta}, \tag{6}$$

$$E = \chi\cdot\sigma_m{}^{\upsilon}\cdot t^{\psi} \tag{7}$$

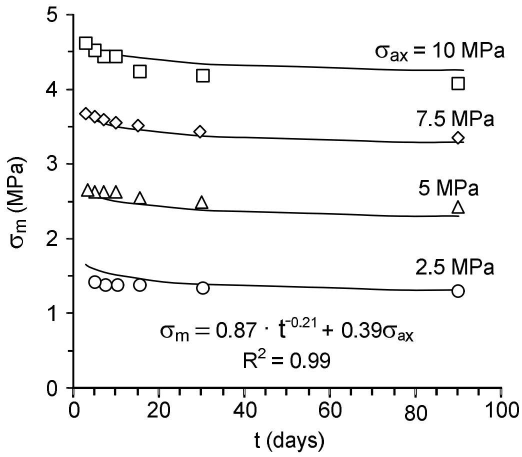

Fig. 6. Mean stress (σ_m) as a function of time (t) for different axial stresses (σ_{ax}).

$$k = \alpha \cdot exp(\beta \cdot \sigma_m \cdot t) \quad (8)$$

where $\rho(t)$ is density as a function of time, ρ_0 is initial density (g/cm^3), σ_c is uniaxial compressive strength of crushed salt specimen (MPa),t is time for consolidation (days), and ω, κ,λ,φ, δ, and $\eta$are empirical constants. Good correlation between the constitutive equation and the test data is obtained. The equation can be used to predict density,uniaxial compressive strength, elastic modulus andintrinsic permeability under varied mean stresses ranging from 1 to 5MPa and consolidation time at6 months are shown in Figs. 7, 8 and 9.

5. Discussion and Conclusions

The consolidation of crushed salt increases with increasing brine content until the optimum brine content is reached, which is 5% by weight. The volumetric strain and density increase with consolidation stresses and time. These findings agree well with those from other researchers (Stührenberg, 2007; Loken and Statham, 1997; Hansen and Mellegard, 2002; Salzer, 2007). The test results are used to develop a set of empirical equation as a function of mean stress and time. The empirical equation can be used to predict the volumetric strain and density occurred after time periods and under any mean stresses. The predictions indicate that the density of consolidated crushed salt will be similar intact salt (2.2 g/cm^3) after 6 months under mean stress of5MPa.

The uniaxial compressive strength and elastic modulus increase with the consolidation magnitude and period.The predictions indicate that the uniaxial compressive strength of consolidated crushed salt will be close to the intact salt (27.3MPa) after 6 months under mean stress of5MPa. The elastic modulus is 0.37GPa after 15 days of consolidation.

The intrinsic permeability decreases as the consolidation increases. The lowest intrinsic permeability is observed for 10 MPa consolidation stresses which equal to 1.15×10^{-11} m^2 after 30 days of consolidation. The predictions indicate that the intrinsic permeability will be reduced to an order of magnitude of the permeability of intact salt ($\approx 1.0\times 10^{-21}$ m^2, Loken and Statham, 1997) after about 4 months under mean stress of5MPa.

The proposed empirical equations can be used to predict the mechanical properties of crushed salt after installation as backfill material in the mine openings. Such application however requires that the volumetric closure and the stressed at the contact between the opening wall and the backfill material are known. As a result numerical simulation may be performed to provide the closure strains and contact stresses at the mine opening and backfill interface.

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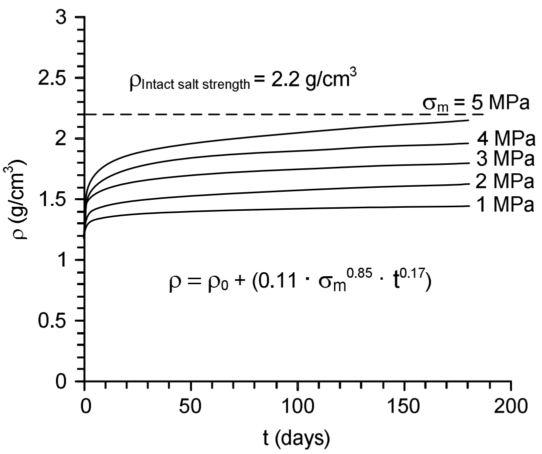

Fig. 7.Predicted density (ρ) time curves for different mean stresses (σ_m).

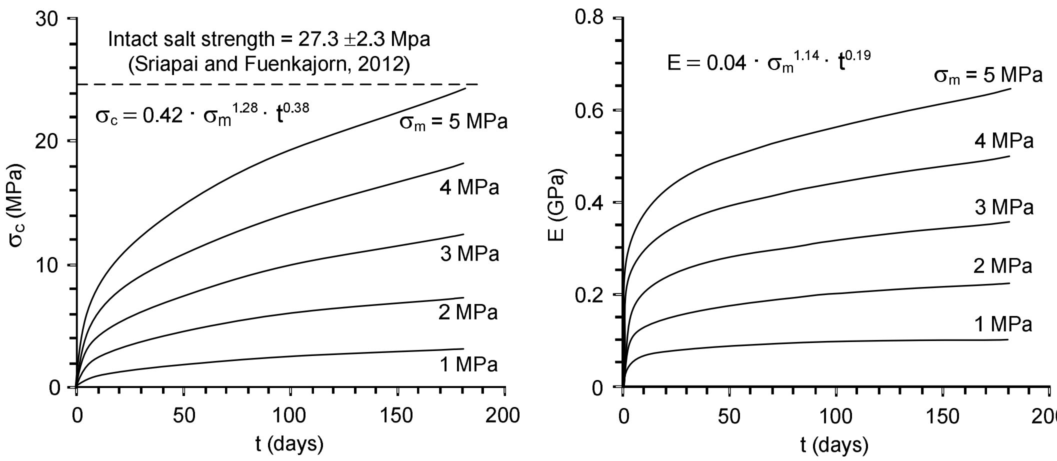

Fig. 8. Predicted uniaxial compressive strength (σ_c) as a function of time (t) for different mean stresses (σ_m).

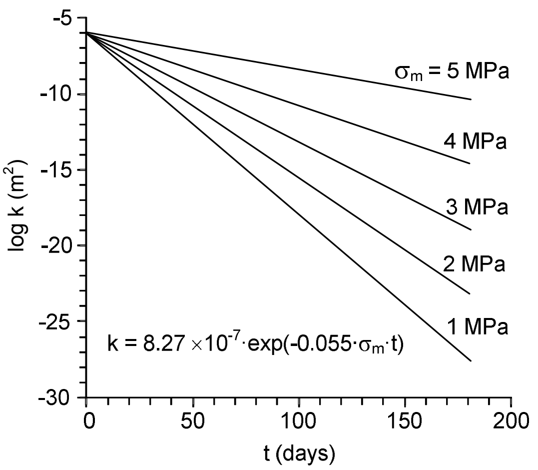

Fig. 9.Intrinsic permeability (k) as a function of mean stress (σ_m) and time (t).

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