LABORATORY ASSESSMENT OF COMPRESSIVE STRENGTH AND PERMEABILITY OF CRUSHED SALT DURING CONSOLIDATION

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นายสมพงศ์ โสมทอง

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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สมพงศ์ โสมทอง : การทดสอบกำลังกดและความซึมผ่านของเกลือหินบดระหว่างการอัดตัวคายน้ำ (LABORATORY ASSESSMENT OF COMPRESSIVE STRENGTH AND PERMEABILITY OF CRUSHED SALT DURING CONSOLIDATION)
อาจารย์ที่ปรึกษา : ศาสตราจารย์ ดร.กิตติเทพ เฟื่องขจร, 66 หน้า.

วัตถุประสงค์ของการศึกษานี้คือเพื่อศึกษาค่ากำลังกดและค่าความซึมผ่านของตัวอย่างเกลือหินบดคละขนาด (ตั้งแต่ 0.075 ถึง 4.75 มิลลิเมตร) ภายใต้ผลกระทบของความเค้นกดและระยะเวลาในการกดอัดที่สภาวะอุณหภูมิห้อง การทดสอบเพื่อหาปริมาณน้ำเกลือที่ทำให้ตัวอย่างเกลือหินบดมีความหนาแน่นสูงสุด ผลที่ได้คือส่วนผสมระหว่างเกลือหินบดและน้ำเกลือเข้มข้นในอัตราส่วนร้อยละ 5 โดยน้ำหนัก การทดสอบดำเนินการโดยให้ความเค้นกดแก่ตัวอย่างเกลือหินบดในกระบอกทดสอบด้วยความเค้นกดในแนวแกน 2.5, 5, 7.5 และ 10 เมกะปาสคาล เป็นระยะเวลา 3, 5, 7, 10 และ 15 วัน ระหว่างการทดสอบทำการตรวจวัดค่าความซึมผ่านเชิงกายภาพอย่างต่อเนื่อง และทำการทดสอบค่ากำลังกดสูงสุดในแกนเดียวหลังจากนำตัวอย่างเกลือหินบดออกจากกระบอกทดสอบเมื่อครบระยะเวลาการกดทดสอบของแต่ละตัวอย่างการทดสอบแล้ว ความเครียดในแนวแกนของตัวอย่างเกลือหินบดถูกตรวจวัดเพื่อใช้คำนวณค่าการยุบตัวและความหนาแน่น ผลการทดสอบสรุปว่าค่าการยุบตัว ความหนานแน่น และค่ากำลังกดของตัวอย่างเกลือหินบดมีค่าเพิ่มขึ้นตามความเค้นกดและระยะเวลา ในขณะที่ค่าความซึมผ่านเชิงกายภาพ และอัตราส่วนช่องว่างมีค่าลดลงเมื่อความเค้นกดและระยะเวลาเพิ่มขึ้น ผลการทดสอบสามารถนำมาสร้างความสัมพันธ์ทางคณิตศาสตร์เพื่อประยุกต์ใช้ในการคาดคะเนพฤติกรรมการอัดตัว ค่ากำลังกดสูงสุดและค่าความซึมผ่านของตัวอย่างเกลือหินบด เพื่อเป็นแนวทางในการออกแบบและเลือกใช้เกลือหินบดเป็นวัสดุถมกลับในช่องว่างเหมืองเกลือและโปแตสในระยะยาวต่อไป

สาขาวิชา เทคโนโลยีธรณี ลายมือชื่อนักศึกษา________________________
ปีการศึกษา 2556 ลายมือชื่ออาจารย์ที่ปรึกษา___________________

SOMPONG SOMTONG : LABORATORY ASSESSMENT OF COMPRESSIVE STRENGTH AND PERMEABILITY OF CRUSHED SALT DURING CONSOLIDATION. THESIS ADVISOR : PROF. KITTITEP FUENKAJORN, Ph.D., P.E., 66 PP.

BACKFILL/CONSOLIDATION/PERMEABILITY/STRENGTH/SEALING

The objective of this study is to determine the strength and permeability of crushed salt as affected by applied stresses and consolidation period. The crushed salt has grain sizes ranging from 0.075 to 4.75 mm. The optimum brine content is determined as 5% by weight. The consolidation tests are performed by applying constant axial stresses to the crushed salt samples installed in the 54 mm diameter steel cylinders. The axial stresses are 2.5, 5, 7.5 and 10 MPa. The permeability is continuously monitored while the uniaxial compressive strengths are measured after the samples have been consolidated for 3, 5, 7, 10 and 15 days. The axial strains are monitored and used to calculate the magnitude of the consolidation for each specimen. The consolidation magnitude and density of the crushed salt samples increases with the applied stresses. The uniaxial compressive strength increases with the consolidation. The porosity and intrinsic permeability decreases as the consolidation increases. The test results are used to develop a set of empirical equations to design the initial installation parameters in terms of the physical, mechanical and hydraulic properties of the crushed salt. The consolidated crushed salt is tentatively used as sealing materials in the voids and gaps occurred in the underground salt and potash mines.

School of Geotechnology — Student's Signature ________________

Academic Year 2013 — Advisor's Signature ________________

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Sompong Somtong

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SYMBOLS AND ABBREVIATIONS

ρ	=	Density
μ	=	Dynamic viscosity
α	=	Empirical constant
β	=	Empirical constant
φ	=	Empirical constant
δ	=	Empirical constant
η	=	Empirical constant
ν	=	Poisson's ratio
ρ_0	=	Initial density
ε_2, ε_3	=	Lateral strain
σ_2, σ_3	=	Lateral stress
ε_{ax}, ε_1	=	Axial strain
σ_{ax}, σ_1	=	Axial stress, Consolidation stress
σ_C	=	Uniaxial compressive strengths
γ_f	=	Unit weight of fluid
Δh	=	Head different
ΔL	=	Length changes over time
σ_m	=	Mean stress
ΔP	=	Pressure different

SYMBOLS AND ABBREVIATIONS (Continued)

$\Delta v/v$	=	Volumetric strain
A	=	Cross section area of flow
A	=	Empirical constant
B	=	Empirical constant
C	=	Empirical constant
D	=	Empirical constant
E	=	Elastic modulus
E	=	Empirical constant
e	=	Void ratio
F	=	Empirical constant
k	=	Intrinsic permeability
K	=	Permeability coefficient
L	=	Length
m	=	Weight
N_2	=	Nitrogen gas
Q	=	Flow rate
t	=	Time of consolidation
v	=	Volume

CHAPTER I

INTRODUCTION

1.1 Background of problems and significance of the study

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. The crushed salt can be compacted and its initial porosity and permeability will decrease. Over long time periods, the crushed salt is expected to gradually reconsolidate into a material comparable to intact rock salt (SalzerK et al., 2007). 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.

Crushed salt backfill has long been investigated as a potential backfill and seal material through laboratory testing to determine the fundamental properties, such as permeability, porosity and creep rate which can be reduced by pressure and time through consolidation. 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), hydrological (porosity and permeability) and mechanical (strength and elasticity) properties of crushed salt after installation have rarely been established.

1.2 Research objectives

The objectives of this study are to experimentally determine the mechanical and hydraulic performance of consolidated crushed salt under ambient temperatures, and to derive mathematical relationships between the physical, hydrological and mechanical properties of crushed salt as affected by applied stresses and time.

The samples are prepared by crushing of the Maha Sarakham salt. The test results are used to develop a set of empirical equations to design the initial installation parameters in terms of the physical, mechanical and hydraulic properties of the crushed salt.

1.3 Research methodology

The research methodology shown in Figure 1.1 comprises 6 steps; including literature review, crushed salt preparation, fabrication of test cylinder, consolidation permeability and uniaxial compressive strength testing, development of empirical equations and discussions and conclusions.

1.3.1 Literature review

Literature review is carried out to study the previous research on consolidation testing, mechanical and hydraulic properties of crushed salt. The sources of information are from text books, journals, technical reports and conference papers. A summary of the literature review were given in chapter two.

1.3.2 Crushed salt preparation

Crushed salt used in this study have been obtained from the Middle member of the Maha Sarakham Formation in the Korat basin, northeastern Thailand. The salt cores are crushed by hammer mill (2HP-4 POLES, Spec jis c-4004) until to obtain grain size ranging from 0.075 to 4.75 mm. 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.

1.3.3 Consolidation tube

The cylindrical steel tube with 54 mm internal diameter, 64 mm outside diameter and 200 mm height is used as consolidation tube. Two load platens having 53 mm diameter with 100 mm length are to applied axial load to the crushed salt specimens. Two o-rings are installed around each load platen. There is a 10 mm diameter hole at the center of the top and bottom load platens for use as inlet of N_2 to specimens for permeability testing and drained water from specimen.

1.3.4 Mechanical and hydraulic testing

The consolidation tests are performed by applying constant axial stresses from a hydraulic load pump to the crushed salt samples installed in the 54 mm diameter steel cylinders. The constant axial stresses are 2.5, 5, 7.5 and 10 MPa. All tests were conducted under ambient temperature. The axial displacement was continuously measured by dial gage to calculate the axial strain, density, and void ratio that change over time. Permeability test was continuously monitored every 6 hour by installed 10 psi pressure N_2 into the tube to measure permeability of crushed salt at that time. The uniaxial compressive strengths were measured by removing the consolidated crushed salt from the test tube after the samples are consolidated for 3, 5, 7, 10 and 15 days.

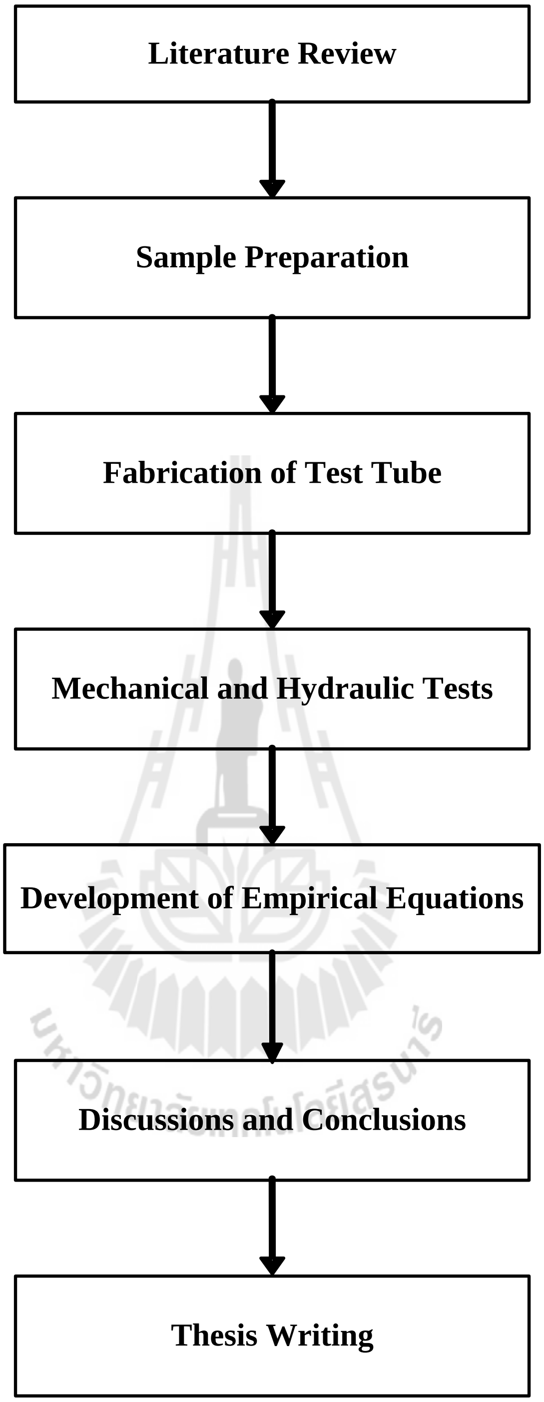

Figure 1.1 Research methodology

1.3.5 Derivation of empirical equations

The test results are used to develop a set of empirical equations to design the initial installation parameters in terms of the physical, mechanical and hydraulic properties of the crushed salt. The equations will correlate the applied axial stresses, consolidation periods, uniaxial compressive strengths, void ratios, densities and permeability of the consolidated crushed salt

1.3.6 Conclusion and thesis writing

All research activities, methods, and results were documented and complied in the thesis. The research or findings will be published in the conference proceedings or journals.

1.4 Scope and limitations of the study

The scope and limitations of the study include as follows.

1. Laboratory experiments will be conducted on crushed salt specimens from the Maha Sarakham formation. The crushed salt has grain sizes ranging from 0.075 to 4.75 mm.
2. The consolidation tests will be performed by applied constant axial stresses to the crushed salt samples installed in the 54 mm diameter steel cylinders with length 200 mm.
3. The crushed salt is consolidated for 3, 5, 7, 10, and 15 days with applied constant axial stresses of 2.5, 5, 7.5 and 10 MPa.
4. All tests will be conducted under ambient temperature.
5. The research findings will be published in conference paper or journal.

1.5 Thesis contents

This first chapter introduces the thesis by briefly describing the rationale and background and identifying the research objectives. The third section identifies the research methodology. The fourth section describes scope and limitations. The fifth section gives a chapter by chapter overview of the contents of this thesis.

The second chapter summarizes results of the literature review. Chapter three describes crushed salt preparation and the fabrication of test cylinder. The laboratory tests and results of all tested are presented in chapter four. The development of empirical equations are describes in chapter five. Chapter six discusses the research results. Chapter seven provides the conclusions and recommendations for future research studies.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Relevant topics and previous research results are reviewed to improve an understanding of the mechanical and hydraulic behavior of crushed salt and the consolidation techniques. The initial results of literature review are summarized below.

2.2 Literature review

Kelsall et al. (1985) propose to use crushed salt as a major backfill component in schematic designs for penetration seal for salt repositories. Creep closure of the storage room, tunnels, and shafts is likely to compress the crushed salt backfill and create an impermeable monolith to retard ground water flow and radionuclide migration.

Shor et al. (1981) first suggest that the consolidation of granular salt may be greatly enhanced by the presence of brine. Investigations by Miller (1993), Liedtke and Bleich (1984), IT Corporation (1987), Pfeifle et al (1987), and Holcomb and shields (1987) confirm the increased consolidation rate upon the addition of small amounts of water.

Ran and Daemen (1995) study and present results of laboratory compaction testing to determine the influence of particle size, size gradation and moisture content on compaction of crushed rock salt. Included is a theoretical analysis of the optimum size gradation. The objective is to evaluate the relative densities that can be achieved with tamping techniques. Initial results indicate that compaction increases with maximum particle size and compaction energy, and varies significantly with particle size gradation and water content until the optimum water content is reached (5%), and decreases with further water content increases (Figure 2.1).

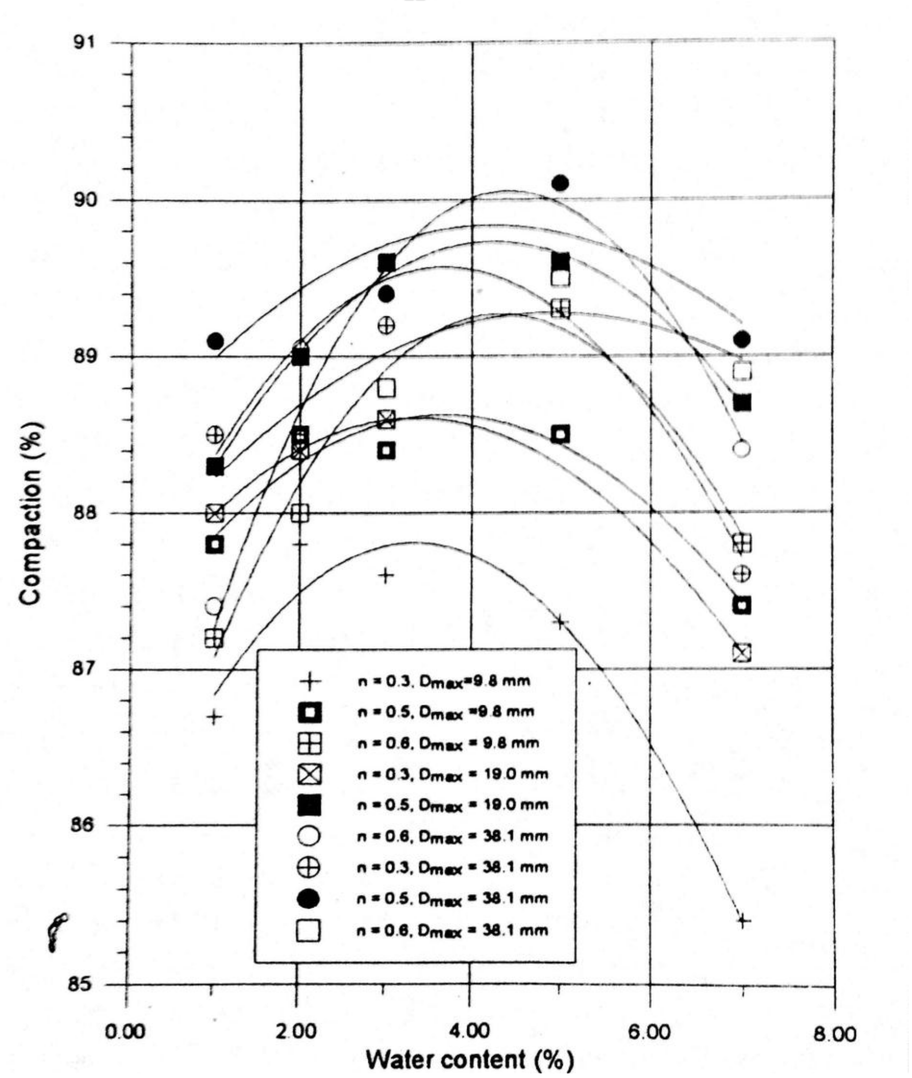

Figure 2.1 Compaction as a function of water content and particle size gradation (Ran and Deamen, 1995).

Case and Kelsall (1987) study the potential of crushed for required sealing access shafts and drifts for long periods. Crushed salt backfill is being investigated as a potential backfill and seal material through laboratory testing to determine how fundamental properties such as permeability, porosity and creep rate are reduced by pressure and time through consolidation. The test program reported in this paper consisted of four consolidation tests using crushed salt obtained from the Waste Isolation Pilot Plant and the Avery Island Mine. Tests with one- or two-month durations were conducted on samples with maximum particle sizes of 1, 10, and 20 mm, with initial porosities ranging from 26 to 36%, moisture contents of zero and 2%, and initial permeability from 10^{3} to 10^{5} m^{2}. The tests were performed at ambient temperature and confining pressures ranging from 0.34 MPa to 17 MPa. The most significant observation from the tests was the influence of moisture on changes in permeability, porosity and volumetric creep strain rate. The final permeability and porosity of one moist sample were reduced after one month to about 10^{-5} m^{2} and 5%, respectively, compared to about 10^{-2} m^{2} and 14 to 19% for the dry samples. In addition, the consolidation rate for the moist sample was more rapid at comparable porosities. In all of the tests, the volumetric creep strain rate tanged from 10^{-8} to 10^{-6} /sec, and did not achieve steady state values after 1 to 2 months of load application.

Butcher (1991) concludes that a 70% by weight salt and 30 % by weight bentonite mixture is preferable to pure crushed salt as backfill for disposal rooms in the Waste Isolation Pilot Plant. The performance of two backfill materials is examined with regard to various selection criteria related to compliance with the transuranic radioactive waste standard 40 CFR 191, Subpart B, such as the need for low liquid permeability after closure, chemical stability, strength, ease of emplacement, and sorption potential for brine and radionuclides. Both salt and salt/bentonite are expected to consolidate to a final state of permeability ≤ 10^{-18} m^2, which is adequate for satisfying government regulations for nuclear repositories. The real advantage of the salt/bentonite backfill depends, therefore, on bentonite's potential for absorbing brine and radionuclides. Estimates of the impact of these properties on backfill performance are presented.

Ran et al. (1997) propose to use bentonite as a primary material for sealing shafts of nuclear waste repositories. It possesses low permeability, chemical and physical stability, and compatibility with most host rock masses and groundwater chemistries. This paper investigates the construction properties of bentonite and evaluates the use of dynamic compaction in constructing an effective bentonite shaft seal. Extensive laboratory tests of dynamic compaction have been conducted to study the densification of granular bentonite mixed with distilled deionized water or with brine from the Waste Isolation Pilot Plant (WIPP). Results of the dynamic compaction investigations delineate the influence of moisture content, compactive energy, mixed brine content, lift thickness, and rammer weight on the achievable dry density. Dynamic compaction can densify bentonite to a dry density of 1.86 Mg/m^3 when mixed with WIPP brine and 1.74 Mg/m^3 when mixed with distilled deionized water. At these densities bentonite exhibits permeabilities on the order of 1.0×10^{-19} m^2.

Pudewills and Krauss (1999) present the numerical modeling of the thermomechanical behavior of crushed salt using a viscoplastic constitutive model. In the ADINA finite element code the viscoplastic model that considers both volumetric and deviatoric strain rates under hydrostatic and shear stress conditions proposed by Hein (Hein HJ. Ein stoffgesetz zur Beschreibung des thermomechanischen Verhaltens von Salzgranulat. Dissertation, RWTH Aachen, 1991) is implemented. A series of exercises were designed to verify the numerical implementation and the theoretical formulation of the proposed model. The applicability of the model to predicting the consolidation of a crushed salt specimen with step-wise stress increase and decrease, performed in laboratory tests. Mathematical equation proposed by Hein (1991) is as follows:

$$\dot{\varepsilon}_{ij} = A \cdot \exp^{-Q/RT} \cdot (h_1 \cdot p^2 + h_1 \cdot q^2)^n \cdot (\frac{1}{3} h_1 \cdot p \cdot I + h_2 S_{ij}) \tag{2.1}$$

$$h_1 = \frac{a}{[((\eta_0 / \eta)^c - 1) / \eta_0^c + d]^m} \tag{2.2}$$

$$h_2(\eta) = b \cdot h_1(\eta) + 1 \tag{2.3}$$

where $\dot{\varepsilon}_{ij}$ is the strain occurring, η is the porosity, η_0 is the initial porosity, T is the absolute temperature, p is the mean stress perpendicular, I was the Tensor metric, Q is the activation energy, R is the gas constant, q is the a variation of stress S_{ij} is the stress deviation tensor, A, b, c, d, m, n are constants of the equation, and the Q / R is a constant equal to 6520 K^{-1} of the consolidation (Oedometer test) with strain rate $6.9x10^{-9}$ s^{-1}. The results are consistent with the results of laboratory tests. The simulation model and compression stresses increase to 3 levels by 15 days/step, compared to the average stress and the changes of porosity. The results of simulation and experiment were found to be consistent as well. The simulation results will provide a slightly lower value (Figure 2.2).

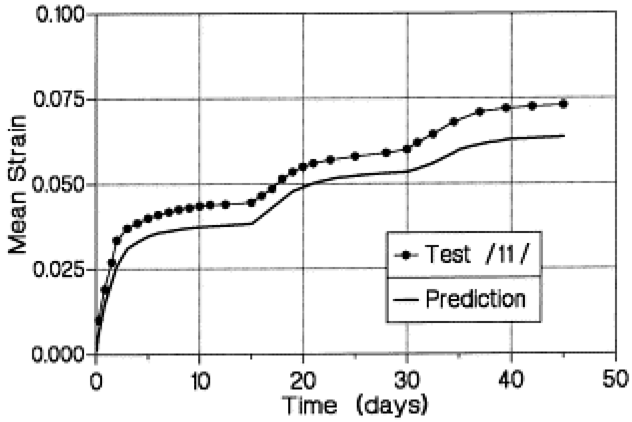

Figure 2.2 Numerical predicted and test measured mean strain. (Pudewills and Krauss, 1999).

Wagner et al. (1990) present the numerical calculations of disposal room configurations at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM are presented. Specifically, the behavior of either crushed salt or a crushed salt-bentonite mixture, when used as a backfill material in disposal rooms, is modeled in conjunction with the creep behavior of the surrounding intact salt. The backfill consolidation model developed at Sandia National Laboratories was implemented into the SPECTROM-32 finite element program. This model includes nonlinear elastic as well as deviatoric and volumetric creep components. Parameters for the models were determined from laboratory tests with deviatoric and hydrostatic loadings. The performance of the intact salt creep model previously implemented into SPECTROM-32 is well documented.

Development of the creep consolidation constitutive equation used in SPECTROM-32 was guided by general consideration with specific functional forms taken from empirical relations matched to available laboratories data. Two continuum internal variables were assumed, the average inelastic volumetric strain, ε_{eq1}^{c} , and the average equivalent inelastic shear strain, ε_{eq2}^{c}

$$\dot{\varepsilon}_{ij}^{c} = \dot{\varepsilon}_{eq1}^{c} \frac{\partial \sigma_{eq1}^{f}}{\partial \sigma_{ij}} + \dot{\varepsilon}_{eq2}^{c} \frac{\partial \sigma_{eq2}^{f}}{\partial \sigma_{ij}} \tag{2.4}$$

$$\dot{\varepsilon}_{eq1}^{c} = \dot{\varepsilon}_{v}^{c} (\sigma_m) \tag{2.5}$$

$$\dot{\varepsilon}_{v}^{c} = \frac{(1+\varepsilon_v)^2}{\rho_0} B_0 \left[1 - e^{-b_1 \sigma_m}\right] e^{\frac{A\rho_0}{1+\varepsilon_v}} \tag{2.6}$$

where

$\varepsilon_v = \varepsilon_{kk}$, total volumetric strain

$\varepsilon_v^c = \varepsilon_{kk}^c$, volumetric creep strain

$\sigma_m = \frac{\varepsilon_{kk}}{3}$, mean stress

ρ_0 = initial density

B_0, B_1, A = material constants

Results from the SPECTROM-32 analyses were compared to a similar study conducted by Sandia National Laboratories using the SANCHO finite element program. The calculated deformations and stresses from the SPECTROM-32 and SANCHO analyses agree reasonably well despite differences in constitutive models and modeling methodology. These results provide estimates of the backfill consolidation through time. The trends in the backfill consolidation can then be used to estimate the permeability of the backfill and subsequent radionuclide transport.

Loken and Statham (1997) proposed to use crushed salt from the host Salado formation as a sealing material in one component of a multicomponent seal system design for the shafts of the Waste Isolation Pilot Plant (WIPP), a mined geological repository for storage and disposal of transuranic radioactive wastes located near Carlsbad, New Mexico. The crushed salt will be compacted and placed at a density approaching 90 percent of the intact density of the host Salado salt. Creep closure of the shaft will further compact the crushed salt over time, thereby reducing the crushed-salt permeability from the initial state and creating an effective long-term seal. A structural model and a fluid flow model have been developed to provide an estimate of crushed-salt reconsolidation rate as a function of depth, time, and pore pressure. Model results are obtained in terms of crushed-salt permeability as a function of time and depth within the salt column.

The fluid in the crushed salt was assumed to behave as a linear elastic material in which the fluid pressure is related to the volume strain through the bulk modulus as:

$$P = \text{MIN}\{P_0 + K(1 - V/V_0), P_{max}\} \tag{2.7}$$

where:

P = fluid pressure (MPa)

P_0 = initial fluid pressure (MPa)

K = fluid bulk modulus (MPa)

V = current volume 0f crushed salt (m^3)

V_0 = initial volume (based on 90 percent fractional density) (m^3)

P_{max} = maximum fluid pressure (MPa)

A model was developed that relates permeability and density of crushed salt. Laboratory measurements indicate that the permeability decreases as density increases (Figure 2.3). Furthermore, the density of the crushed salt in the column seal will increase with time during reconsolidation because of creep of the surrounding salt. It was determined that a linear model relating permeability (transformed into logarithmic space) and fractional density was a good approximation to the laboratory data over the range of density tested. A linear least-square fit was performed using the following model:

$$\log(k) = m\rho + b \tag{2.8}$$

where k is intrinsic permeability with units of m^2, ρ is the dimensionless fractional density based on an intact salt density of 2,160 kg/m^3, and m and b are fitting parameters determined to be -54.885 m^2 and 34.613 m^2, respectively. For a fractional density of one (i.e., density equivalent to intact salt), the model predicts a permeability of 5.34 x 10^{-21} m^2, which is within an order of magnitude of the assumed permeability for intact salt; i.e., 1.0 x 10^{-21} m^2

Model results indicate that average salt column permeability will be reduced to 3.3x10^{-20} m^2 in about 100 year, which provides for an acceptable long-term seal component.

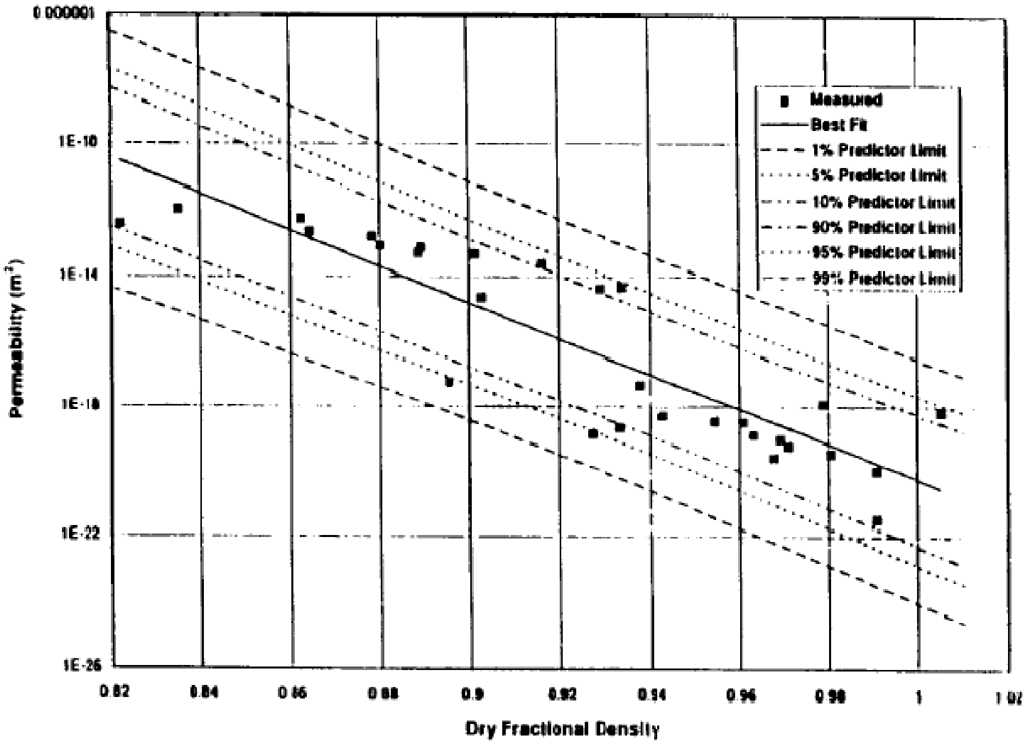

Figure 2.3 Measured and predicted permeability versus dry fractional density for the compacted crushed salt column (Loken and Staham, 1997).

Hansen and Mellegard (1999) study the dynamic compacted crushed salt specimens with a diameter of 100 mm and lengths up to 200 mm which are derived from the full scale compaction demonstration and from a laboratory scale dynamic compaction study. Starting material was wetted to moisture contents of nominally 1.6 % by weight. Test procedures included shear consolidation tests, constant strain rate tests and permeability tests.

Test data suggest that permeability decreases as fractional density increases. Figure 2.4 plots volumetric strain as a function of time on the primary axis and brine flow as a function of time on the secondary axis. Permeability testing of the dynamically compacted crushed salt provided further evidence that the permeability decreases as the fraction density of the salt increases. This conclusion agrees with and augments previous results. Shear consolidation creep test results were added to a database of similar results for the purpose of estimating parameter in a constitutive model that represents the behavior of crushed salt (Callahan and Hansen, 1999). Current testing was performed at higher initial fractional densities (0.9) and stresses (1 to 5 MPa) than were used in previous programs to give better coverage of the range of conditions likely to be experienced by salt seal element at the WIPP. The constitutive model predicted that stress states exist where the radial strain rate would initially be positive (consolidation) and then reverse direction and become negative as the specimen density increases. This phenomenon was clearly observed in multiple tests.

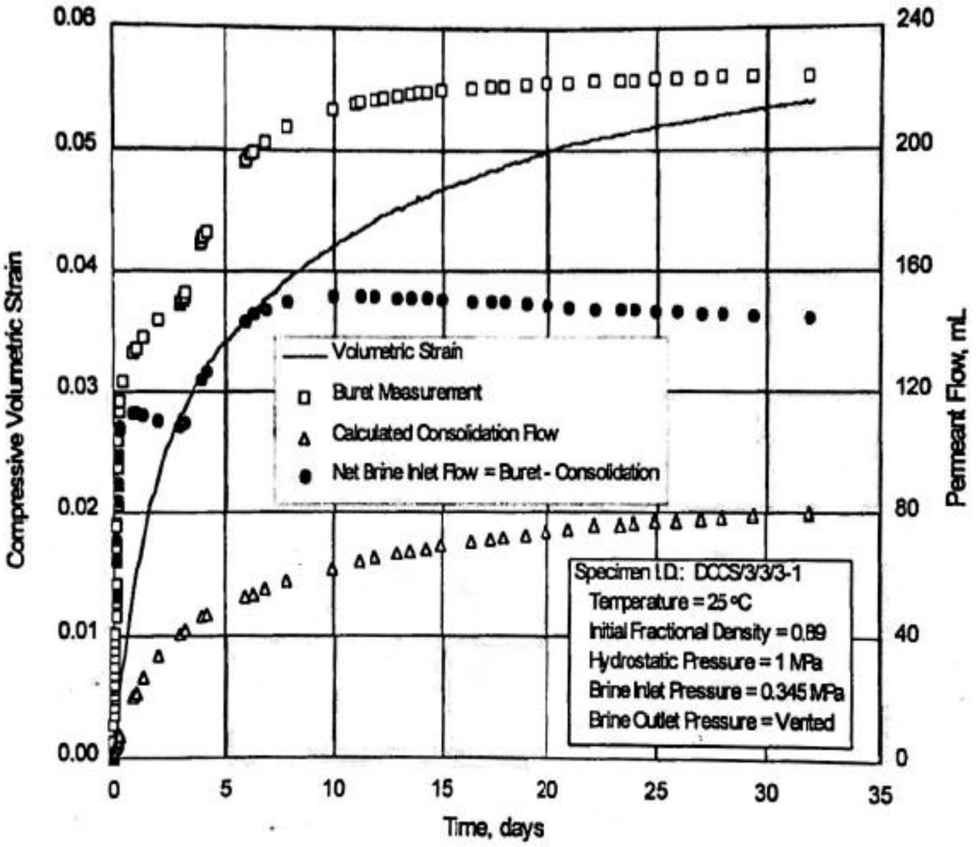

Figure 2.4 Volumetric strain and brine flow as function of time (Hansen and Mellegard, 1999).

CHAPTER III

SAMPLE PREPARATION

3.1 Crushed salt preparation

Crushed salt used in this study is prepared from the Middle member of the Maha Sarakham Formation in the Korat basin, northeastern Thailand. The salt cores were donated by Asean Potash Mining Co. They are crushed by hammer mill (2HP-4 POLES, Spec jis c-4004) to obtain grain size ranging from 0.075 to 4.75 mm (Figure 3.1). The sieve analysis determines the grain size distribution of the crushed salt. The crushed salt is passing through sieve number 4, 8, 18, 40, 60, 100, 140 and 200. Their openings are 4.75, 2.36, 1, 0.425, 0.25, 0.15, 0.106 and 0.075 mm. The grain size distribution of the prepared crushed salt is shown in Figure 3.2.

3.2 Saturated brine

Saturated brine is prepared by mixed 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 (kg/m^3) equal 1,000 kg/m^3. The specific gravity of the saturated brine in this study is 1.211 at 21°C.

The salt core are crushed by hammer hill

Crushed salt for sieve analysis

Figure 3.1 Salt core crushed by hammer mill

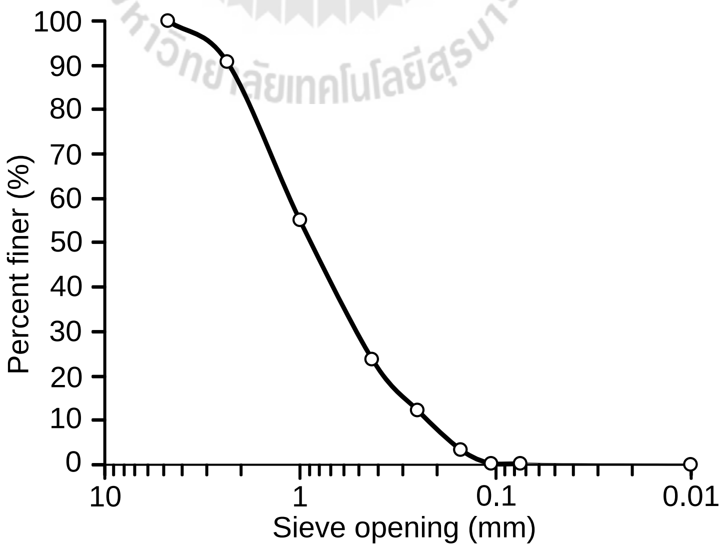

Figure 3.2 Grain size distribution of the prepared crushed salt

3.3 Fabrication of test cylinder

There cylindrical steel tubes with 54 mm internal diameter, 64 mm outside diameter and 200 mm height are used as consolidation tube. Two O-rings are installed around each load platen. Two load platens having 53 mm diameter with 100 mm length and are to apply axial load to the crushed salt specimens. They have 10 mm diameter hole for use as inlet of N_2 to specimens for permeability testing (Figure 3.3).

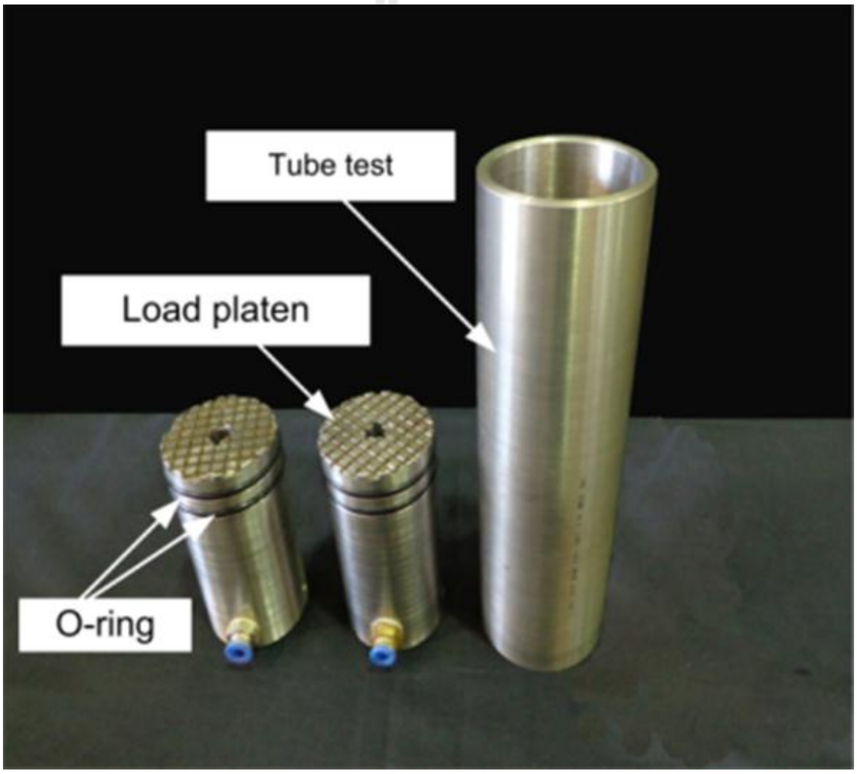

Figure 3.3 Load platens and tube test

CHAPTER IV

LABORATORY TESTING AND TESTING RESULTS

4.1 Introduction

The objective of this section is to experimentally determine the mechanical and hydraulic properties of crushed salt during consolidation as affected by the applied stresses and consolidation period. This chapter describes the test method and results.

4.2 Suitable brine content

The suitable brine content are determined by applying axial stresses via loading steel pistons to the crushed salt mixed with 0, 5 and 10% of saturated brine installed in test tube. The axial stresses are varied from 5, 10, 15 to 20 MPa. All tests are conducted under ambient temperature for 96 hours. Figure 4.1 shows density results measurement as a function of time. The results indicate that density increases with increasing brine content. At the 5% and 10% of brine content by weight density are comparable. Crushed salt samples for all tests in the research are prepared from dry crushed salt mixed with the saturated brine. The proportion of saturated brine to crushed salt in this study is 5% by weight.

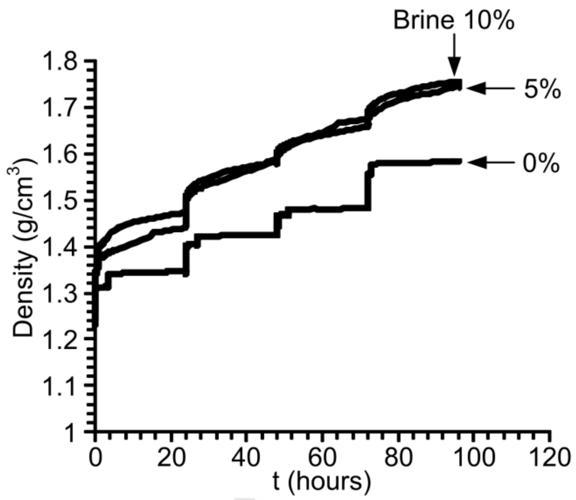

Figure 4.1 Density as function of brine content and time.

4.3 Consolidation tests and results

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 (Figure 4.2). The constant axial stresses are 2.5, 5, 7.5 and 10 MPa. All tests are conducted under ambient temperature for 3, 5, 7, 10 and 15 days, for each condition. 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 consolidation magnitude (axial strains, ε_{ax}) can be calculated using the equation :

$$\varepsilon_{ax} = \frac{\Delta L}{L} \tag{4.1}$$

where ε_{ax} is the axial strain of consolidated crushed salt (mm/mm); ΔL are length changes over time (mm) and L is initial length of the installed specimens.

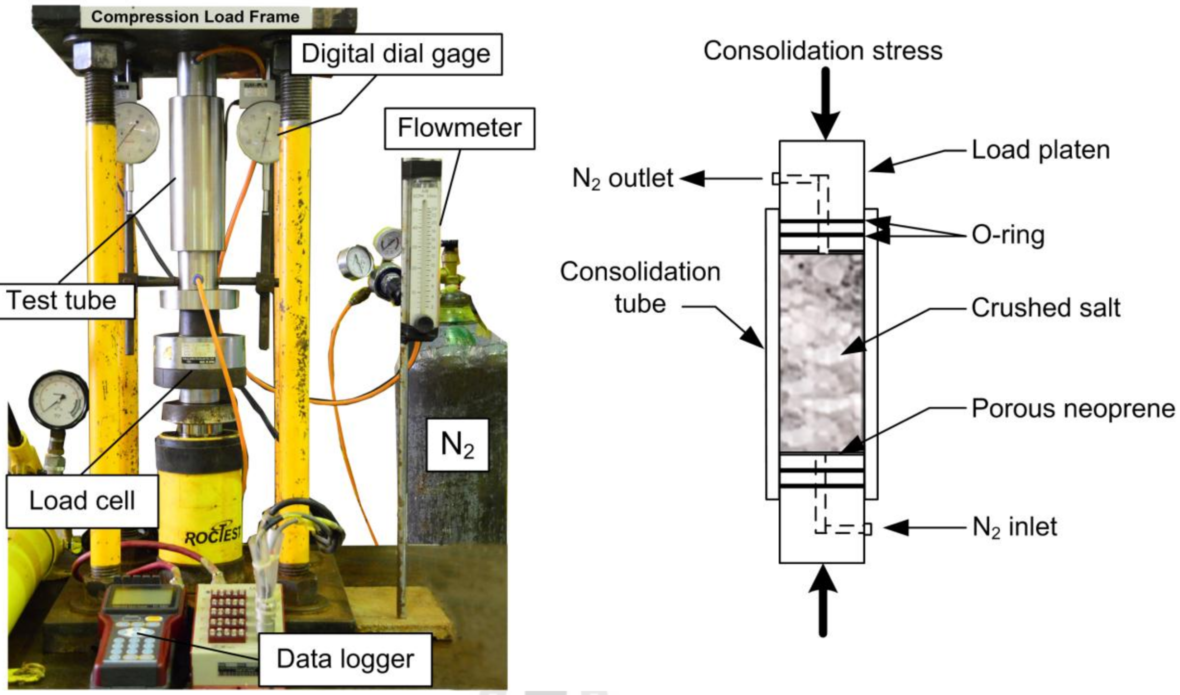

Figure 4.2 Test arrangements for consolidation and permeability testing.

Density of the consolidated crushed salt (ρ) can be calculated using the equation:

$$\rho = \frac{m}{v} \tag{4.2}$$

where ρ is density of consolidated crushed salt (g/cm^3); m is weight of crushed salt specimens (g) and v is volume of specimens (cm^3).

Void ratio of the consolidated crushed salt (e) can be calculated using the equation (Braja M. Das, 2006) :

$$e = \frac{v\rho}{m} - 1 \tag{4.3}$$

where e is void ratio of consolidated crushed salt; v is volume (cm^3); ρ is dry density (g/cm^3) and m is weight of crushed salt specimen (g).

Results indicate that the consolidation magnitude and density of the crushed salt samples increase with applied axial stresses and consolidation time. The void ratio decreases as the consolidation increases. Figures 4.3 through 4.5 plot the axial strain, density and void ratio as a function of time (t)

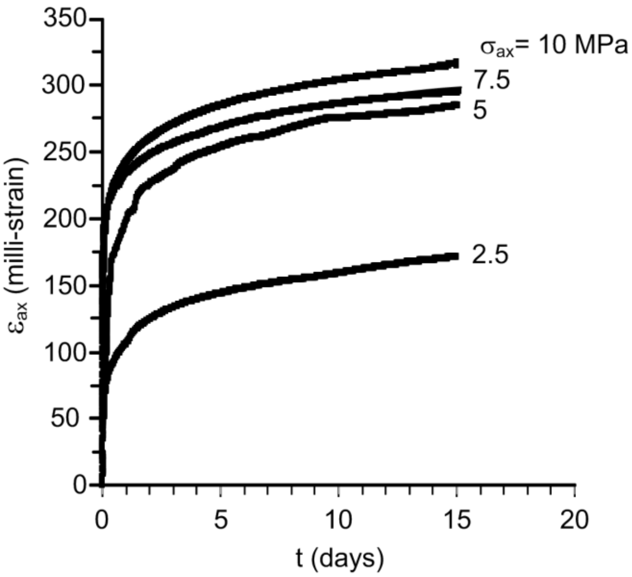

Figure 4.3 Axial strain (ε_{ax}) as a function of time (t) for different axial stresses (σ_{ax}).

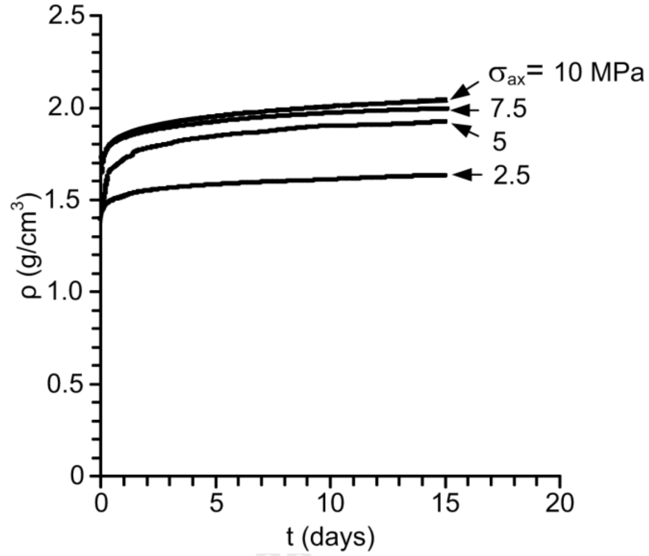

Figure 4.4 Density (ρ) as a function of time (t) for different axial stresses (σ_{ax}).

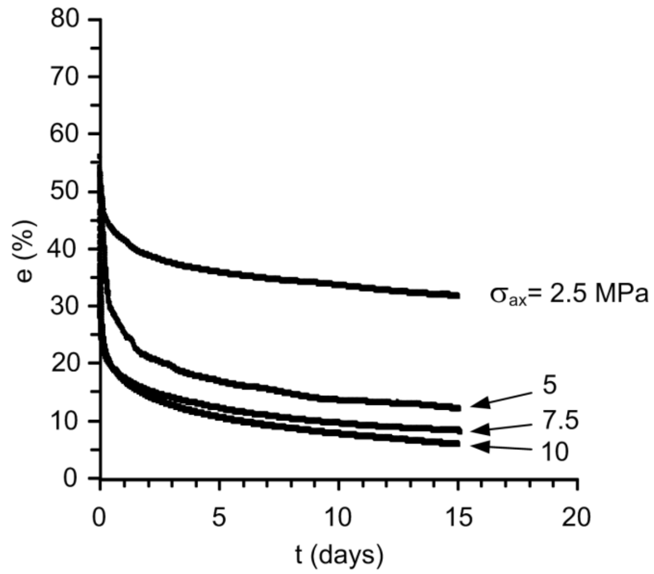

Figure 4.5 Void ratio (e) as a function of time (t) for different axial stresses (σ_{ax}).

4.4 Permeability test and results

The gas (N_2) flow testing is performed to determine intrinsic permeability (k) 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 and 15 days of each test conditions. Nitrogen gas (N_2) is injected under 10 psi into the tube test to measure permeability of crushed salt sample. The test arrangement (Figure 4.6) comprises a N_2 tank pressure, regulating vale, high pressure tubing and air flowmeter.

The permeability coefficient (K) can be calculated by ASTM (D2434-68): $\Delta h=(\Delta P/\gamma_f)$ 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 (Indrarata and Ranjith, 2001).

$$Q = KA\ (\Delta h/L) \tag{4.4}$$

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:

$$k = (K\mu/\gamma_f) \tag{4.5}$$

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 (Loken et al, 1997), as shown in Figure 4.7.

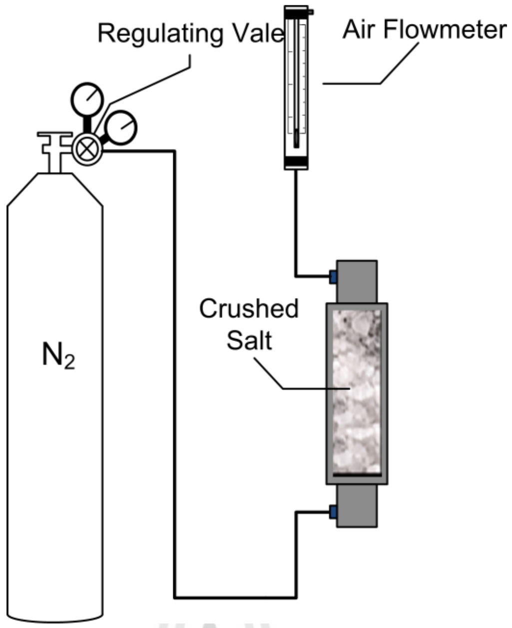

Figure 4.6 Flow testing arrangement

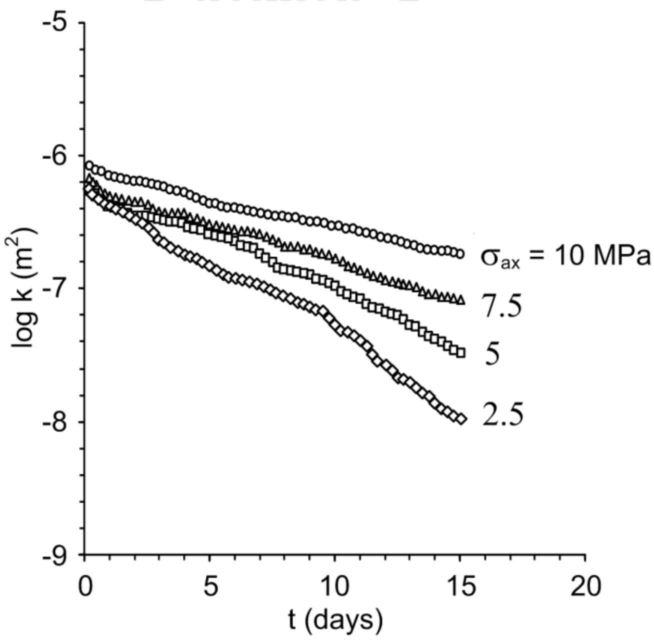

Figure 4.7 Intrinsic permeability (k) as a function of time (t) and for different axial stresses (σ_{ax})

4.5 Uniaxial compressive strength test and results

The test procedure follows the ASTM (D7012) standard practice and the ISRM suggested methods. 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 (Figures 4.8 and 4.9). Neoprene sheets are used to minimize the friction at the interfaces between the loading platen and the sample surface. Uniaxial compressive strengths measurements are made after 3, 5, 7, 10 and 15 days of consolidation. The crushed salt samples are loaded at the constant rate of 0.5-1 MPa/second until failure. The axial and lateral displacements are monitored by displacement dial gauges. The elastic modulus (E) and Poisson's ratio (ν) are determined from the tangent about 50% of the failure stress for each specimen. Figure 4.10 shows some post-test specimens of crushed salt after uniaxial compressive strength testing.

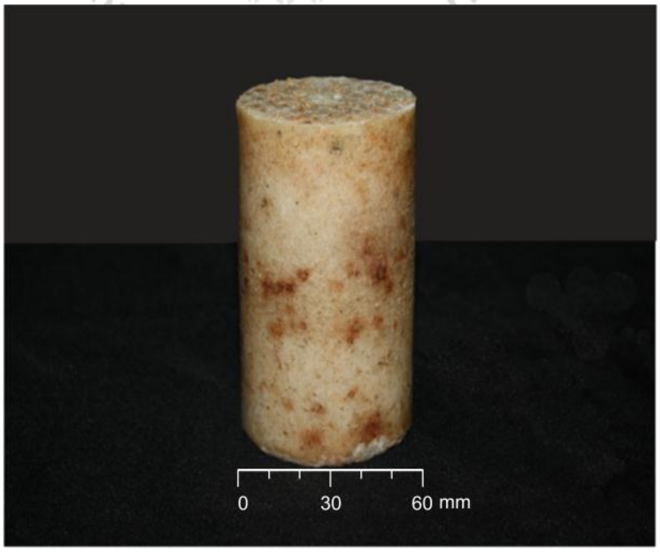

Figure 4.8 A crushed salt specimen after consolidated

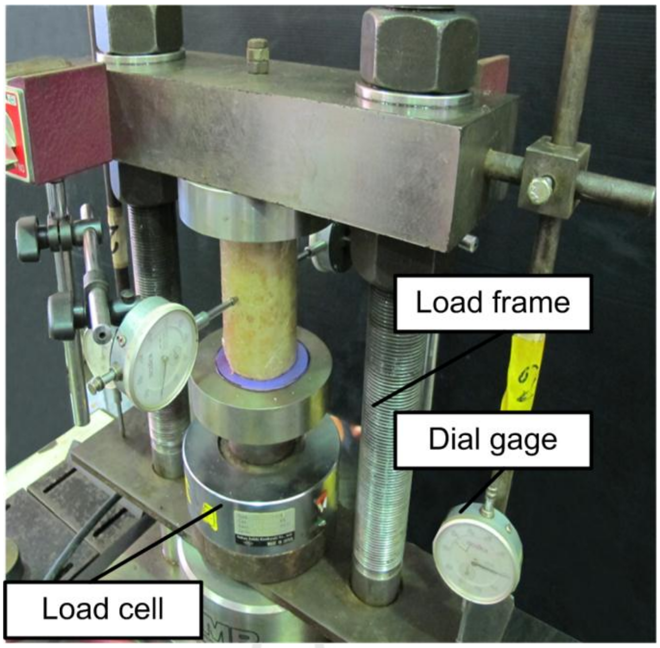

Figure 4.9 Uniaxial compressive strength testing.

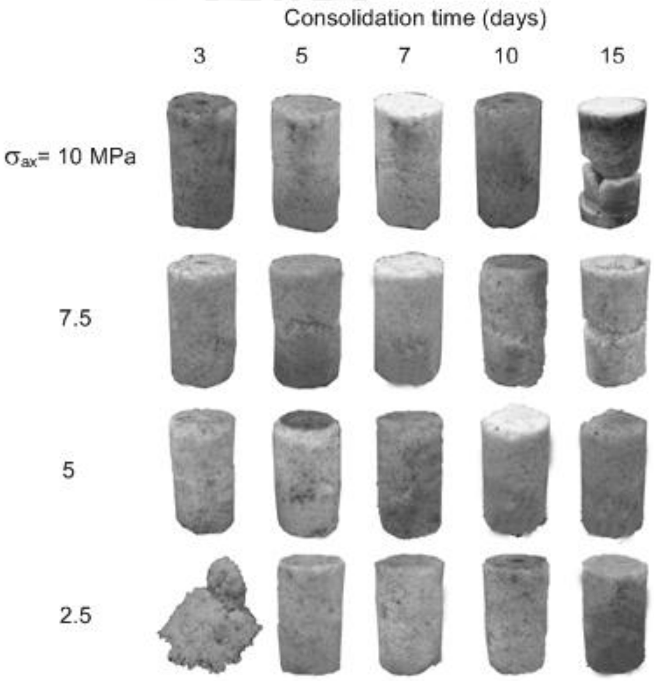

Figure 4.10 Some post-tested salt specimens after uniaxial compressive strength testing.

The results indicate that the uniaxial compressive strength, elastic modulus, shear modulus increase with the axial stress and consolidation duration. The Poisson′s ratio decreases as the axial stresses and consolidation increases. The results are shown in Figures 4.11 through 4.18

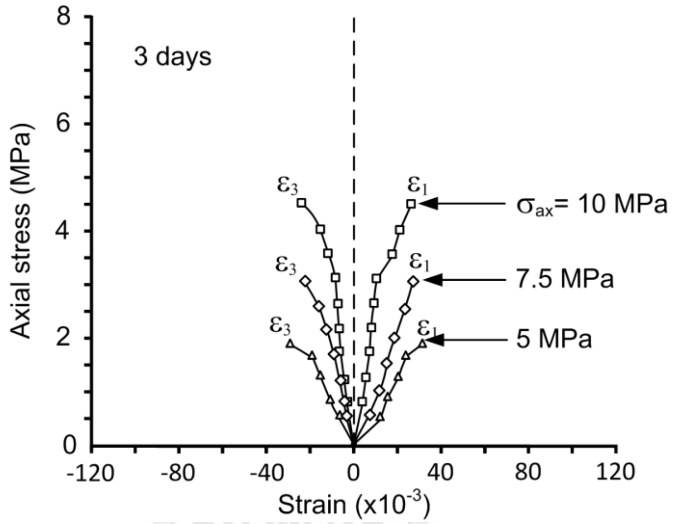

Figure 4.11 Uniaxial stress–strain curves of specimens after 3 days consolidation.

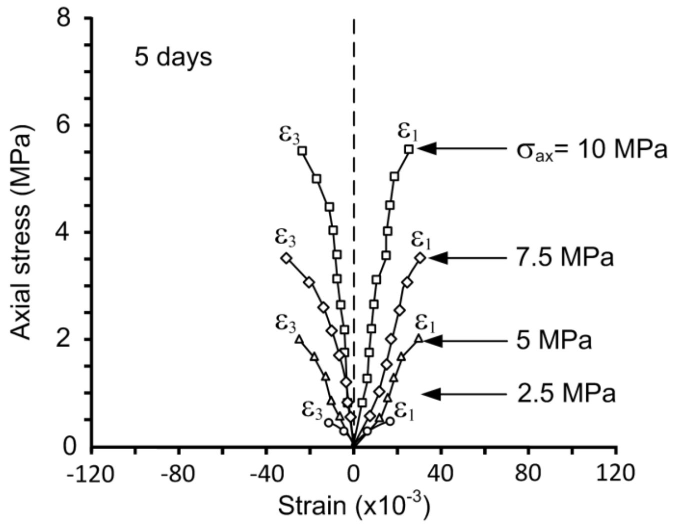

Figure 4.12 Uniaxial stress–strain curves of specimens after 5 days consolidation.

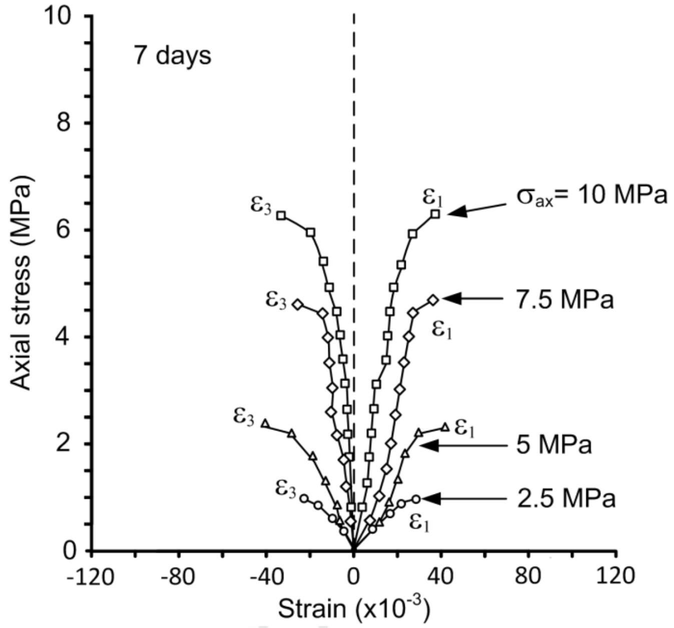

Figure 4.13 Uniaxial stress–strain curves of specimens after 7 days consolidation.

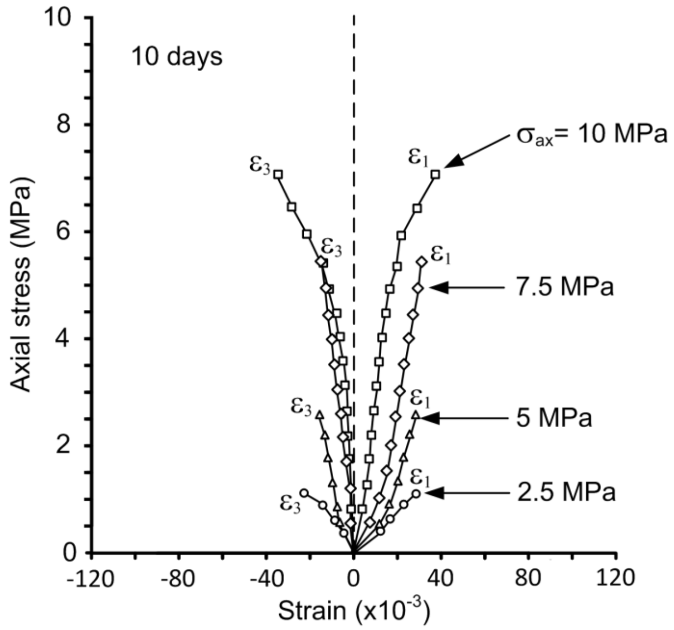

Figure 4.14 Uniaxial stress–strain curves of specimens after 10 days consolidation.

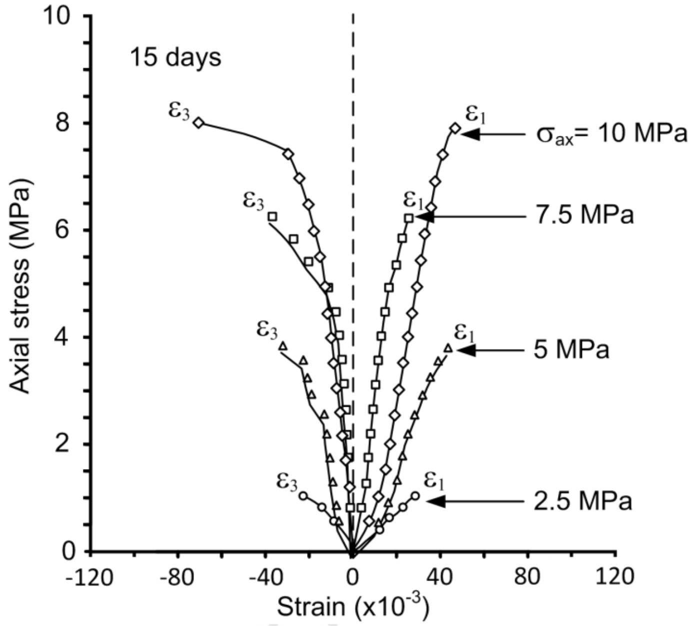

Figure 4.15 Uniaxial stress–strain curves of specimens after 15 days consolidation.

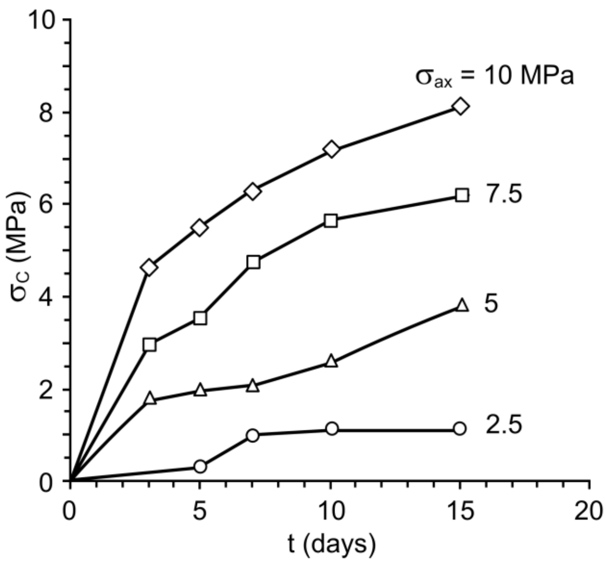

Figure 4.16 Uniaxial compressive strength (σ_c) as a function of consolidation time (t) for different consolidation stresses (σ_{ax}).

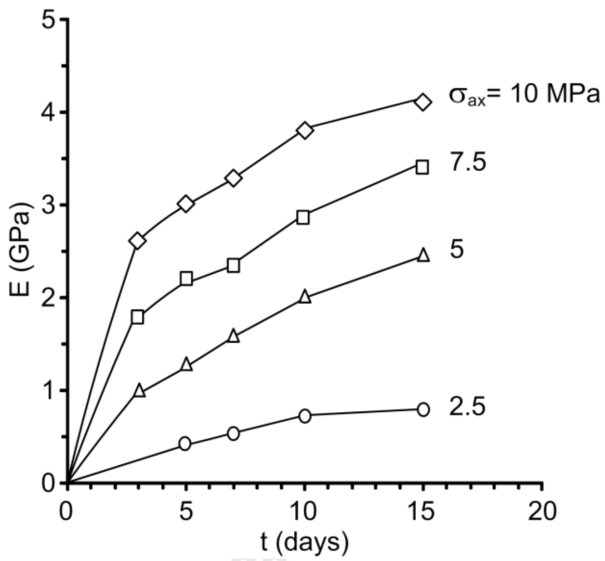

Figure 4.17 Elastic modulus (E) as a function of consolidation time (t) for different consolidation stresses (σ_{ax}).

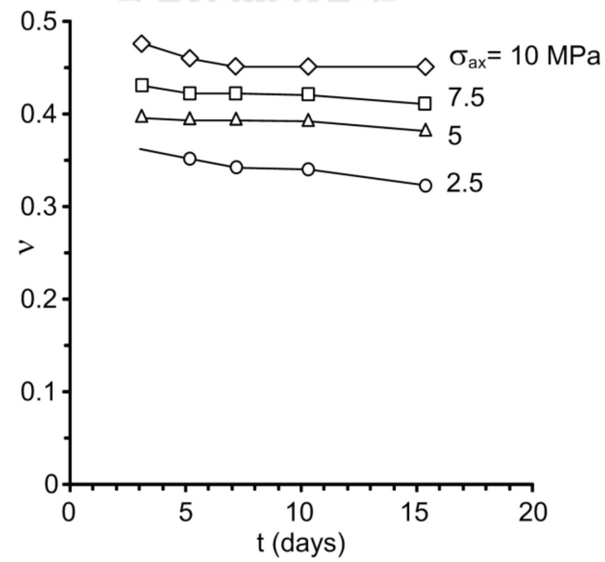

Figure 4.18 Poisson's ratio (ν) as a function of consolidation time (t) for different consolidation stresses (σ_{ax}).

CHAPTER V

DEVELOPMENT OF EMPIRICAL EQUATIONS

5.1 Introduction

The purpose of this chapter is to describe the empirical equations for predicting the volumetric strain, density, intrinsic permeability and uniaxial compressive strength of crushed salt specimens after consolidating under uniaxial strain condition. The regression analysis on the test data using IBM SPSS Statistics 19 (Wendai, 2000) is performed to determine the relevant parameters. Results from laboratory measurements in terms of the axial strain, density, intrinsic permeability and uniaxial compressive strength of crushed salt specimens under various consolidation stresses and time will be used to formulate mathematical relations. The objective is to predict the mechanical and hydraulic properties of consolidated crushed salt as a function of time under different mean stresses.

5.2 Uniaxial strain condition

The test results are calculated 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 salt specimens. Figure 5.1 shows volumetric strain of crushed salt specimens as function of time for different applied axial stresses.

Poisson's ratio from the uniaxial compressive strength and axial strain is used to calculate the lateral stresses (σ_3) as follows (Jaeger et al., 2007)

$$\sigma_2=\sigma_3=[\nu/(1-\nu)]\sigma_1 \quad (5.1)$$

where σ_2 and σ_3 are lateral stresses, ν is Poisson's ratio and σ_1 is consolidation stress (σ_{ax}). The results indicate that the lateral stresses decrease with the axial stresses and time. Figure 5.2 shows the lateral stresses as a function of time for different axial stresses. The mean stresses (σ_m) are also determined using the following relations (Jaeger et al., 2007):

$$\sigma_m=(\sigma_{ax}+2\sigma_3)/3 \quad (5.2)$$

where σ_m is mean stress, σ_3 is consolidation stress, σ_3 is lateral stress. Mean stresses decrease with the increase of axial stresses and time. Figure 5.3 shows the mean stresses as a function of time for difference axial stresses.

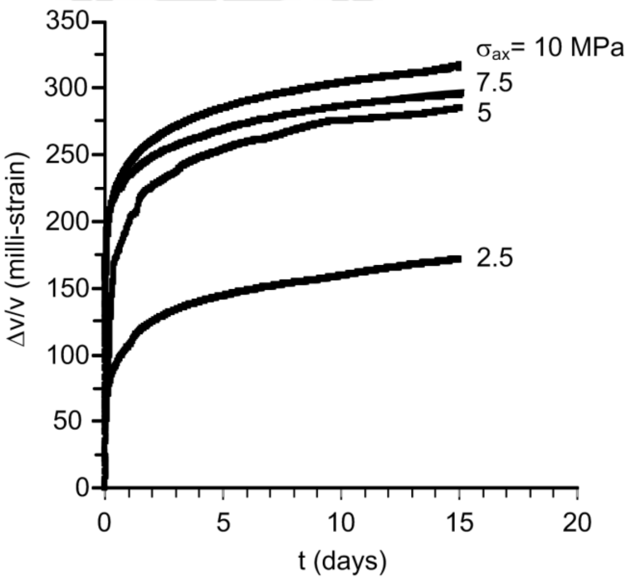

Figure 5.1 Volumetric strain ($\Delta v/v$) as a function of time (t) for different axial stresses (σ_{ax})

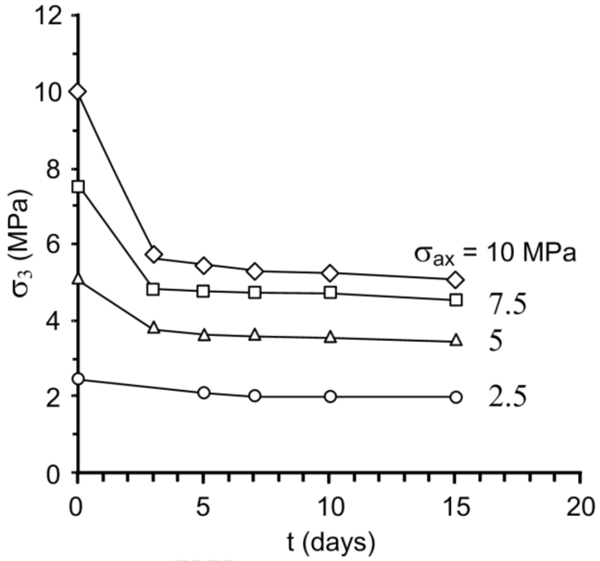

Figure 5.2 Lateral stresses (σ_3) as a function of time (t) for different axial stresses (σ_{ax}).

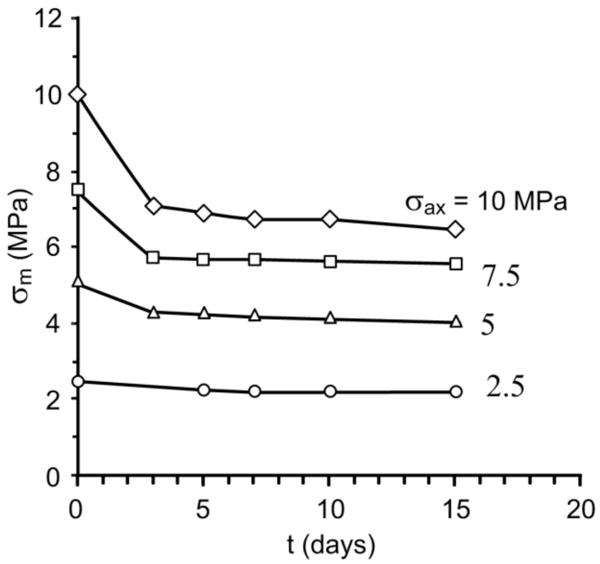

Figure 5.3 Mean stress (σ_m) as a function of time (t) for different axial stresses (σ_{ax}).

5.3 Empirical equations

5.3.1 Crushed salt density

The volumetric strain and density of the crushed salt specimens increase with the applied axial stresses and consolidation time. The results are used to develop a set of empirical equation as a function of mean stress and time. The relationships are non-linear which can be represented by sets of power equations:

$$\Delta v / v = A \cdot \sigma_m^B \cdot t^c \tag{5.3}$$

$$\rho = \rho_0 + \left(D \cdot \sigma_m^E \cdot t^F\right) \quad (g/cm^3) \tag{5.4}$$

where $\Delta v/v$ is volumetric strain, ρ is density at over time, ρ_0 is initial density (g/cm^3), σ_m is mean stress (MPa), t is time for consolidation (days), A, B, C, D, E and F are empirical constants. Regression analysis on the test data using SPSS statistical software can determine these constant (Table 5.1). Good correlation (R^2 = 0.940 and 0.915) between the constitutive equation and the test data is obtained. Figures 5.4 and 5.5 compare the test data with the back prediction of the proposed equation. This equation can be used to predict the volumetric strain and density occurred at consolidation periods and under any mean stresses. The predictions of volumetric strain and density under varied mean stresses ranging from 1 to 4 MPa and consolidation time for 12 months are shown in Figures 5.6 and 5.7

Table 5.1 Parameters of volumetric strain and density relationship

Constant Parameter	Values	Coefficient of correlation
A	0.086	0.940
B	0.538	
C	0.125	
D	0.088	0.915
E	0.833	
F	0.176	

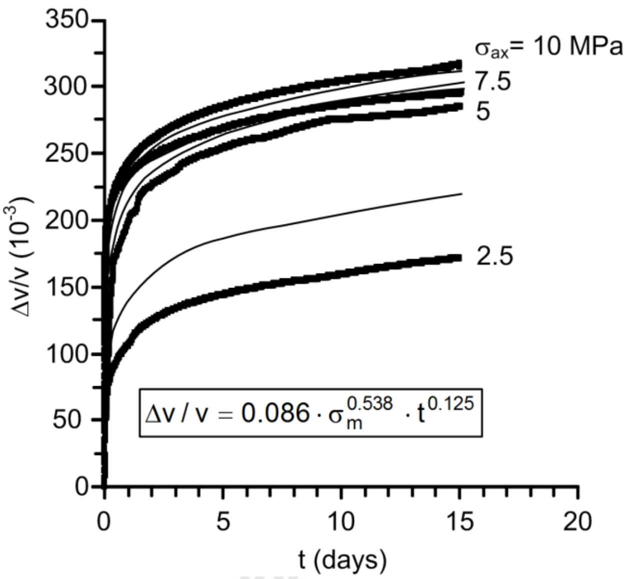

Figure 5.4 Volumetric strain (Δv/v) as a function of mean (σ_m) stress and time (t),

test results (points) and calculation (lines).

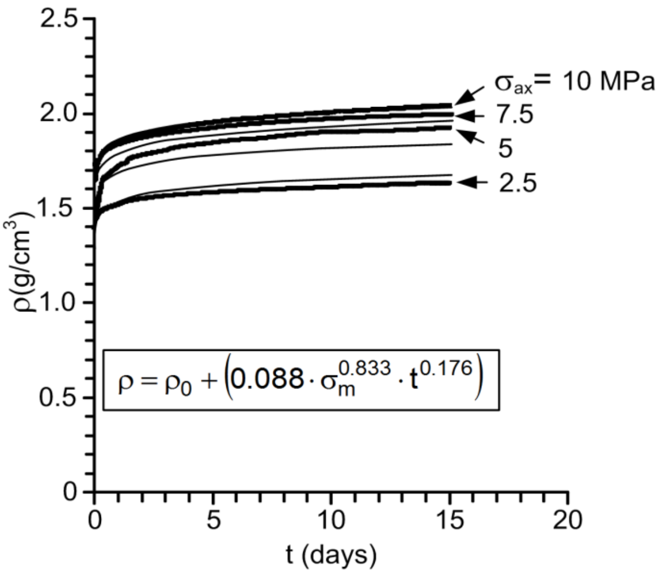

Figure 5.5 Density (ρ) as a function of mean (σ_m) stress and time (t),

test results (points) and calculation (lines).

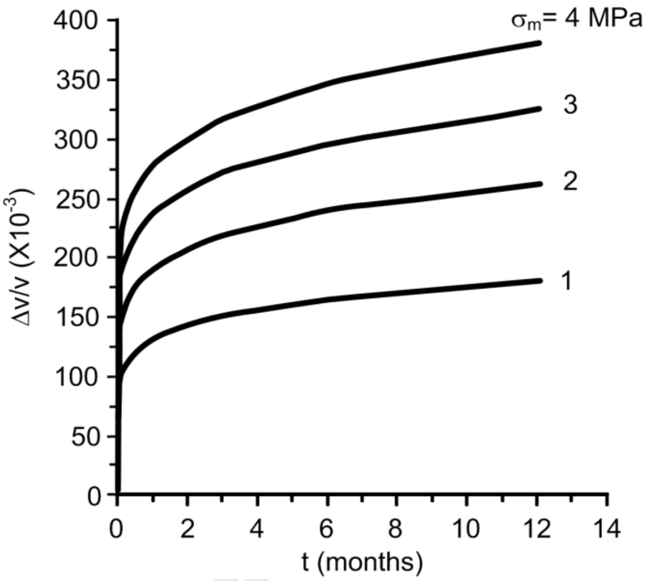

Figure 5.6 Predicted volumetric strain ($\Delta v/v$) as a function of mean stress (σ_m) and time (t)

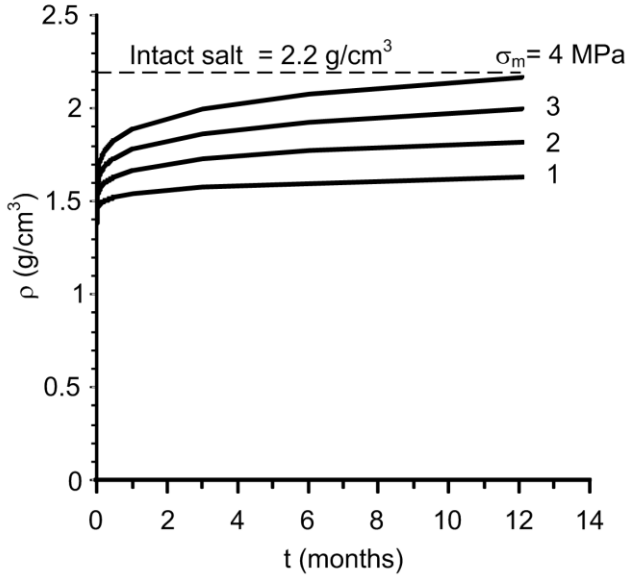

Figure 5.7 Predicted density (ρ) as a function of mean stress (σ_m) and time (t)

5.3.2 Crushed salt permeability

The intrinsic permeability of the crushed salt specimen decreases with increasing the applied axial stresses and consolidation time. The results are used to develop a set of empirical equation as a function of mean stress and time. The relationship is non-linear which can be represented by sets of exponential equations:

$$k = \alpha \cdot \exp(\beta \cdot \sigma_m \cdot t) \qquad (m^2) \qquad (5.5)$$

where k is intrinsic permeability of crushed salt specimen (m^2), σ_m is mean stress (MPa), t is time for consolidation (days), α and β are empirical constants. Regression analysis on the test data using SPSS statistical software can determine these constant (Table 5.2). Good correlation (R^2 = 0.966) between the constitutive equation and the test data is obtained. Figure 5.8 compares the test data with the back prediction of the proposed equation. This equation can be used to predict the intrinsic permeability occurred at any consolidation periods and under any mean stresses. The predictions of intrinsic permeability under varied mean stresses ranging from 1 to 4 MPa and consolidation time for 12 months show in Figure 5.9.

Table 5.2 Parameters of intrinsic permeability relationship

Constant parameter	Values	Coefficient of correlation
α	6.837×10^{-7}	0.966
β	-0.037	

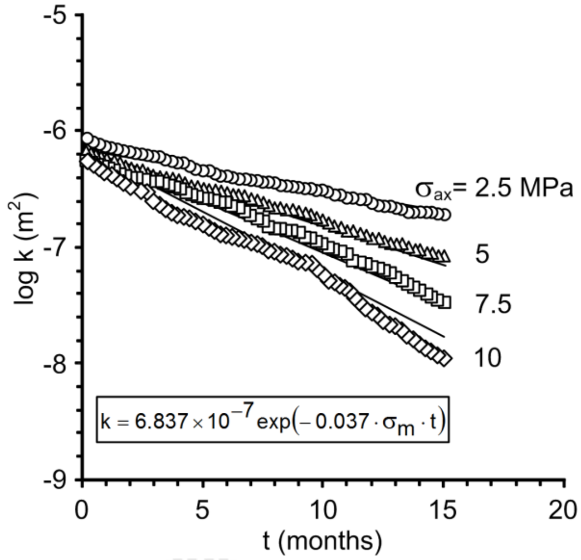

Figure 5.8 Intrinsic permeability (k) as a function of mean stress (σ_m) and time (t), test results (points) and calculation (lines).

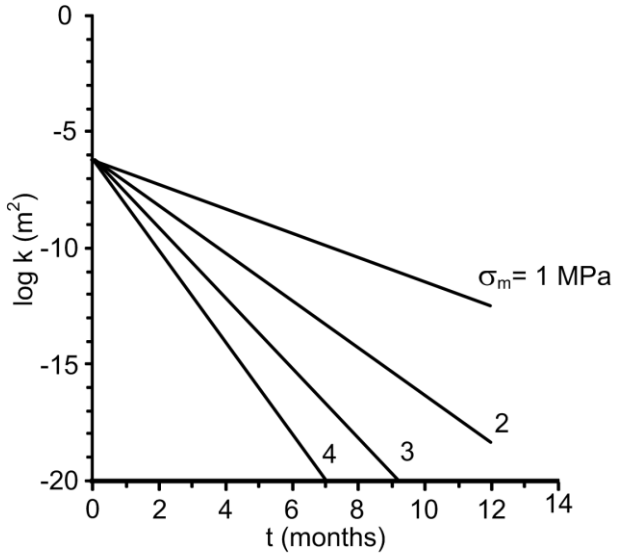

Figure 5.9 Predicted intrinsic permeability (k) as a function of mean stress (σ_m) and time (t).

5.3.3 Uniaxial compressive strength of crushed salt

Uniaxial compressive strength of the crushed salt specimen increase with applied axial stresses and consolidation time. The results are used to develop a set of empirical equation as a function of mean stress and time. That the relationship is non-linear which can be represented by sets of power equations:

$$\sigma_c = \varphi \cdot \sigma_m^{\delta} \cdot t^{\eta} \qquad \text{(MPa)} \qquad (5.6)$$

where σ_c is uniaxial compressive strength of crushed salt specimen (MPa), σ_m is mean stress (MPa), t is time for consolidation (days), φ, δ, and η are empirical constants. Regression analysis on the test data using SPSS statistical software can determine these constant (Table 5.3). Good correlation (R^2 = 0.998) between the constitutive equation and the test data is obtained. Figure 5.10 compares the test data with the back prediction of the proposed equation. This equation can be used to predict the uniaxial compressive strength at consolidation periods and under any mean stresses. The predictions of uniaxial compressive strength under varied mean stresses ranging from 1 to 4 MPa and consolidation time for 12 months show in Figure 5.11

Table 5.3 Parameters of uniaxial compressive strength relationship

Constant parameter	Values	Coefficient of correlation
φ	0.075	0.998
δ	1.821	
η	0.479	

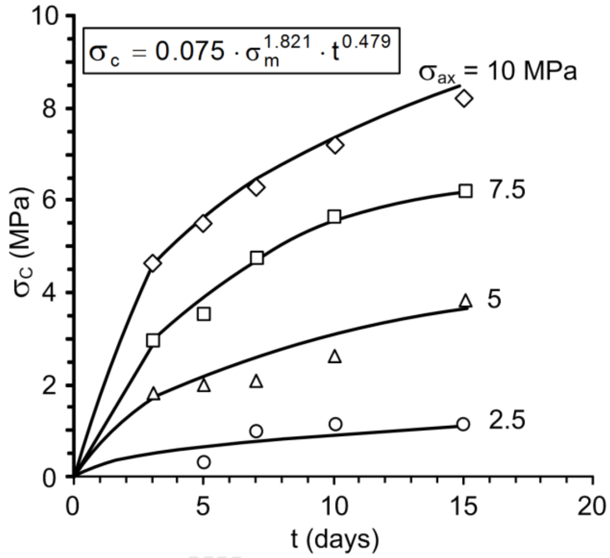

Figure 5.10 Uniaxial compressive strength (σ_c) as a function of mean stress (σ_m) and time (t), test results (points) and calculation (lines).

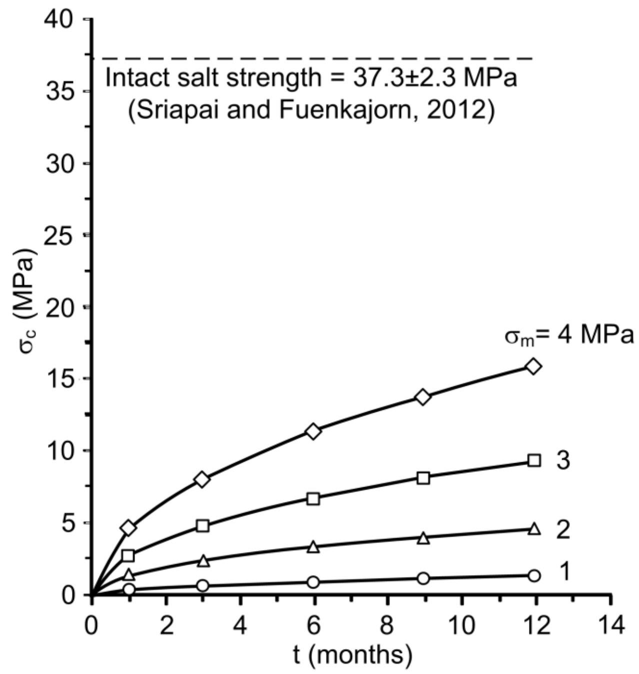

Figure 5.11 Predicted uniaxial compressive strength (σ_c) as a function of mean stress (σ_m) and time (t).

CHAPTER VI

DISCUSSIONS OF THE RESULTS

All the research results as expected. The compaction of crushed salt increase with increasing water content until the optimum water content is reached, that equal to 5% brine by weight (Deamen, 1995). The volumetric strain and density increases with applied consolidation stresses and consolidation time. The crushed salt can be compacted and its initial void ratio and permeability will decrease with increasing of the density (Mellegard and Hansen, 1999; Case and Kelsall, 1987Loken et al.,1997; Hansen and Mellegard, 2002; Stührenberg, 2007; Salzer et al., 2007). The highest density observed for 10 MPa consolidation stress for 15 days which equal to 2.04 g/cm^3. 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 12 months under mean stress equal 4 MPa.

The void ratio and intrinsic permeability decreases as the consolidation increases. The lowest intrinsic permeability is observed for 10 MPa consolidation stress which equal to 1.1×10^{-8} m^2 after 15 days of consolidation. The test results are used to develop a set of empirical equation as function of mean stress and time. The empirical equation can be used to predict the intrinsic permeability will be occurred after time periods and under any mean stresses. The equation indicate that intrinsic permeability will be reduced to an order of magnitude of the permeability of intact salt (≈1.0×10^{-21} m^2, Loken and Statham, 1997) after around 10 months of consolidation and under the consolidation stress over 3 MPa.

The uniaxial compressive strength and elastic modulus increase with the consolidation magnitude. The lowest compressive strength is observed for 2.5 MPa consolidation stress at 3 days. The highest compressive strength is observed for 10 MPa consolidation stress which equal to 8.1 MPa. The elastic modulus is 4.10 GPa after 15 days of consolidation. The test result 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 compressive strength will be occurred after time periods and under any mean stresses.

All test results are used to develop set of empirical equation to predict the mechanical and hydraulic properties of crushed salt consolidated. The equations have good determined properties and behavior of crushed salt in limited of time, that incomprehensive determined for over long time because the shortly rang of testing time.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

7.1 Conclusions

The objective of this study is to determine the mechanical and hydraulic performance of consolidated crushed salt mixed with saturated brine under ambient temperature. The maximum brine content corresponding to the maximum consolidation is also determined. The results indicate that the suitable brine content for the crushed salt is 5% by weight. After applied axial stresses 2.5, 5, 7.5 and 10 MPa to crushed salt specimen installed in consolidation tube for 3, 5, 7, 10 and 15 days, for each condition. The consolidation magnitude and density of the crushed salt samples increases with applied axial stresses and time. The crushed salt can be compacted and its initial void ratio and permeability will decrease with increasing of the density. Uniaxial compressive strength of the crushed salt specimens increases with the applied consolidation stresses and time.

The knowledge from the research results can used to design the initial installation parameters in terms of the physical, mechanical and hydraulic properties of the crushed salt which will tentatively be used as sealing materials in the voids and gaps occurred in the underground salt and potash mined.

7.2 Recommendations for future studies

The test results for the crushed salt have been limited to consolidation stresses and time. To confirm the conclusions drawn in this research, more testing is required as follows:

1. Similar test should be performed on a wider range of consolidation periods and consolidation stresses.

2. The varied of consolidation stress step should be varied.

3. Grain size distribution of crushed salt specimens should be determined.

4. A relationship between the temperature and mechanical and hydraulic properties of crushed salt during consolidation should be investigated.

5. The Poisson's ratio and dilation of lateral strain should be obtained from crushed salt specimen while installed in consolidation tube.

6. The hydraulic head should be applied at different levels and using other fluids as flow medium.

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APPENDIX

PUBLICATION

Publication

Somtong, S., Tepnarong, P. and Fuenkajorn, K. (2013). Strength and Permeability of Consolidated Crushed Salt. In **Proceedings of the EIT-JSCE International Symposium on International Human Resource Development for Disaster-Resilient Countries 2013**, September 12-13, Imperial Queen's Park Hotel, Bangkok, Thailand, 9 pp.

Strength and Permeability of Consolidated Crushed Salt

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ABSTRACT: The objective of this study is to determine the strength and permeability of consolidated crushed salt mixed with saturated brine under ambient temperatures. The crushed salt has grain sizes ranging from 0.075 to 4.76 mm. The brine content is 5% by weight. The consolidation tests are performed by applying constant axial stresses to the crushed salt samples installed in the 54 mm diameter steel cylinders. The constant axial stresses are 2.5, 5, 7.5 and 10 MPa. The permeability is continuously monitored while the uniaxial compressive strengths are measured after the samples are consolidated for 3, 5, 7, 10 and 15 days. The axial strains are monitored and used to calculate the magnitude of the consolidation for each specimen. The consolidation magnitude and density of the crushed salt samples increases with the applied axial stresses. The uniaxial compressive strength increases with the consolidation. The porosity and intrinsic permeability decreases as the consolidation increases. The test results are used to develop a set of empirical equations to design the initial installation parameters in terms of the physical, mechanical and hydraulic properties of the crushed salt. The consolidated crushed salt is tentatively used as sealing materials in the voids and gaps occurred in the underground salt and potash mined.

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, 1999; Case and Kelsall, 1987). The crushed salt can be compacted and its initial porosity and permeability will decrease. Over long time periods, the crushed salt is expected to gradually reconsolidate into a material comparable to intact rock salt. 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, 1996). Present German concepts on nuclear waste repositories in rock salt formations also envisage the use of crushed salt as backfill material for disposal and access drifts as well as for borehole plugs.

Crushed salt backfill is being investigated as a potential backfill and seal material through laboratory testing to determine the fundamental properties, such as permeability, porosity and creep rate which can be reduced by pressure and time through consolidation. The understanding of the consolidation behavior of crushed salt is also an important precondition for repository design and for long-term safety assessment.

2. CRUSHED SALT PREPARATION

Crushed salt used in this study is prepared from the Middle member of the Maha Sarakham Formation in the Korat basin, northeastern Thailand. The salts are crushed by hammer mill (2HP-4 POLES, Spec jis c-4004) until has grain size ranging from 0.075 to 4.75 mm. The grain size distribution of the prepared crushed salt is shown in Figure 1. Saturated brine is prepared by mixed 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 (kg/m^3) equal 1,000 kg/m^3. The specific gravity of the saturated brine in this study is 1.211 at 21°C. Crushed salt samples for all tests are prepared from dry crushed salt mixed with the saturated brine. The proportion of saturate brine to crushed salt in this study is 5% by weight.

3. CONSOLIDATION TESTS

The consolidation tests are performed by applying constant axial stresses on loading steel piston to the crushed salt samples installed in the 54 mm diameter steel cylinders (Figure 2). The constant axial stresses are 2.5, 5, 7.5 and 10 MPa. All tests are conducted under ambient temperature for 3, 5, 7, 10 and 15 days. The axial displacement are continuously measured as a function of time by dial gages to calculate the changes of axial strain, density, and void ratio.

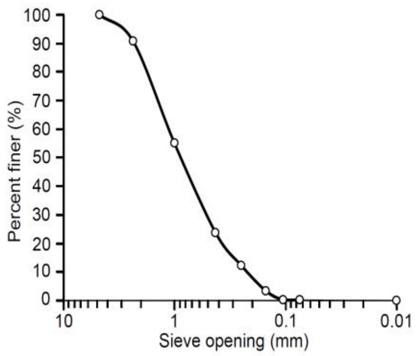


Figure 1 Grain size distribution of crushed salt specimen

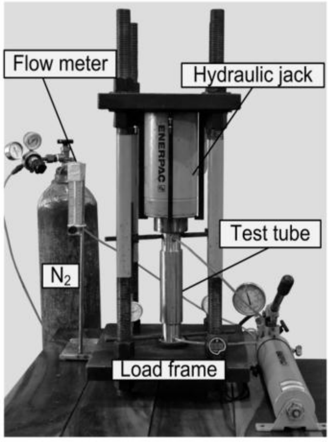


Figure 2 Test arrangements for consolidation test

Results indicate that the consolidation magnitude and density of the crushed salt samples increase with applied axial stresses and consolidation time. The void ratio decreases as the consolidation increases. The test results are used to develop a set of equations to describe behavior of crushed salt consolidation as a function of axial stresses and time. The increase of consolidation, density and the decrease of void ratio are non-linear which can be represented by sets of power equations:

$$\varepsilon_{ax} = A \cdot \sigma_{ax}^{B} \cdot t^{C} \quad (1)$$

$$\rho = D \cdot \sigma_{ax}^{E} \cdot t^{F} \quad (2)$$

$$e = G \cdot \sigma_{ax}^{H} \cdot t^{I} \quad (3)$$

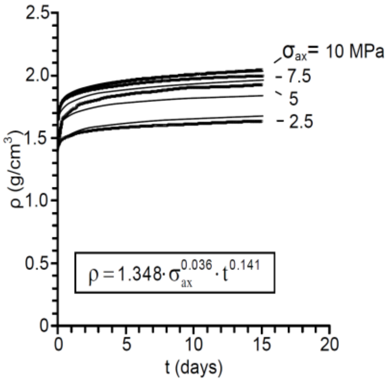
where ε_{ax} is the axial strain, ρ is density and e is void ratio of consolidated crushed salt. A, B, C, D, E, F, G, H, and I are empirical constants.

Regression analysis on the test data using SPSS statistical software (Wendai, 2000) can determine these constants. The results are shown in Figures 3 through 5.

4. FLOW TESTS

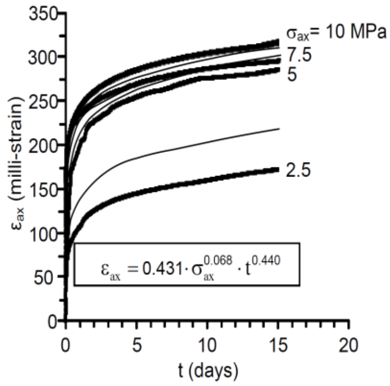
The gas (N_2) flow testing is performed to determine intrinsic permeability (k) of crushed salt consolidation that changes over time. The flow rates under constant head are continuously monitored every 6 hours. Nitrogen gas (N_2) is injected under 10 psi into the tube test to measure permeability of crushed salt sample. The test arrangement (Figure 6) comprises a N_2 tank pressure, regulating vale, high pressure tubing and air flowmeter.

The permeability coefficient can be calculated by ASTM (D2434-68): $\Delta h = (\Delta P/\gamma_f)$ 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).



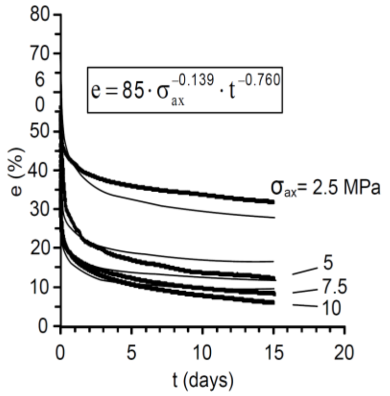
Parameters	Values	Coefficient of correlation
D	1.348	0.915
E	0.036	
F	0.141	

Figure 4 Density (ρ) as a function of time (t). Test results (points) and calculation (lines)



Parameters	Values	Coefficient of correlation
A	0.431	0.940
B	0.068	
C	0.440	

Figure 3 Axial strain (ε_{ax}) as a function of time (t). Test results (points) and calculation (lines)



Parameters	Values	Coefficient of correlation
G	85	0.905
H	-0.139	
I	-0.760	

Figure 5 Void ratio (e) as a function of axial stress (σ_{ax}) and time (t). Test results (points) and calculation (lines)

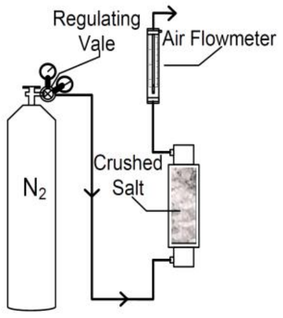
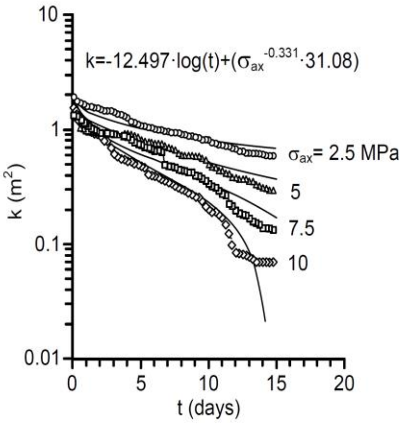


Figure 6 Flow testing arrangement



Parameters	Values	Coefficient of correlation
A′	-12.497	0.943
B′	-0.331	
C′	31.080	

Figure 7 Intrinsic permeability plotted as a function of time (t) for various axial stresses (σ_{ax}).

The hydraulic conductivity is obtained from:

$$Q = KA\,(\Delta h/L) \qquad (4)$$

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 calculated the intrinsic permeability (k) by (Indraratna and Ranjith, 2001):

$$k = (K\mu/\gamma_f) \qquad (5)$$

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 Figure 7. The test results are used to develop a set of equations to describe intrinsic permeability of consolidated crushed salt as a function of axial stresses and time. The decrease of intrinsic permeability is non-linear which can be represented by a logarithmic equation:

$$k = A' \cdot \log(t) + (\sigma_{ax}^{B'} \cdot C') \qquad (6)$$

where A′, B′, and C′ are empirical constants. Regression analysis on the test data using SPSS statistical software (Wendai, 2000) can determine these constants. The results are shown in Figure 7.

5. UNIAXIAL COMPRESSIVE STRENGTH

The test procedure follows the ASTM (D2938) standard practice and the ISRM suggested methods. 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 (Figure 8). Neoprene sheets are used to minimize the friction at the interfaces between the loading platen and the sample surface. Uniaxial compressive strengths measurements are made after 3, 5, 7, 10 and 15 days of consolidation. The crushed salt samples are loaded at the constant rate of 0.5-1 MPa/second until failure. The axial and lateral displacements are monitored by displacement dial gauges. Figure 9 shows some post-test specimens of crushed salt after uniaxial compressive strength testing.

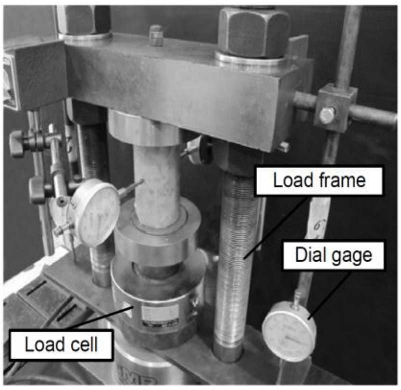


Figure 8 Uniaxial compressive strength tests

The uniaxial compressive strength, elastic modulus, shear modulus and Lame′s parameters increase with the axial stress and consolidation duration. The Poisson′s ratio decreases as the axial stresses and consolidation increases.

The results are reported in Tables 1 and 2 and Figures 10 and 11. The uniaxial compressive strength, elastic modulus, Poisson's ratio, shear modulus and Lame's parameters of crushed salt as a function of constant axial stress and consolidation time is non-linear which can be represented by:

$$\sigma_c = \alpha \cdot \sigma_{ax}^{\delta} \cdot t^{\beta} \quad (7)$$

$$E = \varphi \cdot \sigma_{ax}^{\gamma} \cdot t^{\Omega} \quad (8)$$

$$\nu = \varphi \cdot \sigma_{ax}^{\vartheta} \cdot t^{\kappa} \quad (9)$$

$$G = \omega \cdot \sigma_{ax}^{\ell} \cdot t^{\zeta} \quad (10)$$

$$\lambda = \psi \cdot \sigma_{ax}^{\partial} \cdot t^{\xi} \quad (11)$$

where σ_c is uniaxial compressive strength, E is elastic modulus, ν is Poisson′s ratio, and parameters α, β, δ, φ, η, Ω, λ, κ, ϑ, ω, ℓ, ξ, ψ, ∂ and υ are empirical constants.

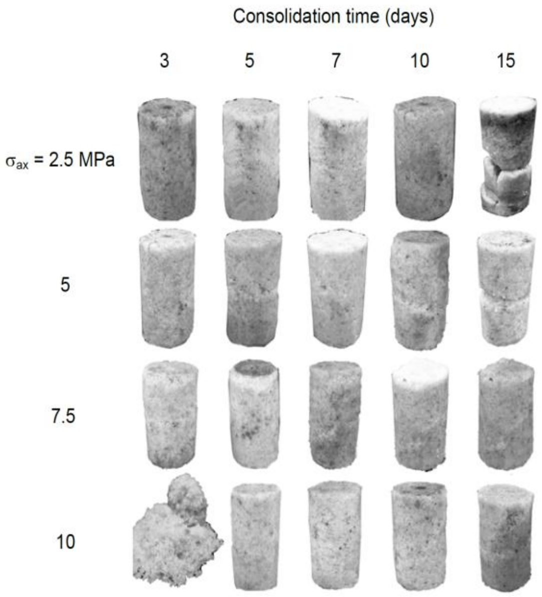


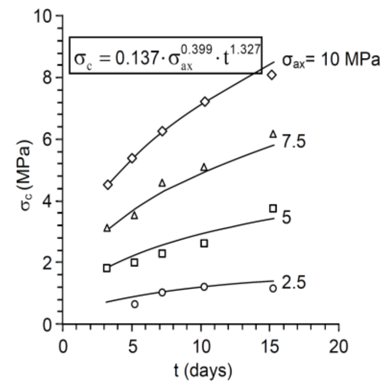
Figure 9 Some post-test specimens of crushed salt after uniaxial compressive strength testing

Table 1 Mechanical properties of consolidated crushed salt

Axial stress (MPa)	Consolidation time (days)														
	3			5			7			10			15		
	σ_c (MPa)	E (GPa)	ν	σ_c (MPa)	E (GPa)	ν	σ_c (MPa)	E (GPa)	ν	σ_c (MPa)	E (GPa)	ν	σ_c (MPa)	E (GPa)	ν
2.5	-	-	-	0.35	0.43	0.46	1.03	0.54	0.45	1.20	0.73	0.45	1.10	0.79	0.45
5.0	1.85	1.00	0.43	2.00	1.30	0.42	2.40	1.60	0.42	2.60	2.03	0.42	3.80	2.45	0.41
7.5	3.00	1.78	0.39	3.54	2.23	0.39	4.76	2.24	0.39	5.76	2.86	0.39	6.20	3.40	0.38
10.0	4.61	2.60	0.39	5.50	3.00	0.35	6.30	3.28	0.34	7.23	3.81	0.34	8.10	4.10	0.32

Table 2 Mechanical properties of consolidated crushed salt

Axial stress (MPa)	Consolidation time (days)														
	3			5			7			10			15		
	σ_3 (MPa)	G (GPa)	λ (GPa)	σ_3 (MPa)	G (GPa)	λ (GPa)	σ_3 (MPa)	G (GPa)	λ (GPa)	σ_3 (MPa)	G (GPa)	λ (GPa)	σ_3 (MPa)	G (GPa)	λ (GPa)
2.5	-	-	-	0.19	0.15	1.68	0.23	0.19	1.90	0.29	0.25	2.26	0.34	0.27	2.45
5.0	0.46	0.31	1.93	0.54	0.44	2.11	0.63	0.61	2.40	0.80	0.71	2.89	0.93	0.87	3.30
7.5	0.56	0.61	2.17	0.68	0.80	2.54	0.79	0.81	2.86	0.91	0.95	3.18	1.11	1.13	3.78
10.0	0.67	0.95	2.46	0.81	1.10	2.84	0.93	1.22	3.17	1.11	1.36	3.67	1.29	1.58	4.10



Parameters	Values	Coefficient of correlation
α	0.137	0.981
β	0.399	
δ	1.327	

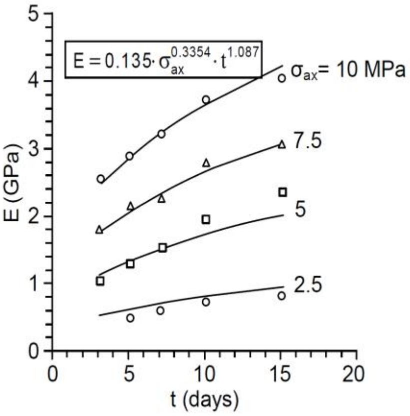
Figure 10 Uniaxial compressive strengths (σ_c) as a function of consolidation time (t)

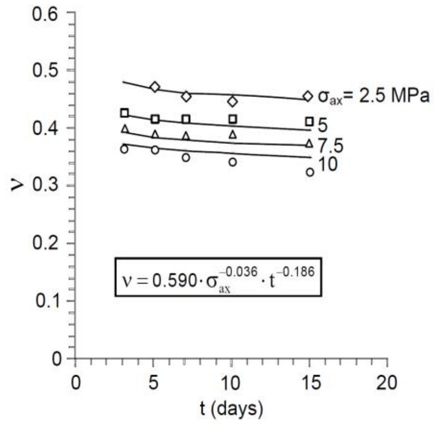
The Lame′s parameter and axial strain used to calculate the lateral stresses (σ_3) for the uniaxial strain condition ($\varepsilon_1 \neq 0$, $\varepsilon_2 = \varepsilon_3 = 0$, $\sigma_2 = \sigma_3 \neq 0$). The lateral stresses increase with the Lame′s parameter and axial strain. The results are reported in Table 2 and Figure 12. The lateral stress of crushed salt as a function of constant axial stress and consolidation can be represented by:

$$\sigma_3 = \sigma_2 = \lambda \cdot \varepsilon_{ax} \qquad (12)$$

substituting equations (1) and (11) into (12) we obtain:

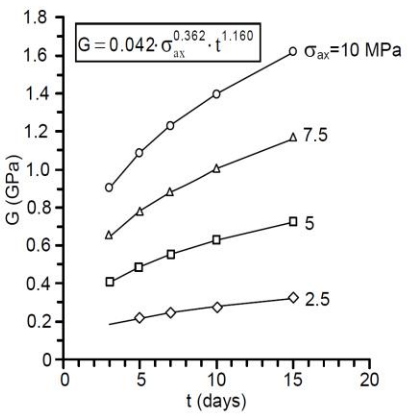
$$\sigma_3 = A \cdot \psi \cdot \sigma_{ax}^{(\partial + B)} \cdot t^{(\xi + C)} \qquad (13)$$

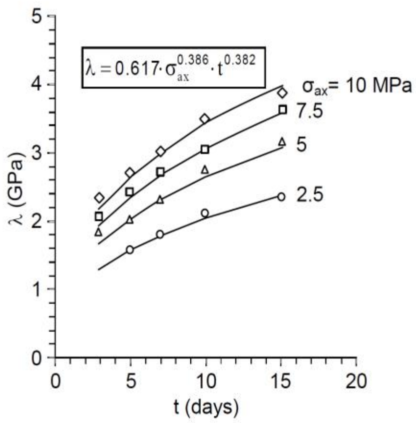




Parameters	Values	Coefficient of correlation
φ	0.135	0.973
η	0.354	
Ω	1.087	

Parameters	Values	Coefficient of correlation
λ	0.590	0.891
κ	-0.036	
ϑ	-0.186	





Parameters	Values	Coefficient of correlation
ω	0.042	0.994
ℓ	0.362	
ζ	1.160	

Parameters	Values	Coefficient of correlation
ψ	0.617	0.933
∂	0.386	
υ	0.382	

Figure 10 Elastic modulus (E), Poisson's ratio (ν), Lame′s parameter (λ) and shear modulus (G) as a function of axial stress (σ_{ax}) and consolidation time (t)

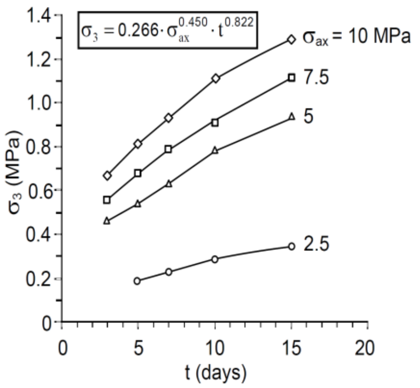


Figure12 Lateral stresses (σ_3) as a function of axial stress (σ_{ax}) and time (t) during consolidation

6. DISCUSSION AND CONCLUSIONS

The objective of this study is to determine the mechanical and hydraulic performance of consolidated crushed salt mixed with saturated brine under ambient temperature. The maximum brine content corresponding to the maximum consolidation is also determined. The results indicate that the suitable brine content for the crushed salt is 5% by weight. The consolidation magnitude and density of the crushed salt samples increases with applied axial stresses. The uniaxial compressive strength, elastic modulus, shear modulus and Lime′s parameter increase with the consolidation magnitude. The porosity and intrinsic permeability decreases as the consolidation increases. The test results are used to develop a set of empirical equations to design the initial installation parameters in terms of the physical, mechanical and hydraulic properties of the crushed salt which will tentatively be used as sealing materials in the voids and gaps occurred in the underground salt and potash mined.

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