

INTRINSIC VARIABILITY OF THE MECHANICAL PROPERTIES OF MAHA SARAOKHAM SALT

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Abstract

A series of laboratory mechanical tests were carried out to study the intrinsic variability of rock salt specimens obtained from the Middle and Lower Salt members of the Maha Sarakham formation. Prior to the mechanical tests, the types and amount of inclusions were identified by visual examination and after testing by X-ray diffraction and dissolution methods. The uniaxial compressive strength of the specimens linearly increases linearly from 27 MPa to about 40 MPa as the anhydrite inclusion increases from 0% (pure halite) to 100% (pure anhydrite). The combined stiffness between the salt and anhydrite also causes an increase of specimen elasticity from 22 GPa (pure salt) to as high as 36 GPa (pure anhydrite). Tensile strengths increase with increasing anhydrite inclusion, particularly when the inclusion is beyond 60% by weight. Below this limit the anhydrite has an insignificant impact on the specimen tensile strength. The tensile strength of salt crystals can be as high as 2 MPa, while that of the inter-crystalline boundaries is estimated as 1 MPa. The salt visco-plasticity increases exponentially with crystal size as dislocation glide mechanisms becomes predominant for the specimens comprising large crystals. Pure salt specimens with fine crystals are deformed mostly by dislocation climb mechanisms, and hence reduce the specimen's visco-plasticity.

Keywords: Strength, rock salt, anhydrite, inclusion, elasticity, plasticity

Introduction

Rock salt in the Maha Sarakham formation in the northeast of Thailand is separated into 2 basins: the Sakon Nakhon basin and the Khorat basin. Both basins contain three distinct salt units: Upper, Middle and Lower members. Figure 1 shows a typical stratigraphic section of the Maha Sarakham formation. The Sakon Nakhon basin in the north covers an area of approximately 17,000 square kilometers. The Khorat basin in the south covers more than 30,000 square kilometers (Figure 2). Warren (1999) gives a detailed description of the salt and geology of

the basins. From over 300 exploratory boreholes drilled primarily for mineral exploration, Suwanich (1978) estimates the geologic reserve of the three salt members from both basins as 18 MM tons. Vattanasak (2006) has re-compiled the borehole data and proposes a preliminary design for salt solution mining caverns based on a series of finite element analyses, and suggests that the inferred reserve of the Lower Salt member of the Khorat basin is about 20 billion tons. This estimate excludes residential and national forest areas.

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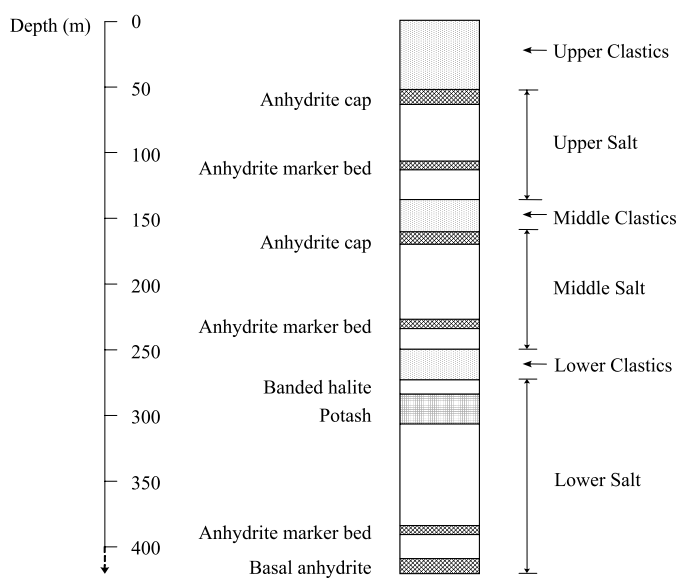


Figure 1. A typical section of the Maha Sarakham formation (Modified from Suwanich, 1986)

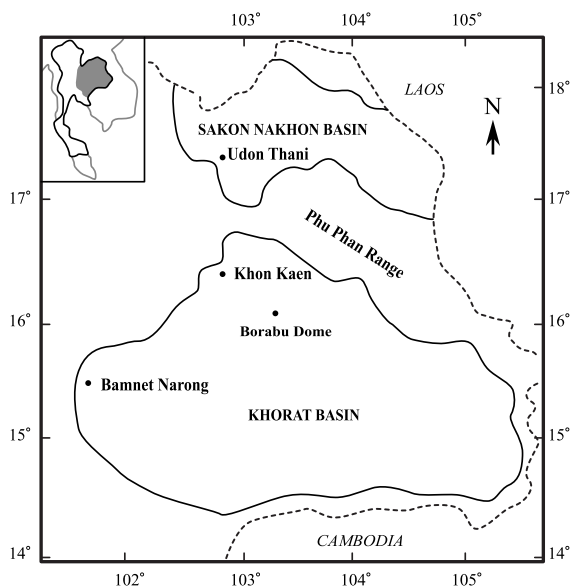


Figure 2. Khorat and Sakon Nakhon salt basins in the northeast of Thailand (Japan International Cooperation Agency, 1981)

Due to the fact that the salt and associated mineral deposits are widely spread and in enormous quantities, they have become important resources in both basins for mineral exploitation and for use as host rock for product storage. For over four decades, local people have extracted the salt by using an old fashioned technique, called here the 'brine-pumping' method. A shallow borehole is drilled into the rock unit directly above the salt. Brine (saline groundwater) is pumped through the borehole and left to evaporate on the ground surface. Relatively pure halite with slight amounts of associated soluble minerals is then obtained. This simple and low-cost method can however cause an environmental impact in the form of unpredictable ground subsidence, sinkholes and surface contamination (Fuenkajorn, 2002). The brine pumping practice has therefore been limited to strictly controlled areas, isolated from agricultural areas and farmlands. Since 1972, a safer and more productive approach has been taken by Pimai Salt Co., Ltd. (PSC) which has extracted the salt by using a solution mining technique. Solution caverns spaced safely far apart have been created in the Middle Salt member with nominal diameters ranging between 45 and 70 m. A salt roof with a pre-designed thickness is left intentionally above the caverns which serves as a supporting beam to prevent excessive ground movement and subsidence. Currently the annual production rate of salt from PSC is about 1.5 million tons.

Potash has also become one of the prominent ores associated with Maha Sarakham salt. In the Sakon Nakhon basin, Asia Pacific Potash Corporation (APPC) has carried out an extensive exploration program, and drawn a detailed mine plan for extracting sylvanite from the upper portion of the Lower Salt member (Crosby, 2005). It has been estimated that the inferred reserves of sylvanite are about 302 million tons for the Udon South deposit and 665 million tons for the Udon North deposit. In the Khorat basin, Asean Potash Mining Company (APMC) has also conducted extensive studies and developed exploratory inclined shafts to investigate the feasibility of extracting carnallite

from the Lower Salt member.

The Office of Atomic Energy for Peace (OAEP) and the Thailand Research Fund have supported a research program to make a preliminary assessment of the geomechanical performance of the Maha Sarakham salt as a nuclear waste repository host rock (Fuenkajorn and Wetchasat, 2001; Fuenkajorn and Klayvimut, 2004). The possibility of waste disposal in both solution mine caverns and dry mine openings has been examined. Fuenkajorn and Jandakaew (2003) performed mechanical tests in the laboratory and numerical simulations to investigate the feasibility of developing a compressed-air energy storage facility in the Lower Salt member in both basins. This tentative project is planned to store excess electrical energy during the off-peak period, and then to release it to meet the high demand during peak usage in the northeast region.

The rapid growth of resources exploitation and the potential development of underground space utilization has called for a true understanding of the mechanical behavior of the Maha Sarakham rock salt, particularly those of the Middle and Lower members. Little, however, has been known or published about the salt mechanical properties as compared to other geological data of the formation. Table 1 summarizes some laboratory-determined mechanical properties. One distinct implication is that the mechanical properties of Maha Sarakham salt tend to have high variations. These variations may be caused by internal (intrinsic) factors (i.e., differences in grain sizes, inclusion contents, and cohesive forces between grains), and by external factors (differences in specimen sizes, loading rate, stress-paths, and testing temperature). These uncertainties have raised a question about the representation and reliability of laboratory-determined properties when applied to the design and analyses of engineering structures in salt mass.

The objective of this study is to determine the causes of intrinsic variability of the mechanical properties of salt specimens from the Maha Sarakham formation. The research study involves the determination of mineral composi-

tions by X-ray diffraction and dissolution methods, the determination of salt specimen stiffness, strengths and visco-plasticity by laboratory mechanical tests, and performing a series of finite element analyses to simulate the time-dependent behavior of salt specimens. The Middle and Lower members of the Maha Sarakham salt from both basins were used as test specimens. The research findings will be useful in gaining more understanding of the high intrinsic variability of the mechanical properties and the representation of the laboratory-determined properties of the specimens when applied to the in-situ conditions.

Internal Factors Influencing Salt Properties

Experimental results by Langer (1984); Aubertin (1996) and Fokker (1996) suggest that large size salt crystals increase the effect of the crystallographic features (i.e., cleavage planes) on the mechanics of deformation and failure of the samples. The creep rate is affected by the grain

boundaries, particularly for small-grained salts subjected to low stress. This situation results in a creep rate dominated by the dislocation climb mechanism at the grain boundaries (i.e. deformation caused by displacement between crystals). For large-grained salt (larger than the travel distance of dislocations) the deformation mechanism is mainly governed by the dislocation glide of the cleavages within the salt crystals. Bonding between crystals can also affect the creep rate and the strength of the salt. The rock salt tends to have weak bonding between crystals, as experimentally evidenced by Fuenkajorn and Daemen (1988); Allemandou and Dusseault (1996). Franssen and Spiers (1990); Raj and Pharr (1992); Senseny *et al.* (1992); Wanten *et al.* (1996) and Franssen (1996) investigated the plastic flow of salt crystals and concluded that the shear strength and deformation of halite crystals are orientation-dependent, and that the small size of the sample may not provide good representative test results. This conclusion leads to a standard requirement of the specimen size by American Society for Testing and Materials (ASTM) that

Table 1. Published mechanical properties of Maha Sarakham salt

Properties	Salt Member	Phueakphum (2003)	Jandakeaw (2003)	Wetchasat (2002)	Boontongloan (2000)
Uniaxial Compressive Strength (MPa)	Middle Salt	23.8-35.8 (5) 30.2 ± 4.8	32.7-37.1 (6) 34.7 ± 2.2	-	23.8-26.0 -
	Lower Salt	31.1 ± 6.7 -	-	11.0-39.3 (13) 27.4 ± 2.3	24.9-32.7 -
Brazilian Tensile Strength (MPa)	Middle Salt	1.4-2.4 (15) 1.9 ± 0.3	1.0-2.4 (12) 2.0 ± 0.4	-	1.4-2.2 -
	Lower Salt	1.4-1.9 (2) 1.7 ± 0.3	0.9-2.4 (8) 1.5 ± 0.4	0.6-2.3 (13) 1.5 ± 0.1	2.02 -
Elastic Modulus (GPa)	Middle Salt	19.0-30.0 (8) -	-	-	26.2 -
	Lower Salt	-	-	5.1-29.8 (9) 19.9 ± 8.9	25.1 -
Poisson's Ratio	Middle Salt	-	0.32-0.46 (5) 0.37 ± 0.05	-	-
	Lower Salt	-	0.37 (1)	-	-
Visco-Plastic Coefficient (GPa.day)	Middle Salt	-	5.1-21.1 (8) 12.3 ± 4.9	-	-
	Lower Salt	-	5.1-15.0 (2) 10.4 ± 5.0	6.9-27.6 (3) 17.2 ± 10.4	-

Notes: Min - Max (Number of samples)

Mean ± Standard Deviation

in order to minimize the effect of grain size the sample diameter should be at least ten times larger than the average grain size of the rock (ASTM D2664, D2938, and D3967). Senseny (1984) has studied the influence of specimen size on the creep of salt under both transient and steady-state deformation, and concludes that the rate of transient creep strain of the small specimens is higher than that of the larger specimens. This implies that constitutive laws developed from laboratory data may over-predict the deformation measured in the field, especially if the formulation results largely from transient creep. Mirza *et al.* (1980) and Mirza (1984) suggest that the size effect on the steady-state deformation is small, especially for a fairly homogeneous salt mass. This is understandable, because due to the nature of salt, cracks or weakness planes are nonexistent, or if they do exist, they are later healed due to re-crystallization of the material.

Inclusions and impurities in salt can affect its creep deformation and strength. The degree of impurity is different for different scales. Handin *et al.* (1984) state that natural rock salt may contain three forms of impurities: 1) extraneous minerals may be disseminated between halite grains, 2) some water may be trapped in the halite crystal structure or it may appear in brine-filled fluid inclusions or along grain boundaries, and 3) foreign ions such as K^+ , Ca^{++} , Mg^{++} , Br and I may be embedded in the crystal structure. The coupled effects of impurities on the mechanical properties of salt can be very complicated (Franssen and Spiers, 1990; Raj and Pharr, 1992; Senseny *et al.*, 1992). Handin *et al.* (1984) compare the steady-state flow parameters obtained for pure halite with those for salt samples with 0.6% $MgCl_2$ inclusions and with 0.1% KCL inclusions, and conclude that the inclusions appreciably affect the creep rate of salt. The quantitative effect of these inclusions, however, cannot be determined due to insufficient data.

Rock Salt Samples

The rock salt samples used in this study were from boreholes BD99-1 and BD99-2 of the Asia Pacific Potash Corporation (APPC), Udon Thani province, and from borehole SS-1 of the Siam

Submanee Co., Ltd., Nakhon Ratchasima province. For the first location core specimens were drilled from the Middle and Lower Salt members of the Maha Sarakham formation in the Sakon Nakhon basin at depths ranging between 200 and 450 m. The salt cores from borehole SS-1 were selected from the Middle and Lower members of the salt formation in the Khorat basin at depths ranging between 200 and 400 m. For both sites, the main inclusions visually observed from the salt specimens were anhydrite and clay minerals. The anhydrite appeared as thin seams or beds perpendicular to the core axis with thicknesses varying from a few millimeters to several centimeters. The clay minerals (normally about 1 - 5% by weight) were scattered between the salt crystals.

Sample preparation for mechanical testing followed the ASTM (D4543) standard practice, as far as practical. To isolate the external effects, the specimen size and shape along with the test parameters were maintained at a constant level. Twenty-four specimens with a constant length-to-diameter ratio (L/D) of 2.5 were prepared for uniaxial compression tests, 76 specimens (with $L/D = 0.5$) for Brazilian tension tests, 14 specimens (with $L/D = 2.5$) for cyclic loading tests, and 10 specimens (with $L/D = 2.5$) for uniaxial creep tests. The samples were cut and ground using saturated brine as lubricant. After preparation, the specimens were labeled and wrapped with plastic film. The specimen source location was identified. Prior to mechanical testing, visual examination was made to determine the type and amount of inclusions.

Laboratory Mechanical Property Testing

Uniaxial Compression Tests

The uniaxial compression test determined the unconfined compressive strength of the salt specimens under various percentages of anhydrite inclusions. The test procedure followed the ASTM standard (ASTM D2938) and the suggested methods by ISRM (Brown, 1981). Twenty-four salt cylinders from the Sakon Nakhon basin were tested under ambient

temperatures. Uniform axial load was applied to the salt cylinder at a constant rate of 0.1 MPa/sec until failure. During loading extension failure mode was observed. In the mid-length of some specimens, micro cracks were generated as detected by milky fragments of salt. This induces radial expansion and specimen dilation.

Figure 3 plots the stress-strain curves for all specimens. The nonlinear behavior of the salt was observed. The average strength was 30.77 ± 5.83 MPa. The compressive strengths of the Maha Sarakham salt obtained from these tests agree with those from other researchers. They are relatively high as compared with those from other sources in the United States and Germany. Figure 4 shows the compressive strength of salt specimens as a function of the amount of anhydrite. The strengths tend to be higher for those specimens with higher percentages of anhydrite. This finding is supported by Hansen and Gnirk (1975) which is that the compressive strength of pure anhydrite can vary from 80 to 120 MPa. The relation between the compressive strength and the amount of anhydrite can be represented by a linear equation: $\sigma_c = 0.15(I_{AN}) + 27.15$ where σ_c is the salt compressive strength in MPa and I_{AN} is the percentage of anhydrite inclusion.

Brazilian Tension Tests

The Brazilian tension test was performed to determine the indirect tensile strength of the salt specimens. The test procedure followed the ASTM (D3967) and the ISRM suggested methods (Brown, 1981). Seventy-six salt specimens with a nominal diameter of 60 mm and L/D of 0.5 were tested. The average tensile strength of the Lower Salt was 1.97 ± 0.73 MPa. Crack surfaces along the loaded diameter were clean which reflected the tensile crack initiation. Standard deviations of the strengths were relatively high (30%). The average crystal size of the salt was $7 \times 7 \times 7$ cm, and in some specimens was as large as $10 \times 10 \times 10$ cm. An attempt to seek a relation between the tensile strength of the salt specimens and the crystal size was made. It seemed, however, that within the parameters tested here, the tensile strength of the salt specimens was independent of the salt crystal size (Figure 5)

Post-failure observations showed that there were two types of fracturing found in the induced cracks of salt specimens: cleavage fracturing (splitting of salt crystals at the cleavages) and inter-granular fracturing (fractures occur at crystal boundaries). Percentages by area of these fractures were mapped from each

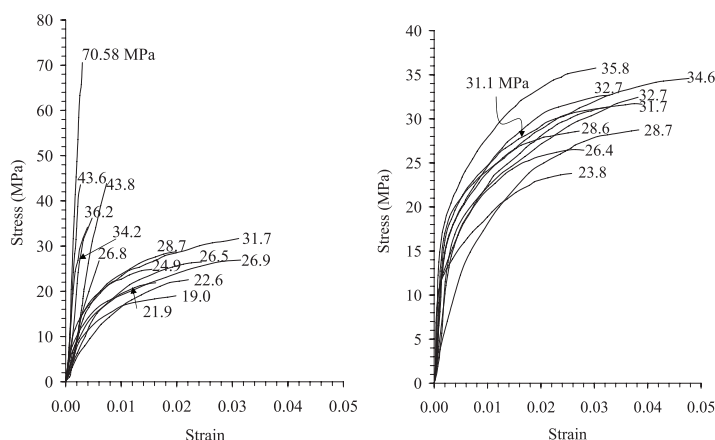


Figure 3. Results of uniaxial compressive strength test of rock salt specimens with anhydrite inclusions. The axial stresses are plotted as a function of axial strain. Numbers indicate stress at failure

specimen. Figure 6 plots the relationship between the salt tensile strength and the percentage of inter-granular fracturing. The tensile strengths decrease linearly as the area of inter-granular fracturing increases. This agrees with observations made by Fuenkajorn and Daemen (1988) and Hardy (1996). The specimens containing only cleavage fracturing have a maximum tensile strength of about 2.05 MPa. The specimens with only inter-granular fracturing have the tensile strength of about 1.05 MPa. This suggests that the salt crystals can have a tensile strength as high as 2 MPa while the inter-granular boundaries have a tensile strength as low as 1 MPa.

Figure 7 plots the salt tensile strength as a function of anhydrite contents varying from 0% (pure rock salt) to 80%. The test results suggest that the anhydrite of less than 50% had an insignificant impact on the Brazilian tensile strength as the strengths were relatively constant at about 2 MPa. The tensile strength increased notably when the amount of anhydrite in specimens was greater than 60%. The figure also compares the tensile strength results with those obtained by Hansen and Gnirk (1975) which showed that the average tensile strength of pure anhydrite could be as high as 6 - 8 MPa.

The results obtained here also showed

that the clay minerals of less than 4% had no significant impact on the salt tensile strength. We believe that the effect of clay minerals on the salt tensile strength may not be detectable unless the rock salt specimens contain higher percentages of clay minerals than those tested here (more than 5%).

Cyclic Loading Tests

The uniaxial cyclic loading tests were performed on fourteen salt specimens obtained from both Khorat and Sakon Nakhon basins. The axial loading and unloading were repeated on salt specimens within a very short period (10 - 15 sec for each cycle). The maximum axial stresses varied from 30% to 60% of the salt compressive strength. Except for the loading scheme, the test arrangement was similar to that of the ASTM (D2938). The axial deformation and time were recorded during the test. The true elastic modulus was determined from the slope of the unloading curves. Figure 8 shows examples of the results from the uniaxial cyclic loading tests.

The minimum and maximum elastic moduli are 20.00 and 34.52 GPa, with the average of 24.92 ± 4.37 GPa. Figure 9 plots the elastic modulus as a function of anhydrite inclusion ranging from 0% (pure rock salt) to 100% (pure anhydrite).

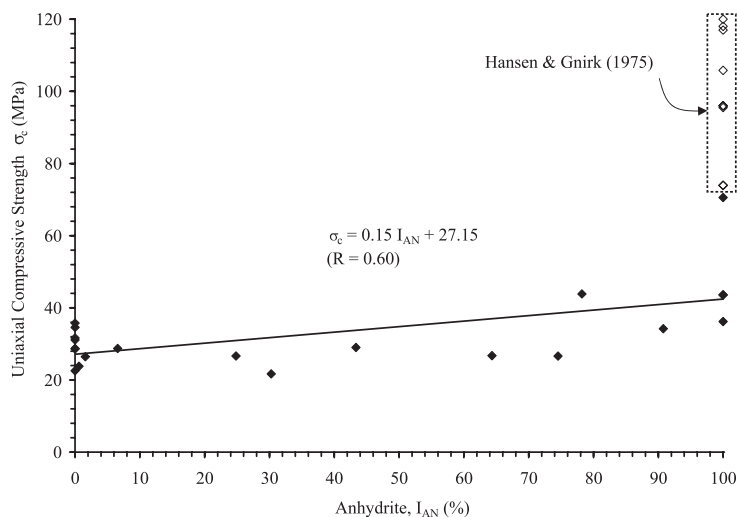


Figure 4. Uniaxial compressive strength plotted as a function of anhydrite inclusion in rock salt specimens

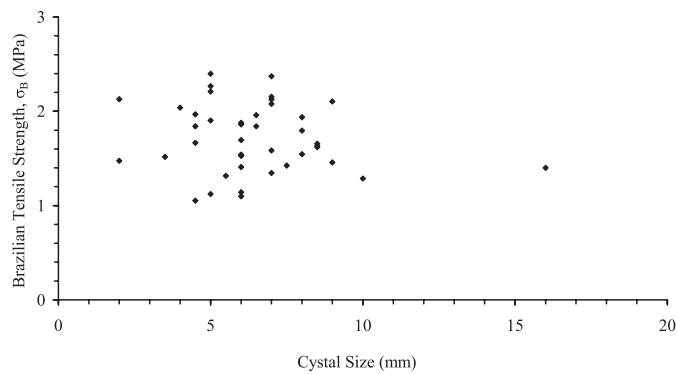


Figure 5. Relationship between Brazilian tensile strength and grain size for pure salt specimens

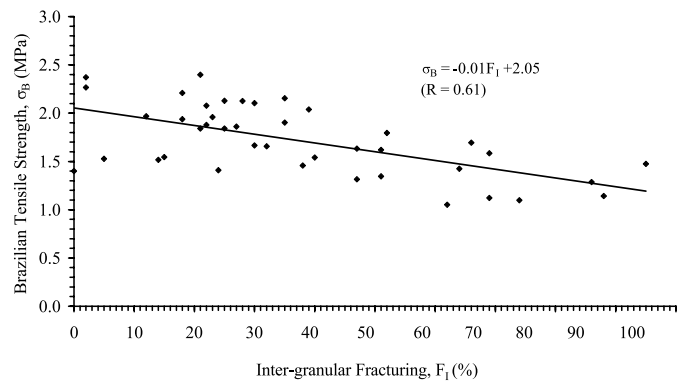


Figure 6. Brazilian tensile strengths plotted as a function of percentage of inter-granular fractures

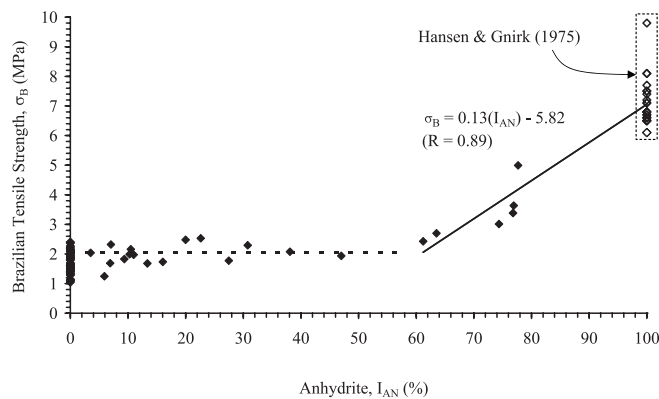


Figure 7. Brazilian tensile strengths plotted as a function of the amount of anhydrite in rock salt specimens

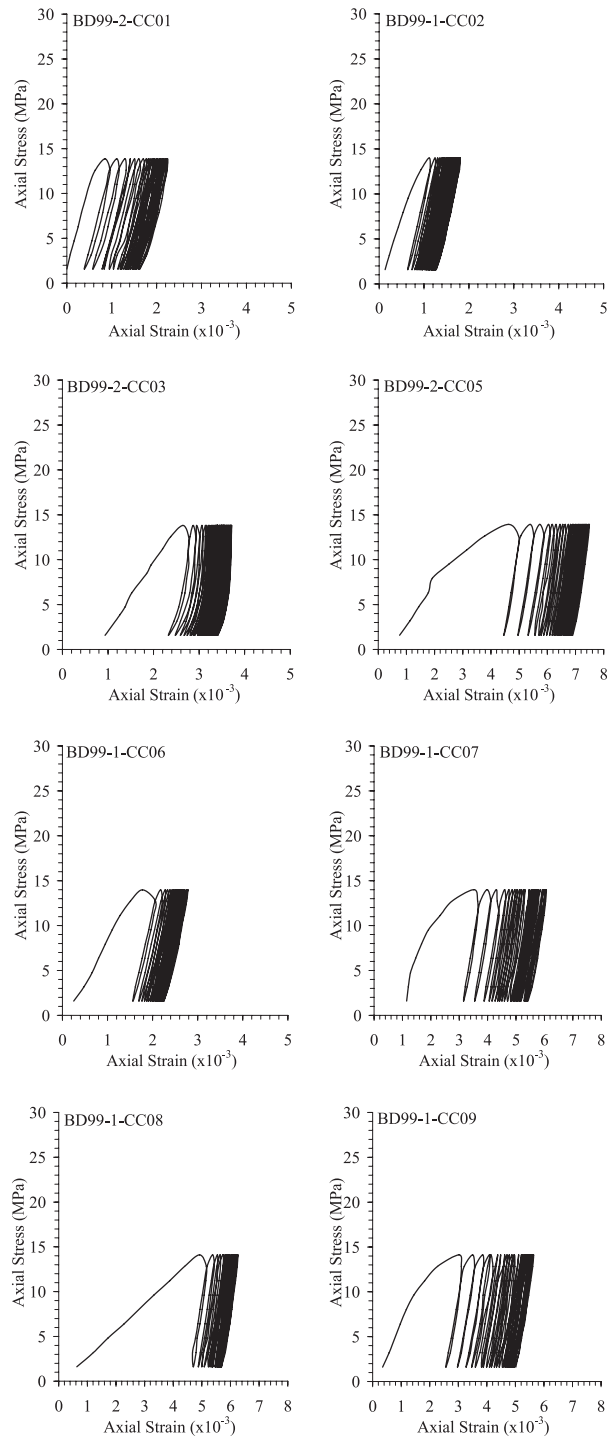


Figure 8. Uniaxial cyclic loading test of salt specimens

A higher amount of anhydrite content results in a higher elastic modulus of the salt specimen. This agrees with the observation by Hansen and Gnirk (1975). A linear relation can be used to describe the variation of the elastic modulus as affected by the amount of the anhydrite, as shown in Figure 9.

Uniaxial Creep Tests

The objective of the uniaxial creep tests is to determine visco-plastic coefficient of the salt specimens under unconfined conditions. The visco-plastic coefficient is of interest here as it reflects the long-term behavior of the salt. The test procedure and sample preparation followed the ASTM (D4405) standard practice. Ten specimens from both source locations were tested with constant uniaxial stresses varied from 12, 16, 18 to 19.5 MPa. The specimens were loaded under a constant stress for a minimum of 15 days, depending on the displacement results. During the test, the axial deformation, time, and failure modes were recorded. The reading intervals were made once every minute for the first two hours of testing and increased to every five minutes for one day, every 15 minute for 2 days, every hour for 3 days and every 3 hours till the end of the test.

The axial strain-time curves resulting from the creep testing are plotted in Figure 10. The visco-plastic coefficient of each specimen was calculated by assuming that the salt behaved as Burger's material. The average visco-plastic coefficient was $18.98 \pm 23.25 \text{ GPa} \times \text{Day}$.

Figure 11 shows the visco-plastic coefficient as a function of crystal sizes varying from 3 to 10 mm. The larger crystal size results in a higher visco-plasticity. The relationship can be best described by an exponential equation as shown in the Figure. This agrees with the results obtained by other researchers that in the steady-state creep phase, the dislocation climb mechanism will dominate the deformation of salt specimens containing large crystals, resulting in a higher visco-plasticity. The relationship between visco-plasticity and anhydrite cannot be determined here due to a lack of specimens with various contents of anhydrite inclusion.

Determination of Inclusions in Salt Specimens

The amount of anhydrite and clay inclusions in salt specimens was determined also by the dissolution method. After the mechanical property test had been conducted, each specimen was weighed and dissolved in water until all the halite was dissolved away, leaving only insoluble materials, defined here as inclusions. The remaining inclusions were taken out from the water using a filter cloth and filter paper no. 42. They were dried and weighed. The X-ray diffraction method (Diffractrometer Model D5005) was used to identify the mineral compositions of the inclusions. The results indicate that the inclusions were anhydrite with trace amount of clay minerals (less than 4 %).

Computer Modelling

A series of finite element mesh models were constructed to simulate the uniaxial creep test of rock salt specimens subjected to a constant axial stress. The anhydrite inclusion in the specimen was defined as thin beds normal to the core axis. This is because all core specimens used in this research were obtained from vertically drilled holes. The non-linear time-dependent finite element program, GEO (Fuenkajorn and Serata, 1994; Stormont and Fuenkajorn, 1994) was used in the simulation. Specimen models had a length-to-diameter ratio of 3.0. Figure 12 shows the mesh models. Due to the presence of two symmetrical planes, only one-fourth of the specimen was modeled and analyzed. The models were classified into four groups with different percentages of anhydrite inclusion: 10%, 30%, 50%, and 70%. Each group had different numbers of anhydrite layers, varying from 1, 3, 5 to 7 layers. The analysis was made according to the axis symmetry. The left side of the model represented the center-line of the specimen. It was the symmetrical axis that did not allow horizontal displacement. The bottom boundary represented the mid-height of the specimen and did not allow vertical displacement. The right side of the mesh model represented the outer surface

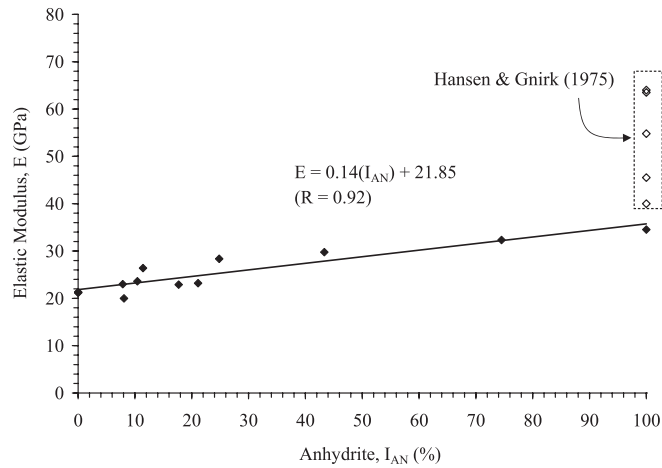


Figure 9. Elastic modulus plotted as a function of anhydrite inclusion

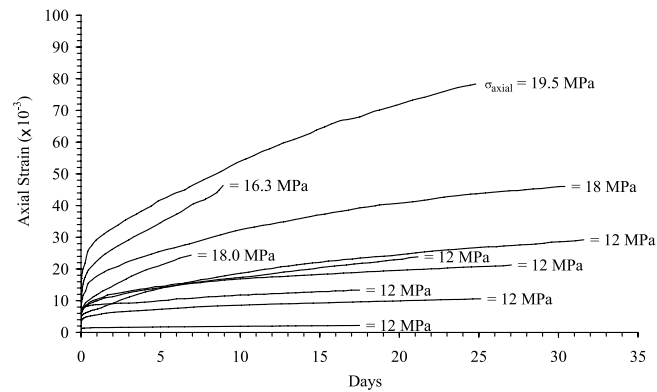


Figure 10. Results of the uniaxial creep testing for different constant axial stresses

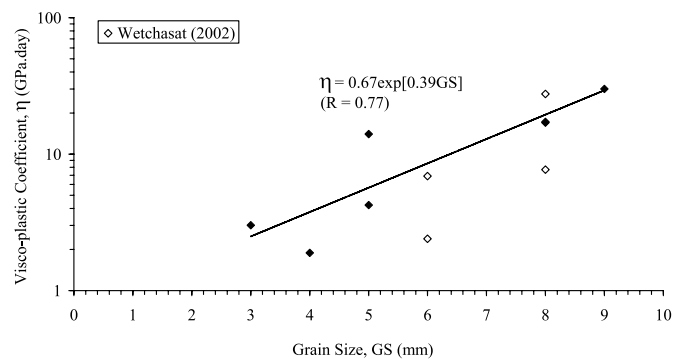


Figure 11. Relationship between visco-plastic coefficient and grain size in rock salt specimens

which was unconfined. On the top of the model was a steel loading platen which was subjected to a uniform and constant axial stress of 12.9 MPa (about half of the compressive strength). Table 2 lists the material property parameters used in the computer simulations. The salt properties were obtained from Wetchasat (2002) and Jandakaew (2003) who performed the relevant tests on the same salt as was used in this research. The anhydrite properties were taken from the GEO database.

Figure 13 shows the axial strain-time curves which resulted from the simulation. The results imply that the presence of anhydrite layers notably reduced the strain rates in the steady-state creep phase. Under the same percentage of anhydrite inclusion, increasing the number of anhydrite layers from one layer to three layers further reduced the strain rate. This was because the added layer of anhydrite increased the number of the interfaces between the anhydrite and salt, and hence further induced lateral resistance (friction) within the salt specimens. This was similar to the end effect of a short (L/D less than 2) uniaxial specimen. It is interesting to note that increasing the number of anhydrite layers beyond three will have no effect on the strain rate. As expected, the higher the percentage of anhydrite, the lower the strain rate of the salt specimens. For 30% and 50% inclusions, the impact of the number of layers is noticeable. Beyond 70% inclusion the impact of the number of anhydrite layers becomes insignificant.

Discussion and Conclusions

It is interesting to note that most of the literature relevant to salt mechanics, is widely scattered in the journals, conference papers and government reports, and does not fully describe the physical properties and mineral compositions of the tested salt specimens. Therefore, even though considerable amount of salt mechanics data has been available, a mathematical relationship between the mechanical properties and mineral compositions or petrology still cannot be developed.

All rock salt samples used in this research were from both the Khorat and the Sakon Nakhon basins. The sources of the core samples tested here were limited only from two boreholes in the Sakon Nakhon basin, and one borehole in the Khorat basin. This caused a difficulty in obtaining a diversity of the amount of inclusions in the salt specimens.

It is not implied here that the inclusions in the Maha Sarakham salt formation are only anhydrite and clay minerals. Nevertheless, the primary inclusions studied here were only anhydrite and clay minerals, because they were most prominent in the salt specimens obtained. Since the clay content in the salt tested here was less than 5%, its impact on the mechanical behavior of the specimens cannot be fully assessed.

Despite the insufficiency of the test data mentioned above, significant conclusions can be drawn from this research. The compressive strength of the salt specimens linearly increases

Table 2. Material property parameters used in the computer simulations (Wetchasat, 2001; Jandakaew, 2003)

	Parameters	Salt	Anhydrite
Elastic	Elastic Modulus (E), GPa	24.8	150
	Poisson's Ratio (ν)	0.20	0.18
	Shear Modulus (G_1), GPa	10.3	69
	Bulk Modulus (K_1), GPa	13.8	82.8
Visco-Elastic	Retard Shear Modulus (G_2), GPa	6.90	69.0
	Retard Bulk Modulus (K_2), GPa	20.7	82.8
	Visco-elastic Viscosity (V_2), GPa	9.0	55.2
Visco-Plastic	Visco-plastic Viscosity (V_4), GPa	17.2	55.2

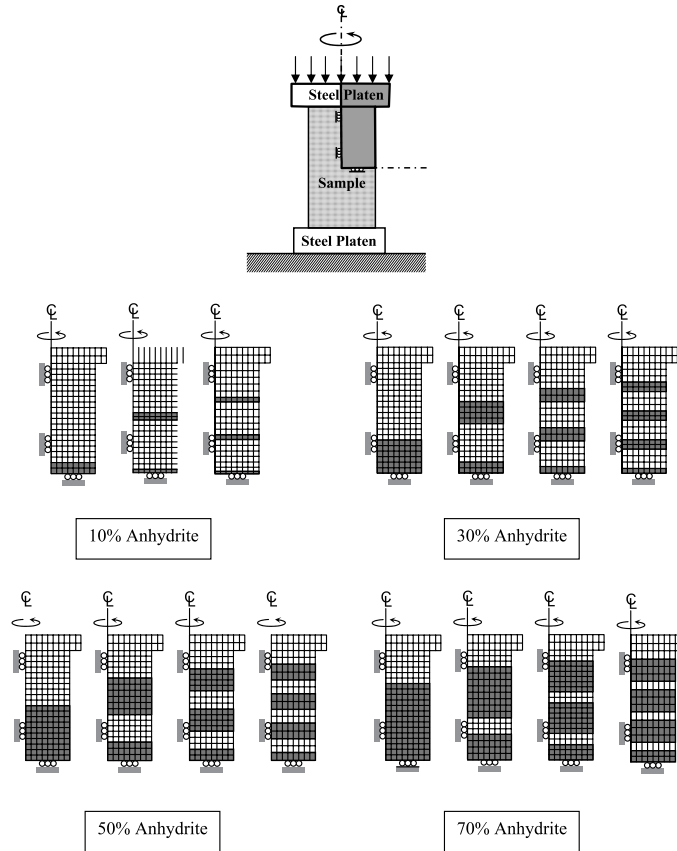


Figure 12. Mesh models of uniaxial creep test specimens with different amounts and distributions of anhydrite (shaded areas)

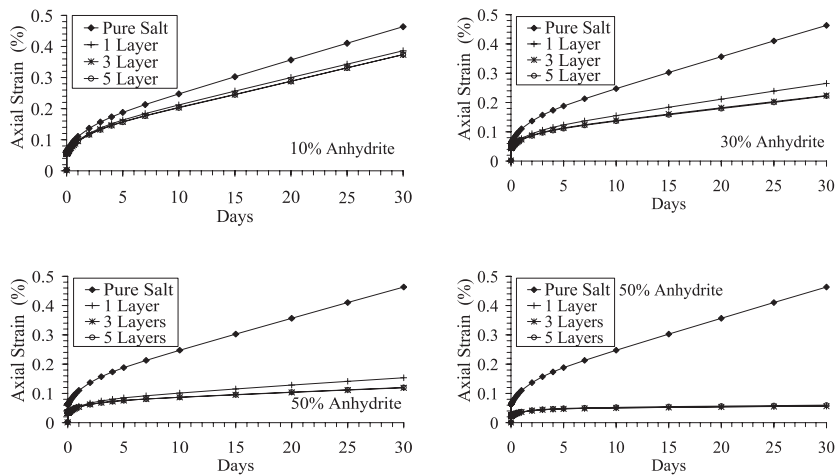


Figure 13. Axial strain-time curves simulated for salt specimens with 10%, 30%, 50%, and 70% anhydrite inclusion

from 27 to 40 MPa as the anhydrite inclusion increases from 0% (pure halite) to 100% (pure anhydrite). The combined effect between the salt and anhydrite stiffness also increases the specimen elasticity from 22 GPa (pure salt) to as high as 36 GPa (pure anhydrite). Tensile strengths of the salt specimens also increase with the anhydrite inclusion particularly when the inclusion is beyond 60% by weight. Below this limit, the anhydrite has an insignificant impact on the specimen tensile strength. For pure salt, the tensile strength is mainly governed by the failure characteristics. Inter-granular fracturing can have a tensile strength as low as 1 MPa while the salt crystal tensile strength can be as high as 2 MPa. The visco-plastic coefficients of salt specimens increase exponentially with the crystal size, as the dislocation glide mechanism dominates the creep deformation for the specimens containing large salt crystals. On the other hand, pure salt specimens with fine crystals are deformed mostly by the dislocation climb mechanism, resulting in a lower visco-plasticity. Results from computer simulations suggest that the amount and number of anhydrite layers can reduce the creep strain in the steady-state phase, and hence increase the visco-plasticity of the salt specimens. The clay mineral content of less than 5% (the highest found in the salt tested) seems to have an insignificant impact on the salt mechanical properties of salt. The effect of clay content beyond 5% remains unclear.

More testing should be performed on salt specimens that contain high percentages of clay inclusions (e.g., between 10% and 50% by weight) to investigate the effect on the salt strength and stiffness within this range. Additional test results on the effects of anhydrite inclusion on the visco-plasticity are also needed to confirm the results of the computer simulations.

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