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Mechanical Behavior of New Mexico Rock Salt in Triaxial Compression up to 200°C

Wolfgang R. Wawersik, David W. Hannum

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MECHANICAL BEHAVIOR OF NEW MEXICO ROCK SALT
IN TRIAXIAL COMPRESSION UP TO 200°C*

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Abstract

An extensive experimental program was conducted to determine the mechanical behavior of New Mexico rock salt in support of the structural design of a Waste Isolation Pilot Plant (WIPP). In this initial report, three groups of tests are discussed to identify the relative and site-specific importance of deviator stress, confining pressure (mean stress), temperature, time (loading rate), and stress path. The three groups of experiments consist of (1) hydrostatic loading, (2) conventional triaxial compression tests ($\sigma_1 > \sigma_2 = \sigma_3 = \text{const.}$), and (3) variable stress path tests including experiments at approximately constant σ_1 and at constant mean stress. All data were generated on 100 mm-diameter specimens.

The rock salt exhibited nonlinear response under all loading conditions, practically zero initial elastic limit and an apparent inseparability of permanent deformations into time-independent and time-dependent components. Pressure and temperature did not alter the elastic constants but affected the principal strain ratio, the

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ratio of volumetric to shear strain, rock salt ductility, and the ultimate stress. In particular, low pressure and temperature permitted pronounced dilatancy and loss in load bearing ability. Under such conditions the volumetric strains reached sizable fractions of the shear strains. Pressure remained important even at high temperature because it influenced the rate of shearing. Load path and stress history may be significant under deviatoric loading conditions and for large variations in pressure.

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CONTENTS

	Page
INTRODUCTION.	1
MATERIAL, CORE HISTORIES AND TEST SPECIMENS	3
EXPERIMENTS	4
Apparatus and Measurements	4
Experimental Procedures.	6
RESULTS	7
Hydrostatic Loading.	7
Deviatoric Loading at Constant Confining Pressure	8
Nonelastic Behavior, Elastic Constants and Pressure Effects at Ambient Temperature.	9
Elevated Temperature Data.	13
Influence of Load Path	14
Reliability of Results	16
DISCUSSION AND CONCLUSIONS.	17
REFERENCES.	22
TABLE 1	25
FIGURES	26

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Schematic of experimental apparatus. Parts key: (1) load frame, (2) hydraulic actuators, (3) pressure vessel, (4) loading piston, (5) heaters, and (6) insulation.	26
2	Comparison of two undeformed samples, 7-2740 and 7-2744 (Fig. 12) with one yet untested specimen, 7-2738. Nominal sample dimensions prior to deformation are 100 mm (diameter) by 220 mm (length).	27
3	Pressure-volumetric strain curves for New Mexico rock salt subjected to hydrostatic compression at ambient temperature. Open and solid circles identify data from linear measurements of ϵ_1 and $\epsilon_2 = \epsilon_3$, respectively. Note abbreviated test code: drillhole No. - depth of core in ft. (H = hydrostatic loading, temperature in $^{\circ}\text{C}$).	28
4	Conventional stress-strain curves for New Mexico rock salt subjected to uniaxial and triaxial compression at ambient temperature. Note abbreviated test code: drillhole No. - core depth in ft. (confining pressure in MPa, test temperature in $^{\circ}\text{C}$).	29
5	Triaxial stress-strain curves for New Mexico rock salt in the regime of small principal stress difference and strain (for test code see Fig. 4).	30
6	Principal stress difference vs. volumetric strain for tests of Fig. 4.	31
7	Triaxial variation of lateral strain vs. axial (greatest compressive) strain for tests of Fig. 4 and one additional experiment at .7 MPa confining pressure. Open squares identify approximate strains at ultimate stresses.	32

8	.....	33
	Triaxial variation of shear strain vs. volumetric strain for tests of Fig. 4 and one additional experiment at .7 MPa confining pressure. Open squares identify approximate strains at ultimate stresses.	
9	.....	34
	Triaxial stress-strain curves for New Mexico rock salt as a function of temperature at 3.5 MPa confining pressure (for test code see Fig. 4).	
10	.....	35
	Variation of lateral vs. axial (greatest compressive) strains for tests of Fig. 9.	
11	.....	36
	Variation of shear strain vs. volumetric strain for tests of Fig. 9.	
12	.....	37
	Triaxial stress-strain curves for New Mexico rock salt as a function of confining pressure at 200°C (for test code see Fig. 4).	
13	.....	38
	Variation of lateral strain vs. axial (greatest compressive) strain for tests of Fig. 12 and one additional experiment in uniaxial compression.	
14	.....	39
	Axial (greatest compressive) strain vs. time for tests of Figs. 12 and 13.	
15	.....	40
	Map of three non-proportional load paths and common stress states (points A, B, D, etc.). For strain data see Table 1.	
16	.....	41
	Comparative stress-strain data for New Mexico rock salt subjected to one or more confining pressures at ambient temperature. The partial code 20.7/3.5/20.7 identifies prevailing confining pressures between $(\sigma_1 - \sigma_3) = 0$ and first unload/reload cycle, first and second unload/reload cycle, and between second unload/reload cycle and final unloading trace.	
17	.....	42
	Variation of lateral strain vs. axial (greatest compressive) strain for tests of Fig. 16.	

INTRODUCTION

Laboratory tests of rock salt are being performed to support the design of a Waste Isolation Pilot Plant (WIPP) for disposal of radioactive wastes in the salt beds of southeastern New Mexico, USA. It is the goal of these tests to develop constitutive relations which can be used in structural design calculations and in predictions of the long-term response of a repository and the local geologic region. Finite element calculations are currently being applied to establish relative rankings of several design and waste emplacement alternatives (Gnirk et al., 1973; 1974; Dawson and Tillerson, 1977). As the program progresses, a combination of finite element computations, empirical mine design methods and in situ validation studies will serve to evaluate all aspects of the WIPP design. Specific concerns pertain to the stability of the facility during its working life, to the influence of ground motions on waste retrieval capabilities and to the effects of waste emplacement on the long-term containment potential of New Mexico salt formations.

To achieve a valid and practical description of the behavior of rock salt from experiments in the laboratory, several conditions must be satisfied. (1) The rock salt behavior must be measured over the domain of stresses and temperatures which are representative for the WIPP; (2) The testing program must permit a generalization of all results to differing stress, deformation and/or temperature histories;

(3) The mechanisms governing salt response must be understood in sufficient detail to justify the extrapolation of laboratory measurements in time; and finally (4) The relation must be established between laboratory samples of rock salt and salt masses in situ.

This paper summarizes one aspect of a series of ongoing laboratory efforts. It presents results from quasi-static compression tests to identify the influence of five experimental variables, the importance of which was suggested by prior mine measurements and by existing laboratory data (Schmidt, 1937; U. S. Corps of Engrs., 1963; Le Comte, 1965; Hofer and Thoma, 1968; Schlichta, 1969; Carter and Heard, 1970; Lomenick, 1971; Dreyer, 1972; Heard, 1972; Serata et al., 1972; Menzel and Schreiner, 1977). The five variables are: pressure (confining pressure, mean stress), principal stress difference (deviator stress), time (loading rate), temperature and load path. Results of additional experiments on creep, aging, petrofabrics, etc., will be reported elsewhere.

All quasi-static compression experiments which will be described served to scope the behavior of New Mexico rock salt under conditions which can be postulated in and around the proposed Waste Isolation Pilot Plant. Specifically, the foregoing tests yielded baseline data that helped identify the class of response of this salt (elastic vs. elastic-plastic vs. viscoplastic, etc.), assess the applicability of existing constitutive models, and define appropriate matrices for creep experiments. The tests were also useful for evaluating

the applicability of laboratory data for rock salt to engineering problems in situ.

The term quasi-static is used in the conventional sense to denote a fixed slow rate of loading. It does not imply that the observed material response was or became time-independent.

MATERIAL, CORE HISTORIES AND TEST SPECIMENS

The rock salt studied was machined from 108 mm diameter core, obtained at depths of 840 to 890 m in two drillholes, AEC #7 and ERDA #9. The salt consisted of >92 modal per cent halite with lesser amounts of clay and silt, polyhalite and anhydrite (Callender and Ingwell, 1977). Grain sizes varied, in order of decreasing abundance, from coarse (> 10 mm) to bimodal, medium (10 mm - 1 mm) to fine grained (< 1 mm). In most instances grain boundaries were moderately tight, that is halite grains touched locally and elsewhere had other mineral constituents occupying the interstices of grains (op. cit.).

Most samples contained numerous small liquid inclusions. Cavities up to 8 mm diameter were also observed (op. cit.). Specific gravities and porosities averaged 2.2 and 0.6%, respectively. Unconfined heating to 300°C produced a mass loss of 0.1 to 1.4% (Kopp and Combs, 1975; Elliot Geophys. Co., 1976; Core Laboratories, 1977; Boultinghouse and Sallach, 1977).

Core histories are important for interpreting laboratory observations. Although actual histories cannot be monitored readily, the following estimates are probably reasonable. If the salt were subjected to a lithostatic pressure before

coring, then the approximate loading during drilling would be determined by the difference in specific gravities of rock and drilling mud. As the specific gravities of the drilling muds in drillholes AEC #7 and ERDA #9 were 1.3 and 0.9, it is likely that the rock salt experienced the following histories. From a lithostatic stress state ($p = 17.9$ MPa) the cores were loaded deviatorically to $(\sigma_1 - \sigma_3) \leq 6.2$ MPa in AEC #7 and to $(\sigma_1 - \sigma_3) \leq 9.7$ MPa in ERDA #9, where σ_1 , σ_3 denote the maximum and minimum principal (compressive) stresses. In both cases the load path probably was close to triaxial extension at constant $\sigma_1 = \sigma_2$. All core material was subsequently unloaded to a state of hydrostatic compression equal to the hydrostatic head of each mud column.

Following drilling, the core was stored up to three years before machining and testing. Sample machining consisted of cylindrical and flat-end grinding following documented procedures which were designed to minimize the thickness of any chatter zones at the specimen surfaces. Final specimen dimensions were nominally 100 mm in diameter by 220 mm in length. After machining, the cylindrical surfaces of all samples were coated with a protective layer of RTV silastic.

EXPERIMENTS

Apparatus and Measurements

Details of the experimental apparatus are described elsewhere (Wawersik, 1979). Briefly, the equipment consists

of a standard hydraulic actuator and pressure vessel which was heated externally by a two-zone furnace (Fig. 1). Confining pressure was applied with silicon fluid which was pressurized by an incremental servo-controlled pressure generator. Ram force, confining pressure, and axial deformation were monitored outside the pressure vessel. In addition, lateral (radial) sample deformation was determined in one of two ways. In constant confining pressure experiments a dilatometric technique (Wawersik, 1975) was employed to obtain average values of lateral deformation over the entire sample length. In variable confining pressure tests, two disk gauges (Schuler, 1978) were utilized to record diameter changes at one-third and one-half points along the specimen axis.

The resolution of stress and strain measurements was determined in instrument and system calibrations using metal standards. At $(\sigma_1 - \sigma_3) \geq 1.7$ MPa, the following results were obtained. Axial stress: 0.1 MPa; hydrostatic and/or confining pressure: 0.05 MPa; axial strain ϵ_1 : 0.002%; lateral (radial) strain ϵ_3 : 0.005% for dilatometric measurements and 0.002% for disk gauge measurements. All stresses were calculated from current specimen dimensions.

Test temperature was measured and regulated by means of two thermocouples which were located in the top end of the pressure vessel and in the loading piston, respectively. Temperature was controlled to within 1°C at 200°C. The temperature gradient in salt was less than 2°C at 200°C over the sample length of 220 mm.

To evaluate the accuracy of strain measurements, the greatest strains ϵ_1 and $|\epsilon_2| = |\epsilon_3|$ were compared with those values which were calculated from the average initial and final (unloaded) specimen dimensions. It should be noted that the elastic recovery on unloading was small compared to the permanent deformations. In nearly every case the resulting data agreed better than 2%. Also, the agreement between results from dilatometric and disk gauge measurements was 2% to $\epsilon_3 = 5\%$. In the worst case, at $\epsilon_3 = 9.1\%$, disk gauge measurements exceeded the dilatometric values by 7% of the dilatometric readings.

Experimental Procedures

All tests were carried out in the following manner. Each specimen was placed between fully vented steel end caps and enclosed in a thin Viton jacket. This specimen assembly was placed inside the pressure vessel and pressurized. Next the sample was brought to the desired test temperature. Finally, the desired axial load was applied at a constant rate which was 11.9 N/s in most experiments. Departures from this procedure were made occasionally during unloading and reloading cycles as noted in the subsequent discussion. If σ_c denotes the ultimate stress (Handin, 1966), then the loading rate 11.9 N/s corresponds to $1.7 \leq d(\sigma_1 - \sigma_3)/dt \leq 3.5$ kPa/s for $0.8 \sigma_c \leq (\sigma_1 - \sigma_3) \leq \sigma_c$. A marked drop in stress rate $d(\sigma_1 - \sigma_3)/dt$ near the ultimate stress is due to large changes in specimen area.

RESULTS

Triaxial tests were performed over the following range of conditions: $0 \leq p \leq 34.5$ MPa; $0 \leq \sigma_3 \leq 20.7$ MPa; $0 \leq (\sigma_1 - \sigma_3) \leq 62$ MPa, and $23 \leq T \leq 200^\circ\text{C}$. The symbols p , σ_3 , $(\sigma_1 - \sigma_3)$, and T denote hydrostatic pressure, confining pressure, principal stress differences and temperature. The quantity p also designates the mean stress $p = \left(\frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \right)$. By convention, in triaxial tests two principal stresses are always equal. Therefore, for isotropic materials $(\sigma_1 - \sigma_3)$ is related directly to the second deviatoric stress invariant and to deviatoric strain. In turn, for $\epsilon_2 = \epsilon_3$ the shear strain $(\epsilon_1 - \epsilon_3)$ is related directly to the second deviatoric strain invariant as a general measure of shape changes. Both mean stress and second deviatoric stress invariant take into consideration the effect of all three principal stresses. Coaxiality of the stress and strain tensors is inferred throughout. This assumption is consistent with the observation that most salt cylinders retained their cylindrical shapes on average during deformation as demonstrated in Fig. 2. Local variations in deformations appear to be due to local textural and composition inhomogeneities.

Hydrostatic Loading

Figure 3 shows two hydrostatic loading curves. The volumetric strains of curve 7-2776 were computed as three times the axial strain ϵ_1 . Curve 7-2834.5 fits two sets of data, $\epsilon = 3 \epsilon_1$ and $\epsilon = 3 \epsilon_3$ which were measured on the same sample. The agreement between $3 \epsilon_1$ and $3 \epsilon_3$ indicates that the rock salt was mechanically isotropic prior to testing.

The same conclusion was drawn earlier from measurements of ultrasonic (longitudinal) velocities (Wawersik et al., 1976).

Tangents to various loading and unloading portions of both curves above 6.9 MPa yielded bulk moduli, K , in the range from 10 to 25 GPa. This range of values agrees with published data for polycrystalline salt with less than 1.11% porosity (Bridgeman, 1945; 1948; Heard et al., 1975).

The nonlinearity in p - ϵ behavior at low pressure and the large difference between first loading and unloading data of natural rock salt are surprising but plausible. Usually such observations are attributed to crack closure, grain boundary consolidation and/or pore collapse. While any one or all of these phenomena may have gone on simultaneously, it is interesting that they manifested themselves at pressures below the lithostatic pressure which probably existed in situ. Assuming that some of the hysteresis observed in Fig. 3 is due to crack closure, it is also apparent that the cracks remained closed for the duration of all unload/reload cycles. Regardless of the precise nature of the micro-processes during hydrostatic loading, the net salt consolidation shown in Fig. 3 is somewhat time-dependent; at 20.7 MPa and 34.5 MPa pressure volume reductions continued for several hours.

Deviatoric Loading at Constant Confining Pressure

Deviatoric loading is the process of increasing the principal stress difference (deviator stress) from an initial state of hydrostatic compression. Six parameter spaces

will be utilized to display the main experimental results: $[(\sigma_1 - \sigma_3), \epsilon_1]$, $[(\sigma_1 - \sigma_3), (\epsilon_1 - \epsilon_3)]$, $[(\sigma_1 - \sigma_3), \epsilon]$, $[\epsilon_1, \epsilon_3]$, $[(\epsilon_1 - \epsilon_3), \epsilon]$ and (strain, time). From here on volumetric strain is defined as $\epsilon = (1 + \epsilon_1)(1 + \epsilon_3)^2 - 1$. Conventional plots $(\sigma_1 - \sigma_3)$ vs. ϵ_1 relate the present data to virtually all results for rock salt in the literature (e.g. Schmidt, 1937; Heard, 1972; Dreyer, 1972; Menzel and Schreiner, 1977). However, strain-strain plots are particularly suited to demonstrate the influence of pressure and temperature on rock salt behavior and to identify qualitatively both the nature and the interaction of groups of governing deformation mechanisms.

Nonelastic Behavior, Elastic Constants and Pressure Effects at Ambient Temperature

Figures 4 through 8 summarize typical data which were obtained in constant confining pressure tests at ambient temperature. Samples and test parameters for each curve in these figures are identified by means of the following abbreviated code: drillhole No. - depth of core in ft. (nominal confining pressure in MPa, test temperature in °C). Thus the designation 9-2601 (3.5, 23) identifies core from drillhole #9, core depth of 2601 ft, 3.5 MPa confining pressure and 23°C. Identifications of core depths in feet rather than meters permit the correlation of laboratory data with the official field drilling records.

The stress-strain curve of sample 9-2601.5 in Fig. 4 depicts a complete experimental record which indicates the manner in which all specimens were loaded. Deviator stress was applied incrementally rather than continuously. Axial force was raised quickly by some predetermined amount and then held constant for between four and fifteen minutes while axial and lateral strains ϵ_1 and $\epsilon_2 = \epsilon_3$ were monitored in time. In most figures part of this detail is omitted. Instead curves are shown which constitute smooth fits to the end points of each step in the actual stress-strain records. Note again, that large changes in specimen area during all load-hold intervals lead to considerable decreases in principal stress difference with time.

Figure 5 shows a stress strain curve for small $(\sigma_1 - \sigma_3)$, ϵ_1 , ϵ_3 . It is apparent from Figs. 4 and 5 that laboratory specimens of New Mexico rock salt are quite nonelastic regardless of their pre-test history; their initial elastic limit is close to zero. This fact is reflected in low values of the secant modulus ($E_s \leq 12$ GPa), high principal strain ratios ($|\epsilon_3/\epsilon_1| \geq .36$) and sizable permanent deformation. It is further indicated by the occurrence of creep during all load-hold periods even at low principal stress difference, $(\sigma_1 - \sigma_3) \approx 3$ MPa. The secant moduli and the principal strain ratios differ from the elastic modulus E and Poisson's ratios ν which were measured during numerous unload/reload cycles (arrows in Fig. 4). According to these data $29.6 \leq E \leq 36.5$ GPa and $0.17 \leq \nu \leq 0.26$.

Obviously, pressure has a considerable effect on all properties of New Mexico rock salt except the elastic constants. Specifically, pressure controls its ductility (Handin, 1966), the ultimate stress and the relationships between all strains (Figs. 4 through 8). Furthermore, it appears that pressure effects are particularly evident at $(\sigma_1 - \sigma_3) \geq 7.5$ MPa, approximately when dilatancy becomes pronounced. At ambient temperature, increases in confining pressure from 0 to 20.7 MPa induce changes in ductility and ultimate stress from $\epsilon_1 \leq 2.4\%$ to $\epsilon_1 > 20\%$ and from $(\sigma_1 - \sigma_3) = 23.3$ MPa to $(\sigma_1 - \sigma_3) > 62$ MPa, respectively. It is not clear whether New Mexico rock salt from the 840 m horizon has a peak load bearing ability at 20.7 MPa confining pressure which is synonymous with material collapse. Based on data for other rock salt (Dreyer, 1972; Menzel and Schreiner, 1977) fracture might be reached at large strains, $\epsilon_1 \geq 40\%$. Alternatively, it is conceivable that an ultimate stress could simply be a saturation stress associated with steady state creep.

Figures 7 and 8 indicate considerable variations in the relationship between axial and lateral strains ϵ_1 , ϵ_3 and between volumetric and shear strains, ϵ , $(\epsilon_1 - \epsilon_3)$. For example, the numerically greatest ratios ϵ_3/ϵ_1 and $\epsilon/(\epsilon_1 - \epsilon_3)$ vary from -2.1, -1.0 to -.668, -0.094. Isovolumetric conditions are approached at 20.7 MPa confining pressure implying a predominantly ductile mode of deformation. However, over the entire range of confining pressure studied here the volu-

metric strains can amount to significant fractions of the shear strains (Fig. 8). Also, data at elevated temperature demonstrate clearly that even comparatively minor amounts of dilatancy have a considerable effect on the rate of what appears to be pure ductile flow.

Interestingly, Figs. 7 and 8 exhibit smooth transitions between the pre-and post-failure behavior of New Mexico rock salt. To indicate the dividing points between the two regions each curve is marked by an open square which designates the approximate strains at the ultimate stress. Accordingly, Figs. 7 and 8 define a type of failure loci in strain space for the prevailing rate of loading, confining pressures and temperature. Figure 8 also shows that the volumetric strains at the ultimate stress are not constant. This suggests that the distribution of microfractures governing dilatancy prior to macroscopic collapse is pressure dependent. Similar observations are well known for other, more brittle rocks.

Note the unloading and reloading cycles of specimens 7-2837 and 9-2691 which are indicated by arrows in Fig. 4. Sample 7-2837 was unloaded and reloaded quickly throughout (≈ 0.5 MPa/s), and the specimen does not appear to have noticed the excursion in load path. On the other hand, 9-2601.5 was unloaded the same way but the reloading rate was slowed down to 3.5 kPa/s when the stress had reached 75 to 80% of the previously attained peak load. The latter history is clearly reflected in the top portion of the reloading record of test 9-2601.5 in Fig. 4. It is remembered by the specimen and,

based on other experimental observations, it is not readily forgotten.

Elevated Temperature Data

Elevated temperature experiments were carried out in two groups. First, the influence of temperature was considered at fixed confining pressures, for example 3.5 MPa (Figs. 9 to 11). Then the effect of pressure was evaluated at 200°C (Figs. 12 through 14). As expected (Lomenick, 1971; Heard, 1972; Dreyer, 1972), temperature reduces the ultimate stress and increases the ductility (Fig. 9). Also, increasing the temperature is qualitatively equivalent to increasing confining pressure at ambient temperature: cataclastic effects with considerable dilatancy are suppressed in favor of deformation modes which proceed at constant or nearly constant volume (Figs. 10 and 11). At 3.5 MPa confining pressure the numerically greatest observed ratios ϵ_3/ϵ_1 and $\epsilon/(\epsilon_1 - \epsilon_3)$ were -0.75, -0.16, and -0.69, -0.09 at temperatures of 100°C and 200°C, respectively. These numbers compare with values of -0.9, -0.31 at 23°C at the same maximum shear strain $(\epsilon_1 - \epsilon_3) \approx 35\%$.

The influence of pressure at the peak temperature of 200°C was unexpected (Figs. 12 through 14). For equal values of $(\sigma_1 - \sigma_3)$ the shear strains in Fig. 12 differ by nearly 100% as a function of confining pressure, $3.5 \leq \sigma_3 \leq 20.7$ MPa. This difference occurred although plots of $(-\epsilon_3)$ versus ϵ_1 (Fig. 13) are almost identical suggesting that the deformation mechanisms were the same in both samples. Note that Fig. 13 also includes

one experiment in uniaxial compression. The key to an explanation of these measurements probably lies in the fact that some dilatancy developed even at high temperature, and that this dilatancy was caused by microfracturing. Using these observations, it is assumed that the microfracturing, which by itself is sensitive to changes in pressure, was equivalent to the removal of barriers to pure isovolumetric glide. For this reason, it is assumed that the salt could deform at a faster rate at low confining pressure, in the presence of fewer barriers at a fixed, externally controlled rate of loading. The latter suggestion is consistent with the strain-time plots in Fig. 14.

Influence of Load Path

In 1972, Serata et al. published data which showed a significant influence of hydrostatic loading on the results of conventional triaxial experiments for rock salts from Mississippi and Texas. To check for similar effects, numerous hydrostatic loading histories were evaluated early during the experimental program on New Mexico rock salt. All of the observations indicate, that hydrostatic loading to 34.5 MPa for up to 48 hours has no measurable influence on subsequent triaxial (deviatoric) compression data.

Variable deviatoric load paths were considered for three non-proportional conditions. In addition to conventional tests at constant confining pressure (load path I), experiments were performed at constant mean stress (load path II) and at approximately constant maximum compression σ_1 (load path III). The three load paths are drawn in Fig. 15 in the space $[(\sigma_1 - \sigma_3),$

$\sigma_2 = \sigma_3$]. Figure 15 also identifies one test which combined load paths III and I passing through points A, D, G and H.

Table 1 provides examples of strains at several common stress states which we reached along the stress paths of Fig. 15. It is clear that the strains ϵ_1 and ϵ_3 are numerically greatest along the path of constant confining pressure (load path I). The smallest ϵ_1 and ϵ_3 were obtained along the path of maximum pressure, either confining pressure or mean stress (load path III).

It is reiterated that the foregoing stress paths were traced out at stress rates $1.7 \leq d(\sigma_1 - \sigma_3)/dt \leq 3.5$ kPa/s. Therefore, the observed differences in the strains ϵ_1 and ϵ_3 at points A, B, etc. in Fig. 15 (table 1) are largely due only to stress path rather than stress path and time. To avoid other ambiguities, it is also emphasized that one and the same technique was used to measure all axial strains. In turn, lateral strains were measured dilatometrically on two samples, 7-2725 and 9-2601 at 3.5 MPa confining pressure. In all other cases, lateral strain was monitored by means of two disk gauges.

To evaluate load path effects even further, a third group of tests was carried out. In these experiments, one sample was deformed in three successive stages at 20.7, 3.5, and again at 20.7 MPa confining pressure. The response of this specimen was then compared with the stress-strain behavior of three samples which had been loaded deviatorically at 20.7 MPa and 3.5 MPa confining pressure, respectively. The results

of the latter tests are shown in Figs. 16 and 17. This last group of experiments does not only probe the influence of stress path but also the combination of stress path, stress and strain histories.

Reliability of Results

Overall, the results shown were not only qualitatively but also quantitatively reproducible. Significant variability of measurements occurred only in hydrostatic compression and in isolated triaxial tests at ambient temperature. Fig. 3 brackets the range of measurements which were collected under hydrostatic loading. In view of the observed scatter the validity of these hydrostatic loading data was checked and verified by means of three techniques, including strain gauges. In turn, Figs. 16 and 17 show examples of deviatoric loading data at 20.7 MPa confining pressure. They characterize the general agreement of results for New Mexico rock salt of this study. Given any combination of principal stress difference, confining pressure and temperature, normally the measured strains differed by less than 20% of the smallest observed reading. This observation is further substantiated by the trend in the strain comparisons in Table 1, that is, the magnitudes of the strains ϵ_1 , ϵ_3 were consistently greatest along the path of constant confining pressure (load path I). An extreme variation in strains (50%) at equal $(\sigma_1 - \sigma_3)$ was recorded in one set of experiments at 3.5 MPa confining pressure. However, at least part of this discrepancy is attributed

to differences in the number of unload/reload cycles and to large differences in the loading rates during these unload/reload cycles (Fig. 4).

It is emphasized that the overall trends and reproducibility of results also suggest that the size of samples tested was large enough to be unaffected by local variations in grain size. Additionally, the conditions at the interfaces between specimen ends and end-caps were such as to produce little barreling except relatively far into the post-failure regime (Fig. 2). Therefore, strong indications exist that the stress field in all experiments was well defined.

DISCUSSION AND CONCLUSIONS

The present laboratory data establish summary guidelines which should be observed in modeling the mechanical behavior of New Mexico rock salt at relatively low confining pressure up to fracture and/or massive flow ($\epsilon_1 \geq 20\%$) and at temperatures up to 200°C. Obviously, New Mexico rock salt in the laboratory is very nonlinear under all loading conditions with an initial elastic limit $(\sigma_1 - \sigma_3) \approx 0$. Its elastic properties can be evaluated accurately only in load/unload/reload cycles provided the imposed loading rate is sufficiently high or the range of stresses, either p or $(\sigma_1 - \sigma_3)$ is well below the previously attained peak stress. Additionally, the elastic deformation of rock salt subject to deviatoric loading constitutes a very small fraction of the total deformation.

A complete description of the nonelastic behavior of New Mexico rock salt requires that several observations will have to be considered. (1) "Quasi-static" and recovery measurements indicate that practically all nonelastic deformation is permanent. (2) So far it has been impossible to separate the permanent deformation of rock salt into time-independent and time-dependent components even at the relatively high loading rate, $d(\sigma_1 - \sigma_3)/dt \approx 3 \text{ MPa/s}$. (3) At the low pressures of this study, New Mexico rock salt exhibits two regimes in which deformation approaches isovolumetric conditions and in which deformation is associated with large dilatancy due to local fracturing. It appears that the near isovolumetric, ductile behavior predominates at low deviator stress, high pressure and/or high temperature. However, it is important to note that some volume increase occurred even under the most extreme conditions, 200°C and 20.7 MPa confining pressure. (4) The nonelastic behavior of New Mexico rock salt depends both on temperature and on pressure. In particular, low pressure and temperature permit pronounced dilatancy and loss in load bearing ability (macroscopic failure). Under such conditions, the volumetric strains reach sizable fractions of the shear strains. Pressure remains important even at high temperature because it influences the rate of shearing.

Given the nonelastic nature of New Mexico rock salt, it is not surprising that stress path and stress history may alter its response. The greatest compressive strain ϵ_1 and the numerically greatest ratios ϵ_3/ϵ_1 are attained along the path of lowest

pressure. Besides affecting the total strains, stress path also influences the magnitudes of the strain increments and the ratios of strain increments at common stress states (data not shown). This observation implies that the effects of stress history and of the resulting strain history are remembered for some time. Although these effects do not appear to be permanent Fig. 16 suggests that they may be carried through shear strains exceeding $(\epsilon_1 - \epsilon_3) = 10\%$.

The primary objective of this paper was to identify and summarize the major mechanical properties of New Mexico rock salt which can be observed in short-term, "quasi-static" experiments. In view of the indicated complexities, it has been impossible so far to cast the results into a general material model. However, certain limitations of existing constitutive concepts have become apparent. Several of these concepts have been utilized routinely to describe rock salt in the past.

The data clearly indicate that the behavior of rock salt is not governed by its elastic properties and by a fracture envelope which can be ascertained in quasi-static tests. Furthermore, the notion of a unique fracture envelope appears questionable because the strengths/ultimate stresses (cohesion and internal friction coefficient) of New Mexico rock salt are time- and temperature-dependent. Finally, rock salt fracture is associated with very large differences in strains. We believe that these differences should be considered in a practical definition of failure.

As alternatives to elastic analyses, a number of assumptions have been invoked (Langer, 1969; Nair, K., 1970; Serata et al., 1972; Gnirk et al., 1973; Menzel and Schreiner, 1977; Wahi et al., 1977; Dawson and Tillerson, 1977). These assumptions are necessary to justify the application of established constitutive concepts which were previously derived for metals, polymers or soil (Drucker et al., 1957; Fung, 1965; Perzyna, 1966; Malvern, 1969; Krieg, 1977; and Krieg et al., 1978). The two main sets of postulates are (1) Material incompressibility and independence between pressure and shear strain; (2) existence of unique initial and subsequent threshold stress states (loading functions) to define the onset of nonelastic deformations. Depending on whether or not all nonelastic deformations are separable into time-independent and time-dependent fractions, one or more loading functions are then utilized to define corresponding relationships between permanent strain increments or strain rates on one hand and stress on the other. Most often this is accomplished by means of the so-called associated flow rule. In the simplest case, zero threshold stress, the resulting equations define a viscous fluid with a constant or temperature-dependent viscosity.

Recalling all the results of this experimental study, it appears that only some of the postulates of the established non-elastic constitutive theories are satisfied. Hence, additional modeling research is required particularly at high deviator stress and low confining pressure when pressure sensitive dilatancy is most pronounced. The complexities of the

mechanical behavior of rock salt from southeastern New Mexico also emphasize the importance of validation studies in which the accuracy of design calculations is evaluated.

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Table 1. Deviatoric Load Path Data

Reference Point in Fig. 14	Load Path	$(\sigma_1 - \sigma_3)$	$\sigma_2 = \sigma_3$	p	ϵ_1	$-\epsilon_3$
		MPa	MPa	MPa	%	%
A	I	11.0	20.6	17.4	.18	0.09
	II	11.0	20.9	17.6	.17	0.07
	III	11.1	21.4	18.0	0.08	0.05
B	I	10.3	3.6	5.8	.36	0.18
	II	10.5	3.6	5.9	.31	.17
D	II	22.0	7.6	12.4	1.35	.79
	III	21.7	7.6	12.3	0.73	.45
G	I	25.7	1.7	9.7	2.63	1.99
	III	26.0	1.7	9.8	1.50	1.01
H	I	36.1	1.7	13.2	8.58	7.81
	III & I	35.3	1.7	12.9	6.41	5.46
	II	36.7	1.9	13.5	5.74	3.79

Fig. 1 Schematic of experimental apparatus. Parts key:
 (1) load frame, (2) hydraulic actuators,
 (3) pressure vessel, (4) loading piston,
 (5) heaters, and (6) insulation.

Fig. 2 Comparison of two undeformed samples, 7-2740 and 7-2744 (Fig. 12) with one yet untested specimen, 7-2738. Nominal sample dimensions prior to deformation are 100 mm (diameter) by 220 mm (length).

Fig. 3 Pressure-volumetric strain curves for New Mexico rock salt subjected to hydrostatic compression at ambient temperature. Open and solid circles identify data from linear measurements of ϵ_1 and $\epsilon_2 = \epsilon_3$, respectively. Note abbreviated test code: drillhole No. - depth of core in ft. (H = hydrostatic loading, temperature in $^{\circ}\text{C}$).

Fig. 4 Conventional stress-strain curves for New Mexico rock salt subjected to uniaxial and triaxial compression at ambient temperature. Note abbreviated test code: drillhole No. - core depth in ft. (confining pressure in MPa, test temperature in °C).

Fig. 5 Triaxial stress-strain curves for New Mexico rock salt in the regime of small principal stress difference and strain (for test code see Fig. 4).

Fig. 6 Principal stress difference vs. volumetric strain for tests of Fig. 4.

Fig. 7 Triaxial variation of lateral strain vs. axial (greatest compressive) strain for tests of Fig. 4 and one additional experiment at .7 MPa confining pressure. Open squares identify approximate strains at ultimate stresses.

Fig. 8 Triaxial variation of shear strain vs. volumetric strain for tests of Fig. 4 and one additional experiment at .7 MPa confining pressure. Open squares identify approximate strains at ultimate stresses.

Fig. 9 Triaxial stress-strain curves for New Mexico rock salt as a function of temperature at 3.5 MPa confining pressure (for test code see Fig. 4).

Fig. 10 Variation of lateral vs. axial (greatest compressive) strains for tests of Fig. 9.

Fig. 11 Variation of shear strain vs. volumetric strain for tests of Fig. 9.

Fig. 12 Triaxial stress-strain curves for New Mexico rock salt as a function of confining pressure at 200°C (for test code see Fig. 4).

Fig. 13 Variation of lateral strain vs. axial (greatest compressive) strain for tests of Fig. 12 and one additional experiment in uniaxial compression.

Fig. 14 Axial (greatest compressive) strain vs. time
for tests of Figs. 12 and 13.

Fig. 15 Map of three non-proportional load paths and common stress states (points A, B, D, etc.). For strain data see Table 1.

Fig. 16 Comparative stress-strain data for New Mexico rock salt subjected to one or more confining pressures at ambient temperature. The partial code 20.7/3.5/20.7 identifies prevailing confining pressures between $(\sigma_1 - \sigma_3) = 0$ and first unload/reload cycle, first and second unload/reload cycle, and between second unload/reload cycle and final unloading trace.

Fig. 17 Variation of lateral strain vs. axial (greatest compressive) strain for tests of Fig. 16.

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