

Failure Behaviour of Rock Salt Around Underground Cavities

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ABSTRACT

Knowledge of the geomechanical behaviour of rock salt is important for model calculations for the dimensioning and safety analysis of mines, caverns, and repositories for radioactive or toxic wastes in salt domes or bedded salt. Knowledge of the failure behaviour of rock salt around underground cavities is particularly important.

True triaxial tests at elevated hydrostatic pressures have been conducted on cubic samples under various test conditions. A conservative equation for failure strength at elevated hydrostatic pressures as a function of mean stress, load path, and temperature has been derived from the results. In addition, an exact equation for failure strength for compressional load geometry is given. The true triaxial tests were also used to determine the boundary between compressibility and dilatancy. At stress states above this line rock salt dilates and creep rupture may occur.

At low hydrostatic pressures, failure occurs when there is tensile stress in at least one direction. Therefore, biaxial tests on cubic samples, as well as tension tests under uniaxial and triaxial conditions on dogbone-shaped samples, have been conducted for this stress range. The triaxial tension tests are especially difficult to perform but are of great value. The experiments show that the tensile strength of rock salt is an inverse function of hydrostatic pressure. Above a certain stress level, i.e. the stress corresponding to biaxial strength, extensional failure occurs even with compressive stresses on all sides of the sample.

The results of the different experimental methods are in good agreement. The results of the biaxial tests and the tension tests are not yet included in a failure criterion. Finally, *in situ* observations are compared with the experimental results.

INTRODUCTION

Knowledge of the geomechanical behaviour of rock salt is important for the dimensioning and safety analysis of mines, caverns, and repositories for toxic and radioactive wastes in natural salt formations. Rock salt is also often used as a model material in the materials sciences. Therefore, much experimental and theoretical work has been carried out in this field during the last two decades, mainly on creep and failure behaviour. Test results and laws for the creep behaviour have been published, e.g. by Heard (1972), Menzel and Schreiner (1977), Albrecht and Hunsche (1980), Carter and Hansen (1983), Lux and Heusermann (1983), Munson and Dawson (1984), Langer (1984), Wawersik and Zeuch (1986), Wawersik (1988), and Hunsche (1988). Failure has been described, e.g. by Serata et al. (1972), Dreyer (1974), Georgi et al. (1975), Wawersik and Hannum (1980), Wallner (1983), Diekmann et al. (1986), Desai and Varadarajan (1987), Hunsche and Albrecht (1990), Hunsche (1991,1992), Cristescu and Hunsche (1991,1992).

This publication only deals with the failure behaviour of rock salt. Knowledge of the failure behaviour of rock salt around underground cavities is particularly important. The results of a purely elastic model calculation by Cristescu (1993) for the stress state around a deep tunnel immediately after excavation are shown in Fig. 1. This demonstrates that failure can occur under these circumstances due to the following failure conditions: (1) failure at low mean stresses due to tension, (2) failure at intermediate or high mean stresses under different load geometries (e.g. compression and extension), and (3) creep failure due to dilatancy after a longer time interval in a certain range of stress states. Because none of the published failure equations can be considered as really satisfactory, much experimental and theoretical work still has to be performed in this field.

Several kinds of tests are carried out at the BGR to evaluate failure under various conditions. These include quasi-static tests on cylindrical and cubic samples at many load or deformation rates under triaxial conditions at intermediate or high mean

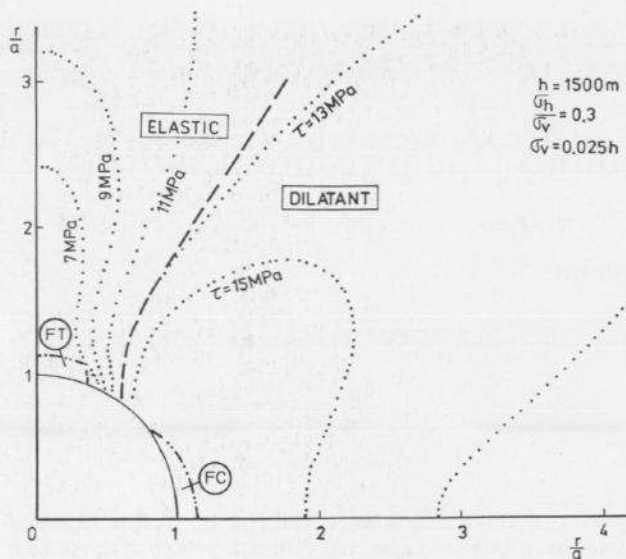


Fig. 1. Domains of failure, dilatancy, and compressibility around a tunnel with radius (a) excavated in a salt deposit at a depth of 1500 m. Stresses were calculated purely elastically. σ_h or σ_v : horizontal or vertical far field (primary) stresses. The vertical and horizontal axes represent the vertical and horizontal distances (r) from the tunnel centre. FT: Tensional failure at low mean stress; FC: failure at high mean stress. (Plot after Cristescu, 1992).

stresses, and uniaxial or triaxial tension tests, as well as biaxial and uniaxial compression tests at low mean stresses. The final aim is to develop reliable physically and experimentally based constitutive equations for rock salt which describe (1) elastic behaviour, (2) failure and related phenomena, such as dilatancy and compressibility due to the opening and closing of microcracks, and (3) creep phenomena.

Results of true triaxial quasi-static failure tests on cubic samples, the results of uniaxial and triaxial tension tests, and results of biaxial tests are described in this publication. Rock salt has been used for all the tests. The uniaxial and triaxial tension tests, as well as the biaxial tests, were carried out on specimens from the Asse mine (northern Germany). They consist of very clean rock salt from the Zechstein 3. The true triaxial tests were carried out on samples of various types of rock salt from five deep boreholes into the Gorleben salt dome (northern Germany). In general, these samples were also rather clean.

Emphasis is placed on the presentation of results for failure strength and the description by suitable equations. For the determination of a constitutive equation for rock salt which also incorporates dilatation and deformation, see Cristescu and Hunsche (1991, 1992) and Cristescu (1993). The experimental procedures and the analysis of the empirical data are described for the biaxial and the true triaxial tests in Hunsche and Albrecht (1990) and Hunsche (1992).

FAILURE AT INTERMEDIATE AND HIGH MEAN STRESSES

In many cases, e.g. for the dimensioning of an underground cavity, it is advisable to use a conservative failure equation that is fitted to the lower limits of the measured failure strength. Such a conservative equation for failure strength has been derived on the basis of twelve quasi-static test series consisting of various rock salt types (350 tests). Each series consists of ca. 20 true triaxial tests at room temperature and 5 tests between 60 and 260°C, as well as some uniaxial and biaxial tests, all performed on cubic samples (Hunsche and Albrecht, 1990; Hunsche, 1991, 1992). The results were used to derive the equation which describes failure strength and residual strength as a function of mean stress σ , load geometry m , and temperature T (see below). For the variables and basic formulae, see Table 1. The test results at room temperature and the resulting functions for compression ($m = -1$) and extension ($m = +1$) are presented in Fig. 2. It shows all the tests at room temperature grouped according to the value of m . It is important to note that the extension tests exhibit the lowest strengths, averaging about 30% less than the compression tests. This is different from the behaviour of metals but is usual in rocks. The effect decreases at high mean stress σ , however. Generally, failure strength depends on loading rate or strain rate. However, in additional tests it was found that strain rates below about 10^{-1} s^{-1} influence strength of rock salt only slightly; loading rates below about 300 MPa/min have a somewhat larger

TABLE 1

Variables discussed in this paper. Compression: positive values

$\sigma_1, \sigma_2, \sigma_3$	Principal stresses
$\sigma = 1/3(\sigma_1 + \sigma_2 + \sigma_3)$	Mean stress, octahedral Normal stress
$s_1 = \sigma_1 - \sigma$	Stress deviator
$\tau = [1/3(s_1^2 + s_2^2 + s_3^2)]^{1/2}$	Octahedral shear stress
$J_m = \frac{m(9 - m^2)}{(3 + m^2)^{1.5}}$	Invariant of load geometry
$m = \frac{3s_2}{s_1 - s_3}; s_1 > s_2 > s_3$	Stress path, load geometry, Lode parameter
$\epsilon_i = (l_i - l_0)/l_0$	Principal strains
$\epsilon_V = (l_1 \cdot l_2 \cdot l_3)/V_0 + \text{correction}$	Relative volume change
l_1, l_2, l_3	Actual edge lengths
l_0	Initial edge length
V_0	Initial (reference) volume
τ_B	Failure strength

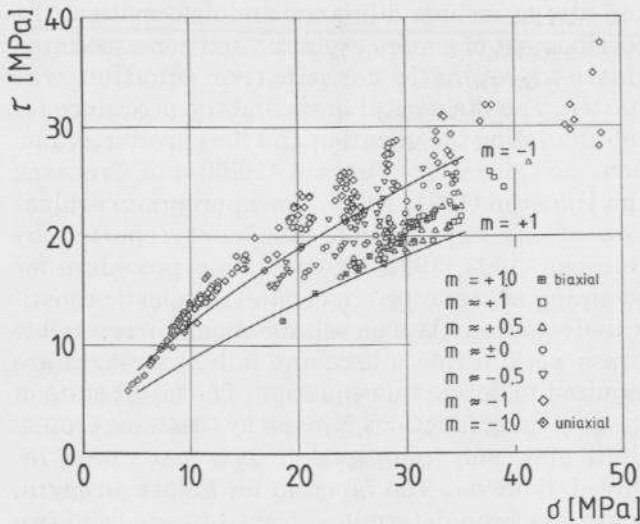


Fig. 2. Failure strength for twelve series of true triaxial tests on cubic samples of different rock salt types from the Gorleben salt dome, grouped according to the value of load geometry m ; $T = 30^\circ\text{C}$. The lines represent the conservative failure equation at $m = -1$ (compression) and $m = +1$ (extension).

TABLE 2

Conservative failure equation for rock salt

Conservative failure equation (Hunsche, 1991, 1992)

$$\tau_B = f(\sigma) \cdot g(m) \cdot h(T) \quad : \text{failure strength}$$

$$f(\sigma) = b (\sigma/\sigma_*)^p$$

$$g(m) = 2k/[(1+k) + (1-k)J_m]$$

$$h(T) = \begin{cases} 1 & \text{for } 20^\circ\text{C} \leq T \leq 100^\circ\text{C} \\ 1 - c(T - 100^\circ\text{C}) & \text{for } 100^\circ\text{C} \leq T \leq 260^\circ\text{C} \end{cases}$$

$$b = 2.7 \text{ MPa} \quad p = 0.65$$

$$k = 0.74 \quad \sigma_* = 1 \text{ MPa}$$

$$c = 0.002 \text{ K}^{-1}$$

$$\tau_R = \tau_B(m = +1) \quad : \text{residual strength}$$

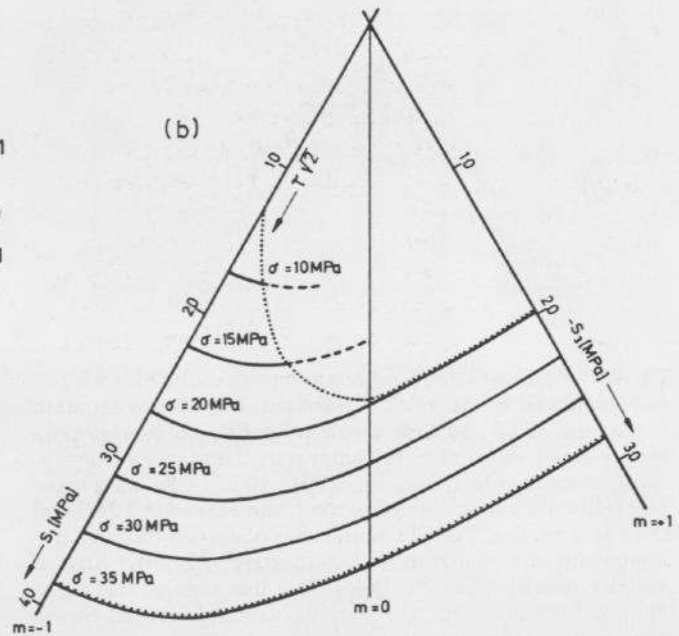
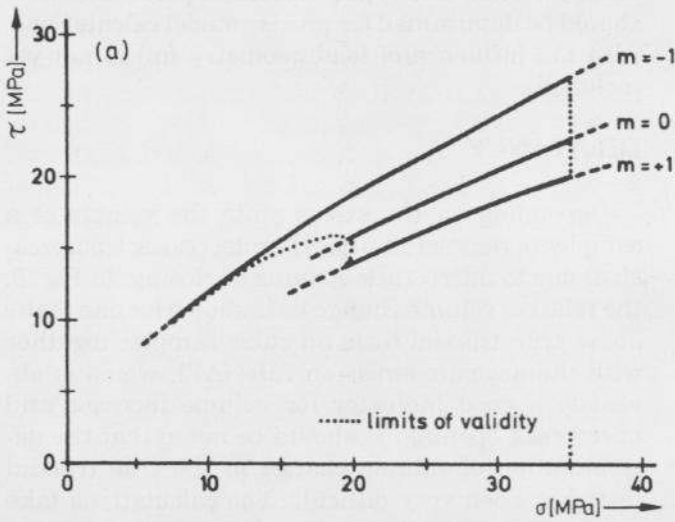


Fig. 3. Plots of the conservative failure equation for rock salt (Table 2) at $T \leq 100^\circ\text{C}$: (a) in a graph of τ vs. σ (octahedral shear stress vs. mean stress) and (b) in the octahedral plane.

but not very important influence.

Figure 2 also demonstrates how the conservative failure equation was fitted to the lower strength boundary of all tests with the same load geometry, m . The analysis results in the formulae shown in Table 2. The dependence of the failure strength on temperature, as well as the result for the residual strength (τ_R), are also given. The residual strength τ_R is not dependent on m and has about the same

value as the strength for extension at the same mean stress σ . Figure 3 displays the failure equation in the τ - σ section (octahedral shear stress vs. mean stress) and in the octahedral plane. The upper and lower limits of validity are caused by lack of tests beyond these lines; below the lower limit, tension has to be applied in one or two directions for failure (see below). However, in general it is a safe assumption that the tensional strength is equal to zero below the

TABLE 3

Equations for rock salt

Failure equation (only $m = -1$) (Cristescu 1992):

$$-r \frac{\tau}{\sigma_*} - s \left(\frac{\tau}{\sigma_*} \right) + \frac{\sigma}{\sigma_*} = 0$$

$$r = 0.825 \quad s = 1.37 \cdot 10^{-8} \quad \sigma_* = 1 \text{ MPa}$$

Compressibility/dilatancy boundary (only $m = -1$) (Cristescu and Hunsche, 1992):

$$-\frac{\tau}{\sigma_*} + f_1 \cdot \left(\frac{\sigma}{\sigma_*} \right)^2 + f_2 \frac{\sigma}{\sigma_*} = 0$$

$$f_1 = -1.68 \cdot 10^{-2} \quad f_2 = 0.86 \quad \sigma_* = 1 \text{ MPa}$$

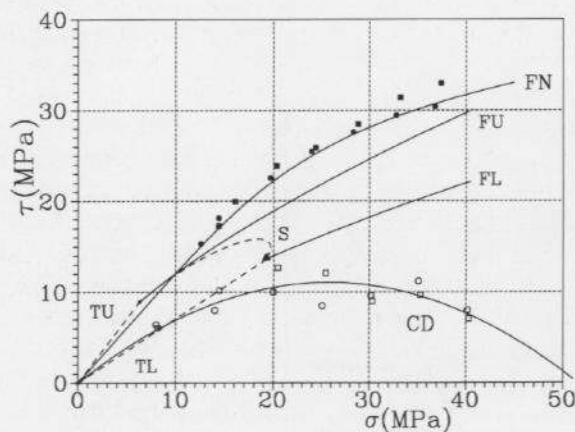


Fig. 4. Plots of various equations and test results for rock salt (series S8 and S9) in the $\tau - \sigma$ section. FN: failure equation (Cristescu, 1992) and \bullet : test results; FU, FL: conservative failure equation for $m = -1$ (compression) and $m = +1$ (extension), respectively (Hunsche, 1991, 1992); CD: compressibility/dilatancy boundary (Cristescu and Hunsche, 1992) and \square : test results; TU, TL: boundaries above which tension is applied for $m = -1$ and $m = +1$, respectively; S: lower limit of validity (see also Fig. 3). Below this line tension has to be applied for failure for the various values of m . \blacktriangle : Stress condition for biaxial tests.

lower limit of validity. Thus, this statement can be included in the conservative failure equation. It has to be mentioned that there are distinct differences between different types of rock salt, with the strength τ_B varying by up to 4 MPa at the same conditions (Hunsche and Albrecht, 1990; Hunsche, 1992).

For the exact and realistic prediction of the failure behaviour, an *exact failure equation* has to be used that is not conservative. This is the case, e.g. in a safety analysis and in model calculations for certain tests in the laboratory or *in situ*. For this purpose,

and also to include dilatancy and deformation, the development of a more sophisticated non-associated elasto-viscoplastic constitutive equation was started. The theoretical basis and the procedure for determining the equation and the governing functions are given by Cristescu (1989) and Cristescu and Hunsche (1991, 1992). The appropriate evaluation of the experiments used are reported by Hunsche (1991, 1992). It contains a procedure for obtaining an appropriate elasto-viscoplastic constitutive equation. Data on volume change, irreversible stress work during a test, and failure strength are required to derive this equation. The latest state of the governing functions is given by Cristescu (1993). Until now, only compression tests have been included, however. The function for failure strength, which has been determined from 14 tests from two test series (S8 and S9) on rock salt types exhibiting similar failure behaviour and comparatively high failure strength is given in Table 3. This function (FN) and the data used for failure strength are drawn in Fig. 4, together with the conservative failure equation for compression and extension (FU and FL). Due to the different failure behaviour of different rock salt types, different parameter sets should be determined for precise model calculations. Also the influence of load geometry (m) is not yet included.

DILATANCY

Depending on the stress state the volume of a sample increases (dilatancy) or decreases (compression) due to microcrack opening or closing. In Fig. 5, the relative volume change ϵ_v is shown for one of the above true triaxial tests on cubic samples together with the acoustic emission rate (AE), which is obviously a good indicator for volume increase and microcrack opening. It should be noted that the determination of volume change in the true triaxial tests has been very difficult. The calculations take into account the deformation of the platens and pistons, as well as the small amount of salt which is squeezed out between the platens at the edges of the cubic samples. The stress conditions for minimum volume of all above 14 tests are plotted in Fig. 4. They are the basis for the determination of the corresponding compressibility/dilatancy boundary, which is given in Table 3 and also drawn in Fig. 4 (CD). At stress states above this line, rock salt dilates and may increasingly loosen and fail after some time due to creep rupture. Failure occurs when a certain amount of damage has been exceeded. To specify this condition, volume change or the irreversible volumetric stress work (see Cristescu and Hunsche,

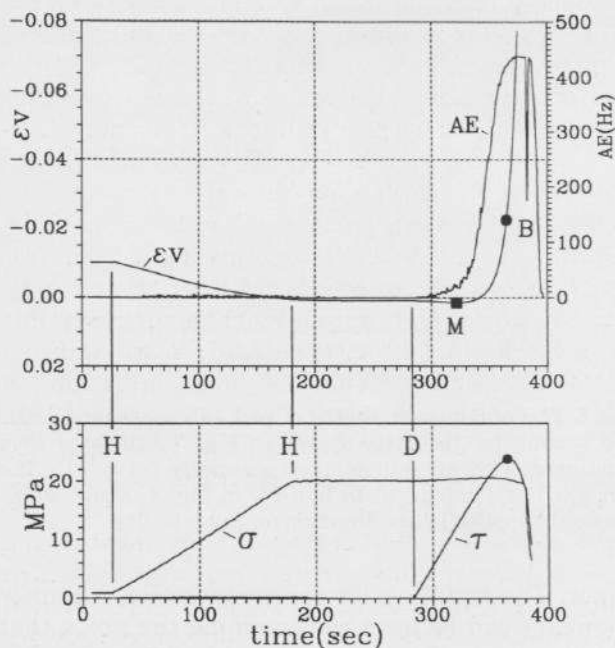


Fig. 5. Volume change (ϵ_V), acoustic emission rate (AE), mean stress (σ), and octahedral shear stress (τ) vs. time in one of the true triaxial compression tests on cubic rock salt samples. The initial compaction is caused by the hydrostatic loading to $\sigma = 20$ MPa.

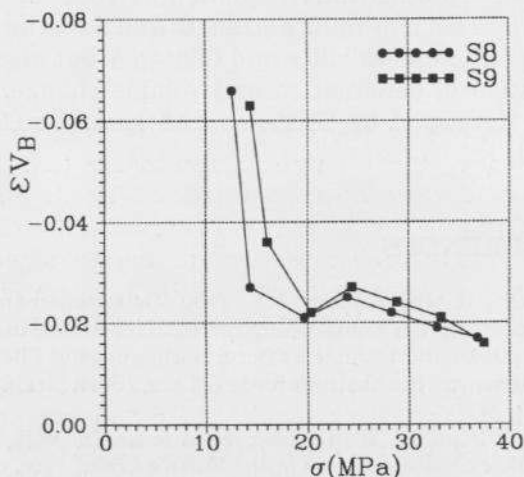


Fig. 6. Volume increase (ϵ_{VB}) at failure for series S8 and S9. For details, see Hunsche (1992).

1991, 1992) can be used as a damage parameter. To give an impression of the amount of damage at failure, the volume increase at failure (ϵ_{VB}) derived from these tests is shown in Fig. 6 (range 1.6 and 6.6%). Below the compressibility/dilatancy boundary, the rock is compressed until all voids are closed and no creep failure occurs. Although this boundary passes through $\tau = 0$ at $\sigma = 51.4$ MPa, additional experiments indicate that the compressibility

domain may extend to a slightly higher mean stress σ . The influence of load geometry (m) on volume change still has to be evaluated, as well as the influence of rock salt type.

TENSILE STRENGTH

Below the lower limit of validity in Figs. 3 and 4, tension has to be applied in one or two directions for failure. This range is not usually experimentally covered because tensional stresses cannot be applied in regular triaxial tests. Therefore, the range of low mean stresses was covered by specially designed triaxial and uniaxial failure tests on dogbone-shaped samples with tension in one direction using an idea of Brace (1964) for the triaxial tests. It is possible to produce tensional stress along the axis of a cylindrical specimen in an ordinary Karman cell if the sample has a smaller cross section in the middle than at the ends. The experimental technique for the triaxial tension tests is very difficult because small differences in stress along the sample axis have to be determined. However, such experiments are of great value because they provide data for a wide range of confining pressures. This is made possible by the use of various sample shapes. In addition, biaxial tests have been carried out whose stress state corresponds to a certain stress condition on the limit of validity (see Fig. 4). All these tests are extensional ones (i.e. load path $m = +1$). The material near underground cavities is exposed to all possible load geometries (m) and therefore the above tests give a lower limit of the failure strength. The tests were conducted at stress rates between 1 and 15 MPa/min. In practice, this difference in stress rate does not influence the failure strength of rock salt.

The results of tension tests and biaxial tests on one type of rock salt are shown in Figs. 7 and 8. It follows that the tension stress (σ_z) along the sample axis at failure is a function of mean stress σ (or confining pressure p). The value of σ_z decreases with increasing mean stress and reaches zero at $\sigma = 30$ MPa ($p = 45$ MPa), the stress condition under which the biaxial tests are conducted. The triaxial tension tests and the biaxial tests are in good agreement. The uniaxial tension strength of about 2 MPa is also in good agreement with our own Brazilian tests and results in the literature. It can be concluded from Fig. 7 that extension failure does not generally occur when the lowest principal stress (here σ_z) is equal to the uniaxial tensile strength. The value of σ_z depends on σ and is even positive at $\sigma > 30$ MPa. This can be explained by the effect of inhomogeneities (e.g. grains or flaws) which induce local tensile stresses. This seems to be common for rocks, as

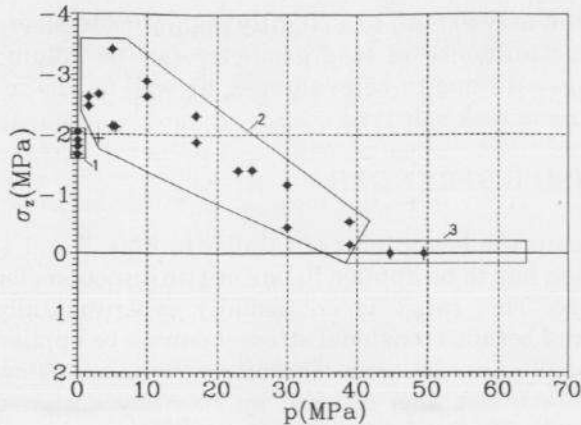


Fig. 7. Plot of failure strengths σ_z as a function of confining pressure p determined in uniaxial and triaxial tension tests on dogbone-shaped rock salt specimens, as well as the results of biaxial tests on cubic specimens. σ_z is the stress along the sample axis. All these tests were carried out on one type of rock salt from the Asse mine. (1) Uniaxial tension tests on dogbone-shaped specimens, (2) triaxial tension tests on dogbone-shaped specimens, (3) biaxial tests on cubic specimens.

mentioned by Paterson (1978). It should be noted that the strains to failure observed in tensional failure tests on dogbone-shaped specimens are very low; this is brittle failure.

The results of tensional tests are not yet included in the failure equation. However, the complex set of data and the already determined failure equations provide a reliable basis for considering failure and creep rupture in a great variety of model calculations.

IN-SITU OBSERVATIONS

It is very common in salt mining that spalling occurs in tunnels excavated in rock salt formations. This is mostly caused by large fissures parallel to the crown and floor. In general, this is due to tensional stresses. However, fissures produced by extensional failure at high mean stress look quite similar. Of course, such fissures are often seen in boreholes, too.

Walls, crown or floor of a tunnel can be examined in boreholes or slots for dilatancy. Observation shows that the thickness of the dilating rock volume exhibiting fissures and loosening increases with time and can reach a thickness of several meters.

CONCLUSIONS

Two kinds of equations for failure strength have been presented, namely a conservative equation and an exact one. The latter is not yet complete, however. This must be done on the basis of the numerous laboratory tests which have been discussed in this

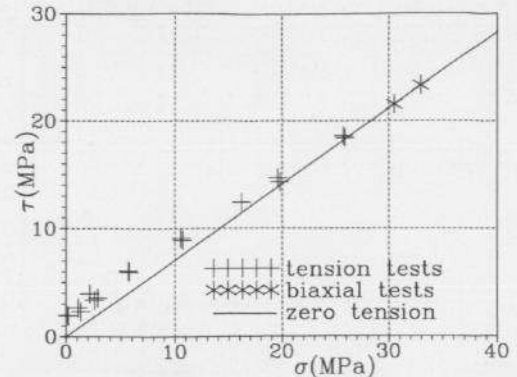


Fig. 8. Plot of failure strengths of rock salt specimens in the τ - σ section for the tests shown in Fig. 7. All tests were conducted with extensional load geometry ($m = +1$). The straight line is identical to line TL in Fig. 4, above which tension is applied in one direction for $m = +1$.

paper. The equation for the compression/dilatancy boundary can be used to determine the areas that may be affected by creep rupture. Dilatancy also increases permeability which has to be considered in repositories for radioactive or toxic wastes. The equations and test results can be used for dimensioning underground openings, for safety analysis, and for comparison with *in situ* observations. The first version of a constitutive equation for rock salt that describes not only failure strength and the boundary between compressibility and dilatancy but also the evolution of deformation and volume change, has been developed by Cristescu and Hunsche (1991, 1992).

REFERENCES

- Albrecht, H. and Hunsche, U., 1980. Gebirgsmechanische Aspekte bei der Endlagerung radioaktiver Abfälle in Salzdiapiren unter besonderer Berücksichtigung des Fließverhaltens von Steinsalz. Fortschr. Miner., Stuttgart, 58 (2): 212-247.
- Brace, W.F., 1964. Brittle fracture of rocks. In: W.R. Judd (Editor), State of Stress in the Earth's Crust, Proc. of the Int. Conf., Santa Monica (USA), 1963. Am. Elsevier, New York, pp. 111-178.
- Carter, N.L. and Hansen, F.D., 1983. Creep of rock salt. Tectonophysics, 92: 275-333.
- Cristescu, N., 1989. Rock Rheology. Kluwer Acad. Publ., Dordrecht, 336 pp.
- Cristescu, N., 1993. Constitutive equation for rock salt and mining applications. In: H. Kakihana, H.R. Hardy, Jr., K. Toyokura and T. Hoshi (Editors), Seventh Symposium on Salt. Vol. I. Elsevier, Amsterdam. pp. 105-115.
- Cristescu, N. and Hunsche, U., 1991. A constitutive equation for salt. In: Proc. Seventh Int. Congr. on Rock Mech., Aachen, Sept. 1991, v. 3: Workshop on Rock Salt Mech. Balkema, Rotterdam.
- Cristescu, N. and Hunsche, U., 1992. Determination of a

- nonassociated constitutive equation for rock salt from experiments. In: D. Besdo and E. Stein (Editors), *Finite Inelastic Deformations. Theory and Applications. Proc. IUTAM Symp. Hannover, Germany. Springer, Berlin.* pp. 511–523.
- Desai, C.S. and Varadarajan, A., 1987. A constitutive model for quasi-static behavior of rock salt. *J. Geophys. Res.*, 92 (B 11): 11445–11456.
- Diekmann, N., Hunsche, U. and Meister, D., 1986. Über das geomechanische Verhalten von Steinsalz bei erhöhten Temperaturen. *Z. dt. geol. Ges.*, Hannover, 137: 29–56.
- Dreyer, W., 1974. *Gebirgsmechanik im Salz.* F. Enke Verlag, Stuttgart, 205 pp.
- Georgi, F., Menzel, F. and Schreiner, W., 1975. Zum geomechanischen Verhalten von Steinsalz verschiedener Salzlagertstätten der DDR, Teil I: Das Festigkeitsverhalten. *Neue Bergbautechnik*, Jg. 5, Heft 9: 669–676.
- Heard, C.H., 1972. Steady-state flow in polycrystalline halite at pressure of 2 kilobars. In: H.C. Heard, I.Y. Borg, N.L. Carter and C.B. Raleigh (Editors), *Geophysical Monograph Series*, v. 16, Flow and Fracture of Rocks; AGU, Washington, pp. 191–209.
- Hunsche, U., 1988. Measurements of creep in rock salt at small strain rates. In: H.R. Hardy, Jr. and M. Langer (Editors), *The Mechanical Behavior of Salt II*, Proc. of Second Conf., Hannover (FRG), 1984. *Trans Tech Publ., Clausthal*, pp. 187–196.
- Hunsche, U., 1991. Volume change and energy dissipation in rock salt during triaxial failure tests. In: A. Cocks and A. Ponter (Editors), *Mechanics of Creep Brittle Materials-2*, Proc. of Coll. Mechanics of Creep Brittle Materials 2, Leicester (UK). Elsevier, Amsterdam, pp. 172–182.
- Hunsche, U., 1992. True triaxial failure tests on cubic rock salt samples-experimental methods and results. In: D. Besdo and E. Stein (Editors), *Finite Inelastic Deformations. Theory and Applications. Proc. IUTAM Symp. Hannover, Germany. Springer, Berlin.* pp. 525–536.
- Hunsche, U. and Albrecht, H., 1990. Results of true triaxial strength tests on rock salt. *Engineering Fracture Mechanics*, 35 (4/5): 867–877.
- Langer, M., 1984. The rheological behavior of rock salt. In: H.R. Hardy, Jr. and M. Langer (Editors), *The Mechanical Behavior of Salt*, Proc. of First Conf., University Park (USA), 1981. *Trans Tech Publ., Clausthal*, pp. 201–240.
- Lux, K.H. and Heusermann, S., 1983. Creep tests on rock salt with changing load as a basis for the verification of theoretical material laws. In: B.C. Schreiber and H.L. Harner (Editors), *Proc. Sixth Int. Symp. on Salt*, Toronto, 1983, vol. I. The Salt Institute, Alexandria (USA), pp. 417–435.
- Menzel, W. and Schreiner, W., 1977. Zum geomechanischen Verhalten verschiedener Salzlagertstätten der DDR, Teil II: Das Verformungsverhalten. *Neue Bergbautechnik*, Jg. 7, Heft 8: 565–571.
- Munson, D.E. and Dawson, P.R., 1984. Salt constitutive modeling using mechanism maps. In: H.R. Hardy, Jr. and M. Langer (Editors), *The Mechanical Behavior of Salt*, Proc. of First Conf., University Park (USA), 1981. *Trans Tech Publ., Clausthal*, pp. 717–737.
- Paterson, M.S., 1978. *Experimental Rock Deformation — The Brittle Field.* Springer, Berlin, 254 pp.
- Serata, S., Sakurai, S. and Adachi, T., 1972. Theory of aggregate rock behavior based on absolute three-dimensional testing (ATT) of rock salt. In: K.E. Gray (Editor), *Basic and Applied Rock Mechanics.* The Am. Inst. Mining, Metallurgical Engineers, Inc., New York, pp. 431–473.
- Wallner, M., 1983. Stability calculations concerning a room and pillar design in rock salt. In: *Proc. 5th Int. Congr. on Rock Mechanics*, Melbourne, 1983, vol. II. Balkema, Rotterdam, pp. D9–D15.
- Wawersik, W., 1988. Alternatives to a power-law creep model for rock salt at temperatures below 160°C. In: H.R. Hardy, Jr. and M. Langer (Editors), *The Mechanical Behavior of Salt II*, Proc. of Second Conf., Hannover (FRG), 1984; *Trans Tech Publ., Clausthal*, pp. 103–128.
- Wawersik, W. and Hannum, D.W., 1980. Mechanical behavior of New Mexico rock salt in triaxial compression up to 200°C. *J. Geophys. Res.*, 85 (B2): 891–900.
- Wawersik, W. and Zeuch, D.H., 1986. Modelling and mechanistic interpretation of creep of rock salt below 200°C. *Tectonophysics*, 121: 125–152.