REVIEWING THE LAWS AND RHEOLOGICAL MODELS OF ROCK SALT

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Abstract: *In the first stages, the research objectives consisted in the study of the stability of the classical mining of salt and potassium salts, the extraction of which was carried out mainly by means of rooms and safety pillars. Recently (and here we consider a period of more than twenty years), specialists and researchers pay special attention to and interest in creating storage cavities for petroleum products in particular but also for other types of substances, underground gaps obtained by exploiting salt on a liquid path. As a result of the numerous researches that have been carried out and are still underway, there are various studies regarding the use of salt as a "host" rock of a possible storage of radioactive waste. In specialized literature, there are numerous studies concerning the mechanical behaviour of rock salt. However, these studies leave unanswered questions or contradictory answers to some key questions of rock salt rheology. Most of these studies have been carried out on a microstructural plan and therefore quantitative and qualitative conclusions on the macroscopic aspect could not be formulated. In this paper the attention is focused mainly on the study of the inelastic - rheological behaviour of rock salt, more precisely on reviewing the existing rheological behaviour laws.*

Key words: *rock salt, behaviour law, rheological model, microcracking, time*

1. Introduction

The framework for using the results included in this paper, within the limits of which I have basically set out to develop it, is the knowledge of the behaviour of the salt at the microscopic and macroscopic level, while considering the idea that the underground voids created will have another destination after the exploitation of salt deposits. Regarding the formation of salt structures, there are today a number of theories, which are presented in table 1 [33]. Broadly speaking, the diapiric structure is defined as a geological process by which bed series originally located at deeper levels in the earth's crust have through or appear to be through the bed series located at lower depths.

Table 1. *The main theories referring to the mechanism of salt migration [33]:*

Designation' theory	Authors	Brief characterization of theory
Isostatic theory	Harbourt (1910, 1913)	Explains salt lifting on tectonic fractures lines due to its plasticity at high pressures and of specific weight smaller than this one of overlying rocks that press it.
Autoplastic atectonic theory	Lachman R. (1911)	The upward pushing of salt is the result of existing force in its own mass and consists of an upward molecular movement. The salt, due to its moisture, dissolves in the maximum pressure areas and by recrystallization, because salty water, is deposited in the areas of minimum pressure, phenomenon called "autoplastic displacement".
Redistribution' theory	Belusov (1911)	Consider that initially the salt was deposited in the higher areas, after which, through vertical movements, due to three forces, namely: primary (differential - vertical, antigravity); secondary (tangential, centrifugal) and tertiary (vertical) the salt has begun to vaulted, to be oblated and expelled under a high pressure in neighbouring salt field.
Vertical compression' theory	Tagheev (1943) Harbort, Arrhenius Beischlog, Seidl	The salt should be able to move vertically under the action of the oscillatory movements of foundation, and due to the influence of fold forces.
Halotectonic halokinetic theory	Trusheim (1957, 1960)	Consider the formation of domes salt as a result of the optimal difference between the density of deposits from roof and of salt. In the context of this theory Woidt (1980), Jackson and Talbot (1989) present six mechanisms of kalokinetic
The theory of diapirism	Posepny (1871) Mrazec (1906) Barton (1925) Kusaghin (1962) Harbort (1910) Hettleton (1934) Dumitrescu (1958) Gussow, Tanher, Williams (1968) Ticleanu (1974)	Diapirism is considered to be a product of unequal action of tangential forces on a complexity of layers, namely the layers on depths were stronger puckered, while the superficial, free and uncovered ones are slightly or no touched by folding.

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2. Geo-mechanic characteristics

The behaviour of salt or potash during a uniaxial compression test presents a contraction phase followed by a dilatancy phase which corresponds to the opening of pre-existing cracks or the appearance and development of microcracks. During a deviatoric loading test, the response of the material makes it possible to define the characteristic points: the peak of stress determined only in compression for a confining pressure of less than 10 MPa; the threshold of contraction - dilatancy defined in compression as the stress corresponding to the minimum of the total volumetric strain; the limit of linearity which is the stress corresponding to the end of linearity of the elastic contraction.

The deviatoric loading can cause a cracking which will affect more or less the elastic parameters.

Salt subjected to deformation at constant velocity and at a given temperature hardens as a function of time. The hardening phenomenon was studied by Pouya, using two micro-macro approach models: the Kröner model and Berveiller & Zaoui model [25]. It shows that the simplicity of the structure of NaCl and the hypothesis of perfect plasticity, makes possible an analytical calculation of the response of the polycrystal to any radial loading according to the two above-mentioned models. In the case of NaCl the state of perfect plasticity will never be reached, the energy stored during the loading increases indefinitely and therefore the hardening curve will have a non-zero slope. Under high confinement pressures, the behaviour of the salt is fragile; the strain hardening curve shows a peak at a stress of approximately 30 MPa and a strain of 3%. Consequently, because of the high confining pressure, cracking is excluded and the only involved phenomena are inter and intragranular hardening of the polycrystalline medium.

Rock salt has a specific behaviour under the effect of damage phenomena. Pre-existing cracks or generated cracks by stresses can develop and macroscopically determine a variation in volume, therefore dilatancy. These phenomena lead to a significant increase of the salt permeability and the initial sealing of this one is diminished. For the mentioned reasons, the damage phenomenon is irreversible [1], [8], [10], [13], [19], [20], [21], [31], [32].

The characteristic stress - strain curve offers the possibility to qualify roughly the rocks in a certain behaviour class; that remains useful for the choice of the viscous constitutive law. The studies carried out on the salt show that this one presents an elastic - viscous-plastic behaviour. The three phases of creep are commonly observed with a viscous-plastic flow which sometimes occurs with dilatancy; for the same level of stress the viscous strains can be greater than the instantaneous strains and are characterized by a quasi total irreversibility.

Regarding of hardening phenomenon by strain, we will mention only the personal opinions and conclusions [30], [31], [32]. The literature presents several hypotheses based on the increase of elastic strength, the creep flow limit or the flow limit that occurs at the same time as the development of a deposit. G.T. Belby (1921) specifies that there is an extremely disordered state, analogous to amorphous materials, and that gradually, during deformation, the crystals turn into an amorphous state. Consequently, the physical properties of the solids may be altered compared to the original properties.

A detailed discussion of the "disorder" of amorphous materials as compared to the deformation mechanisms of crystalline solids is presented by A. Kochendorter (1954). Based on this work, A. Seeger (1958) characterizes the static deformation of crystalline solids as plastic and the deformation of amorphous materials as a viscous one. Of course, there is a fundamental difference between plastic deformation and amorphous materials. The theory of plastic deformation in crystals involves the presence of numerous dislocations, which are the result of certain shear stresses materialized in time in intercrystals. One of the weaknesses of this theory, in terms of plasticity of crystals, is the very little understanding and sometimes even the mistaken, mainly of the network base, of the grating structure of undeformed crystals. This "base" structure makes us to understand the definition of dislocation arrangement before the deformation starts. The distribution of these dislocations determines not only the shear stresses in the crystalline materials in which plastic deformation can occur, but at the same time it develops during the deformation a number of dislocations and therefore will cause the phenomenon of hardening by deforming the crystalline materials. Generally, with respect to the crystal rearrangement structure, it was proposed by C.F. Frank and M.F. Mott (1958) the so-called crystals hardening. However, there are a number of experimental and theoretical reasons which considers that the impurities of the crystals determine the manifestation of the plasticity of crystals, especially in the case of rocks constituted of single crystals, for example quartz, calcite, salt crystals.

Most natural crystals combine the structural defects that occur during the increasing of the individual crystal. So, the crystals are designed, really arranged in the form of a mosaic crystal network. The areas with perfect structures transform into mosaic blocks. The size of these blocks may vary greatly and may be at least one constant structure dependent on the type of crystal. Mosaic blocks located at the boundary of the structure and having different directions are called "block boundaries" or "boundary blocks". These blocks constitute the disordered planes with atomic dimensions, along which dislocations densities are high. Generally, they form plane surfaces of dislocation and therefore they create essential conditions for the development of inner stresses. The last ones explain practically the effect of hardening that can be observed in a single crystal and therefore in the whole structure of the rocks constituted of those singular crystals and this is clear and obvious in the case of the structure of the salt rock [28], [29], [32].

We could assume that sliding and translational movement do not occur simultaneously with the plastic deformation in all mosaic blocks, but, to a certain degree, they occur only in a few blocks where the sliding planes have a favourable orientation with respect to the directions of the main stresses. The small crystals of polycrystalline aggregates, the mosaic blocks produce flow stresses of different sizes, with values that depend on the accuracy and the precision of the measurements.

According to the modern theories of dislocation, the hardening deformation, and thus the hardening, is considered an obstacle, an impediment in the movement of dislocation and which occurs at the same time as the increase of deformation. The effect corresponds to a pre-existing interaction and to an induced deformation in network or in crystalline structure. Mainly, two mechanisms responsible for decreasing the density of dislocation due to the development and mobility of the dislocations are accepted. G.I. Taylor (1934) explains the hardening as an obstacle to movement, to displacement due to some previous stresses at the points of interaction of the dislocation, points that are becoming more numerous at once with the advancing deformation. Equally, the relative movement of dislocation requires a strong energy of activation. Therefore, the dislocations are combined into dislocation groups or dislocation lines that have the role of developing the sliding planes.

The main difference between sliding and a plane network and a single dislocation is that in the first case the slip occurs simultaneously among the planes, while in the second case, the sliding gradually develops over the sliding line and the systems of plane sliding. A linear dislocation always constitutes the boundary between two different areas where the sliding occurs or not. The concept of linear sliding between sliding areas implies that a linear dislocation does not occur abruptly, but occurs gradually within the crystal [26], [30], [31], [33], [33], [34].

The second modern hypothesis, developed by E. Orowan (1954), is the "progressive blocking" concept in plane sliding blocks that occur with increasing deformation. According to this complete hypothesis "exhaustion hypothesis", the hardening deformation occurs due to the fact that the active dislocation sources are located at several points (or sources) and are subjected to a high critical stress during the development of the sliding.

What concept is correct at the current stage? It is difficult to specify and clarify this matter. In the future, it is possible that both mechanisms can be accepted or not. On the other hand, the dislocation mechanism can also be described on the basis of the continuous environment theory. Generally, dislocation includes so many atoms that it might be possible a description in terms of a quasi-continuous environment. Consideration of dislocations using continuum theory has been described and developed by E. Kroner (1958). From the rheological point of view, the phenomenon of hardening can be explained using the model shown in figure 1, in which the crosshead shoes have different plasticity thresholds (σ_p and σ'_p, with $\sigma_p > \sigma'_p$) and the stress σ varies between σ_2 and σ_1, with $|\sigma_2| < \sigma_1$.

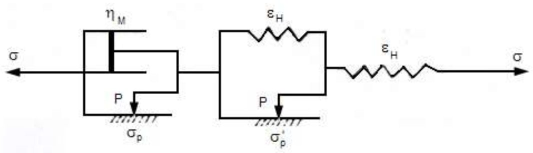

Fig. 1 *Rheological model that describes the phenomenon of hardening*

3. The mechanisms and creep laws of rock salt

Compared to most rocks, the behaviour of salt depends on the active mechanisms present in the structure of the grains; the deformations of halite crystals are: dislocation movements; diffusion which produces a plastic deformation due to diffusion of the material inside the rock.

The influence of these different mechanisms on the total creep depends on the nature of rock, its structure and at the same time on stress and temperature. The decisive mechanisms of deformation are: dislocation sliding; polygonization; diffusion and the sliding of neighbouring grains. Sliding by dislocation occurs at high stresses and low temperatures (the fusion temperature T_m = 1074 K = 801 °C). At a high increase in the strain rate or for high temperatures the diffusion creep is dominant; it appears for maximum stress σ = 4.5 bar and it depends on the temperature.

In general, transient creep (primary), stationary (secondary or stabilized) and tertiary creep and also the appropriate laws are related to certain deformation mechanisms.

Primary creep (transient) (fig. 2). At low stresses and low temperature logarithmic creep will occur; dislocations are considered sunt considerate as obstacles. Due to the hardening phenomenon, a creep in successive stages will occur. In this case, the movement of dislocations does not play an important role in recovery and the law of creep is:

$$\varepsilon = a_1 \lg t + c_1 \quad (1)$$

At high stresses and temperatures, the recovery mechanism becomes more and more apparent; the empirical law is an exponential one, called the Andrade creep:

$$\varepsilon = \beta \cdot t^{1/3} \quad (2)$$

Secondary creep (stationary or stabilized) (Figure 2). Creep rate is constant if the hardening process will be produced with the same rate as for the process of recovery. Such recovery processes can be observed by rotation of dislocations, voids diffusion, polygonization, fine grain migration and recrystallization. The creep law is the following:

$$\dot{\varepsilon} = A \cdot e^{\frac{U}{KT}} \cdot f(\sigma) \quad (3)$$

Tertiary creep (fracturing or breakage creep) (Figure 2) is characterized by high stresses and an activation of an additional deformation mechanism, called sliding of the grains. Such a mechanism determines a gradual decrease in grains boundaries and will produce their separation. Due to the fact that the fracture creep is mainly dependent on the appearance of non-elastic deformations, this dependence should be considered in the fracturing phenomenon by a flow criterion. Principally, fracturing – breakage depends on the maximum deformation. Consequently, for the tertiary creep, the breakage criterion will not be chosen depending on the stress state, but in relation to the deformation state. For example, here are the old hypotheses of Bach, namely: the maximum normal main deformation respectively shear deformation; the condition of deformation energy stored before fracturing - Druker – Prager criterion.

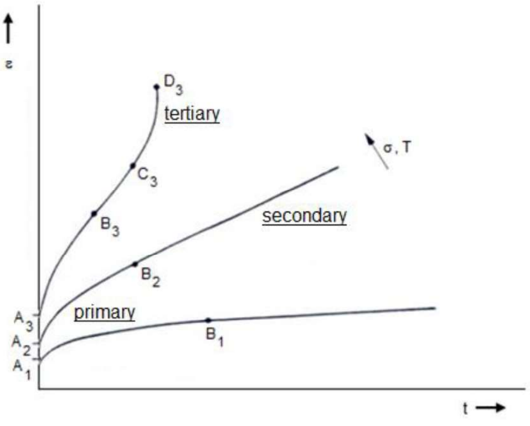

Fig. 2 *Creep curves*

The fracturing occurs at the high application rates of creep or deformation which are assigned to the charging stress very close to the strength breakage. In this case, high stresses are concentrated to the grains boundaries, the mechanism (Griffith theory [14]) of fracture will be activated (unstable crack propagation existing or appearance of new cracks). This phenomenon of fracture, for different types of rocks, has been studied in 1967 by Bieniawski [33].

Special behaviour to deformation of rock salt. The rheological behaviour of rock salt has been studied by many authors [2], [3], [4], [5], [6], [7], [9], [11], [12], [15], [16], [17], 18], [22], [23], [24], [27]. In their works, they show the phenomenon of creep and salt plasticity. In fact, salt is the ideal material for study, especially since crystalline and granular structures are relatively simple. For salt, the most important is the secondary creep (stationary).

These mechanisms are reflected at the solid scale by a rheological behaviour represented by Maxwell's viscous-plastic body, devoid of any viscous flow threshold. The results of the creep tests carried out on the salt show that the viscous strains appear whatever the level of the applied stress deviator. The amplitude of these deformations strongly depends on this deviator and temperature; it can be very important under high or negligible loads if the deviator of the stresses is very low. As long as it is under stress the salt continues to flow slowly. The viscous deformations also depend on the temperature: the higher the temperature, the greater the deformations; the influence of temperature on the viscous behaviour is expressed by Arrhenius' exponential law.

Rock salt is characterized by a full creep curve: under a stress and temperature deviator, primary creep (transient) or attenuated where the strain rate decreases continuously; secondary creep (stationary) or stabilized or the installed flow stage or the viscous-plastic flow zone; tertiary creep or gradual flow, the area where the salt will register the appearance of cracks and therefore a structural change. For salt, the most important is secondary (stationary) creep.

Relaxation is the dual property of creep. Relaxation tests make it possible to follow the evolution of a mechanical quantity as a function of time, namely the stress within a material system or the sample. Relaxation is defined as the stress decrease in time at the instantaneous cessation of deformation. In the laboratory only the axial deformation and not the strain tensor is maintained constant.

Under low load the asymptotic creep tends towards a certain value of strain which is difficult to determine. If the imposed load exceeds the maximum deviator that can reach the material system in a quasi-static regime, then we will always have an indeterminacy on as to the trend of the evolution of long-term creep. On the other hand, in relaxation the long-term asymptotic equilibrium can always be determined in theory.

In practice, the relaxation phase is preceded by a uniaxial or triaxial loading at a constant and high strain rate in order to increase the amplitude of the stress likely to be restored; this preliminary phase induces an additional difficulty in the interpretation of the results of relaxation tests. Relaxation tests allow highlighting the viscosity and hardening of a rock by studying the history of stresses. In the literature there are few experimental data obtained by relaxation tests.

4. Rheological laws behaviour

4.1. Empirical laws

The magnitude of rheological deformations of rock salt raises the question of predominant role of the rheological characteristics of this material in the study of stability of underground structures. In the neighbourhood of underground excavations and in saliferous geological formations (domes, strata), the field of tension develops very slowly over time, which allows it to approach the state of evolution through creep. The proposed models in the literature for the salt creep are numerous. Table 2 presents some examples of empirical laws compiled by Linder and Brady [24]; other examples were brought together by Rolnik (1984) and a wider bibliographic presentation of the proposed rheological models for salt was made by Aubertin et al. (1987) [2].

The models presented in Table 2.5 can be divided into two groups, as they admit or not the hypothesis of a steady (stationary) state creep. According to this hypothesis, requiring a constant stress on a sample, after the transient phase in which the creep rate decreases, it tends towards a constant rate regime. The models that do not allow this hypothesis assume that the rate decreases continuously due to hardening [19], [28], [29]. Laboratory tests do not allow for or against of this hypothesis.

Table 2. *Empirical creep laws of rock salt (according to Linder & Brady, 1981) [8], [13], [20], [24]:*

Equation form	Source	Test conditions
$\varepsilon = A + B \log t + C t$ $A = 1.16 \cdot 10^{-3}$ $B = 1.09 \cdot 10^{-3}$ $C = 2.50 \cdot 10^{-7}$	Laboratory test Singular crystal Size: 1.1 x 1.1 x 2.06 cm (Griggs, 1939)	Uniaxial compression test Axial load: 0.61 MPa Temperature: 23 °C Time: 1000 hours
$\varepsilon = A + B t^n$ Date 01 : $A = 7.0 \cdot 10^{-4}$ $B = 1.39 \cdot 10^{-3}$ $n = 0.305$ Date 02 : $A = 8.2 \cdot 10^{-3}$ $B = 6.8 \cdot 10^{-4}$ $n = 0.642$ $n = 7.5 - 0.011\ (\theta - 273)$ $B = 1.2 + 0.30\ (\theta - 273)$	Laboratory test Artificial salt Diameter: 3.18 cm Height: 0.13 cm Le Compte (1965)	Triaxial compression test *Dates 01*: Axial load: 6.9 MPa Lateral load: 23 MPa Temperature: 100 °C Time (hours): 100 *Dates 02*: Axial load: 107 MPa Lateral load: 100 MPa Temperature: 104.5 °C Time (hours): 100 - 150 The equations to establish the parameters n and B result graphically Temperature: 294 °C
$\varepsilon = A\ \theta^m\ t^n\ s^p$ $A = 1.19 \cdot 10^{-31}$ $m = 9.5$ $n = 0.3$ $p = 3.0$	Laboratory test Halite Diameter: 10 cm Height: 7.6 cm Lomenick (1977)	Uniaxial compression test Axial load: 13.8 – 68.9 MPa Temperature: 22.5 - 200 °C Time: 600 - 1000 hours
$\varepsilon = A\ t^n\ S^p$ $A = 2.13 \cdot 10^{-6}$ $n = 0.38$ $p = 2.52$	Laboratory test Halite Diameter: 5.08 cm Height: 10.2 cm Hansen (1977)	Triaxial compression test Axial load: 10.3 – 41.4 MPa Lateral load: 0 – 10.3 MPa Temperature: 22 °C Time: 120 - 250 hours
$\dot{\varepsilon} = A \exp(-B - Ct)$ $A = 8.2 \cdot 10^{-1}$ $B = 3.0$ $C = 4.2 \cdot 10^{-2}$	In situ test Depth: 215 m Serata & Gloyna (1960)	Time: 8760 hours Time after exploitation: 5 / 10 years

$\varepsilon = A + B t + C [1- \exp(Dt)]$ $A = 4.2 \cdot 10^{-2}$ $B = 2.15 \cdot 10^{-5}$ $C = 2.25 \cdot 10^{-2}$ $D = 4.50 \cdot 10^{-3}$	Laboratory test Halite Diameter: 10.0 cm Height: 7.6 cm Obert (1965)	Uniaxial compression test Axial load: 13.8 – 68.9 MPa Temperature: 23 °C Time: 600 - 1000 hours
$\varepsilon = A\, t^n\, S^p$ $A = 2.22 \cdot 10^{-7}$ $n = 0.382$ $p = 3.36$	Laboratory test Halite Size: N / A Hair & Deere (1968)	Uniaxial compression test Axial load: 10.3 – 27.6 MPa Temperature: N/A Time: 10 – 1000 hours
$\dot{\varepsilon} = G S^p$ G = N / A ; p = de 2.4 à 3.3 $\varepsilon = \frac{A t}{B + C t} + D$ $A = 5.1 \cdot 10^{-3}$; $B = 5.3 \cdot 10^{-5}$ $C = 1.4 \cdot 10^{-3}$; $D = 1.2 \cdot 10^{-2}$	Laboratory test Halite Size: 4 x 4 x 10 cm Dreyer (1972)	Uniaxial compression test Axial load: 620 kPa/cm^2 Temperature: 18 °C Time: 3600 hours
$\dot{\varepsilon} = A S^p$ $A = 4.28 \cdot 10^{-3}$ $p = 2.7$	In situ test Depth: variable Medley (1967)	Time after exploitation: variable (3 – 40 years)
$\dot{\varepsilon} = A S^p$ $A = 3.78 \cdot 10^{-13}$ $p = 5.24$	Laboratory test Halite Diameter: 10.2 cm Height: 20.3 – 130.5 cm Thompson & Ripperberger (1964)	Uniaxial compression test Axial load: 9.6 – 16.5 MPa Temperature: 32 °C Time: 16.7 hours
$\dot{\varepsilon} = A \log(1 + Bt)$ $A = 9.56 \cdot 10^{-3}$ $B = 2.13 \cdot 10^{-4}$	In situ test Depth: 520 m Nuir & Cochran (1961)	Time: (2.9 years) 25200 hours Time after exploitation: 5 / 10 years
$\dot{\varepsilon} = A \exp(-Bt)$ $A = 0.03$ $B = 7.3 \cdot 10^{-5}$	In situ test Depth: 215 m Reynolds & Gloyna (1961)	Time: (2 years) 17500 hours Time after exploitation: 5 / 10 years
$\varepsilon_t = A\, \theta^n\, t^m\, S^p$ $A = 4.68 \cdot 10^{-35}$ $m = 11.4$; $n = 0.46$ $p = 3.3$ $\varepsilon_t = A\, t^m S^p \exp\left(-\frac{Q}{R\theta}\right)$ $A = 1.48 \cdot 10^{-1}$; $m = 0.5$; $p = 3.5$; Q = 36.0 kJ/mol $\varepsilon_s = A S^p \exp\left(-\frac{Q}{R\theta}\right)$ $A = 1.48 \cdot 10^{-2}$ $p = 3.3$; Q = 45.2 kJ/mol	Laboratory test Halite (New Mexico & Louisiana) Diameter: 10.2 cm Height: 20.3 – 130.5 cm Hansen & Carter (1980)	Triaxial compression test Axial load: 5.5 – 41.4 MPa Lateral load: 0.1 – 20.7 MPa Temperature: 22 °C – 200 °C Analysis of 86 transient creep curve Equations represent different expressions for basic data ε_t – transient creep; ε_s – secondary creep
$\dot{\varepsilon}_s = A S^p \exp\left(-\frac{Q}{R\theta}\right)$ $A = 7.5 \cdot 10^{-3}$ $p = 5.0$; Q = 54.24 kJ/mol	Laboratory test Halite Diameter: 10.0 cm Height: 25.0 cm Langer & Walner (1979)	Uniaxial compression test Axial load: N / A Temperature: 27; 100; 150; 200; 300 °C
$\dot{\varepsilon}_s = A \left(\frac{S}{G}\right)^p \exp\left(-\frac{Q}{R\theta}\right)$ $A = 9.0 / 29.5 \cdot 10^{-12}$ G = 12.4 MPa; Q = 50.2 kJ/mol; R = 8.319 J/mol·°K	Laboratory test Halite (New Mexico) Diameter: from 5 to 10 cm Hermann et al. (1980)	Triaxial compression test Axial load: 7 – 41 MPa Confinement pressure: 0 – 21 MPa Temperature: 22; 70; 100; 200 °C Time : N / A
$\dot{\varepsilon}_s = A S^p$ $A = 3.67 \cdot 10^{-12}$; $p = 5.5$	In situ test Depth: 1250 m Prij & Mengelers (1980)	Convergence results (Asse Mine – Germany); finite elements method
Notifications: t – time (hours); θ - temperature (°K); S – stress deviator (MPa); A – structure factor.		

The difficulty comes from the fact that the deformation characterizing the end of the transient phase, have not been specified and this is a weak point of the stationary creep hypothesis.

A first interpretation of these empirical creep laws shows that the creep is described by means of linear, power and exponential equations; the last type of equations seems appropriate from microcrystalline point of view because they also introduce the influence of activation energy [32].

All these laws are obtained differently from each other, because the tests have been performed in different conditions of load (uniaxial, triaxial, and in situ). Laws of type (1) and (6) obtained by uniaxial compression tests can describe the transient and stationary creep; they consider that temperature has no influence on the rheological behaviour; the measured deformation is axial, so no information about the evolution of volumetric deformations; these laws consider that the dilatancy is null [32].

The law type (2) obtained from the triaxial compression tests in the laboratory on artificial salt takes into account the influence of temperature on the salt behaviour, the deformations varying according to a power law time depending of time; it can describe both the transient creep and the stationary creep; we cannot know if this law expresses the variation of axial, lateral or volumetric deformations.

Power laws type (3) and (13) differ in the manner in which the tests are carried out (uniaxial, respectively triaxial compression), temperature conditions being the same; In this case, the deformation depends on the temperature and stress deviation, so these laws admit the existence of dilatancy; they describe the transient creep.

Power laws type (4) and (7) obtained by uniaxial and triaxial compression tests show the deformation dependence of the stress deviator - the dilatancy phenomenon is considered; but excludes temperature dependence of behaviour.

Exponential (5), (12) and logarithmic (11) laws type obtained through in-situ tests at mean and great depth may be valid, but only under the conditions specified in Table 3.5 and they express the change of deformations around an underground cavity [32].

Laws of type (8), (9), (10), (18) obtained by laboratory tests in uniaxial compression and in situ tests, show the dependence of deformation on the stress deviator; they describe the stationary creep of salt; for in situ tests can also consider a certain influence of depth on salt behaviour around a cavity.

Exponential laws type (14) ÷ (17) describe the transient creep (the law (14) which also expresses the influence of time) and the stationary salt obtained by laboratory tests at triaxial compression (only the law (16) results from a uniaxial compression test); the tests were performed on halite, parameters such as: temperature, confinement pressure and axial load being almost the same [28], [29], [32].

Most of these laws take into account the structure's influence on salt creep behaviour. However, all the models proposed for salt agree on a few points. All these models admit that the deformation under a constant load is not limited and this one does not tend to infinite if its rate decreases; and at the same time, all admit that the flow threshold is much reduced, even null.

These common points are important for predicting the long-term behaviour of underground excavations and reduce the divergence between different points of view [28], [29], [32]. They actually ensure that if these excavations are subjected to a free convergence under the effect of an internal pressure lower than the lithostatic pressure, their convergence will be until the complete closure of the excavations

4.2. Empirical laws

The formulation of the different rheological behaviour laws existing in the literature is generally based on stress tensors, deformation and load rates, time and temperature. Behaviour laws may correspond either to empirical models obtained directly through laboratory tests (but which are not general laws), or to analogue models that express different types of behaviour: elastic, plastic, viscous, elastic-plastic, elastic-viscous, elastic-viscous-plastic etc. (for example, simple models: Hooke in combination with Newton, Maxwell, Kelvin - Voight, or complex models: Bingham, Poynting-Thomson, Burgers, etc.). These types of models consider that time has an important influence on the behaviour of material systems and, implicitly, of the rocks [1], [15], [16], [22], [32], [33].

Rock salt is characterized by a complete creep curve (creep primary, secondary and tertiary); the beginning time of each creep phase, respectively its duration depends on the value of the stresses. Regarding the main expressions of laws relating to the different creep regimes mentioned in the literature, they can be regrouped in the following manner [28], [29], [32]:

a) Primary creep can be described through the following laws:

- parabolic law;
- logarithmic law;
- exponential law (or power law);
- law $\dot{\varepsilon}_p = f(\varepsilon)$, which expresses the creep rate depending on deformation. This law was proposed by Munson and Dawson in case of the metal creep and which, according to Langer, would be best adapted to the salt problem;

b) the deformation registered in the stage of secondary creep is easier to describe and can be expressed by the following relationship:

$$\dot{\varepsilon}_s = A \exp\left(-\frac{Q}{R\,T}\right)\sigma^n \qquad (4)$$

where: A – structural factor that allows integration of the effects due to structural variations and those corresponding to the presence of impurities; Q – activation energy; n – exponent; R – the universal constant of perfect gas; T – temperature; σ - normalized stress, $\sigma = \frac{\sigma_{eff}}{\sigma^*}$;

c) if the primary creep is considered an exponential law and for the secondary creep the form (4) (if the elastic deformation is not taken into account), then the global creep results from the summing of the two types of creep, namely:

$$\dot{\varepsilon}_g = B \exp\left(-\frac{Q}{R\,T}\right)\sigma^n\left[1-\exp\left(-m\,t\right)\right] + A \exp\left(-\frac{Q}{R\,T}\right)\sigma^n\,t \qquad (5)$$

d) the creep registered in triaxial tests can be expressed as such:

$$\dot{\varepsilon}_i = \frac{C}{R\,T}\exp\left(-\frac{Q}{R\,T}\right)J_2^m\,s_i \qquad (6)$$

where: m = 2; $J_2 = \frac{1}{2}\left(s_1^2+s_2^2+s_3^2\right)$; $s_i = \sigma_i - \sigma_0$;

C – structural factor.

e) behaviour law used by Pouya for salt from Ain:

$$\varepsilon^{vp}(t) = B\left(1-e^{-\beta t}\right) + C\,t \qquad (7)$$

where: BB, C and β are constants dependent on the (σ, T) for each test; the first term corresponds to the primary (transient) creep and the second term to the stationary creep. The author specifies that this law is one of the most commonly used for salt creep modelling and that parameters B, C and β are dependent on the duration of test, However, these variations are very slow and may be neglected for extended periods exceeding 750 hours. The values of constants B and C are approximated depending on (T) and (σ), according to the following equations:

$$B(\sigma,T) = b\,\sigma^m\,e^{-\frac{K_p}{T}} \qquad C(\sigma,T) = c\,\sigma^m\,e^{-\frac{K_s}{T}} \qquad (8)$$

The formulation of the various rheological constitutive laws existing in the literature is generally carried out as a function of the tensors of the stresses, of the strain rates and stresses rates, time and temperature (table 3).

Table 3. *The obtained parameters for different constitutive laws:*

Constitutive law	Parameters	Internal variable	χ(t)	Δχ	Observations and results
Lemaître	α, β, K	$\dot{\xi} = \left(\frac{F}{K}\right)^{\beta/\alpha}$	ξ^α	$\left[\xi(t)+\dot{\xi}(t+\Delta t)\right]^\alpha - \xi^\alpha(t)$	α<1 : hardening α>1 : attenuation α = 0.295 β = 4.23 K = 17.7 bar
Transient power law	α, β, K		$\int_0^t \alpha\left(\frac{F}{K}\right)^\beta t^{\alpha-1}dt$	$\alpha\left(\frac{F(t+\Delta t)}{K}\right)^\alpha (t+\Delta t)^{\alpha-1}\Delta t$	α<1 : hardening α>1 : attenuation F = ct. Identical as the Lemaître law A = 0.015 β = 3.70
Norton - Hoff Power law	A, β		$\int_0^t A\,F^\beta dt$	$A\,F^\beta(t+\Delta t)\,\Delta t$	The special case of the Lemaître law and the transient power law if α=1 α = 0.933 β = 3.325 K = 23.94
Munson - Dawson	A_1, β_1, B_1 A_2, β_2, B_2 F_0, μ K_0, C, m, q α_w, β_w α_r, β_r A_1, A_2, B_1 et B_2 are temperature functions	$\dot{\xi} = (G-1)\dot{\varepsilon}_s$ $G = \begin{cases} \exp\left[\Delta\left(1-\frac{\xi}{\varepsilon_c}\right)^2\right] \\ \exp\left[-\delta\left(1-\frac{\xi}{\varepsilon_c}\right)^2\right] \end{cases}$	$\int_0^t G\,\dot{\varepsilon}_s\,dt$ cu: $\dot{\varepsilon}_s = A_1\left(\frac{F}{\mu_1}\right)^{\beta_1} + A_2\left(\frac{F}{\mu_2}\right)^{\beta_2} + \lvert H\rvert(B_1+B_2)\sinh\left[\frac{q(F-F_0)}{\mu}\right]$	$G(t+\Delta t)\dot{\varepsilon}_s(t+\Delta t)\Delta t$ cu: $G(t+\Delta t) = \begin{cases} \exp\left[\Delta\left(1-\frac{\xi(t+\Delta t)}{\varepsilon_c}\right)^2\right] \\ \exp\left[-\delta\left(\frac{\xi(t+\Delta t)}{\varepsilon_c}-1\right)^2\right] \end{cases}$	It considers multiple creep mechanisms and two creep stages (transient and stationary); stationary creep is described by a combined power law. $A_1=1.077\times10^{16}$ (με/d) $\beta_1 = 5.2$ $B_1=5.2583\times10^{17}$ (με/d) $A_2=5.627\times10^{16}$ (με/d) $\beta_2 = 5.0$ $B_2=2.6214\times10^9$ (με/d)

			$\varepsilon_c = K_0 \exp(CT)\left(\frac{F}{\mu}\right)^m$ $\Delta = \alpha_w + \beta_w \log\left(\frac{F}{\mu}\right)$ $\delta = \alpha_r + \beta_r \log\left(\frac{F}{\mu}\right)$	$\xi(t+\Delta t) = \xi(t) +$ $[G(t+\Delta t) - 1]\mathring{\varepsilon}_s(t+\Delta t)\Delta t$ $G(t+\Delta t)$ et $\xi(t+\Delta t)$ should be calculated by an implicit scheme	F = 205.7 bar μ = 124000 bar K_0=6.275x10^{11} ($\mu\varepsilon$/d) C = 0.009198 M = 3.0 Q = 5335.0 α_w = 17.37 , ρ_w = -7.2

The fundamental difference between these behaviour laws arises from the manner to consider the behaviour of the salt, namely, the salt presents or not a hardening deformation. For example, such a difference appears clearly in the case of the Norton-Hoff power law (without hardening) and the other presented laws. Some of the models consider that the hardening deformation is dependent on strain at a given time and thus depends indirectly on time compared to the power law of transient creep in which this deformation is strictly linked to time [26], [27].

Norton's law is a particular case of Lemaître's law for m = 1 and has been formulated in a uniaxial configuration; its generalization in triaxial is expressed in the same way as Lemaître's law.

5. Discussion regarding the models developed for rock salt

We will present a brief summary of personal views on the various models developed for rock salt.

Pouya's model allows the explanation of behaviour aspects resulting only from the deformation of grains and their mutual interactions. The proposed behaviour law is derived from a stationary creep model, complemented by an exponential transient creep.

Model based on Boltzmann's formulation represents fairly well the salt creep whatever the stress deviator, if the temperature is high. At medium temperature and for high stresses deviators, this formulation appears to be slightly insufficient.

Norton-Hoff power law type used around the world describes the phase of transient creep; it considers that over this phase the creep rate is stabilized.

Law of J. Lemaître, used mainly in France and to a lesser extent in Germany, describes the phenomenon of continuous hardening related to the decrease of creep rate. This law does not distinguish between the transient creep and the secondary creep, considering that the creep rate decreases very slowly in time. In this case, the viscous-plastic deformation also depends on the deformation rate. Predictions obtained with Lemaître model are good for creep, whatever the duration of test, temperature or stresses deviator. Such an adjusted model for a cyclic tensile test gives the parameters of the same order as those resulting from the Lemaitre model adjusted in the case of a creep compression test.

Robinson's model treats only non-elastic deformations through kinetic law that includes an isotropic hardening variable and other directional or kinematic hardening;

Munson-Dawson's model based on the hardening deformation law (Boltzmann superposition principle) describes the variation of transient creep component following the decrease of creep rate and secondary creep component at a constant creep rate. The advantage of Munson-Dawson's model is that it can model creep behaviour for different degrees of stress and different temperatures.

Garofalo's model established depending on the power of hyperbolic sinus of deviator; represents good and seems appropriate to estimate the rheological behaviour of salt from Etrez and Varangéville, being a model capable to predict the partial recovery.

Suvic model is a unified model with internal state variables, formulated for the ductile and semi-brittle regimes, where the inelastic deformation is poorly influenced by microcracking phenomenon. This model prevails to represent a large number of salt parameters, but requires a certain cost in the laboratory. It has the advantage of being based on physical considerations, which brings it closer to the real salt behaviour.

Composite model of plastic deformation according to heterogeneity of the dislocation structure, able to predict the rheological and thermomechanical behaviour of long-term salt around an underground storage cavity; the model is based on microstructure and physical deformation mechanisms. The constitutive behaviour equation expresses the transient creep and steady creep, irreversible volumetric changes (dilatancy and / or compressibility) during the creep, creep and microcracking induced through creep and failure. This model offers the possibility to know the area around an underground cavity in which the microcracking phenomenon becomes possible and progressive and at the same time, the way of cracks propagation in the rock massif. The composite model can generally be used in the case of crystalline rocks.

A fundamental difference between these models or behaviour laws consist in taking into account or not the hardening deformation. For example, such a difference appears clearly in the case of the Norton-Hoff power law (without hardening) and the other presented laws. It is observed, for most models, that they do not consider the phenomenon of dilatancy. In fact, the fast triaxial salt tests demonstrate that lateral deformations can overcome axial deformations, namely the salt is characterized through dilatancy. It constitutes the effective indicator of the appearance of microcracking, phenomenon leading to a significant increase of salt permeability and thus diminish its initial tightness, phenomenon that cannot be neglected in the analysis of the stability of underground works carried out in salt massif.

There is little information and experimental data on relaxation in the literature. The difference between the values of the rheological parameters obtained by the creep and relaxation tests can occur either by ignoring the leaps recorded by the deformation when changing the stress deviator or by the manner to perform the test (for example, creep in compression and relaxation in tensile) or even by the dependence of parameters on test duration. Knowing the phenomenological aspects of creep and relaxation starting from experimental tests offers the possibility to establish the mathematical equations expressing the influence of various parameters on the rheological behaviour. The validation of a behaviour law and the calculation of parameters involved in the constitutive equation largely depends on the results obtained experimentally and / or in situ. Physical interpretation of experimental rheological parameters must be achieved through quantitative creep theory based on the known micro and macro-mechanisms.

An important source of information is the creep test: a constant axial load (uniaxial test) is applied to a cylindrical specimen, load completed eventually by a fluid pressure (or confinement) exerted on the side surface of the specimen (triaxial test). An instantaneous elastic response is observed, after which a continuation of the axial deformation of the specimen through continuing to maintain the mechanical load. The deformation rate decreases at the beginning during a few weeks (primary or transient creep) and tends to an almost constant value (secondary or stabilized creep, also called „steady-state"). Some researchers estimate that speed continues to decrease slowly, even during this phase (hardening of rock salt), but most authors estimate that this rate remains constant, a statement made based on the arguments founded on the micro-mechanisms produced during deformation [eu]. An experimental proof which can finish the existence of a stabilized creep would undoubtedly require very long tests (even in order of decade) and which, of course, are inaccessible. Measurements of pillars deformation carried out in salt mines, for a period of 30 years after the end of the exploitation, have also highlighted the fact that the pillars have registered a transitory evolution over a period of 15 years, characterized through a decreasing rate of fracture, after which, the very low rate (as a value) reached a constant value, which basically invokes the secondary creep. In fact, the real form of the applied load also intervenes, which must guide us towards the correct formulation of behaviour law: if the structure is subjected, over a long period of time, to the loads actually constant (abandoned ones, liquid hydrocarbon storage, even waste), it is logical to privilege the stabilized creep and neglect the transient phase. On the contrary, the more complex situations (storage of natural gas subject to frequent injection and extraction cycles) "invites" us to a detailed analysis of transient behaviour. A correct behaviour law is always a schema, which must be guided towards the particular nature of the work for which it will be used.

The "secondary" phase has attracted the attention of many researchers, due to the practical importance that it has in case of underground works and it seems that an agreement has been reached on a few ideas (see Figure 3):

There is no "threshold" of creep occurrence, even under loads of less than 0.1 MPa. The absence of such a threshold or occurrence criterion of viscous-plasticity, proves the behaviour of a fluid and explains the frequent existence of geological phenomena characterized by very large deformations of the salt, such as domes or diapires;

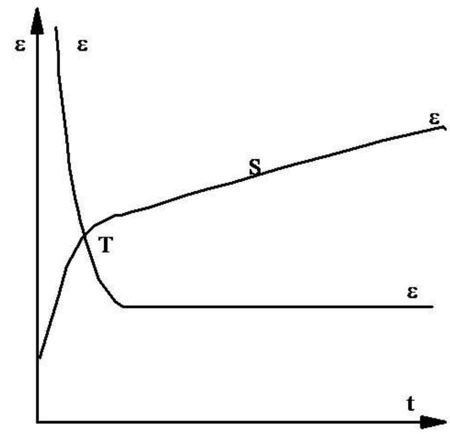

Fig. 3 *Deformation – time and deformation rate – time curves, marking transient (T) and stabilized (S) responses; the applied load is constant [19]*

- Following a stabilized (secondary) creep, the deformation rate is a non-linear function of the applied axial stress or, in the case of a triaxial test, only of the difference between applied axial stress and confinement pressure (lateral). Generally, drawing the curve representing the rate of stabilized creep depending on applied load in a logarithmic diagram „log – log", it is established that the deformation rate of salt is proportional to the "n" power applied stress, the exponent "n" being typically between 3 and 6 (power law type respectively, Norton – Hoff law). In practice, exponent n is often determined by "multilevel" tests (step creep): the applied stress increases periodically, waiting for each level to reach the stabilized regime [19].

The temperature at which the test is performed plays an important role: if the temperature increases by 100 °C, the deformation rate may increase from 10 to 10^2. Following a uniaxial test, it is also ascertaining the effect of hygrometry when the side face is in contact with atmospheric air (the environment), namely the effect of air humidity. The deformation rate can change up to two times when the humidity varies in the range of possible values. These remarks show the importance of verifying the test conditions.

These main presented characteristics can be summarized through following expression of the uniaxial deformation rate (the contractions and compressions are negative):

$$\mathring{\varepsilon} = \frac{\mathring{\sigma}}{E} + \alpha\,\mathring{T} + \mathring{\varepsilon}_t - A\exp\left[\frac{Q}{R\,T}\right]|\sigma|^n \qquad (9)$$

The first two terms in the right member represent the thermoelastic deformations; the third term is the transient deformation, which I did not describe here, but which in time tends to zero, when the load is kept constant. In this very simple model, in the case where σ is between 5 MPa and 15 MPa, the temperature T varies within the limits of 300 K and 400 K, and three constants are sufficient to describe the stabilized creep (A, Q/R, n). The stabilized creep law clearly shows that the depth of work placement will have a considerable influence on its behaviour because it causes the intensity of applied stress (σ) and temperature (T) to increase.

The generalization of creep law to a three dimensional state is realized through admitting that the creep occurs at constant volume (which means that $\mathrm{tr}\,\dot{\varepsilon} = 0$); deviator equivalent stress, $\sqrt{3}\,J_2$, plays an equivalent role to that the stress σ has in the case of an uniaxial test.

Absolutely, the above description does not exhaust the complexity of the salt behaviour, but it is nevertheless useful in case of works for which the loading history is quite simple (mines, storage of oil products kept at constant pressure). Practical, partial discharge test illustrates this complexity; it consists in performing a creep test, then, when the stabilized creep is reached, diminishing the applied axial stress (or, generally, of deviator equivalent stress) from 20 % to 50 % (see Figure 4).

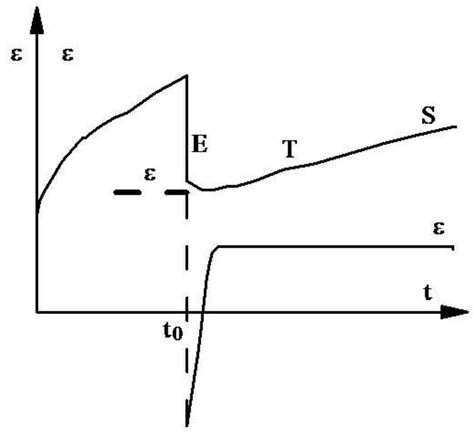

Fig. 4 *Deformation – time and deformation rate – time curves, on which the elastic (E), transient (T) and stabilized (S) responses are distinguished - the case of a partial discharge; applied load is reduced to the moment t0 [19].*

After the elastic discharge, a creep phase with axial dilatancy is observed (it is obvious that a sample subjected to axial compression deforms, recording vertical shortening and horizontal elongations). Further, the deformation rate, which is initially positive, decreases progressively (the contractions are negative) until it reaches the stabilized creep rate (negative) corresponding to the new applied stress. The transition to this new steady state can be extremely high duration; we are talking about hesitation to creep [19].

In practice this phenomenon can present importance, for example, in case of tightness tests of storage caverns. At the beginning of test, the fluid pressure is sensitively increased, for which its evolution will be followed in order to check the tightness. At the beginning of test the salt is thus subjected to a reduction of deviator stress and the cavity increases its volume over a period of several days, causing a sudden decreasing of fluid pressure contained there and consequently the illusion of a loss of fluid.

The phenomenon should be modelled through introducing an internal variable that takes into account the kinematic hardening. This methodology allows the approach of the third problem, namely the effect of cyclic loads, non-symmetrical. In the case of these loads, the mean value of applied stress is not zero and the amplitude of the cycles is that in which the specimen is never subjected to a tensile. Simple models, as it is the model proposed by J. Lemaître for metals:

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + \alpha\,\dot{T} + \dot{\varepsilon}_{vp}$$
$$\dot{\varepsilon}_{vp} = A\exp\left[-\frac{Q}{R\,T}\right]\varepsilon_{vp}^{-m}|\sigma|^n \quad , \qquad m < 1 \qquad (10)$$

which provide a fairly accurate representation of the transient creep, we could say in a convenient manner, take into account the results of cyclic tests or transient phases of creep tests in stress or temperature steps.

These models allow establishing the behaviour of underground voids (caverns) subjected to variable pressures with results in a good agreement with the observed volume variations (such as, for example, those used to store natural gas).

A more precise modelling would require it to be included a combination of kinematic and isotropic hardening, in which case the models will require the establishment of a large number of parameters. However, generally, there is only a relatively "rough" determination of the actual behaviour of an underground work, it is often very difficult to completely validate sophisticated models coarse, especially taking into account the fact that the results of laboratory tests are often dispersed. It also comes to a common difficulty for the rock mechanics ensemble, namely: laboratory tests and numerical calculus have seen an impressive development (and why not admit here, they are, in many cases, less expensive) compared to in situ tests; a large part of the predictions made or established in one or another situation cannot be verified with a high precision.

To conclude, we would like to highlight here some of the current research trends: the creep under a small load (of the order of $\sigma < 3$ MPa, T = 300 K), seems to be achieved at higher rates than the extrapolation of the stabilized creep law (relationship 9) with significant practical consequences.

On the other hand, we said that the steady creep took place without volume variation: in fact, if the applied stresses go out (or exceed) from a domain described by a parabolic form criterion in the Mohr plane, then there is a dilatancy associated with a diffuse microcracking of material. Its effect is to increase spectacularly the influence of ambient hygrometry (humidity) or salt permeability, with significant practical consequences, since the permeability of salt is one of its essential qualities for which it is exploited for certain purposes.

The relationships between stress state, pore fluid pressure and permeability are an important subject of current research related to the storage issue of liquid waste in the underground cavities [8], [21], [26]; [27]. [32].

6. Conclusions concerning the rheological behaviour of salt

It is often asserted that the response of the materials to a mechanical load was instantaneous (even if this response could have depended on the way followed to the considered current state). In fact, it is often observed in the laboratory, but especially in the underground works, a series of non-elastic effects. Among the materials or more accurately, the rocks that have such effects, the salt is the most studied example, due in particular to the numerous underground works (drillings, salt exploitation, underground storage) carried out in the underground salt formations. The behaviour of this material is very complex, and, as is well known, the engineer does not have the necessary ambition to describe this behaviour in an exhaustive manner; the engineer tries to determine a relationship of behaviour within a certain range of stresses, temperatures, and ways of load which are useful for the actual problem that he searches to solve [32].

In order to obtain the equation of state describing the rheological behaviour, we must establish from the beginning the specific features of the salt mechanical behaviour, namely:

- nonlinearity of stress - deformation under the action of a constant load;
- variation of creep deformation at constant load;
- the presence of microcracking and consequently the increase in volume, phenomena that depend on dilatancy.

The stress - strain characteristic curve offers the possibility to classify the rocks into a particular behaviour class; this is also useful for choosing the law of rheological behaviour. The studies performed on salt show that it exhibits elastic – viscous - plastic behaviour. It is observed currently all three creep phases with a plastic flow - inelastic, which is sometimes produced with dilatancy; even for the same level of stress, the inelastic - rheological deformations may be upper to instantaneous deformations and are characterized by a quasi-total irreversibility.

In order to be able to know the actual behaviour and to correctly establish the salt behaviour law, we need to analyse the factors or parameters that influence the behaviour of salt and the mechanical effects caused by these parameters (see Figure 5) [21]

The analogy of the creep curve of rock salt with the curve of metals determined the researchers to consider two main phases (or stages) for the creep (without breakage): transient and stationary, the latter mainly being of interest (in fact, the stationary or secondary or stabilized creep phase is basically interested to analyse the long-term stability of any underground work). Therefore, they estimate that salt creep should have the same properties as in the secondary phase of the metal creep, namely: homogeneity and isotropy; deformation with constant volume; only the influence of stress deviator.

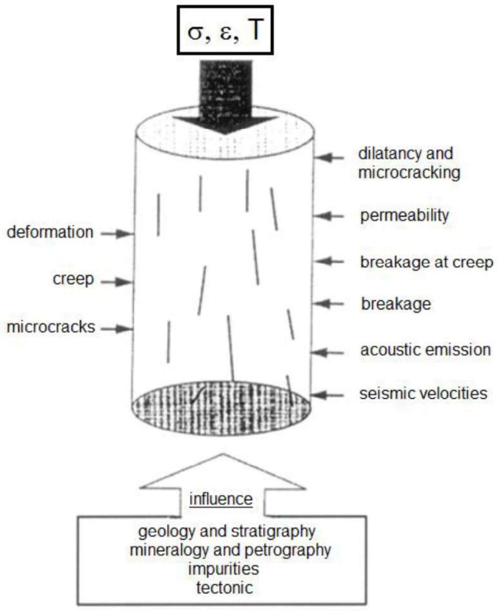

Fig. 5 *Mechanical effects and parameters of influence on deformation behaviour of a salt sample [21].*

If the salt is subjected to constant stress, after having recorded a decreasing creep phase corresponding to transient creep phase, the salt tends towards a regime characterized by a constant deformation rate. However, I recall that there is a controversy over the difference between the two phases of creep.

Many studies in the literature present micro-mechanisms capable to release the salt deformation. Salt is a polycrystalline rock composed of NaCl crystals, in its atomic structure showing defects or dislocations. In the moment of charging the salt, in the initial state, the structure of the dislocations' changes is very small, after which it becomes almost heterogeneous at the beginning of the transient phase, a deformation begins to occur and the dislocations move towards to a stable state. One of the movements of dislocations is sliding, a phenomenon that occurs on the stationary creep, in low temperature conditions and important loads. If dislocations encounter obstacles in their way, then we are talking about increases of dislocations, a phenomenon that produces polygonization of crystals. This is characteristic of temperatures above 100 °C and low stresses (after the diminishing of the stress that has allowed sliding of the dislocations). Other phenomena that determine deformations are: diffusion, which causes a plastic deformation; recrystallization, mainly corresponding to the generation and movement of intergranular borders.

The microscopic phenomena and the different macroscopic characteristics of salt creep are influenced by external factors such as: temperature; hygrometry (the presence of a fluid, especially brine); stresses or loading rate (through stresses tensor and deviator); anisotropy; time.

The influence of confinement stress has been the subject of many discussions in the salt rheology study in laboratory. It is asserted that the higher the confinement stress, the lower the deformation percentage, particularly in the phase of transient creep, which seems to fade in the secondary phase. The 3.5 MPa value considered the stress threshold from which the percentage of deformation is mainly dependent on stress deviator. If salt is thought to deform without microcracking, it appears that only the stress deviator has a real influence on deformations. Typically, the effect of confinement stress is neglected in the formulation of rheological behaviour law of salt.

Salt seems to show a memory of the subsequent suffered load. The most recent thermomechanical histories greatly influence the current deformation. After a certain period of time salt will forget these histories, so it is a material without memory. The studies of microscopic and macroscopic scales have made it possible to identify the characteristics of the rheological behaviour of salt in laboratory and to develop different rheological models of behaviour. The main characteristics of salt in laboratory are: creep; tendency to hardening under load; recovery or unload; relaxation; memory.

In relation through to the type of micro-mechanism or considered creep type, the salt behaviour laws can be divided into three classes: (1) logarithmic or exponential laws that model the transient and stationary creep phases; (2) power laws that describe the stationary creep phase and also hardening; (3) hyperbolic sinus laws, inspired by the microstructural phenomena responsible for the occurrence and development of deformation. They model the stationary creep or hardening.

The formulation of the various laws of behaviour is generally based on stresses tensors, deformation and stresses rate, time and temperature. Behaviour laws may correspond either to empirical models (but not to general laws) obtained directly through laboratory tests, or to analogue models that express different types of behaviour: elastic, plastic, viscous, elastic – plastic, elastic – viscous, elastic – viscous - plastic etc. The latest models consider that time has an important influence on the behaviour of rocks

References

1. **Allemandou, X., Dusseault, M.**
Procedures for cyclic creep testing of salt rock, results and discussions. In : Proc. Of the 3th Conference on Mechanical Behavior of Salt, M. Ghoreychi, P. Bérest, H. Hardy, M. Langer (Eds), PP. 207 – 218, Trans. Tech. Publication, Clausthal, ISBN 0-87849-100-7 (1993)

2. **Aubertin et al.**
Le comportement rhéologique du sel : revue bibliographique. Rapport EPM / RT – 87 / 32. Ecole Polytechnique de Montreal (1997)

3. **Berest, P. et al.**
Effets thermiques dans les cavités en couches salifères. In : Proc. 4ème Congrès de la Société Internationale de Mécanique des Roches, Montreaux, Balkema, Rotterdam (1979).

4. **Blum, W.**
Stationäre Verformung von polykristallinem Natriumchlorid. Dissertation, Univ. Erlangen – Nürnberg (1969).

5. **Burke, P.M.**
High temperature creep of polycrystalline sodium chloride. Ph. D. dissrtation, 112 S., Stanford Univ., Stanford, California (1968).

6. **Carter, N.L., Heard, H.C.**
Temperature and rate dependent deformation of halite. Am. J. Science, 269, S. 193 – 249 (1970).

7. **Charpentier, J.P.**
Prise en compte de la dispersion des caractéristiques différées du sel de Bresse. Rapport 624 RP G3S 91-003 (1991).

8. **Chugh, Y.P.**
Viscoelastic behaviour of geologic materials under tensile stress. A.I.M.E., Vol. 256, S. 259 – 264. (1974)

9. **Coble, R.L.**
A model for boundary diffusion controlled creep in polycrystalline materials. J. Appl. Phys., 34, S. 1679 – 1682 (1963).

10. **Durup, J.G.**
Comparative Study of Certain Constitutive Laws used to Describe the Rheological Deformation of Salts. In : Salt Behavior III, p. 74 – 83 (1993).

11. **Fairhurst, C.E., Hudson, J.A.**
Draft ISRM suggested method for the complete stress-strain curve for intact rock in uniaxial compression. International Journal of Rock Mechanics and Mining Sciences. 36, pp 279-289 (1999).

12. **Gloyna, E., Reynolds, T.**
Permeability measurements of rock salt. J. Geophys. Res., Vol. 66, No 11, PP 3913 – 3912 (1961).

13. **Goodman, R.E., Ohnish, Y.**
Undrained shear testing of jointed rock. Rock Mechanics 5, pp 129-149 (1973).

14. **Griffith, A.A.**
The phenomena of rupture and flow in solids. Phil. Trans. Roy. Soc. London, A221 :163 – 198 (1920).

15. **Griggs, D.T.**
Creep of rocks. Journ. Geology, 47, S. 225 – 251 (1939).

16. **Griggs, D.T.**
Experimental flow of rocks under conditions favouring recrystallisation. Geol. Soc. Am. Bull., Vol. 51, S. 1001 – 1002 (1940).

17. **Heard, H.C.**
Steady – state flow in polycrystaline halite at pressure of 2 kbars – in: Flow and fracture of Rocks. Geophys. Monograph, No 16, Editors Hear, C.H. et al., AGU, S. 191 – 209, Washington (1972).

18. **Herring, C.**
Diffusional viscosity oh a polycrystalline solide. J. Appl. Phys., 21, S. 437 – 445 (1950)

19. **Homand, F., Duffaut, Berest, P.**
Manuel de mécanique des roches. Éditeur Paris: Les Presses de l'École des mines, Bibliothèque scientifique. TA 706 C733 2000 1 (2000)

20. **Houpert, F.E., Homand-Etienne, F.**
Influence de la température sur le comportement mécanique des roches. The 4th Int. Congress of Rock Mechanic (1979).

21. **Hunsche, U., Humpel, A.**
Rocke salt – the mechanical properties of the host rock material for a radioactive waste repository. Engineering Geology 52, 271 – 291 (1999).

22. **Kutter, H.K.**
Transient creep behaviour of Schilfsondstein in multistage loading and unloading tests, Proc. ISeM. Symp. Eurock 92 Chester 14 - 17 sept. 1992, Thomas Telford, London, 1992.

23. **Langer, M., Kern, H.**
Temperatur- und belastungsabhängiges Deformations – verhalten von Salzgesteinen. Vortrag V. Int. Salzsymposium, Hamburg (im Druck) (1978).

24. **Linder & Brady**
Memory Aspects of Salt Creep. Proc. Of the 1st Conf. on ''The Mechanical Behaviour of Salt'', Pensylvania State University (1981).

25. **Pouya, A.**
Comportement rhéologique du sel gemme. Application à l'étude des excavations souterraines. Thèse de l'Ecole Nationale des Ponts et Chaussées, Paris (1991).

26. **Stolle, D.F.E.**
Vâscoelasticity and plasticity numerical stability revisited. Proc. 3rd Int. Symp. On Numerical Models in Geomechanics, Niagara Falls 8-11 May 1989, Elserer Applied Scien., London, (1989).

27. **Stormont, J.C., Howard, C.L., Daemen, J.J.K.**
Changes in rock salt permeability due to nearby excavation, Rock Mechanics as a Multidiciplinary Science, Roeggiers (Ed.), PP 899 – 907, Rotterdam. (1991).

28. Toderaş, M.
Comportement des ouvrages souterrains dans le sel. Séminaire International Sciences et Ingénierie des Ressources, Procédés, Produits, Environnement, 8 – 9 avril ISBN 2-9518564-0-7, INPL Nancy, France (2003).

29. Toderaş, M.
Le comportement du sel synthèse bibliographique, Laego, INPL, Nancy, France, Juillet (2003).

30. Toderaş, M.
Rocks rheology in the stability of underground mining works. Study case: Sedimentary rocks from Jiu Valley, Romania. Saarbrücken, Germany - Scholars' Press International Publishing House, Lambert Academic Publishing, OmniScriptum GmbH & Co. KG Germany, ISBN 978-3-639-76796-4. 549 pg., (2015).

31. Toderaş, M.
Mecanica rocilor, pământurilor şi construcţii subterane. Editura Universitas, Petroşani, ISBN 978-973-741-381-9, 1167 pg., Vol.I-II, (2014).

32. Toderaş, M., Danciu, C.
Stability analysis methods of underground mining works. Lambert Academic Publishing. International Publishing House, OmniScriptum Management GmbH, Bahnhofstraße 28, D-66111 Saarbrücken. ISBN 978-620-2-19847-9, 380 pg., (2017)

33. Todorescu, A.
Reologia rocilor. Editura Tehnica, Bucuresti. (1986).

34. Yahya, O.M.L., Aubertin, M., Julien, M.R.
A unified representation of the plasticity, creep and relaxation behavior of rocksalt. Int. J. of Rock Mech. & Min. Sci. 37, pg. 787 – 800 (2000)