Revista Minelor – Mining Revue
ISSN-L 1220-2053 / ISSN 2247-8590
vol. 29, issue 3 / 2023, pp. 26-43

RHEOLOGICAL CHARACTERISTICS OF THE ROCK SALT FROM SLANIC PRAHOVA, HORIZON XIV BELOW LEVEL OF 200m

Mihaela TODERAȘ[1*], *Ștefan MILITARU*[2]

[1]University of Petrosani, Romania, toderasmihaela@yahoo.com
[2]University of Petrosani, Romania, stefan.militaru@yahoo.com

DOI: 10.2478/minrv-2023-0021

Abstract: *The long-term response and stability of underground mining works are crucial for ensuring the safety of workers, preventing costly accidents, and maintaining efficient operations. This is primarily due to the critical role these structures play in various industries, including mining, construction, and transportation. Understanding the long-term response and stability of such structures is an important factor for ensuring their durability and safety. Additionally, advancements in technology and engineering practices have allowed for more accurate assessments and predictions of long-term behaviour, leading to improved design and maintenance strategies. By examining the creep and relaxation behaviour, scientists can gain insights into the mechanical properties and stability of rocks under different conditions. The time-dependent experiments involve subjecting the rocks to varying rates of loading or deformation to understand their behaviour under different conditions. These methods provide valuable insights into the time-dependent properties of rocks, allowing researchers to better understand their response to various geological processes and engineering applications. This study was carried out in order to determine the rheological characteristics of the rock salt from Slanic Prahova mine, horizon XIV, and to analyse the local stability and the general stability of the resistance structures. The results of the experimentally determined rheological characteristics showed that the analysed salt has a pronounced tendency to creep, being able to be classified in creep category 5, which is a pronounced creep. The values obtained for the dilatancy threshold confirm the fact that salt is a material system that exhibits dilatancy.*
Keywords: *salt, creep, rheological coefficients, dilatancy, stability, stress-strain isochronous curves, load degree*

1. Overview of the rheological behaviour of salt

The behaviour of rocks in relation to time is a particularly important problem in the field of underground structures performed in rock massifs. There are many factors that affect the rheological behaviour and stability of rooms and pillars.

All rocks, including salt rock, exhibit time-dependent behaviour. Understanding the time-dependent behaviour of rocks is a particularly important problem for engineers to ensure the stability, durability and safety of engineering structures performed in rock massif. This knowledge enables them to accurately predict and mitigate potential long-term deformations or instabilities that may arise over the lifespan of these structures. Additionally, it allows engineers to implement appropriate maintenance and monitoring strategies to ensure the continued stability and performance of underground structures carried out in rock massif.

The extraction of minerals in room and pillar mines can lead to the formation of voids and subsidence, which can pose significant risks to the surrounding areas. Furthermore, once the mines are abandoned, the stability of the remaining pillars and roof becomes also of great concern in order to prevent collapse and ensure long-term safety [1], [2]. The earlier studies of Jaeger & Cook (1979) [3] and Cristescu & Hunsche (1998) [4] aimed to understand how rocks respond to changes in temperature, pressure, and stress over time. They laid

* Corresponding author: Mihaela Toderaș, Prof.Ph.D / Mining Engineering, Surveying and Civil Engineering Department, University of Petrosani, Petrosani, Romania (University of Petrosani, 20 University Street, +40-741501143, toderasmihaela@yahoo.com)

vol. 29, issue 3 / 2023
pp. 26-43

the foundation for further research in the field of rock mechanics and have been instrumental in developing models that predict the rheological behaviour of rocks under various geological conditions. These studies aimed to assess the long-term stability and integrity of halides under various environmental conditions. The results provided valuable insights into the potential for creep or migration of radioactive materials from the waste repositories. Most of the salt creep tests were carried out under uniaxial and/or triaxial compression at different constant temperatures [5], [6]. Creep characteristics and rheological parameters of rocks are very important for assessing the long-term stability of underground mining works.

Some inelastic effects are frequently observed, both in the laboratory and especially in underground works. Among the materials, or, more correctly, the rocks that present such effects, salt is the most studied example, due, in particular, to the numerous underground works (drilling, salt mining, underground storages) carried out in the saline underground formations. The behaviour of this material is very complex [7].

In order to obtain the equation of state that describes the rheological behaviour, we must establish from the beginning the particularities of the mechanical behaviour of the salt, namely: the non-linearity stress—deformation under a constant load; creep strain variation under a constant load; the presence of microcracks; and, consequently, the increase in volume, phenomena that depend on dilatancy.

The characteristic stress-strain curve offers the possibility of classifying the rocks into a certain behaviour class; this is also useful for choosing the rheological behaviour law. The studies carried out on rock salt show that it has an elastic-viscous-plastic behaviour. The three phases of creep with a plastic-inelastic flow are currently observed, which sometimes occurs with dilatancy. Even at the same stress level, inelastic rheological deformations can be superior to instantaneous deformations and are characterised by quasi-total irreversibility.

Mineral composition is one of the factors that influence the creep properties of salt rock. The impurities can affect the creep properties of salt rock by altering its crystal structure and introducing defects. Additionally, impurities can also impact the mechanical strength and stability of salt rock, further influencing its creep behaviour [1], [4]. From a microstructural point of view, in the salt rock structure, between the rock salt crystals, there are cleavage planes that are easy to separate. And rock salt crystals easily slide along these planes; this is a reason why salt rock has very good rheological properties. For impurity salt categories, the existence of associated minerals can limit the overall deformation capacity of the salt rock. Therefore, the purer the salt rock, the better the rheological properties [7]-[10].

As one of the most important mechanical properties of salt rock, rheological behaviour is a main factor influencing the lifetime, safety, and stability of underground works carried out in salt massifs. Salt has pronounced creep properties. Salt creep occurs due to the rearrangement of salt crystals over time. Because of this fact, salt can generate large creep strains even under lower deviatoric stress after a long period of time. Therefore, to ensure the long-term safety and stability of underground works carried out in salt massifs, it is necessary to study their creep properties.

The factors influencing the creep characteristics of salt rock are: stress level, stress path (in the case of triaxial stresses), temperature, mineralogical composition, the presence of stratification, and its mechanism of deformation on a microscopic scale. In general, during creep, the stress and temperature are constant, but the structure and, at the same time, the internal state of stress will be (or can be) changed with increasing strain and therefore creep rate. Hence the empirical laws of transient creep (primary) and stationary creep (secondary) result [7].

Compared to most rocks, the behaviour of rock salt depends on the active mechanisms present in the grain structure. The deformations of halite crystals are: displacements of dislocations; diffusion, which produces a plastic deformation due to a diffusion of matter inside the rock; solution-precipitation; crystallisation at the crystal boundary.

The influence of these mechanisms on the total creep is different depending on the nature of the salt, the structure, the stress conditions, and the temperature. The decisive deformation mechanisms are dislocation glide, polygonization, diffusion, and grain boundary sliding. Dislocation slip exists at high stresses and low temperatures relative to the fusion temperature, T_m = 1074 K = 801 °C. At an accentuated increase in the strain rate or for high temperatures, creep by diffusion is dominant; it appears for a maximum stress σ = 4.5 bar and depends on the temperature [7].

In general, transient (primary), stationary (secondary, stabilized), and tertiary creep and the corresponding laws are related to certain deformation mechanisms. Salt is characterised by a complete creep curve (figure 1): under a stress and temperature deviator, primary (transient) or attenuated creep occurs where the strain rate decreases continuously; secondary (stationary) or stabilised creep occurs at the stage of set flow or viscous-plastic flow zone; tertiary creep occurs at the stage of progressive flow, an area in which the rock salt will register the appearance of cracks and therefore a structural change. For rock salt, secondary (stationary) creep is most important.

vol. 29, issue 3 / 2023
pp. 26-43

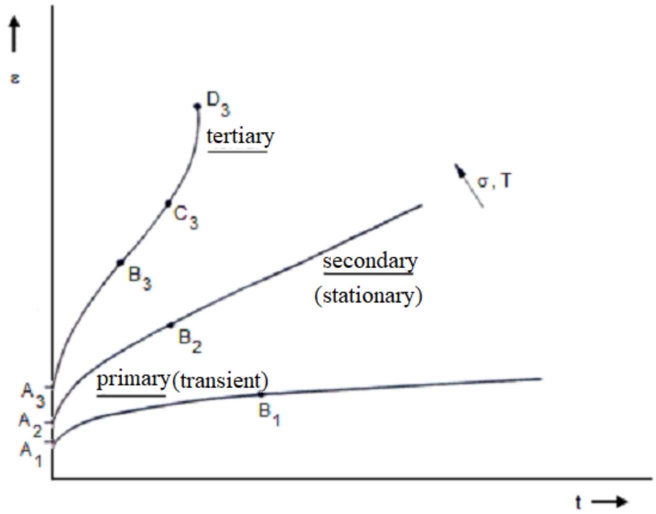


Figure 1. Creep curves

Primary (transient) creep. At low stresses and low temperatures, logarithmic creep occurs; dislocations are considered obstacles. Due to the creep phenomenon, creep will occur in successive stages. In this case, the movement of dislocations does not play an important recovery role, with the latter mechanism becoming more apparent at high stresses and temperatures.

Secondary (stationary) creep. The creep rate is constant if the hardening process occurs at the same rate as the recovery process. Such recovery processes can be observed by the rotation of dislocations, diffusion of voids, polygonization, migration of fine grains, and recrystallization [7].

Tertiary creep (fracturing creep, breakage creep) is characterised by high stresses and the activation of an additional deformation mechanism called grain sliding. Such a mechanism causes a gradual decrease in grain boundaries and will produce their separation. Due to the fact that fracturing creep is mainly dependent on the occurrence of inelastic deformations, this dependence must be considered in the fracturing phenomenon by a flow criterion. Mainly, fracturing or breakage depends on the maximum strain. Consequently, for tertiary creep, the failure criterion will not be chosen according to the stress state but in relation to the strain state. For example, Bach's old hypotheses can be mentioned here, namely: the maximum normal principal strain, respectively the shear strain; the condition of stored strain energy before fracturing – the Druker-Prager criterion.

Fracture occurs at high strain rates, or creep strains, that are attributed to loading stresses very close to breaking strength. In this case, high stresses are concentrated at the grain boundaries, and the mechanism (Griffith's theory) of fracturing will be activated (unstable propagation of existing cracks or the appearance of new cracks).

Laboratory tests are the simplest way to analyse the creep behaviour of any type of rock. Compared to in situ measurements, even if these laboratory tests are time-consuming, they allow long-term observation of rock behaviour, do not involve high costs, and can be repeated by considering only the main factors and strictly controlling the experimental conditions. The results of laboratory tests can not only reveal the creep behaviour of salt under different experimental conditions but also provide relevant parameters for establishing the constitutive creep model. Current studies on the creep properties of salt are mainly focused on aspects of the macro creep properties and microscopic deformation mechanisms of rock salt.

Currently, uniaxial and triaxial creep tests are most often used in the study of the rheological behaviour of salt and, implicitly, in determining the rheological parameters that characterise this behaviour.

The formation of salt rock deposits is closely related to geological movement; therefore, their appearance and shape are different. Depending on the thickness of the salt deposit, it can be divided into salt domes and extended salt deposits. A salt deposit refers to interbedded salt composed of salt layers with different structures, different components, and different physical-mechanical properties, which usually contain intermediate layers. Due to the difference in lithology, different deformation easily occurs between salt layers and intermediate layers under external loads. This leads to the development of additional stress on the contact plane between the salt layer and the interlayers, which can cause breakage of the salt in the layer.

Many researchers have compared the difference in creep properties between pure salt and layered salt under the same experimental laboratory conditions [11, 12, 13, 14, 15, 16, 17]. The test results showed that the stress sensitivity and creep properties of pure salt are stronger than those of salt with intercalations; in other words, the creep strain of the first type of salt is greater than that of the latter (figure 2). Results were also reached where the constant creep rate of the pure salt was about 7 times higher than that of the salt with intercalations, located under the same experimental conditions [15].

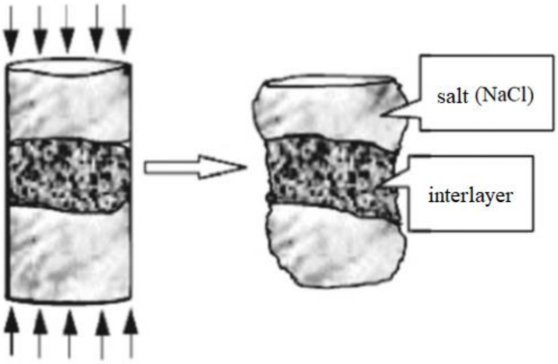


Figure 2. Flowchart of interlayered salt creep failure

According to theoretical studies and based on rheological tests on salt, shear stress is generated at the interface between two rocks due to the difference in physical and mechanical properties and different deformation between pure salt and interlayers [1], [4], [18], [19]. As the creep time increases, the shear stress increases progressively. Only when the shear stress exceeds the shear strength of the interface does creep failure of the intercalated salt occur. The rupture of this type of salt occurs in combination with the additional stress resulting from the difference in creep strain and stress in the same direction of effect. Only when this pressure exceeds the tensile strength of the interlayer does a rupture of the salt intercalation occur.

Salt is a typical crystalline material, and its creep behaviour under stress is basically a macroscopic reflection of the internal microstructural changes that take place. This means that, under the action of external conditions, important changes will occur in the microstructure of the salt, which can lead to variations in its mechanical properties [18], [19].

The main purpose of micromechanics studies on salt during the creep process is to distinguish the mechanisms of creep deformation under different conditions [20]. The first studies on the deformation mechanism at the micro-creep level of salt were carried out until the 1970s. Ashby (1972) [21] first proposed the microstrain mechanism diagram for metal, ceramic, and alkali halides under different stress levels and temperatures. Munson and Dawson [22] use this diagram to describe the creep deformation mechanism of salt. The salt creep process (Figure 3) is mainly governed by dislocation mechanisms (dislocation slip and dislocation climb) or diffusion processes, depending on temperature and deviatoric stress. We note that the undefined mechanism in Figure 3 is different from dislocation and diffusion mechanisms but also contributes to the creep process of rock salt. Regarding the association of these mechanisms with micromechanical models, as stated by many scientists, there are still many unclear aspects [2], [4], [8], [21], [23].

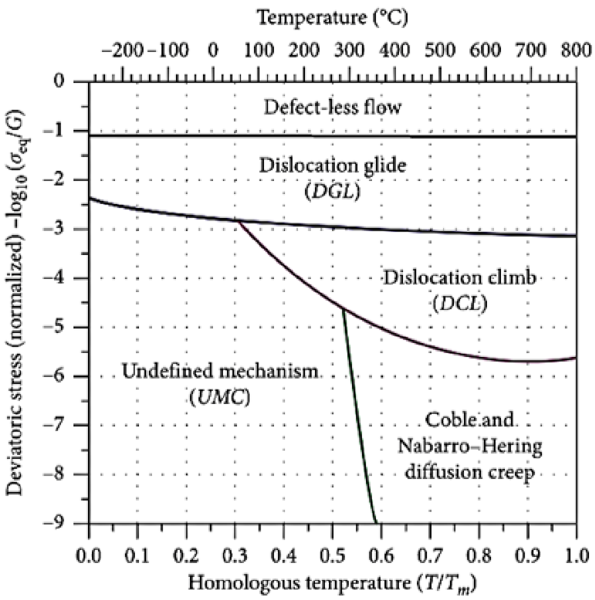


Figure 3. Salt deformation mechanism map: G is the elastic shear modulus of the salt and T is the melting temperature of the salt, taken as 1077 K ([23], [24])

vol. 29, issue 3 / 2023
pp. 26-43

The creep phenomenon of salt can be controlled by several mechanisms that occur in parallel in most cases.

Analysing the variation of the characteristics of the acoustic emission signals, the change in the characteristics of a salt sample during uniaxial compression creep tests, and the evolution of the appearance and development of cracks until rupture can be represented as in figure 4. From the laboratory tests carried out by different researchers [25, 26, 27, 28, 29], following the evolution of the axial deformation, it was found that the whole process of salt creep is divided into three stages: diminishing creep stage (creep time $0 < t < 200$ days), constant creep stage (creep time $200 \leq t < 320$ days), and accelerated creep stage (creep time $t \geq 320$ days). From figure 4, it can be observed the quantities and distribution of points in space-time of the acoustic emission signals in a salt sample at different creep times, quantities that show an obvious difference. (1) In the diminishing stage, these points are distributed in the middle and at the two ends of the salt sample due to the closure of the initial defects of the salt and the stress effect, and the activity of the acoustic emission signals of the salt is relatively active. (2) In the steady creep stage, the stress effect of the salt sample gradually weakens, and splotches in the space-time of the acoustic emission signals develop towards the middle of the sample. The interaction between the salt crystals is in dynamic equilibrium, and these points in space-time of the acoustic emission signals gradually decrease with increasing creep time. (3) In the tertiary creep stage, a lot of cracks are generated in the salt, and the spatial-temporal points of the acoustic emission signals grow rapidly, extend to both ends of the sample, and finally cover the entire salt sample. The long-term damage and breakage path of the salt is in the form "end part - center part - whole sample".

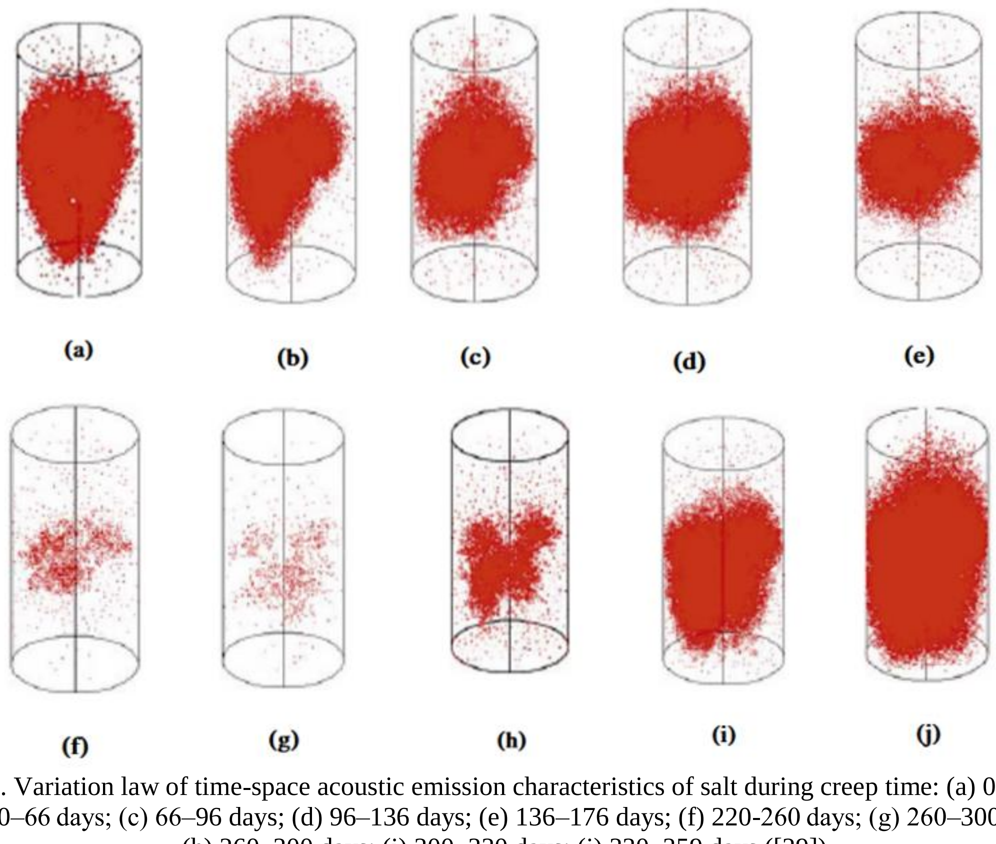


Figure 4. Variation law of time-space acoustic emission characteristics of salt during creep time: (a) 0–30 days; (b) 60–66 days; (c) 66–96 days; (d) 96–136 days; (e) 136–176 days; (f) 220-260 days; (g) 260–300 days; (h) 260–300 days; (i) 300–330 days; (j) 330–359 days ([29])

To conclude, we can indicate here some of the current research trends: under a small stress (load) (of the order of $\sigma < 3$ MPa, T = 300 K), creep seems to occur at higher speeds than those predicted by extrapolation of the stabilised creep law, with important practical consequences. On the other hand, we specified that stabilised creep occurs without volume variation; in fact, if the applied stresses leave (or exceed) a domain described by a parabolic shape criterion in Mohr's plane, then an associated dilatancy occurs with a diffuse microcracking of the material. Its effect is to spectacularly increase the influence of the ambient hygrometry (humidity) or the permeability of the salt, with important practical consequences since the permeability of the salt is one of its essential qualities for which it is exploited. The relationships between the stress state, pore fluid pressure, and permeability are an important topic of current research related to the problem of liquid waste storage in underground cavities [7].

vol. 29, issue 3 / 2023
pp. 26-43

2. Constitutive model of salt creep

The constitutive model is the most basic and important part of the rock mechanics theory of rheology, and it is also an imperative link that applies experimental results to engineering practice. Currently, based on experimental creep results, a large number of constitutive models are proposed by researchers to describe the creep behaviour of salt [1], [7], [30], [31]. Generally, the constitutive creep models of salt established by different researchers can be divided into the following categories, presented below.

2.1. Empirical model

The empirical model is an expression of the function established by the mathematical regression method through the statistical processing of a large number of results from salt creep tests. However, the parameters of the model lack a clear physical meaning [1], [4], [7], [8, 9, 10, 11], [41], [42]. Empirical models describe the creep response of salt based on a relationship between a constant creep rate and deviatoric stress, energy, and temperature. For the empirical model, the variation law expression that describes the creep response of the salt is either of the form of the exponential function, of the power-type function, or of the form of the logarithmic function [12], [27], [30], [32, 33, 34, 35, 36, 37]. Most empirical models can only reflect the creep response of salt in the primary and secondary stages but cannot describe the creep behaviour in the tertiary creep stage. The empirical model has been widely used to describe the creep properties of rock; however, with the development of the theory of rheological mechanics of rocks, the application of this method is becoming less and less common [1], [4], [8, 9, 10, 11], [39, 40, 41, 42, 43, 44].

2.2. Combined model

The combined model is one of the most important constitutive models in rock rheology theory. The fundamental principle consists of the assumption that several basic elements describe the specific mechanical properties of the rock. The basic elements (elastic, plastic, and viscous) are used to reflect the three properties of rock [7], [38], [39]. The model can be established by combining these basic elements in different forms (series, in parallel, or mixed connection: series-parallel or parallel-series) depending on the specific mechanical properties of the rock (Figure 5).

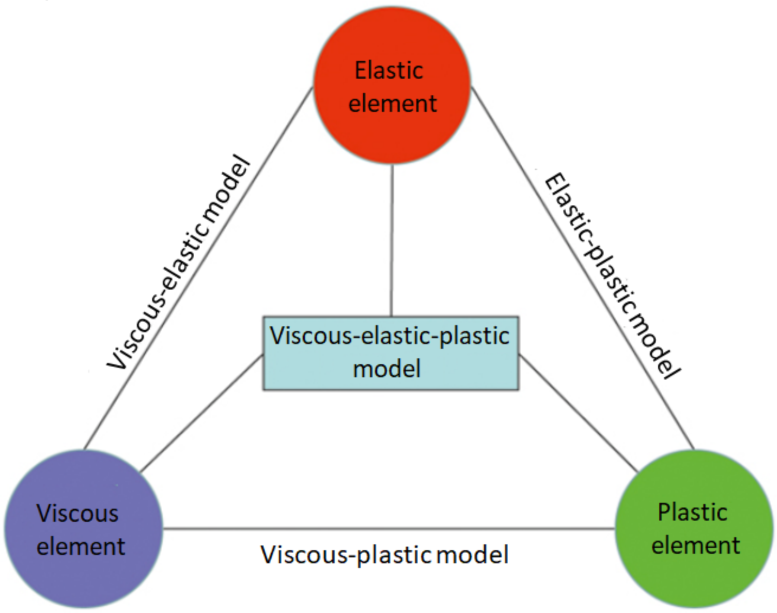


Figure 5. Flowchart of basic elements

Due to the explicit physical meaning of the parameters and the ability to visually represent the complex mechanical properties of rocks, the combined creep model has been widely used in the field of rheological rock mechanics [40]. Currently, a lot of component combination models have been established by scientists [7], [41, 42, 43] to reflect the creep response of salt. The Burgers model is one of the most frequently used. For example, some authors [7], [40], [41], [43], [44] found that the Burgers model can be used to describe the creep behaviour of glauberite, anhydrite, and rock clay. Tang et al., Mansouri & Ajalloeian and Wang et al. [15], [38] described the creep behaviour of salt under uniaxial compression, triaxial compression, and low-frequency cyclic loading (constant axial stress and limited cyclic pressure) using the Burgers model.

Figure 6 shows the isochronous stress-strain curves of salt, curves also obtained by Toderaș (1999, 2015) [7], [42] on different types of rocks, including rock salt.

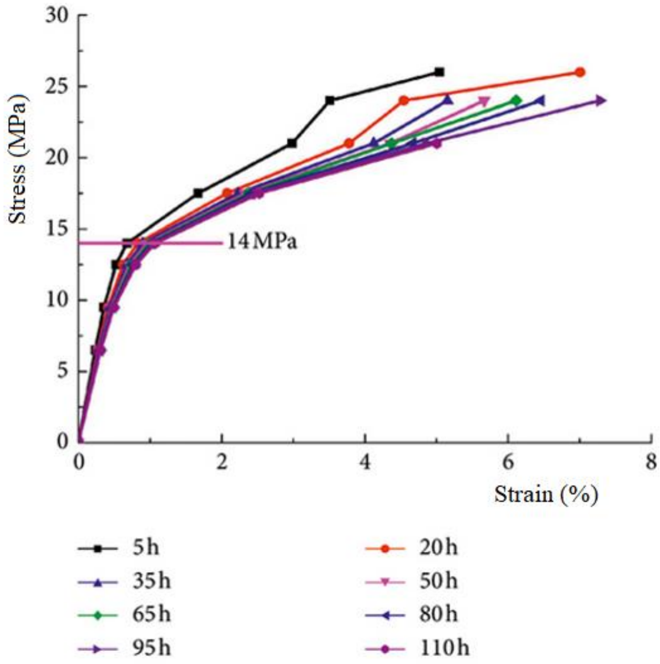


Figure 6. Isochronous stress-strain curves of salt

It can be seen that when the axial stress is less than 14 MPa, the isochronous stress-strain curves can be seen as a straight line that practically overlaps, indicating that the modulus of elasticity (E) of the salt does not change with increasing levels of stress and lengthening the creep time. When the axial stress exceeds the value of 14 MPa, a phenomenon observed by M. Toderaș in the case of the salt samples from the boreholes taken from Slănic Prahova that were rheological analysed, the isochronous stress-strain curves gradually deviate towards the axis of the deformation, indicating that the modulus of elasticity (E) of the salt gradually decreases with increasing stress level and increasing creep time.

As previously stated, we can say that: (1) salt shows clearly non-linear deformation characteristics during the creep phenomenon; the higher the axial stress and the longer the creep time, the more pronounced the nonlinear deformation characteristics; (2) when the axial stress is less than 14 MPa, the modulus of elasticity of the salt does not change with increasing stress level and creep time. Contrary, the modulus of elasticity decreases gradually with increasing stress levels and creep time [7], [8], [42], [44]-[47]. As the creep time increases, the variation law of the axial creep rate during the rock sample loading process can be divided into the following three types: (1) under a low stress level, the axial creep rate gradually decreases and then tends to zero in a short time; (2) under medium and high stress levels, the axial creep rate gradually decreases and then rapidly tends to a stable, non-zero value; (3) below the stress level close to the breaking strength, the axial creep rate gradually decreases to a stable, non-zero value, is maintained for a relatively short period, and then shows a rapid increase.

2.3. Integral type of creep constitutive model

In this case, the approach to the interpretation of the deformation behaviour in time (creep and relaxation) is based on the theory of heredity or integral equations. This direction offers the possibility of determining the parameters of the type of coefficients, which by their nature and significance, according to the principles of the hereditary theory, facilitate the possibility of using the theory of elasticity and plasticity in the rheological approach to the problems that must be solved by rock mechanics in its fields of applicability. Such a possibility is created through the nuclei of the integral equations of hereditary creep and relaxation, which have the property of indirectly introducing the influence of time into the geomechanical processes to be studied rheological based on the theories of elasticity and plasticity, respectively [7], [42].

For a more correct analysis of the rheological behaviour, the studies must be carried out according to the two research directions, namely, the interpretation of the deformation behaviour over time based on the use of the classical (elastic-viscous) theory, i.e., the use of differential equations, and, respectively, the theory of heredity, because today, these two research directions or theories complement and intertwine [44, 45, 46].

 vol. 29, issue 3 / 2023
pp. 26-43

Researchers in the field of rheology specify that the deformation of material systems up to the level determined by the stress can be reproduced by the integral operators made explicit by means of creep kernels, given by different types of functions [7], [42], [44, 45, 46]. In the case of rocks, and implicitly also of salt, the same specialised literature states that the most appropriate types of kernels are ABEL's kernel and ROZOVSKI's kernel, respectively. However, in certain situations, as Toderaș (2015) mentions, salt seems to lose its memory.

- ABEL's kernel belongs to the fractional-exponential function and has the form:

$$L_A(t-\tau) = \delta\,(1-\tau)^{-\alpha} \tag{1}$$

Using this kernel involves replacing it with a creep function Φ_{Abel} established based on Abel's kernel. In the case of creep, we have:

$$\varepsilon(t) = \frac{\sigma}{E}\left(1+L_A\right) = \frac{\sigma}{E} \tag{2}$$

where: $L_A = L(t\,,\,\tau)$ as an integral operator of Volter type, and E is a time operator. Substituting the Abel kernel, we obtain the time function Φ_A of the elastic characteristics (E, Φ):

$$E_t = \frac{E}{1+\Phi_A} \quad ; \quad \mu_t = 0{,}5 - \frac{0{,}5-\mu}{t+\Phi_A} \tag{3}$$

where:

$$\Phi_A = \frac{\delta}{1-\alpha}\,t^{1-\alpha} \tag{4}$$

represents Abel's creep function or kernel, where δ and α are the creep parameters that do not have a well-defined physical meaning [7], and as a result, α is a dimensionless rheological parameter, while δ is considered to have a dimension $t^{\alpha-1}$.

- Rozovski's kernel considers the expression of Voltaire-Rabotnov and makes it explicit in the form:

$$\varepsilon(t) = \frac{f(\sigma)}{E}\left[1+\frac{\chi}{\beta-\chi}\left(1-e^{-(\beta-\chi)\gamma t^{1-\alpha}}\right)\right] \tag{5}$$

where:

$$L_{Rozov}(-\beta+\chi, t-\tau) = (t-\tau)^{\alpha}\sum\frac{\beta^n\,(t-\tau)^{n(1+\alpha)}}{\Gamma(n+1)\,(1+\alpha)} \tag{6}$$

where Γ(n) is gamma function.

Rozovski's kernel is given by the relationship:

$$L_{Rozov}(-\beta+\chi, t-\tau) = 1+\Phi_{Rozov} \tag{7}$$

where the Rozovski function Φ_{Rozov} has the form:

$$\Phi_{Rozov} = \frac{\chi}{\beta-\chi}\left[1-e^{-(\beta-\chi)\gamma t^{1-\alpha}}\right] \tag{8}$$

where: β, χ, γ and α are the experimentally determined creep parameters:

$$\begin{gathered}
\chi = \frac{a_2 b_2}{\gamma} \qquad \beta = \frac{\left(a_2+1\right)b_2}{\gamma} \qquad \chi = \frac{E_0-E_\infty}{E_0\,T_{rel}^{1-\alpha}} \\
a_2 = \frac{E\,\varepsilon_\infty - f(\sigma)}{f(\sigma)} \qquad b_2 = \frac{1}{\gamma\,t^{1-\alpha}}\times\frac{\varepsilon_\infty-\varepsilon(t)}{\varepsilon_\infty-\dfrac{f(\sigma)}{E}} \\
\beta = \frac{1}{T_{rel}^{1-\alpha}} \qquad \gamma = (1-\alpha)^{1-\alpha} \qquad \frac{\chi}{\beta} = \frac{E_0-E_\infty}{E_0}
\end{gathered} \tag{9}$$

2.4. Constitutive model of nonlinear creep

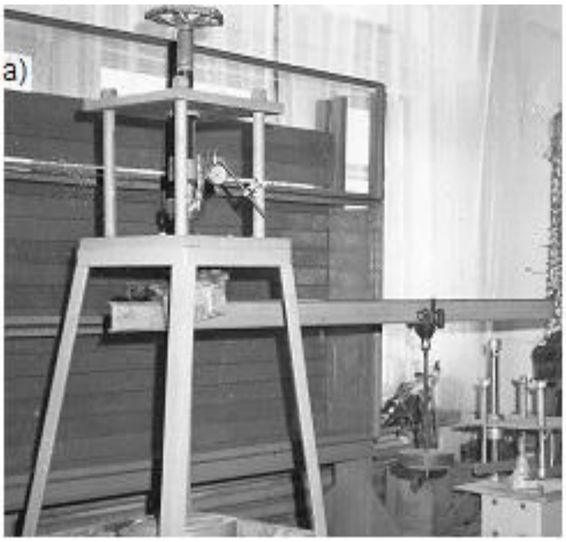
In the case of the traditional model of combining the basic elements, the parameters are all considered fixed constants. This leads to a weak correlation between the theoretical curve and the curve obtained based on the results of experimental tests. In fact, the rheological properties of rock are closely related to time, stress level, state of stress, and temperature [40], [41], [48, 49, 50]. It was pointed out that the strength, deformation, and rheological parameters of rock are clearly time-dependent, and rheological parameters such as elastic modulus (E), shear modulus (G), and viscosity coefficient (η) should be a function of time. Sun (2007) [51] considered that the creep strain of rock exhibits a non-linear increasing trend with increasing stress level, creep time, and stress-strain state.

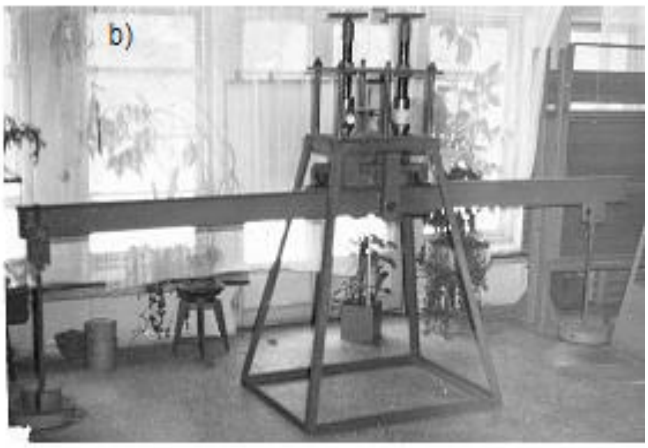
3. Quantitative parameters that define the rheological behaviour of rocks

The research of the deformation behaviour of rocks different in age, structure, and resistance under the action of long-term stresses currently constitutes a sinequanon condition for solving the problems of stability of mining constructions, problems that involve and demand knowledge of the theory, the laws of rheology, and the parameters of the rheological properties of rock massifs and which must be evaluated in a wide range of concrete problems of rock mechanics, implicitly of current mining. In the last period of time, the mining technical literature has given a series of works in which most of the problems related to the mining pressure, stability, and reliability of the mining works are recommended or even solved, taking into account the behaviour of the rocks over time [7], [42]. All these problems involve and demand a study, experimental determination, and interpretation of the rheological parameters of the rock massif, such as the deformation properties of the rocks, instantaneous or elastic deformation, the law of deformation and relaxation in time, the deformation in the stabilised domain, strain rate in the field of stabilised creep, viscosity coefficient value, rock yield strength, delay time, relaxation time, modulus of elasticity due to creep, and Poisson's ratio due to creep. Based on them, it must be possible to write the law or the equation of the rock creep and relaxation, to establish the long-term limit strength, the creep parameters and the creep coefficients that can explain the creep functions, as well as classify the rock from a rheological point of view, all of which find their applicability in solving different problems in the mining field. All these properties and parameters must be evaluated according to the recommendations given by the specialized literature.

4. Determining the rheological behaviour of salt from Slănic Prahova literature

The study of the rheological behaviour of the salt cores obtained from the boreholes extracted from Slănic Prahova deposit, P1-P11 and B1-B13, was carried out in the laboratory through uniaxial compression tests, which also offer the greatest possibilities for making the necessary equipment for testing. The compression creep test was carried out at the existing testing devices in the Rheology Laboratory of the University of Petroşani, equipment that works on the principle of levers (Figure 7).





 vol. 29, issue 3 / 2023
pp. 26-43

Figure 7. Testing device: Mechanical installation for compression creep tests: a) with a single arm; b) with two arms

The deformation measuring device actually used in solving the problem addressed was of a mechanical type, consisting of eight measuring devices: four to measure axial deformations with a precision of 0.01 and four for transversal deformations with a precision of 0.001 mm (Figure 8).

Figure 8. Deformations measuring device

During the uniaxial compression creep test, the following stages were completed: (1) geological characterization and establishment of the main physical properties of the analysed rock type; (2) determination of the uniaxial compression strength σ_{rc}; (3) determining the main momentary deformation parameters of the respective rock (characteristic curve σ - ε, dilatancy, modulus of elasticity, deformation modulus, Poisson's ratio, etc.); (4) depending on the breaking strength in uniaxial compression, the choice of the instantaneous deformation behaviour, and the degrees of load over time (Δ_i); (5) establishing the requested number of samples that must be tested for creep in order to obtain the most correct results; (6) wax removal of the sample bases (the side faces are kept waxed to prevent changes in humidity during the tests); (7) prior checking of creep equipment; (8) after measuring the dimensions, mount the samples in the shortening and lengthening measuring devices; (9) placement of the sample-measuring device system in the testing installations; (10) recording the initial readings of the transverse and longitudinal measuring devices; (11) creating the proposed stress load, keeping it constant, and measuring the instantaneous shortenings and lengthening at time $t = t_0 = 0$; (12) monitoring and periodically noting the deformation of the specimen in the test sheet over time; (13) the stage of processing the data obtained from the test.

To obtain data comparable to the compressive strength limit, modulus of elasticity, etc., and rheological parameters, samples of the same shape with a corresponding slenderness coefficient (λ) were used. Within the test methodology, the specialised literature recommends degrees of load $\Delta_i = (0.2 \div 0.95)\sigma_{rc}$ depending on the nature of the rock, and for rocks with $\sigma_{rc} \geq 40$ MPa additional load degrees: 0.93–0.77. The measurements were made with respect to the time intervals in relation to the mode and intensity of the development of the deformations. The results of creep tests at stress levels of $0.6\sigma_{rc}$ are used to establish the laws of time-stabilised deformation and the computation of the creep parameters. The results obtained for stress degrees greater than $0.6\sigma_{rc}$ are used to establish the dependence between the stress state and time before failure by plotting the long-term limit strength curves σ_{lld}. The creep curves, the isochronous curves, those of the deformation rates, etc., were drawn in order to establish the links that exist between the creep parameters and σ_{lld}. We must specify here the fact that the study of the rheological properties of rocks in the laboratory has its peculiarities related to a limited volume of samples, and, of course, these tests are very time-consuming.

5. Results and discussion

We will further present the experimental and analytical results obtained over a period of 5 months in order to establish the rheological properties of the main categories of salt from the B1-B13 and P1-P11 wells. In order to be able to analyse the rheological behaviour and determine the rheological parameters of the salt, we made a classification of the types of salt encountered in the extracted boreholes. The classification was carried out by salt categories, and within each category, a grouping was carried out according to the breaking strength in uniaxial compression [52].

Analysed on a macroscopic scale through the prism of components and structure, it was found that different varieties of salt were found along the boreholes, from pure white salt with variable grain size to salt with white-grey or grey-white impurities, saccharide with small, medium, or large grain, with or without the presence of phenocrysts, up to varieties of banded salt, some of these varieties appearing in a more compact or less compact form. Taking into account the range of variation of the compressive strength determined in the Rock Mechanics Laboratory of the University of Petroșani, on the extracted cores found in the B1-B13 and P1-P11 boreholes, uniaxial compression creep tests were performed on the salt varieties according to Table 1. The choice of these varieties of salt was made so that the entire range of values obtained for the uniaxial compressive strength could be covered.

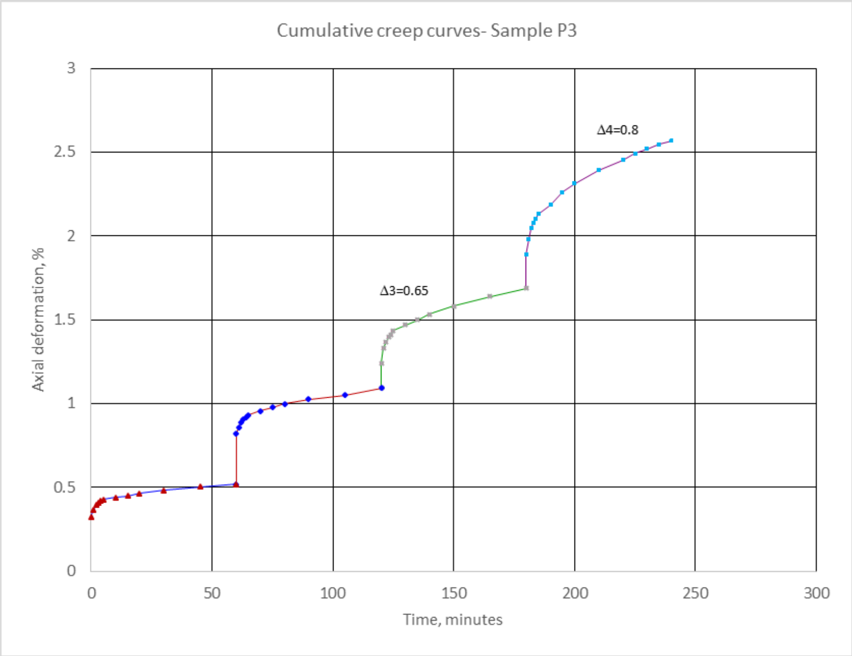
Table 1. Rheological analysed varieties of salt

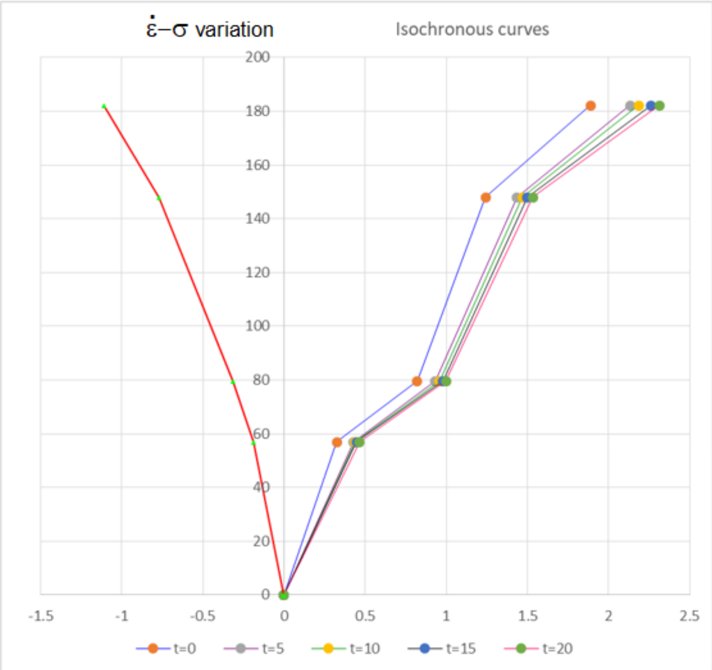
No	Variety of salt	Drilling	Mean uniaxial compressive strength, MPa
1	Rock salt with impurities, grey colour, saccharide, and medium grain size	P1	19.96
2	Rock salt with impurities, grey-white colour, saccharide, medium grain	P3	22.76
3	Rock salt with impurities, grey-white colour, saccharide, medium grain size	P4	25.05
4	Rock salt with impurities, grey colour, saccharide, medium grain	B3	14.7

The results of the uniaxial compression creep tests are shown below on each salt specimen (Figures 9–12). Three long-term creep tests were carried out for the samples from boreholes P1, P4, and B3, and for borehole sample P3, a short-term creep test was carried out. Following the procedure for computing the rheological coefficients presented in sections 2 and 3, their centralised values are shown in table 2.

Figure 9. Salt samples from the experimentally analysed varieties

vol. 29, issue 3 / 2023
pp. 26-43





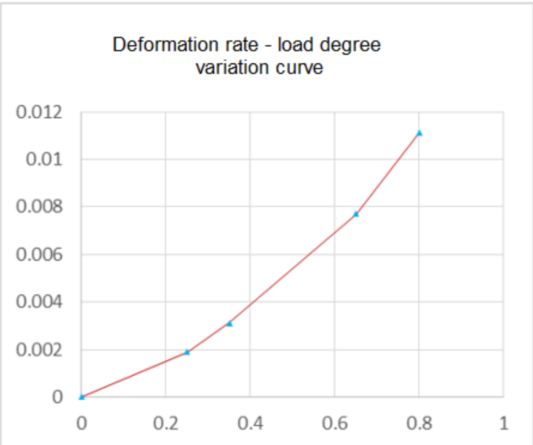


Figure 10. Characteristic rheological curves: drilling sample P3

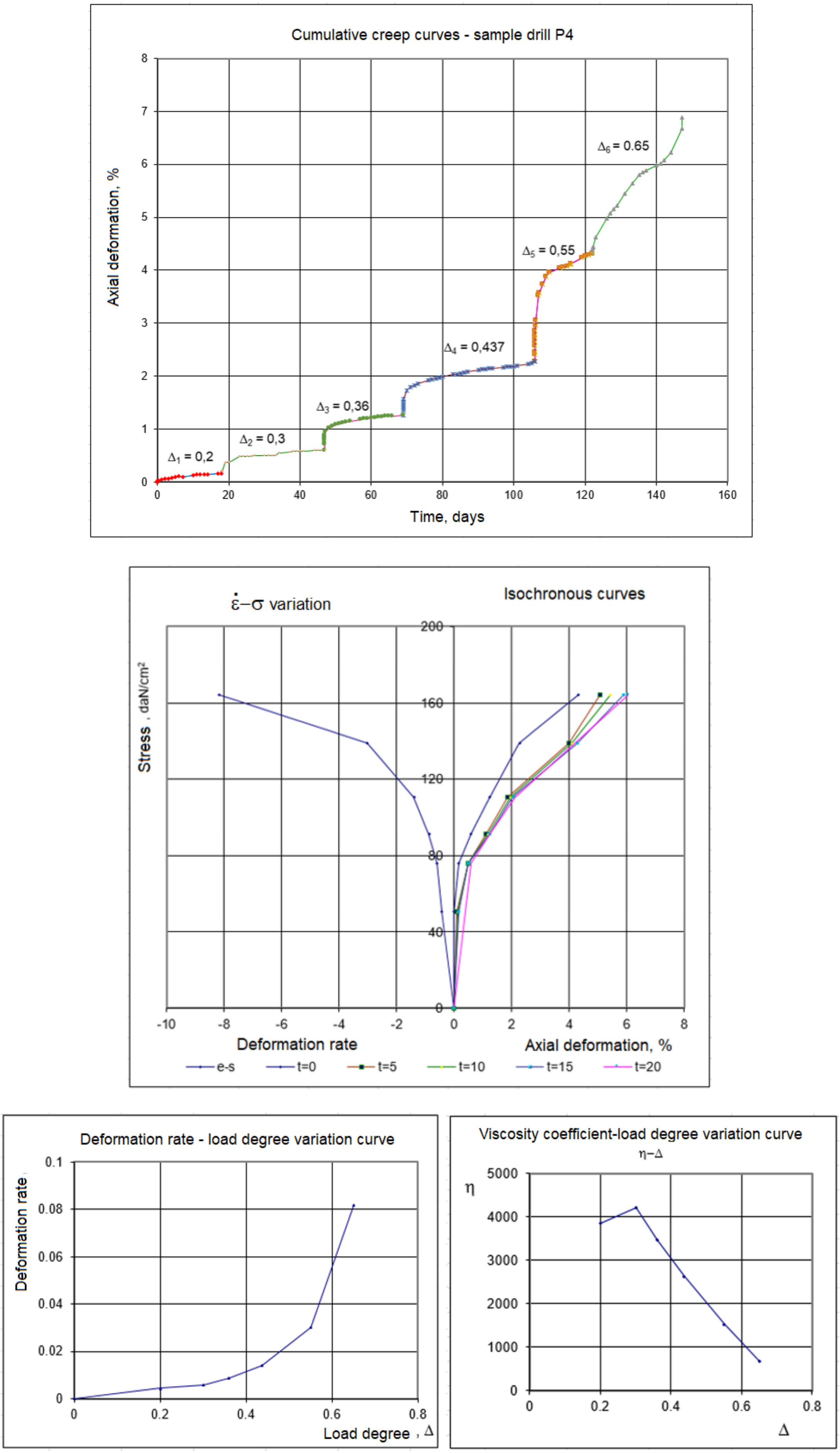


Figure 11. Characteristic rheological curves: drilling sample P4

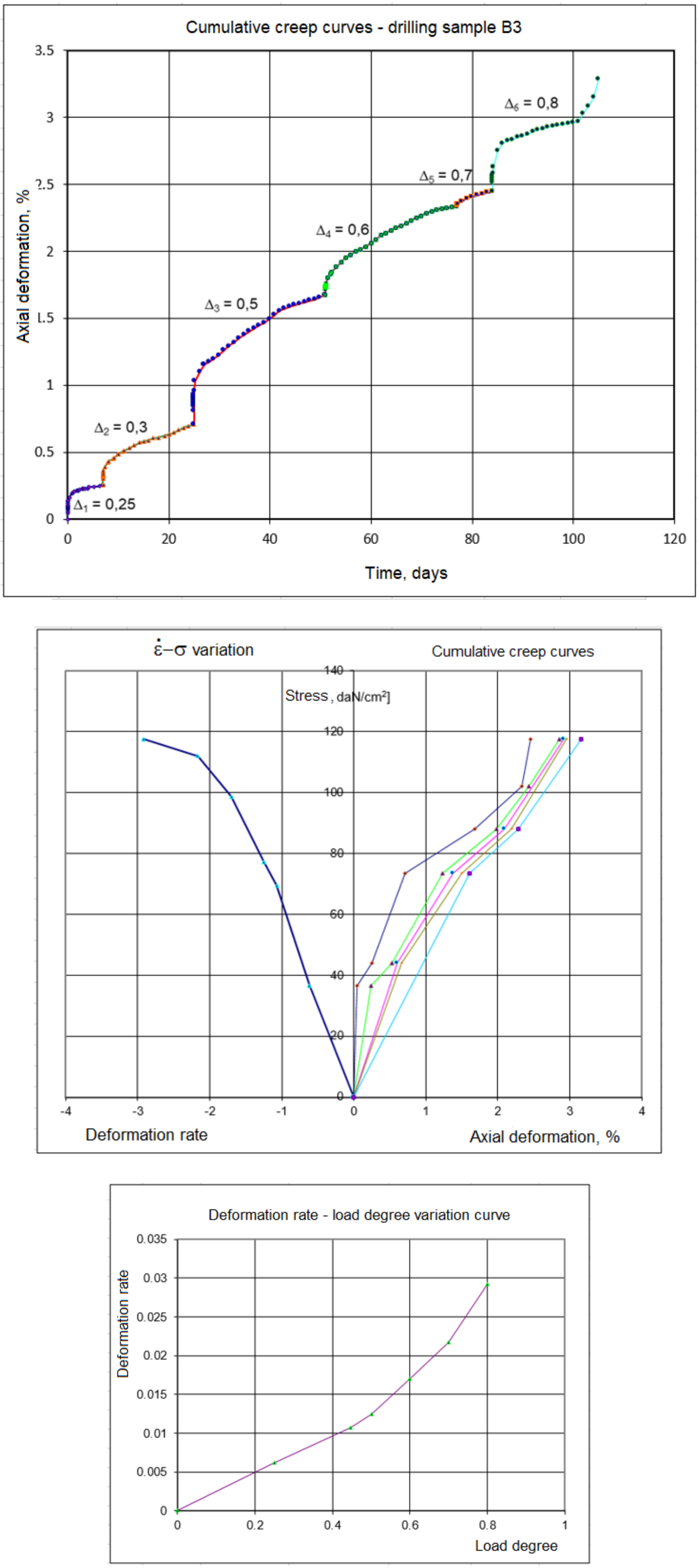


Figure 12. Characteristic rheological curves: drilling sample B3

 vol. 29, issue 3 / 2023
pp. 26-43

Table 2. The values of the rheological coefficients on the varieties of salt analysed

Drilling sample	Rheological coefficients				Creep coefficient, C_F	Deformation at the elastic limit, %	Long-term limit strength, σ_{lld}, MPa	Stability field
	γ	α	β	χ				
P1	0.695651	0.57	0.26834	0.16588	0.61816	0,016524	12.35617	0.2-0.3
P3	0.719779	0.45	0.53847	0.32931	0.611574	0.017246	14.18615	
P4	0.692259	0.64	0.37307	0.22714	0.608833	0,019172	15.66898	
B3	0.701271	0.53	0.3879	0.25254	0.651044	0,014619	8.683657	

From the analytical calculations, it results in a stability time between 7 and 11 years in certain situations, which can reach 15 years, after which the salt enters the field of medium instability with a fairly rapid transition to instability.

6. Conclusions

From the analysis of the rheological behaviour of the salt extracted from boreholes P1-P11 and B1-B13 from Slănic Prahova, the following conclusions can be stated:

1. The instantaneous strain, creep strain, and constant creep rate of salt increase with increasing axial load. The relationship between the constant creep rate of the salt and the axial stress can be described by an exponential-type function and a power-type function. The creep behaviour of salt is particularly related to the state of stress, and we can state that it is independent of the loading path.

2. The rheological properties of impurities in salt are different from those of pure salt grains. The existence of impurities in the salt mass can effectively limit its overall deformation capacity. Therefore, the rheological behaviour of the salt obviously improves with increasing NaCl content. Due to the influence of the geological environment, the more microscopic-scale defects and the more irregular the boundaries between salt grains, the more the salt grains will have the opportunity to interact with each other. This can obviously lead to the phenomenon of strain hardening during the creep process, i.e., the hardening phenomenon.

3. Due to the differences in creep properties between the salt mass and the interlayers or sterile intercalations, the creep deformation of the pure salt mass and interlayers (intercalations) is uncoordinated, leading to the generation of additional stress at the interfaces of the two materials. Only when the additional strength exceeds the stress on the contact planes does creep failure of the salt occur.

4. The creep process of rock salt is very complicated, being mainly governed by dislocation, diffusion, and polygonization mechanisms. The creep process of rock salt can be controlled individually by one mechanism under certain specific conditions, while it is controlled by several mechanisms in parallel in most cases.

5. As for the creep constitutive model, the empirical model can better describe the creep behaviour of rock salt, but the model parameters lack physical meaning, as we specified in the chapter dedicated to the rheological characteristics. The basic elements in the component combination model and the fractional derivatives model—models based on heredity theory—are all linear, and no matter how we try to combine them, the final models established still cannot accurately reflect the non-linear creep behaviour of salt.

6. From the uniaxial compression creep tests of the salt samples, a creep coefficient was found in the range 0.608833–0.651044, with higher values of this parameter for the salt varieties having lower uniaxial compression breakage strengths, which confirms the trend accentuated by the creep of the salt from Slănic Prahova.

7. The long-term limit strength obtained from tests under constant compressive load was found to be included in the range of variation from 8.7 MPa to 15.7 MPa, with an average value of 13.52 MPa.

8. From the results of uniaxial compression creep tests carried out in the laboratory on the samples extracted from the boreholes provided, it turned out that the salt falls into creep category V, i.e., pronounced creep, and the creep behaviour under constant load can be classified in the group of II rheological. After exceeding a degree of stress of 0.28–0.3, in time, the deformations tend to an oblique asymptote.

9. The dilatancy threshold of the salt from Slănic Prahova, for the areas where the cores were extracted from the boreholes, varies from 5.212 MPa to 14.62 MPa. This verifies the statement that salt is a material system that exhibits dilatancy (dilatancy also being a rheological process).

10. The isochronous stress-strain curves gradually deviate towards the strain axis, indicating that the modulus of elasticity (E) of the salt gradually decreases with increasing stress level and creep time. The creep behaviour of these varieties of salt falls into the category of an elastic-viscous-plastic behaviour, which can be described by a complex model corresponding to the 2nd rheological group, a model that can be derived from the Burgers model.

References

[1] **Mottahed, P. & Szeki, A.** 1982
The Collapse of Room and Pillar Workings in a Shaley Gypsum Mine Due to Dynamic Loading. Symp. on Strata Mech. Newcastle. pp. 260–264.

[2] **Doktan, M.** 1983
The Long-Term Stability of Room and Pillar Workings in a Gypsum Mine. PhD Thesis. Newcastle Upon Tyne, Newcastle University

[3] **Jaeger, J.C. & Cook, N.G.W.** 1979
Fundamentals of Rock Mechanics. 3rd edition. London, Chapman & Hall. p. 79, 311.

[4] **Cristescu, N.D. & Hunsche, U.** 1998
Time Effects in Rock Mechanics. New York, NY, John Wiley and Sons. 343 pp.

[5] **Wawersik,W.R.** 1983
Determination of Steady State Creep Rates and Activation Parameters for Rock Salt. In: High Pressure Testing of Rock. Special Technical Publication of ASTM, STP869. pp. 72–91.

[6] **Hunsche, U.** 1992
True Triaxial Failure Tests on Cubic Rock Salt Samples – Experimental Methods and Results. In: Proceedings of the IUTAM Symposium on Finite Inelastic Deformations – Theory and Applications. Hannover, Springer Verlag. pp. 525–538.

[7] **Toderaș, M.** 2015
Rocks Rheology in the Stability of Underground Mining Works. Case Study: 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.

[8] **Zhang, H., Wang, Z., Zheng, Y., Duan, P. and Ding, S.** 2012
Study on Tri-Axial Creep Experiment and Constitutive Relation of Different Rock Salt. Safety Science, vol. 50, no. 4, pp. 801–805.

[9] **Zhang, G., Wu, Y., Wang, L., Zhang, K., Daemen, J. J. K. and Liu, W.** 2015
Time-Dependent Subsidence Prediction Model and Influence Factor Analysis for Underground Gas Storages in Bedded Salt Formations. Engineering Geology, vol. 187, pp. 156–169.

[10] **Chu, Z. Wu, Z., Liu, Q., Liu, B. and Sun, J.** 2021
Analytical Solution for Lined Circular Tunnels in Deep Viscoelastic Burgers Rock Considering the Longitudinal Discontinuous Excavation and Sequential Installation of Liners. Journal of Engineering Mechanics, vol. 147, no. 4, Article ID 04021009.

[11] **Xi, B. P., Zhao, Y. S., Zhao, J. C. and Xu, S. G.** 2008
Study on Coupled Thermo-Mechanical Creep Properties of Bedded Rock Salt. Chinese Journal of Rock Mechanics and Engineering, vol. 27, no. 1, pp. 90–96, 2008.

[12] **Yang, C., Daemen, J. J. K. and Yin, J.-H.** 1999)
Experimental Investigation of Creep Behaviour of Salt Rock. International Journal of Rock Mechanics and Mining Sciences, vol. 36, no. 2, pp. 233–242, 1999.

[13] **Ma, L. J., Xu, H. F., Wang, M. Y. and Li, E. B.** 2015
Numerical Study of Gas Storage Stability in Bedded Rock Salt During the Complete Process of Operating Pressure Runaway. Chinese Journal of Rock Mechanics and Engineering, vol. 34, no. S2, pp. 4108–4115.

[14] **Zhou, Z. W., Liu, J. F., Wu, F. et al**. 2016
Experimental Study on Creep Properties of Salt Rock and Mudstone from Bedded Salt Rock Gas Storage. Journal of Sichuan University (Engineering Science Edition), vol. 48, no. S1, pp. 100–106.

[15] **Tang, M. M., Wang, Z. Y., Ding, G. S. and Ran, Z. N.** 2010
Creep Property Experiment and Constitutive Relation of Salt-Mudstone Interlayer. Journal of China Coal Society, vol. 35, no. 1, pp. 42–45.

[16] **Wang, A. M., Li, X. G., Yang, C. H. and Huang, Z. Q.** 2010
Study of Interaction Between Creep Deformation of Bedded Salt Rock. Rock and Soil Mechanics, vol. 31, no. 12, pp. 3964–3970.

[17] **Zhao,** Y**. L., Zhang, Y. and Wan, W.** 2010
Mechanical Properties of Bedded Rock Salt and Creep Failure Model. Mineral Engineering Research, vol. 25, no. 1, pp. 16–20.

[18] **Xing, W. Zhao, J., Düsterloh, U. et al.** 2014
Experimental Study of Mechanical and Hydraulic Properties of Bedded Rock Salt from the Jintan Location, Acta Geotechnica, vol. 9, no. 1, pp. 145–151.

[19] **Pouya, A.** 2000
Micro-Macro Approach for the Rock Salt Behaviour. European Journal of Mechanics-A/Solids, vol. 19, no. 6, pp. 1015–1028.

[20] **Huang, X. L., Yang, C. H. and Li, Y. P.** 2014
Interface Shear Stress Distribution of Bedded Salt Rock Considering Rheology Effect. Chinese Journal Underground Space Engineering, vol. 10, no. 3, pp. 547–551.

[21] **Ashby, M. F.** 1972
A First Report on Deformation-Mechanism Maps. Acta Metallurgica, vol. 20, no. 7, pp. 887–897.

[22] **Mortazavi, A., Nasab, H.** 2017
Analysis of the Behaviour of Large Underground Oil Storage Caverns in Salt Rock. International Journal for Numerical and Analytical Methods in Geomechanics, vol. 41, no. 4, pp. 602–624.

[23] **Firme, P.A.L.P., Roehl, D., Romanel, C. and Romanel, C.** 2016
An Assessment of the Creep Behaviour of Brazilian Salt Rocks Using the Multi-Mechanism Deformation Model. Acta Geotechnica, vol. 11, no. 6, pp. 1445–1463.

[24] **Munson, D. E., Devries, K. L., Fossum, A. F. and Callahan, G. D.** 1993
Extension of the M-D Model for Treating Stress Drops in Salt. In Proceedings of the 3rd Conference on the Mechanical Behaviour of Salt, H. R. Hardy Jr. and N. larger, Eds., pp. 31–44, Translation Technique Publication, Palaiseau, France, September 1993.

[25] **Horseman, S. T. and McEwen, T. J.** 1996
Thermal Constraints on Disposal of Heat-Emitting Waste in Argillaceous Rocks. Engineering Geology, vol. 41, no. 1–4, pp. 5–16, 1996.

[26] **Carter, N. L., Horseman, S. T., Russell, J. E. and Handin, L.** 1993
Rheology of Rocksalt. Journal of Structure Geology, vol. 15, no. 9-10, pp. 1257–1271.

[27] **Spiers, C. J. and Carter, N. L.** 1998
Microphysics of Rocksalt Flow in Nature. In Proceedings of the 4th conference the mechanical behaviour of salt. Transport Technical Publication, Series on Rock and Soil Mechanics, M. Aubertin and H. R. Hardy, Eds., vol. 22, pp. 115–128, Montreal, Canada.

[28] **Muhammad, N., Spiers, C. J., Peach, C. J. and H. de Bresser,** 2012
Effect of Confining Pressure on Plastic Flow of Salt at 125°C, CRC Press, London, UK.

[29] **Zhou, H. W., Wang, C. P., Mishnaevsky, L., Duan, Z. Q. and Ding, J. Y.** 2013
A Fractional Derivative Approach to Full Creep Regions in Salt Rock. Mechanics of Time-dependent Materials, vol. 17, no. 3, pp. 412–425.

[30] **Cristescu, N. D.** 1993
A General Constitutive Equation for Transient and Stationary Creep of Rock Salt. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, vol. 30, no. 2, pp. 125–140.

[31] **Wang, J. B., Liu, X. R., Huang, M. and Liu, X. J.** 2013
A Bon-Stationary Viscoelasto-Plastic Creep Model for Salt Rock. Disaster Advances, vol. 6, pp. 9–101.

[32] **Cao, W. G., Chen, K., Tan, X. and Chen, H.** 2020
A Novel Damage-Based Creep Model Considering the Complete Creep Process and Multiple Stress Levels. Computer and Geotechnics, vol. 124, Article ID 103599.

[33] **Jin, J. and Cristescu, N. D.** 1998
An Elastic/Viscoplastic Model for Transient Creep of Rock Salt. International Journal of Plasticity, vol. 14, no. 1–3, pp. 85–107.

[34] **Griggs, D.** 1939
Creep of Rocks. The Journal of Geology, vol. 47, no. 3, pp. 225–251.

[35] **Hou, Z.** 2003
Mechanical and Hydraulic Behaviour of Rock Salt in the Excavation Disturbed Zone around Underground Facilities. International Journal of Rock Mechanics and Mining Sciences, vol. 40, no. 5, pp. 725–738.

[36] **Hansen, F. D.** 1977
Case History Rock Mechanics Examination of the Jefferson Island Salt Mine: II. Laboratory Evaluation of Strength and Creep Deformation Characteristics of Dome Salt under Confining Pressure, Office of Waste Isolation, Rapid City, SD, USA, 1977.

vol. 29, issue 3 / 2023
pp. 26-43

[37] **Wang, R., Jiang, Y., Yang, C., Huang, F. and Wang, Y.** 2018
A Nonlinear Creep Damage Model of Layered Rock under Unloading Condition. Mathematical Problems in Engineering, vol. 2018, Article ID 8294390, pp. 1–8.

[38] **Mansouri, H. and Ajalloeian, R.** 2018
Mechanical Behaviour of Salt Rock under Uniaxial Compression and Creep Tests. International Journal of Rock Mechanics and Mining Sciences, vol. 110, pp. 19–27.

[39] **Singh, A., Kumar, C., Kannan, L. G., Rao, K. S. and Ayothiraman, R.** 2018
Estimation of Creep Parameters of Rock Salt from Uniaxial Compression Tests. International Journal of Rock Mechanics and Mining Sciences, vol. 107, pp. 243–248.

[40] **Wang, J. B., Liu, X. R., Huang, M. and Yang, X.** 2014
Analysis of Axial Creep Properties of Salt Rock under Low Frequency Cyclic Loading Using Burgers Model. Rock and Soil Mechanics, vol. 35, no. 4, pp. 933–942.

[41] **Wang, J. B., Liu, X. R., Guo, J. Q. and Huang, M.** 2014
Creep Properties of Salt Rock and Its Nonlinear Constitutive Model. Journal of China Coal Society, vol. 39, no. 3, pp. 445–451.

[42] **Toderaş, M.** 1999
Cercetări referitoare la caracterizarea comportamentului reologic al rocilor din bazinul Valea Jiului şi implicaţiile acestuia în asigurarea stabilităţii lucrărilor miniere orizontale principale, Doctoral thesis, University of Petroşani.

[43] **Xu, S. G., Liang, W. G., Xi, B. P. and Zhao, Y. L.** 2008
Study on Creep Property of Glauberite Salt Rock. Chinese Journal of Rock Mechanics and Engineering, vol. 27, no. S2, pp. 3516–3520.

[44] **Chen, H. J., Xu, W. Y., Wang, W., Wang, R. B. and Shi, C.** 2013
A Nonlinear Viscoelastic-Plastic Rheological Model for Rocks Based on Fractional Derivative Theory. International Journal of Modern Physics *B*, vol. 27, no. 25, Article ID 1350149, 2013.

[45] **Ping, C., Wen, Y. D., Wang, Y. X., Yuan, H. P. and Yuan, B. X.** 2016
Study on Nonlinear Damage Creep Constitutive Model for High-Stress Soft Rock. Environmental Earth Sciences, vol. 75, no. 10, Article ID 900.

[46] **Peng, G., Chen, Z. Q. and Chen, J. R.** 2018
Research on Rock Creep Characteristics Based on the Fractional Calculus Meshless Method. Advances in Civil Engineering, vol. 2018, Article ID 1472840, 6 pages.

[47] **Zhang, S. G. and Liu, W. B.** 2019
The 3D Non-stationary Creep Constitutive Model of Sandstone Based on Fractional Order. Mathematical Problems in Engineering, vol. 2019, Article ID 6031842, 12 pages.

[48] **Lv, X. Q.** 1987
The Creep Calculation Method of Variable Parameters on Rock Mass Engineering. Journal of Wuhan University of Technology, vol. 2, pp. 201–207.

[49] **Yang, S.-Q. and Cheng, L.** 2011
Non-Stationary and Nonlinear Visco-Elastic Shear Creep Model for Shale. International Journal of Rock Mechanics and Mining Sciences, vol. 48, no. 6, pp. 1011–1020.

[50] **Chen, W. L., Zhao, F. S. and Gong, H. J.** 2011
Study of Creep Parameters of Mica-Quartzose Schist during Triaxial Creep Test. Chinese Journal of Rock Mechanics and Engineering, vol. 30, no. S1, pp. 2810–2816.

[51] **Sun, J.** 2007
Rock Rheological Mechanics and Its Advance in Engineering Applications. Chinese Journal of Rock Mechanics and Engineering, vol. 26, no. 6, pp. 1081–1106, 2007.

[52] **Danciu, C., Toderas, M., Marian, D., Onica, I. et al.** 2022-2023
Studiul geotehnic – determinarea parametrilor fizico-mecanici și reologici în orizontul XIV al Minei Cantacuzino, în vederea estimării gradului de stabilitate a acestuia. Services contract no. 89/13.07.2022, with SNS Bucharest.