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Correlation between mechanical behaviour and petrological properties of rock salt

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ABSTRACT: 34 samples taken from cores coming from the Bresse Site (France) were tested by uniaxial compressive creep. An average creep law was formulated using a statistical analysis of the test data. The scattering of the experimental data around this average law was important, diminishing to a great extent its relevance. This led us to search for the origin of this scattering. The classification of the samples following their creep aptitude, namely, their measured creep compared to the average value, revealed a correlation between this aptitude and some petrological characteristics of the samples. Two different petrological varieties of rock salt, the "milky" and the "phenoblastic" varieties, exhibiting different mechanical behaviour were identified and their different creep aptitude was demonstrated by some new tests.

1 INTRODUCTION

The increasing interest of the mechanical behaviour of Rock Salt applied to the underground structures design (for gas and hydrocarbures storage or nuclear disposal and chemical wastes repository) led the "Laboratoire de Mecanique des Solides" and the "Groupement pour l'Etude des Structures Souterraines de Stockage" of Ecole Polytechnique to perform experimental and theoretical studies on this rock. A great part of these studies has concerned the long term creep properties.

The present study concerns samples taken from cores coming from the Bresse Site, where several underground gas storage caverns were leached during the recent twenty years. A potential site for nuclear waste repository is also located in Bresse Deposit.

In the framework of a rheological study, the great scattering of the Bresse salt experimental results led us to carry out a common work with geologists of "Museum National d'Histoire Naturelle" to examine whether this scattering could be related to some petrological differencies between samples.

2 DATA PRESENTATION AND PRIMARY ANALYSIS

Samples were tested by uniaxial compressive creep experiments. They had cylindrical form with ϕ=70mm and H=160 to 180mm. The compressive load σ and the temperature T were kept constant during the tests (some tests included several steps with different σ or different T, but for theses tests in the present study we considered only their first step). The duration of each test was between 250 and 3000 hours and the whole tests lasted 24000 h (3 years). The test temperature T varied between 20 and 200 °C and the compresive load σ , between 2.5 and 20 MPa.

A phenomenological creep law was searched for having the form:

$$\epsilon^{vp}(t) = B\,(1 - e^{-\beta t}) + C\,t \qquad (1)$$

where B,C and β are constants depending on σ and T for each test.

The first term in second member of (1) represents a transient creep (decreasing rate) and the second one, a stationnary creep. The considered law is one of the most usual laws used for the rock salt creep modeling.

B,C and β are calculated by means of the least square method for each individual test. Preliminary studies showed that their values are function of the test duration. This fact confirms Mrugala and Hardy's (1984) observations. That's the B,C and β values calculated taking into account the whole test duration data, differ from those calculated taking into account only a part (corresponding for exemple to the first 300 hours) of data. However, the variation is very slow and can be neglected for the durations greater than 750 h (POUYA 1989). Therefore, the further analysis were carried out on the 750 first hours of the tests, and the tests with a shorter duration were not considered in the analysis. The analised tests were 30 .

B and C values of the individual tests were approximated by the following functions of T and σ :

$$B(\sigma,T) = b\,\sigma^m\,e^{\frac{-K_p}{T}}$$

$$C(\sigma,T) = c\,\sigma^n\,e^{\frac{-K_s}{T}}$$

The constants of these expressions were calculated by the least squares method and the following values were found:

$b = 0.77 \quad m = 3.9 \quad K_p = 4800$ K

$c = 9.9\ 10^{-3}\ h^{-1}$

$c = 9.9\ 10^{-3}\ h^{-1} \quad n = 3.1 \quad K_s = 4100$ K

stress σ : MPa , temperature T : K , time t : hour

The β value was slightly temperature dependent, but because of its weak influence on the creep curve, it was supposed to be constant and equal to the average value of 0.01 h^{-1} .

3 CLASSIFICATION OF THE SAMPLES

A great scattering was observed when the experimental creep curves were compared to the theoretical plot s (predicted by the average law). The ratio between the mesured and the theoretical creep after 750 h varied between 0.3 and 2 .

We thought of classifying the samples according to some variable wich could represent the "creep aptitude" of the samples. This variable must traduce the ratio between the mesured and the average values of some physical quantity related to the creep. The creep strain or the strain rate at the end of the tests could be adopted for this purpose. But some considerations, in particular the local fluctuations of these two variables, led us to search for a more global quantity. Finally the surface under the creep curve "S" was adopted. This variable is not an intrinsic physical quantity, but is easy to use, and we think that replacing it by another "more intrinsic" quantity , will not change the results of this work.

The mesured values for S (deduced from the experimental curves) are presented in the last column of the table 1. "Creep aptitude" (CA) is the ratio between these values and those predicted by the average law. This ratio allows to compare together samples having been tested in different conditions.

The statistical analysis did not show any significant correlation between the CA and the acoustic velocity but a very weak correlation was found between it and the relative density of the samples.

The samples were classified in decreasing order of creep aptitude (First column of table 2). They were then arranged with respect to this classification (Fig. 1). This arrangement showed that samples with similar petrological aspect had some tendancy to be gathered together. At the extremities of high or low creep aptitude were grouped samples with similar petrographical aspects.

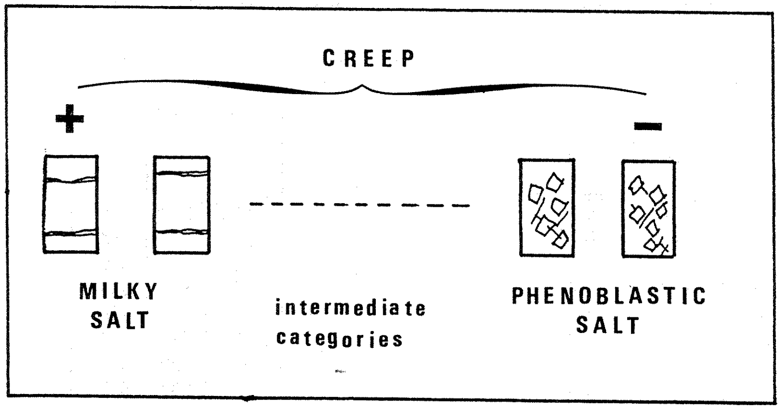

Figure 1 : Arrangement of the samples according to their creep aptitude

Samples with the highest CA belonged to a variety of salt with very low concentration of insoluble impurity, but very rich in brine inclusions wich confer a "milky" aspect to this salt. This variety of salt was called "milky" by geologists MORETTO & CURIAL (1988).

On the other extremity one could observe samples with a high impurity concentration. They belonged to a variety of salt formed by limpid halite crystals embeded in an "argilo-carbonate" matrix and called "phenoblastic" by the same authors.

But this tendency of being grouped according to their petrological aspect was not strictly respected by all the samples and was only a very diffuse and general tendency. Some exceptions were observed. They could be justified by:

a) The classification was not absolutely "intrinsic" because it was based on a phenomenological law and was affected by the errors or imprecisions of this law. Could another creep law lead to a significantly different classification?

b) Only a few samples could be classified into "milky" and "phenoblastic" salt. Most of the samples belonged to intermediate categories. In these categories, it is possible that the influence of factors other than visible petrological aspect became predominant and disturb the classification.

These two possible justifications were examined by the following studies.

4 OTHER CLASSIFICATIONS

The previous classification was based on the comparison of the measured creep at some (σ , T) conditions to the creep calculated by the average law at the same conditions. This average law overestimates certainly the B and C measured values for some (σ , T) conditions and underestimates them for other conditions. Therefore, the samples tested for exemple at a temperature where the average law overestimates the experimental values have tendency to be classified among the low creep aptitude samples independently of their petrological characteristics.

Table 1 : Description of samples, experimental conditions and mesured values of S. * The sample was excluded from the statistical analysis.

Sample N°	Creep Temp. (K)	Creep stress (MPa)	Measured S (h)
S1	20	9.0	0.67
S2	20	9.0	0.66
S3	20	10.4	1.10
S4	20	12.8	1.43
S5	20	15.3	8.81
S6	20	17.5	6.22
S7	20	17.8	16.73
S8	75	5.0	0.56
S9	75	10.0	4.49
S10	100	5.0	0.85
S11	100	7.5	2.06
S12	100	8.0	3.02
S13*	100	11.0	-----
S14	100	11.3	15.50
S15	100	11.5	20.98
S16	100	15.3	26.08
S17	150	2.5	0.93
S18	150	4.8	12.82
S19	150	7.5	30.57
S20	150	10.0	82.17
S21	175	4.8	4.05
S22	200	2.5	2.61
S23	200	3.4	6.68
S24	200	4.4	31.21
S25	200	5.0	50.64
S26	200	7.5	82.56
S27*	20	13.5	-----
S28*	20	20.0	-----
S29	20	2.5	0.43
S30	150	8.0	3.23
S31*	175	5.0	-----
S32	100	5.0	1.08
S33	200	3.0	5.29
S34	200	2.5	1.08

Table 2 : Classification of the samples in the decreasing creep aptitude order.

Order N°	1st Law	2nd Law	3rd Law
1	S25	S18	S25
2	S29	S29	S18
3	S18	S25	S29
4	S24	S19	S24
5	S33	S17	S22
6	S22	S24	S17
7	S 3	S20	S33
8	S17	S32	S23
9	S19	S15	S 3
10	S26	S 7	S 7
11	S 7	S 5	S19
12	S 5	S 3	S 5
13	S23	S33	S26
14	S20	S22	S 6
15	S 6	S 8	S 2
16	S 4	S10	S20
17	S 2	S 6	S 1
18	S 1	S 9	S 4
19	S15	S 2	S 8
20	S 8	S23	S10
21	S32	S 1	S15
22	S34	S14	S34
23	S10	S 4	S 9
24	S 9	S12	S32
25	S14	S11	S14
26	S21	S26	S21
27	S12	S16	S11
28	S11	S21	S12
29	S16	S34	S16
30	S30	S30	S30
...	...	...	...
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The same remark is available for the strain dependency. The time expression (1) can also have some importance. Nevertheless some comparison with experimental data led us to admit that the strain expression σ^n adopted for the average law does not introduce significant perturbation in the classification. Therefore, we limited our study to the examination of the time and the temperature effects.

Two other classifications based on two phenomenological laws with different time and temperature expressions were studied.

4.1 Second creep law

Many studies of the creep of rock salt have shown that the Arrhenius expression for the temperature effect can not give a close approximation of the variation of the experimental data with respect to the temperature on the large intervals of variation of the temperature. The increasing of these data is quicker than what is given by the Arrhenius expression. Many authers have adopted other functions of T for this influence, particularly the sum of two Arrhenuis expressions (for exemple Langer 1981) or the product of an Arrhenius and a polynomial expressions of T (Tijani 1989).

The expression $e^{-K_1/(T-T_f)}$ where T_f is the melting point temperature of salt (1074 K) exhibits also a quicker increasing compared to the Arrhenius law for temperatures between 20 and 200 °C . So , whithout any pretention of physical signification, and considering it only as a phenomenological expression, one can adopt this relationship as an alternative to the Arrhenius one.

With this new expression the creep law was written:

$$\epsilon^{vp}(t) = b\,\sigma^m\, e^{-\frac{K_p}{T-T_f}} (1 - e^{-\beta t}) + c\,\sigma^n\, e^{-\frac{K_s}{T-T_f}}\, t$$

The parameters b,c, K_p,K_s, m, n and β of this law were identified by the same methods that for the first average law and from the same data. The following values were found:

$$\beta = 0.01\ h^{-1} \qquad m = 3.93 \qquad n = 3.07$$

$$K_p = 17200\ K \qquad K_s = 14100\ K \qquad T_f = 1074\ K$$

and : $b = 2.31\ 10^{-17}$, $c = 1.71\ 10^{-17}$
when σ is in MPa and T is in K and t in hour.

The classification according to this law (2nd law) is presented in the third column of the table 2 .

4.2 Third creep law

The Lemaitre-Menzel-Shreiner law is a time hardening law also very frequently used for the modelling of the salt creep. This law leads to the following unidimensionnal creep expression:

$$\epsilon^{vp}(t) = A\ t^{\alpha} \qquad (2)$$

when A can be approximated by: $A = a\,\sigma^n\, e^{-\frac{K_m}{T}}$.

The parameters a, K_m ,n and α were identified by the same methods and the same data used for the other laws. The following values were found:

$$m = 3.79 \quad K_m = 4540\ K \quad \alpha = 0.37$$

and a = 0.133 when σ is in MPa , T in K and t in hour.

The classificaton of the samples according to this third law is presented in the last column of the table 2.

4.3 Comparison between different classifications

The comparision of the three classifications showed that they were in a good agreement. In the first quarter of the very high creep aptitude (8 first samples of each colomn) 5 samples (S25,S29,S18,S24,S17) are the same in all the lists, and in the last quarter of the very low aptitude (8 last samples of each column), 5 samples (S21,S12,S11,S16,S30) are also the same in all the lists.

This demonstrates that even if the choice of the creep law has some effects on the classifications, nevertheless these classifications traduce essentially the samples properties. One can conclude that the correlation observed between the creep aptitude and the petrological characteristics of the samples is not due to the adopted creep law but to a real correlation between different properties of the samples.

5 THE TWO PETROLOGICAL FAMILIES

According to geologists the two extreme petrological families of salt in the Bresse Deposit are the followings:

- The "milky" variety , which is very rich in brine inclusions. This salt is formed by rather fine grains (2 to 10 mm diameter) and has a stratifed structure. Layers of 4 to 7 centimeters thick of milky halite are separated by very fine beds of argilo-carbonate impurities which are more frequently diffused in a region of one or two centimeters thick. This variety is very likely formed by salt settlement in the bottom of the lagoonar environments.

- The "phenoblastic" variety has a very different aspect. It is formed by limpid halite crystals, one to three centimeters diameter and frequently exhibiting a good cubic form, imbeded in a argilo-carbonate impurity matrix. This variety is rich in insoluble impurities and has in average a relative density greater than the first variety. The fine stratification is absent in this salt; a layer of phenoblastic salt can have up to one meter of thickness. This variety of salt is formed very likely by the solution of the primary salt (the first variety), because of a massive arrival of water rich in argilo-carbonate impurities, and the recrystalization of halite in the mixture of brine and mud.

The previous studies showed that the milky salt has a greater creep aptitude than the phenoblastic one. In order to confirm this result, without interference of any creep law, it was decided to test at some given experimental conditions some samples representing each variety and to compare directly their creep curves.

8 new samples were selected for this purpose. 3 of them (samples number 1,2 and 9 in

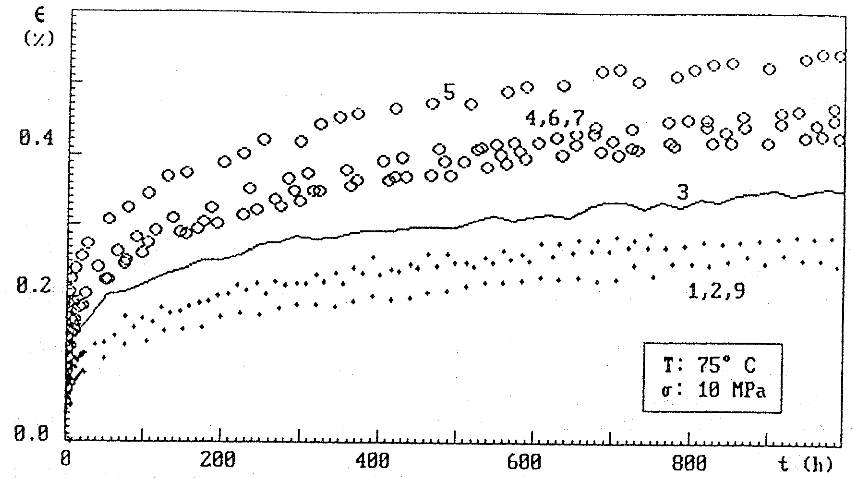

Figure 2 : Creep curves of some representatives of different varieties
Samples 1,2,9 : phenoblastical , 4,5,6,7 : milky , 3 : intermediate

the figure 2) belonged to the phenoblastic variety and 4 others (n° 4,5,6,7) to the milky one. The sample n° 3 was a relatively puresalt without insoluble impurities, like the milky salt, but it has not a well stratified structure and contained great limpid halite crystals. So, it represented some intermediate family of salt.

All these samples were submitted to uniaxial creep tests during one month (700 h) at T = 75 °C and σ = 10 MPa . The measured creep curves are presented in the figure 2. This figure shows clearly that the curves form groups according to their petrological families. The three curves of the phenoblastic family form the group of low creep and the four curves of the other family constitutethe group of high creep. The curve of the sample n° 3 has an intermediate position.

The milky salt exhibites after one month creep a strain two times greater than the phenoblastic one. The creep rate of the milky salt at the end of the tests was in average 1.5 time greater than the creep rate of the phenoblastic variety. These ratios may be, of cours, different at other (σ , T) conditions.

6 CONCLUSION

Bresse salt deposit consists of different petrological varieties. The different mechanical behaviour of these varieties explains a great part of the scattering of the experimental data.

If the distribution of different varieties in the vicinity of the underground structures in this deposit is known, one will be able to establish a more realistic "average" creep law taking into account this distribution and the creep aptitude of different varieties.

In the absence of this knowedge, the determination of the petrological varieties which have the extreme mechanical behaviours allows an experimental determination of the incertainities of the creep parameters (strain exponents, thermal activation energies, etc.). This determiniation will be very usefull for parametric studies such as the study presented by Nguyen Minh D. in this Symposium.

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