A METHODOLOGY FOR THE IDENTIFICATION OF ROCK SALT BEHAVIOR USING MULTI-STEPS CREEP TESTS

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SUMMARY

Within the research program, carried out with B.R.G.M and sponsored by E.E.C, aiming at a comparison between the mechanical properties of rock salt derived from in situ measurements and those derived from laboratory testing a series of triaxial multi-step creep tests has been carried out on Varangeville rock salt.

In order to identify a constitutive law for rock salt and to determine its parameter values, a new fitting method has been developed. The method's principle is based upon the formulation of the material strain hardening.

From this analysis we have derived that, for the studied rock salt, the usual power law doesn't represent accurately enough the influence of the stress on the hardening variable rate. On the other hand, the activation energy seems satisfactory to represent the influence of the temperature.

INTRODUCTION

The long term storage of nuclear waste is considered as one of the most important and stimulating problem that engineers have ever faced.

Rock salt is generally considered as a material specially suited to such an operation. As a consequence, it has regained more interest and its long term behavior is intensively examined.

The correct forecast of the behavior of underground caverns for long time storage operation is not possible without knowing the exact constitutive law of the host rock. The validation of this law and the calculation of its constituting parameters depend on the experimental laboratory and/or in situ results.

The EEC supported research program COSA, which aimed at the validation of the European computer codes used to model the behavior of the underground cavities built in rock salt (Come B., 1987), highlighted great divergences between the various research teams involved in the project about the characteristics of the constitutive law of rock salt.

Hereafter are some points that were subjected to animated debates :

- the existence of strain hardening,
- the intermediate principal stress influence nature,
- the existence and the form of a viscoplastic potential,
- the temperature influence nature.

Within a research program carried out with B.R.G.M (Bureau de Recherches Géologiques et Minières) and sponsored by the Commission of the European Communities, the C.G.E.S, which has been studying for more than twenty years many salts coming from everywhere, has put in practice its experience to select different tests which can contribute effectively to answer the above montionned questions.

Our work aims at putting into evidence a model reflecting the salt behavior and thus providing a way to validate the laboratory tests as well as the in situ ones. In this paper, we will only focus on laboratory tests.

The material chosen for this purpose is the rock salt extracted by Salins du Midi and Salines de l'Est in Varangeville mine (Meurthe et Moselle - France).

The first part of this paper is dedicated to the creep tests with a variation of deviatoric stress and temperature, and the analysis of these data enables to point out qualitatively the influence of stress and temperature. In the second part, we will try to interpret all multi-steps creep tests. This will be done using a specific method that identifies the rock salt behavior at different stress and temperature states.

MULTI-STEPS CREEP TEST EXPERIMENTAL DATA

Description of the test program

The tests done in laboratory are the following :

1) triaxial compression creep tests with low deviatoric stress under an axial stress varying between 5,5 and 7 MPa with a step of 2,5 MPa (the steps lasts 3 months and 2 tests are done with the same interval). Samples EP 06 and EP 19,
2) triaxial compression creep tests with medium deviatoric stress under an axial stress varying between 7,5 and 15 MPa with a step of 2,5 MPa (the steps lasts 3 months and 2 tests are done with the same interval). Samples EP 08 and EP 18,
3) triaxial creep test with constant deviatoric stress (under an axial stress of 13 MPa) and increasing the temperature from 20 to 90 °C with a step of 10 °C each 1,5 month. Sample EP 12,
4) triaxial creep test with constant deviatoric stress (under an axial stress of 13 MPa) and decreasing the temperature from 90 to 20 °C with a step of 10 °C each 1,5 month. Sample EP 14.

All the tests are performed with a confining pressure of 5 MPa.

Samples characteristics and location

Cylindrical samples (Φ = 65 mm, h = 130 mm) come from two drillings (GTC1 and GTC2) with respective lengths of 24,70 and 16,70 m. They were performed by B.R.G.M in two pillars of Varangeville mine. The cores were replaced by dilatometers in order to measure the long term creep and in situ Young modulus.

Results made it easy for us to draw a comparison concerning the material behavior in the laboratory and in situ.

One of the most remarkable characteristic of these samples is their fissuration which is orthogonal to the drilling axis. This shows a phenomenon similar to the disc formation at drilling time. We also observe a noticeable variation of the clay content from one sample to another. These two characteristics may explain why some sound velocities are small and why the specific weights are scattered as shown in the table below.

Table 1 : Sample characteristics and location

Sample	Drilling level (m)	Specific weight (Kg/m^3)	Sound velocities (m/s)
EP 06	08.02 - 09.20	2169	1700
EP 19	07.10 - 07.35	2176	1300
EP 08	09.93 - 10.17	2152	1300
EP 18	19.06 - 19.20	2141	1300
EP 12	10.55 - 10.73	2265	2300
EP 14	07.82 - 08.02	2192	3700

Experimental data

The results obtained for the sample tests EP 06 and EP 19 with a low deviatoric stress are represented on figure 1. We conclude that we cannot observe a strain under deviatoric stress of 0,5 MPa (only few material dilation which is due to ambiant temperature changes).

The results obtained for the sample tests EP 08 and EP 18 with a medium deviatoric stress are represented on figure 2.

Finally, we represent in figures 3 and 4 respectively the results concerning constant deviatoric stress and variable temperature for samples EP 12 and EP 14.

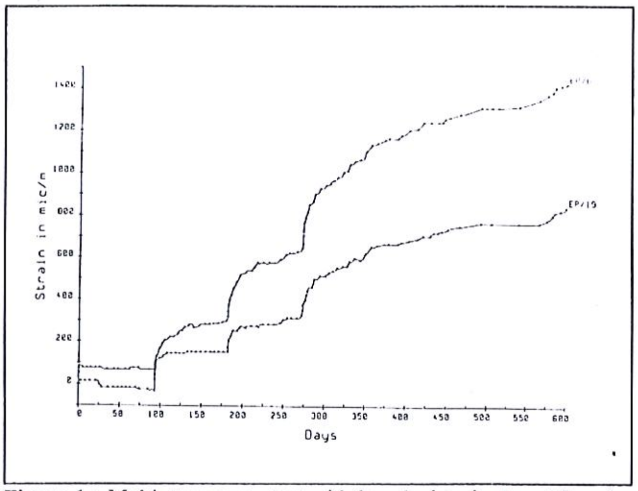

Figure 1 : Multi-steps creep test with low deviatoric stress. Samples EP 06 and EP 19.

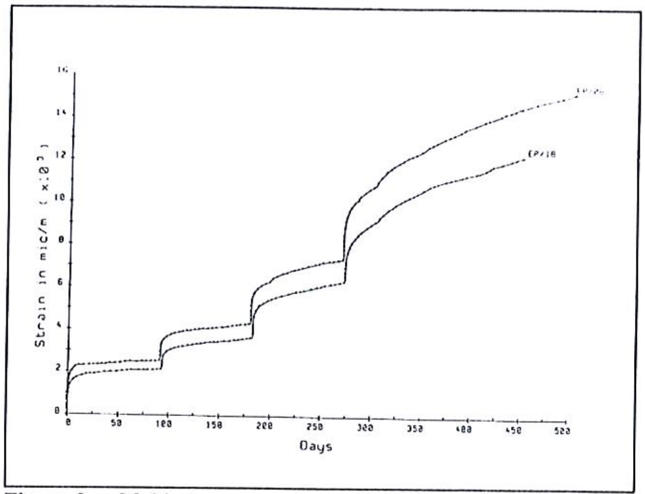

Figure 2 : Multi-steps creep test with medium deviatoric stress. Samples EP 08 and EP 18.

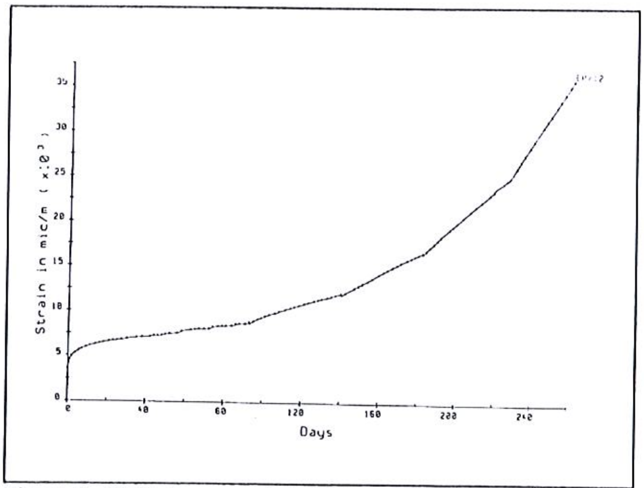

Figure 3 : Multi-steps creep test with inscreasing temperature. Sample EP 12.

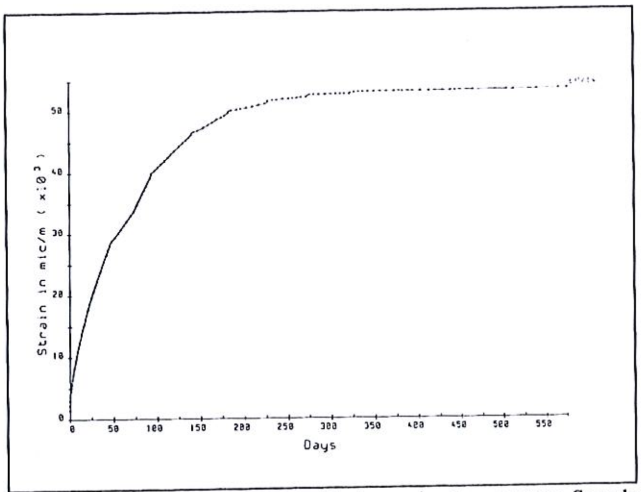

Figure 4 : Multi-steps creep test with decreasing temperature. Sample EP 14.

Figure 3 shows certain anomalies at temperature 30 °C (second step). They are due to the leak of azote from the accumulator which provides the axial pressure, resulting in deviatoric stress decrease.

Figure 4 shows a slope change at the second step level (temperature 80 °C). The reason is a power cut which stopped immediately the heating of the cell.

The effect of stress and temperature

The behavior of Varangeville salt indicates characteristics similar to those of other salts studied in our laboratory. The stress change causes an immediate response followed by another one which rate depends on the deviatoric stress.

The temperature increase, as for the deviatoric stress, results in an increase of the material deformation. This puts into evidence the viscous characteristic of the rock salt.

Figure 4 shows that a decrease in temperature reduces remarkably the sample deformation which was subjected to an important deformation at higher temperatures in the beginning of the test. This phenomenon is strain hardening : the strain rate depends on the stress, the temperature and the previous strain.

RESULTS INTERPRETATION

Introduction

Generally the rheological law derives the viscoplastic strain rate from the stress, the temperature and strain. Taking account of this situation, we have worked out a numerical algorithm that enables to evaluate precisely the derivative of an experimental function represented by a set of points (t_i,ϵ_i). We could have directly evaluated the strain rate during the testing period and showed the effect of the stress, temperature and the existence of strain hardening., Unfortunately the problem was more complicated than expected, so we have turned to study of the variable ξ, explained in the following paragraph.

Principle of the method

Mainly, the method is based on the formulation of the material strain hardening. The viscoplastic strain of the salt is a power law of an internal hardening parameter ξ defined below :

$$\epsilon_{vp} = \xi^{\alpha}, \qquad (\alpha<1)$$
$$\frac{d\xi}{dt} = F(\sigma,T) \tag{1}$$

α : rheologic parameter depending on the material nature,
$F(\sigma,T)$: unknown function, σ and T are the stress and temperature.

The method consists in calculating (using AJUSTE, program using a least squares method) the parameter ξ for each step of stress or temperature as well as the parameter α for all the creep test.

This is possible if data on sample viscoplastic strain is provided. To do this, it is necessary to eliminate from the creep test data base all strain variations produced almost immediately (time, strain, deviatoric stress, temperature).

Results adjustement

The stress and temperature applied law is defined as :

$t<0$ $\quad\sigma=0$ or $T=T_0$
$0\leq t<\tau_1$ $\quad\sigma=\sigma_1$ or $T=T_1$
$\tau_1\leq t<\tau_2$ $\quad\sigma=\sigma_2$ or $T=T_2$
$\tau_2\leq t<\tau_3$ $\quad\sigma=\sigma_3$ or $T=T_3$
etc ...

We suppose that in each interval, $d\xi/dt$ is constant; thus ξ is a linear function of time. The choice of the integration constant enables the continuity of ξ at time change τ_1, τ_2, τ_3,...etc. Finally we have the following results :

if $0 \leq t < \tau_1$ first step
$d\xi/dt = A_1$ = constant
$\xi_1 = A_1 t$
$\epsilon_{vp1} = (\xi_1)^{\alpha}$ **(2)**

if $\tau_1 \leq t < \tau_2$ second step
$d\xi/dt = A_2$ = constant
$\xi_2 = A_2(t-\tau_1)+A_1\tau_1$
$\epsilon_{vp2} = (\xi_2)^{\alpha}$ **(3)**

if $\tau_2 \leq t < \tau_3$ third step

$$d\xi/dt = A_3 = \text{constant}$$
$$\xi_3 = A_3(t-\tau_2)+A_2(\tau_2-\tau_1)+A_1\tau_1$$
$$\epsilon_{vp3} = (\xi_3)^\alpha \qquad (4)$$

etc...

The adjustment of these functions on the points enables to calculate the parameters α, $d\xi_1/dt$, $d\xi_2/dt$, $d\xi_3/dt$, etc... corresponding to the stress steps σ_1, σ_2, σ_3, etc ... or the temperature steps T_1, T_2, T_3, etc... .

Figures 5 to 10 show these results. Theoretical curves (solid lines) seem to match the experimental curves (dashed lines). Details are presented in tables 2 and 3.

Table 2 : The parameters $d\xi/dt$ and α for stress variation tests.

Test	Step	σ (MPa)	$d\xi/dt$	α
EP 06	1	0.5	4.98	0.3076
	2	1.0	$1.31\ 10^5$	
	3	1.5	$0.39\ 10^7$	
	4	2.0	$0.18\ 10^8$	
EP 19	1	0.5	4.97	0.3000
	2	1.0	$1.21\ 10^3$	
	3	1.5	$7.93\ 10^4$	
	4	2.0	$5.00\ 10^6$	
EP 08	1	2.5	$0.22\ 10^8$	0.3002
	2	5.0	$0.26\ 10^9$	
	3	7.5	$0.50\ 10^{10}$	
	4	10.0	$0.86\ 10^{11}$	
EP 18	1	2.5	$0.25\ 10^8$	0.2943
	2	5.0	$0.28\ 10^9$	
	3	7.5	$0.25\ 10^{10}$	
	4	10.5	$0.37\ 10^{11}$	

Table 3 : The parameters $d\xi/dt$ and α for temperature variation tests

Test	Step	T °C	$d\xi/dt$	α
EP/12	1	20	$0.73\ 10^{10}$	0.3087
	2	30	$0.15\ 10^{11}$	
	3	40	$0.65\ 10^{11}$	
	4	50	$0.31\ 10^{12}$	
	5	60	$1.45\ 10^{12}$	
	6	70	$0.62\ 10^{13}$	
EP/14	1	90	$1.16\ 10^{5}$	0.6551
	2	80	$0.78\ 10^{5}$	
	3	70	$0.58\ 10^{5}$	
	4	60	$0.30\ 10^{5}$	
	5	50	$0.92\ 10^{4}$	
	6	40	$0.83\ 10^{4}$	
	7	30	$0.98\ 10^{3}$	
	8	20	$0.97\ 10^{3}$	

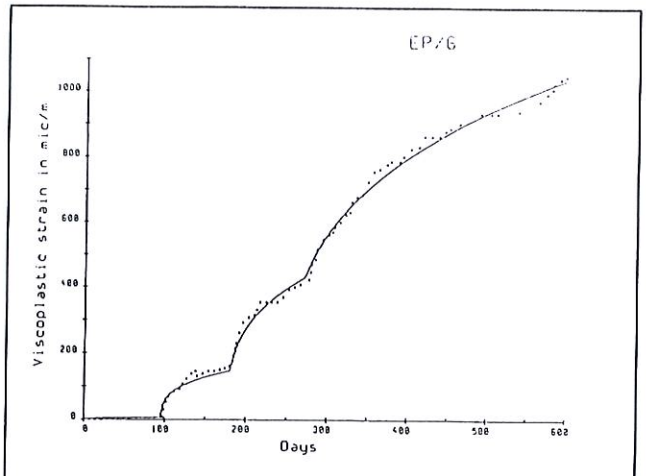

Figure 5 : Comparison of measured and calculated viscoplastic strain, test EP 06.

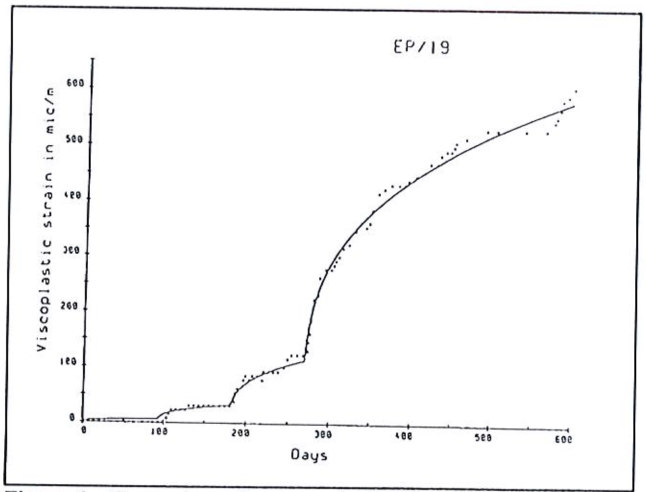

Figure 6 : Comparison of measured and calculated viscoplastic stra in, test EP 19.

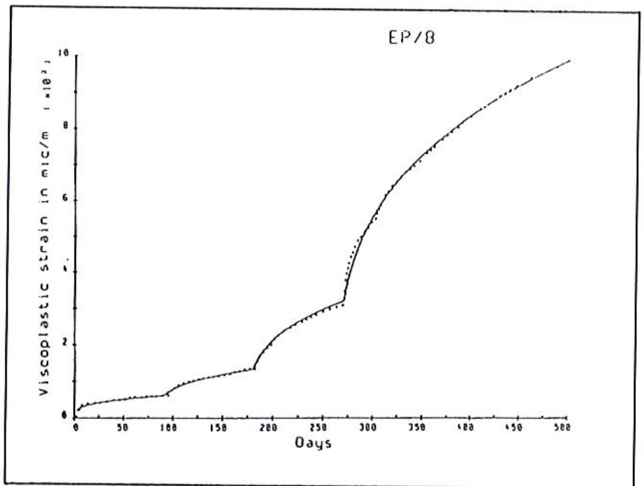

Figure 7 : Comparison of measured and calculated viscoplastic strain, test EP 08.

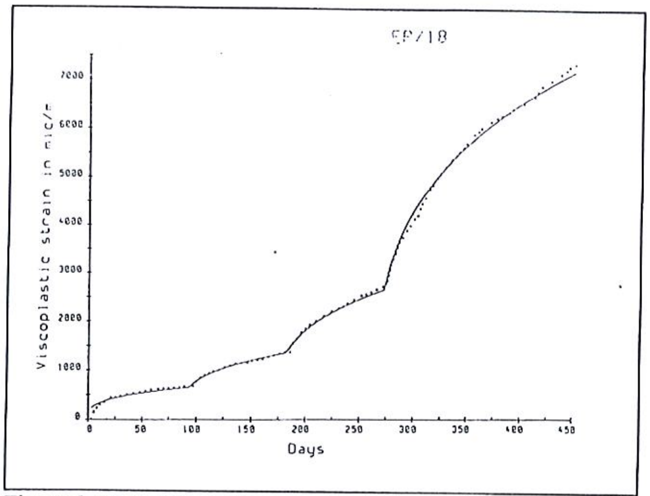

Figure 8 : Comparison of measured and calculated viscoplastic strain, test EP 18.

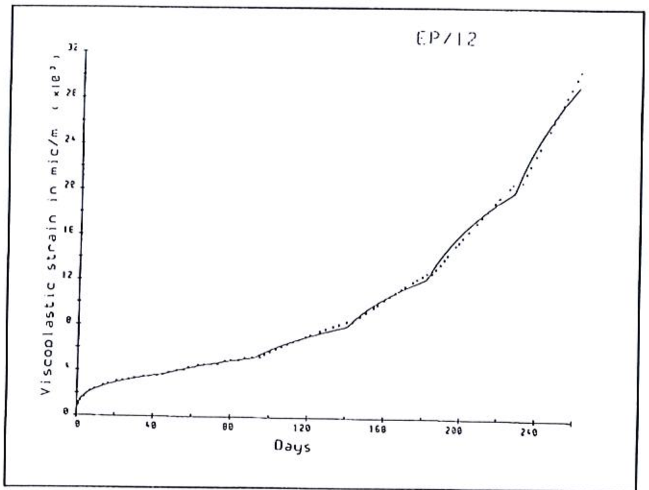

Figure 9 : Comparison of measured and calculated viscoplastic strain, test EP 12.

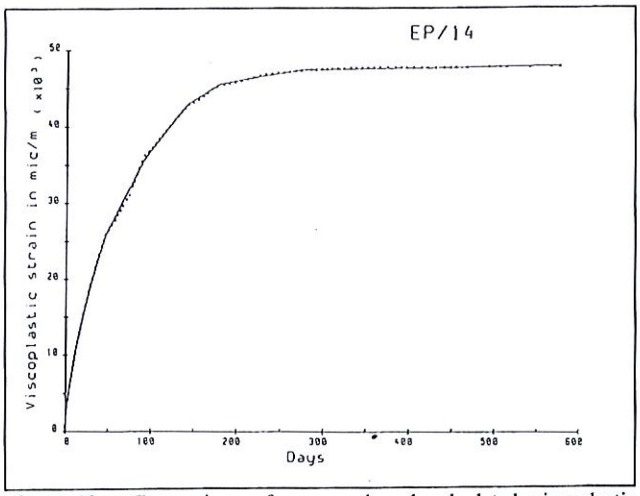

Figure 10 : Comparison of measured and calculated viscoplastic strain, test EP 14.

The assumption that α depends only on the material but not on the stress or the ıperature state seems to be confirmed except for the EP 14 test. If we integrate this test ı global fitting we obtain $\alpha = 0,3$.

IERMOMECHANICAL CHARACTERISTICS OF THE VARANGEVILLE SALT

chanical characteristics

Figure 11 shows a bilogarithmic diagram where $d\xi/dt$ is plotted versus the deviatoric :ss (test EP 06, EP 19, EP 8 and EP 18). There are two families of points which stand re or less in a straight line. The former represents low deviatoric stresses while the later responds to the medium ones.

We are trying to interprete the parameter $d\xi/dt$ using the J.LEMAITRE model (Tijani [. and al, 1983) where $d\xi/dt = (\sigma/K)^{\beta/\alpha}$ is the deviatoric stress power law, α, β and K are ological parameters.

For both families montionned above, the interpretation is performed with a simple :ar regression. Figure 11 and table 4 show the results.

Table 4 : The J.LEMAITRE model parameters (α, β and K)

Test	α	β	K (MPa)
EP 06	0.30	3.455	0.407
EP 19	0.30	2.922	0.445
EP 08	0.30	1.748	0.152
EP 18	0.30	1.512	-

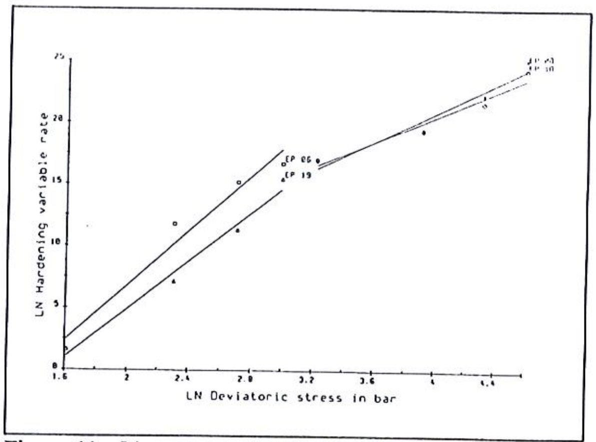

Figure 11 : Linear regression for both families.

The linear regresion carried out for each test, shows that the β parameter corresponding to low deviatoric stress tests is approximatively twice as large as the one related to medium deviatoric stress tests.

Thus we conclude that, compared to experimental results, the J.LEMAITRE model characterised by a unique β parameter, is not accurate enough. This remark brings us to the suggestion that either β depends on the stress or β is a constant in a given range of stress which changes for another range : in our case the transition looks like to be around a deviatoric stress value of 2,5 MPa.

These remarks can be exploited to do further research since it is clear that four tests are not sufficient to draw final conclusions.

Thermal characteristics

To express the effect of temperature we multiply the parameter $d\xi/dt$ by the Arrhenius term :

$$\frac{d\xi}{dt} = \left(\frac{\sigma}{K}\right)^{\frac{\beta}{\alpha}} . e^{-\frac{Q}{R.\alpha}.\left(\frac{1}{T}-\frac{1}{T_0}\right)} = H(\sigma).G(T) = F(\sigma,T)$$

T_0: is a reference temperature which has been taken equal to 300 °K,
Q : is the activation energy,
R : is the perfect gas constant.

Figure 12 and 13 show respectively the results of adjustment for the test EP 12 and EP 14. We have the following results :

EP 12

$A(\sigma)$	=	$(\sigma/K)^{\beta/\alpha}$	=	$6.12163\ .10^{+9}$
Q	=	42.5 KJ		
α	=	0.30		
T_0	=	300 K		
R	=	8.32 J/Mole/K		

EP 14

$A(\sigma)$	=	4794.46
Q	=	30.26 KJ
α	=	0.65
T_0	=	300 K
R	=	8.32 J/Mole/K

In order to evaluate the thermal characteristics of the Varangeville salt, we took into account the fact that characteristics relevant to sample EP 14 differ considerably from those determined before, thus we skipped the data provided by this sample and we kept only the characteristics provided by test EP 12 which were in a good agreement with those determined previously. In addition we observed that the set of points (hardening variable rate, temperature) of the sample 12 was fitted by the Arrhenius law much better than the one of the sample 14.

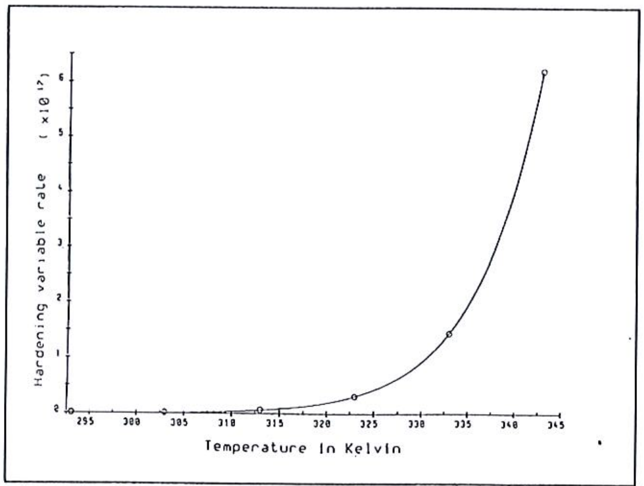

Figure 12 : Effect of the temperature on dξ/dt by the Arrhenius function, test 12.

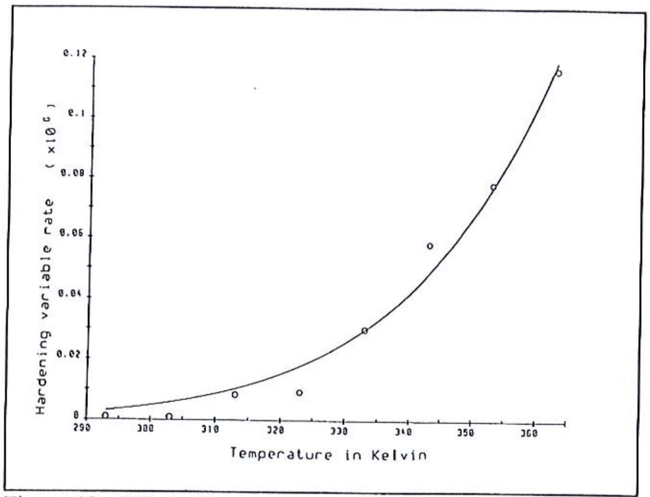

Figure 13 : Effect of temperature on dξ/dt by the Arrhenius functio n, test 14.

CONCLUSION

The study, presented in this paper, has made clear that the J.LEMAITRE model is not sufficient to draw final conclusions on the behavior of our salt, which was fissurated due to drilling action.

The method, worked out to analyse multi-step triaxial creep tests, puts into evidence that the effect of the stress on the strain rate can not be expressed using a unique power law.

In addition, it highlights how the temperature effect can be expressed with an activation energy.

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