SIMILITUDE RELATIONS FOR COMPARISON STUDY OF THERMOMECHANICS STABILITY OF FRACTURE

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ABSTRACT

Injection of a fluid colder than the rock mass,in hydraulic fractures used as heat exchangers in geothermal hot dry rocks reservoirs,can lead to fissuration of the fracture walls.This study consists in determining the difference in temperature between the fluid and the rock,leading to fissuration.These differences,found on granite samples,vary from 10°C to 30°C, depending on the mean temperature of the rock - 200°C to 70°C- Moreover this study shows the influence of the interstitial pressure on the thermal-mechanical behaviour of the rock.For thermal rupture estimation,it appears clearly that one can no longer think in monophasic terms,even in the case of so called "hot dry rocks".

KEYWORDS

Geothermal reservoir; thermal action; fracture; stability; experimental laboratory conditions; similitude relations; conditions "in situ".

INTRODUCTION

Injection of a fluid colder than the surrounding rock,into fractures used as heat exchangers in deep geothermal reservoirs, may lead to fissuration of the rock wall.This study gives fissuration criteria as obtained on laboratory tests,representing thermal actions on granite samples.

ENVIRONMENTAL ROCK PARAMETERS IN "SITU" AND IN LABORATORY

The experimental device should create,around the laboratory sample,experimental conditions as close as possible to the conditions encountered "in situ".This sample is parallelipipedic one face of this sample simulating the rock wall of the heat exchanger,Fig. 1.

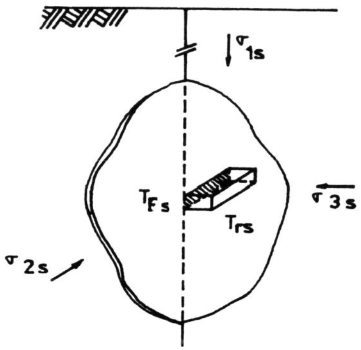


Fig. 1

Initial conditions

Site

$\sigma_{1s}, \sigma_{2s}, \sigma_{3s}$ = principal stresses in the rock mass
p_s = fluid pressure on the wall ($\geqslant \sigma_{3s}$)
T_{rs} = rock mass temperature
T_{fs} = fluid temperature along the wall
$T_{fs} = T_{rs}$ in the initial state

Laboratory

L = 53 cm. , h = 5 cm. , b = 3 cm. sample geometry
p_1= water pression in the cell
T_{f1}= water temperature in the cell
T_{r1}= temperature of the rock sample being equal to the temperature T_{f1} of the fluid at the initial state = T_1

Observation: The effective stresses σ'_{ij} in the rock in situ or in the laboratory are expressed in function of the total stresses σ_{ij} and the pore water pressure p by the equation:

$$\sigma'_{ij} = \sigma_{ij} - \delta_{ij} \cdot k \cdot p \qquad (1)$$

in which k = coefficient connected with the porosity and the shape of the pores ($0 < k < 1$).An alternative consists of covering the rock with synthetic rubber in order to prevent any water penetrating.In the case $\sigma'_{ij} = \sigma_{ij}$.

Actions

In situ

Lowering of temperature T_{fs},which is taken as being slow enough for a uniform temperature gradient to be set up in the rock near the wall.

Laboratory

It is very difficult to impose a temperature gradient on one face of the sample and contain the thermal shrinkage at its extremities.In order to overcome these experimental difficulties, the method used consisted of simulating these thermal shrinkage constraints by means of mechanical loading added to the initial state by means of an installation with circular bending,Fig. 2. The cold wall is simulated by face AB.

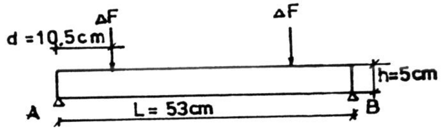


Fig. 2

EQUIVALENCE OF "IN SITU" AND LABORATORY PARAMETERS

Equivalence between the parameters in initial state

Case of strictly dry rock

The equivalence leads to equality between total stresses.In fact,equivalence only applies to the stresses along a plane which is perpendicular to the wall,with the cracks appearing by decohesion by single traction in this plane.

$$\min (\sigma_{1s}, \sigma_{2s}) = p_1 \qquad (2a)$$

$$T_{rs} \text{ or } T_{fs} = T_{r1} \text{ or } T_{f1} \qquad (2b)$$

Case of wet rock

Relation (2) must be modified by using the effective stresses instead of the total stresses as defined by (1).

$$\min \{ (\sigma_{1s} - k_s p_s) , (\sigma_{2s} - k_s p_s) \} = (1-k_1) p_1 \qquad (3a)$$

$$T_{rs} \text{ or } T_{fs} = T_{r1} \text{ or } T_{f1} \qquad (3b)$$

Equivalence between stresses

In situ stresses

Strictly dry rock

Conditions imposed in the neighbourhood of the face:

$\Delta e_{1s} = \Delta e_{2s}$ (strain) $= 0$

$\Delta \sigma_{3s} = \Delta p_s = 0$ assuming $\sigma_{3s} = p_s$

The increase in strain under ΔT_{fs} along a plane perpendicular to the wall is, in elastic theory, given by:

$$\Delta \sigma_{1s} = \Delta \sigma_{2s} = - \frac{\alpha_s E_s \Delta T_{fs}}{1 - \nu_s} \qquad (4)$$

where E_s, ν_s = coefficients of elasticity of the rock

α_s = coefficient of linear dilatation

Wet rock

Expression (4) remains strictly true with effective stresses:

$$\Delta \sigma'_{1s} = \Delta \sigma'_{2s} = - \frac{\alpha_s E_s \Delta T_{fs}}{1 - \nu_s} \qquad (5)$$

Laboratory stresses

Strictly dry rock

Under a ΔF increase of load F, applied at distance d from the corresponding support, only σ_{11} varies :

$$\Delta \sigma_{11} = - \frac{6 \Delta F\, d}{b\, h^2} \qquad (6)$$

Case of wet rock

The variation of effective stresses are given formally by the identical expression:

$$\Delta \sigma_{11} = - \frac{6 \Delta F\, d}{b\, h^2} \qquad (7)$$

Equivalence between parameters at rupture in situ and the laboratory

Case of dry rock

If the values of total stresses on the face perpendicular to the wall are equalled, in situ and in the laboratory, expressions (2a), (4) and (6) are used to obtain the critical cooling of fluid $(\Delta T_{fs})_{crit}$ which causes failure of the sample.

$$(\Delta T_{fs})_{crit} = \frac{1 - \nu_s}{\alpha_s E_s} \{ \min(\sigma_{1s}, \sigma_{2s}) - p_1 + \frac{6d}{b\, h^2} (\Delta F)_{cr}$$

If it is assumed that $p_1 = p_s$ and $p_s = \sigma_{3s}$, the term $\min(\sigma_{1s}, \sigma_{2s}) - p_1$ represents the difference between the mean and minor stresses in the rock. Thus, this term is therefore always positive. In the absence of information concerning this difference, only a lower limit of critical cooling can be deduced:

$$(\Delta T_{fs})_{crit} = \frac{1 - \nu_s}{\alpha_s E_s} \; \frac{6\, d}{b\, h^2} (\Delta F)_{crit} \qquad (8)$$

Case of wet rock

An identical expression is obtained by similar reasoning to the above but with effective stresses

TEST APPARATUS - PROCEDURE

Description of the test apparatus (Fig. 3)

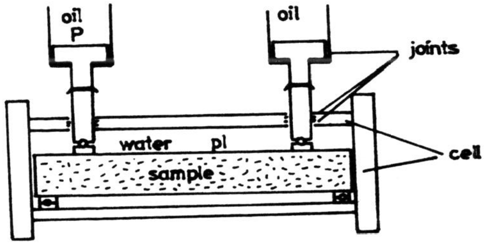


Fig. 3

The parameters involved in the laboratory are the follows:

a) p_1: confining pressure of water around the sample

This is created in a cylindrical cell closed at each end by plates maintained in position by braces. Water is put under a pressure up to 200 bars by means of a hand test pump.

b) T_1: equilibrium temperature of rock and water

Temperature is regulated by a coil of heating cables around the cell and on each plate. A regulator connected to a thermocouple maintains the temperature at the desired value up to a maximum of 200°C.

c) ΔF: loading of the sample to bending

The constant bending moment is created by hydraulic jacks installated outside the cell and fixed to the loading frame. It is transmitted to the cell which is mounted on two simple supports consisting of rollers.

Procedure

The operating sequence is shown schematically in Fig. 4. Only the projection of this sequence in the plane $(p_1, \Delta F)$ is used in the plotting of the results of the experiment.

TESTS - RESULTS AND INTERPRETATION

Tests

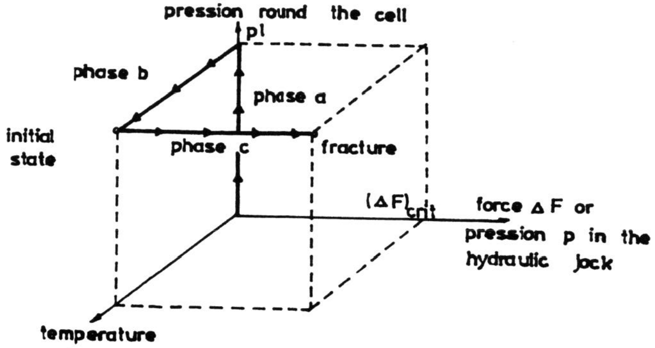


Fig. 4

Three tests modes were used on two sets (A and B) of homogeneous, isotropic granits at the following temperatures and pressures:

T_1 = 70 , 120 , 200° C ; p_1 = 50, 100, 150, 200 bars

Mode 1: non-impermeabilised sample(series I, II, III, IV)
Mode 2: sample impermeabilised by means of synthetic rubber membrane (series V, VI, VII)
Mode 3: the confining pressure was only applied after temperature rise in order to analyse the velocity of the percolation of water in the rock(series VIII)

Results

The results are shown in graphs 1,2 and 3, corresponding to modes 1,2 and 3.

Interpretation

The three tests modes studied bring into play the effect of pore pressure. Tensile strength σ'_r of the rock is expressed as follows using formulae (2a),(6) and (2b),(7) in function of the laboratory parameters:

Strictly dry rock

$$\sigma'_r = p_1 - 6(\Delta F)_{crit} \frac{d}{bh^2} \qquad (9)$$

Wet rock

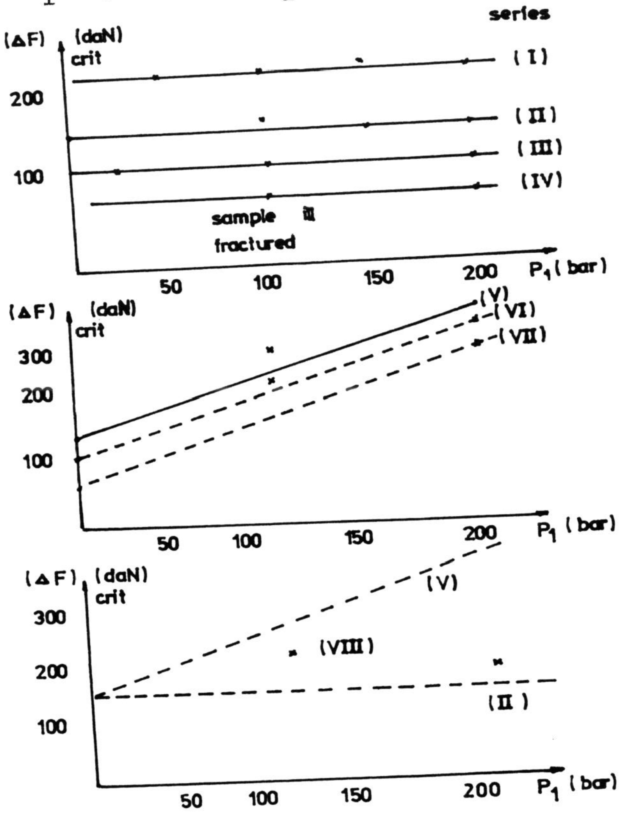
$$\sigma'_r = (1 - k_1)\, p_1 - 6(\Delta F)'_{crit} \frac{d}{bh^2} \qquad (10)$$

The three test modes can be interpreted as follows:

Mode 1: non-impermeabilised rock

At a given temperature it is observed that $(\Delta F)'_{crit}$ is independent of p_1(graph 1). At the temperature envisaged

σ'_r is a physical constant of the rock and so formula (10) leads to $1 - k_1 = 0$, therefore $k_1 = 1$.



Graphs. 1,2,3

The pore pressure in the immediate vicinity of the rock face is therefore the same as the confining pressure.

Mode 2: impermeabilised rock($k_1 = 0$)

At a given temperature, it is observed that $(\Delta F)_{crit}$ displays linear variation in function of p_1(graph 2). At a given temperature, the exactitude of relation(9) is therefore verified for a given σ'_r.

Mode 3: $0 < k_1 < 1$

The results given by mode 3 lie between the two lines characterising mode 1 and mode 2(graph 3). They can be interpreted by calculating a mean coefficient k_1, which shows globally the degree of penetration of water into dry rock when the pressure in increased rapidly. If the value of σ'_r found in series II and V is used($\sigma'_r = -133$ bars), using (10), k_1 can be deduced in function of p_1 at 70 C.For the two experimental points:

k_1 = 0.45 when p_1 = 100 bars;k_1 = 0.85 when p_1 = 185 bars

The difference between the values of k_1 appear to be linked with the pressure.In addition,since the duration of pressure rise was fairly rapid(maximum 15 minutes)in the two tests,it can be concluded that the penetration of the pores at the surface by water occurs more or less instantaneously.In conclusion,only modes 1 remains meaningful in the practical conditions encountered at the geothermal site.However,mode 2 is an indispensable reference and mode 3 makes it possible to judge the velocity of penetration of the rock by water.

CONCLUSION

This study makes it possible to assess in a given rock(granite in the case)the difference in temperature between rock and water at which cracks can appear in the walls of a geothermal exchanger.This temperature difference varies from 10°C to 30°C for rock temperatures of 200°C to 70°C.In addition,these tests have made it possible to show the effect of pore pressure on the thermomechanical fracturing of rock.It would therefore seem necessary to take the pore water pressure into account in failure calculations,i.e. to reason in terms of a biphasic environment after fairly short periods of contact between dry rock and water.

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