Pageoph, Vol. 116 (1978), Birkhäuser Verlag, Basel

A Note on Permeability Changes in Geologic Material Due to Stress

By W. F. BRACE[1])

Summary – Stress produces dramatic changes in fluid permeability of geologic materials. An increase of nearly threefold occurred in granite at high stress, an increase of 20 percent in sandstone, and a hundredfold decrease in compacted sand. Permeability of sand and sandstone did not follow the effective stress law. Flow along joints was very sensitive to effected stress changes, a fourfold change being caused by as little as 1.0 MPa.

Key words: Permeability of rocksand granular materials.

1. *Observations*

Permeability of porous media is known to depend on pore dimensions. Pore dimensions, particularly the aperture, or width, change with stress, so that it is not surprising to find that permeability is quite stress-dependent. Few measurements have been made for geologic materials or for granular aggregates at geologic stresses (see review by WITHERSPOON and GALE [1], and references cited below), although there is an extensive literature for rocks and soils under engineering conditions [2, for example]. Although data relevant to geologic conditions are limited, some general trends are discernible for (a) unjointed rocks with porosity less than 2 percent, (b) unjointed rocks or granular aggregates with high porosity, and (c) jointed rocks like granite or coal.

In most experiments we will describe, the stress state had axial symmetry. $k_{\parallel}$ refers to permeability parallel with, and $k_{\perp}$ perpendicular to the unique stress direction. For the jointed media, k_j refers to a direction parallel with the joint surface, irrespective of stress directions; k_j is the intrinsic permeability of SNOW [3] and NORTON and KNAPP [4].

Low porosity rocks

Among rocks with porosity less than about 0.02, only Westerly granite has been investigated under simulated geologic conditions [5]. At around 80 percent of the

[1]) Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

fracture stress in confined compression tests, $k_{\|}$ increased by a factor of 3 to 4 (Fig. 1) over k_p, the value at 39 MPa effective hydrostatic pressure and zero stress. BRACE [6] showed that this change in k was predictable from crack parameters and electrical resistivity changes for this rock at the same effective confining pressure.

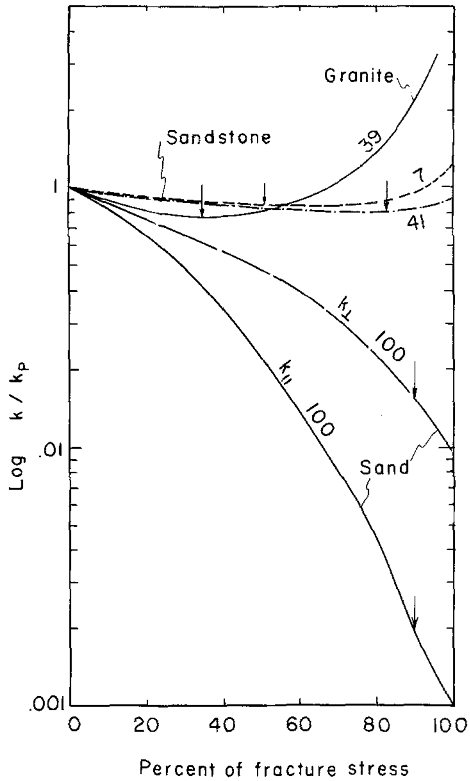

Figure 1

Change of permeability with stress for Westerly granite, Darley Dale sandstone, and Ottawa sand. k is permeability at pressure and stress and k_p at pressure alone. Number on curves gives effective confining pressure in MPa. Arrow shows approximate onset of dilatancy. Flow direction was parallel with the maximum compression except for the upper curve for sand. The sand did not fracture; 'fracture stress' is the maximum stress difference at that pressure.

High porosity rocks and granular aggregates

MORDECAI and MORRIS [7] observed changes in $k_{\|}$ in Darley Dale sandstone (porosity 11 percent) prior to fracture at confining pressures up to 40 MPa. At low pressure, behavior was similar to granite although the actual increase in $k_{\|}$ was only 20 percent (Fig. 1). At 41 MPa $k_{\|}$ actually underwent a 5 percent overall decrease prior to fracture.

ZOBACK and BYERLEE investigated two granular aggregates, crushed Westerly granite [8], and Ottawa sand [9]. At effective confining pressures of 20 and 50 MPa, the starting porosity of the granite sand was 31 and 22 percent respectively. In both cases, $k_{\parallel}$ had dropped by a factor of 50 at peak stress. Although there appeared to be a small amount of dilatancy prior to peak stress, permeability fell monotonically. Three porous sandstones behaved similarly over smaller ranges of stress [10].

$k_{\parallel}$ of Ottawa sand dropped even more (Fig. 1); at 750 bars effective pressure it fell by a factor of nearly 100 at peak stress. $k_{\perp}$ was also obtained, from experiments done in extension; $k_{\perp}$ decreased by a factor of 10 to 20 at peak stress.

ZOBACK and BYERLEE [9, 11] observed that the effective stress law did not hold for k of sandstone and sand with either hydrostatic compression or triaxial stress. Small departures from this law have been evident before [12], although not for permeability and electrical resistivity. The new studies show that for sandstone, for example, permeability under hydrostatic pressure is proportional to $(B P_p - P_c)$ where B is a constant with a value of 2 to 4 depending on direction, P_p is pore pressure, and P_c is confining pressure. B is close to 1 for equilibrium and transport properties which obey the effective stress law [12]. Engelder and Scholz (personal communication, 1977) have also found that B is not equal to 1 for flow through a sand-filled sawcut in Barre granite; here, however, B was apparently less than 1.

Joints and other fractures

In rocks like granite, joints and other planar fractures provide the principal flow paths [1, 3, 13]. The effect of stress on permeability of jointed media is quite dramatic.

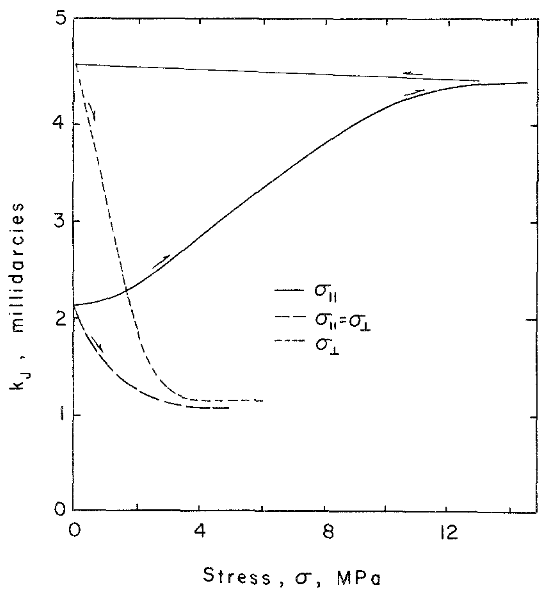

Figure 2

Joint permeability as a function of stress parallel or perpendicular to the joint. Arrows give the loading path. From PRATT *et al.* [1977].

SOMERTON *et al.* [14] showed that k of finely jointed coal dropped 1 to 2 orders of magnitude at 75 percent of the fracture stress in confined compression. No difference between $k_{\parallel}$ and $k_{\perp}$ was apparent.

PRATT *et al.* [15] studied permeability of a 3 meter block of granite containing a joint, as stress was applied normal or parallel with the joint. Uniaxial stress of 12 MPa parallel with the joint raised k_j twofold (Fig. 2), whereas 3 MPa normal to the joint decreased k_j to half the starting value. The constant value of k_j reached at high stress (1.2 md) was still 10 times greater than k of the matrix granite under 10 MPa confining pressure [6].

GALE [16] observed changes in k_j in a large (approximately 1 m) granite core containing joints. Flow rates along a joint could be varied by a factor of 4 to 5 by changes of only 0.5 to 1 MPa in the effective normal stress acting across the joint. As PRATT *et al.* [15] observed, flow through the joint could not be cut off by high normal stress across the joint. Even at 100 MPa normal stress, permeability of granite with a sawcut remained 10^3 greater than matrix permeability in laboratory experiments (Engelder and Scholz, personal communication, 1977).

2. *Discussion*

The trends suggested by available measurements (Fig. 1) reflect the interplay of the two factors, porosity, η, and hydraulic radius, m, upon which permeability depends [18]. Both η and m in turn depend on stress, in a way which evidently varies among the different materials shown in Fig. 1.

For intact rocks, the following relationship is widely applicable:

$$k = \frac{m^2}{k_0}\eta^3 \tag{1}$$

where k_0 is a dimensionless constant which can vary between 2 and 3 [6]. m is one quarter of the diameter of a cylindrical pore and half the aperture, w, of a flat rectangular slot. For dilatant microcracks in low porosity rocks, permeability in the direction of the microcracks, k_j, has a different form [17]:

$$k_j = \frac{m^2}{k_0}\eta \tag{2}$$

For a single set of planar openings, such as microcracks or joints,

$$k_j = \frac{w^3}{KJ} \tag{3}$$

where J is spacing, w is aperture, $K = 4k_0$ and $\eta = w/J$. Equation (3) is virtually identical with the standard equation used to analyze flow in jointed media [4, 13, 18]:

$$k_j = \frac{w^3}{12J}$$

From either equation (1) or (2), k depends on η and m, and both of these may, in general, be affected by stress. Of the three materials in Fig. 1, changes in η and m with stress are only understood for an intact, unjointed granite [6]. Based on other measurements, m was found to change very little with stress, so that most of the change in k shown must be due to change in porosity, η. Evidently η decreases up to the onset of dilatancy; beyond that η increases, at an increasing rate. For the sand and sandstone in Fig. 1, changes of m and η with stress are not known; the changes in k shown could be due to either or both.

It is interesting to note that in the dilatant region, relative change in porosity due to dilatancy of all three materials is about the same. Elsewhere in this volume we give dilatant volume change, D_F, relative to porosity, η_p, at zero stress. For granite it was about 30 to 35 percent, for sandstones similar to the Darley Dale, about 10 to 30 percent, and for the sand, 20 percent; thus, the relative changes in η are comparable. In contrast, k of granite increased nearly four-fold, k of sandstone increased about 10 to 20 percent, and k of sand decreased strongly. These striking differences must reflect the different way m responded to stress in the three materials.

It is difficult to compare data for jointed and unjointed rocks, since stress levels for the former did not approach those for fracture of intact material. It is significant that stress effects are much more dramatic for k_j, however. Twofold to fourfold changes in k_j were produced by a stress of 1 to 10 MPa; twofold to threefold changes required 100 MPa for granite. It is interesting to compare permeability and strain changes for the jointed granite. Joint closure at 3 MPa normal stress was about 100 μm [15]. Joint spacing is about 1 m, so that the strain was 10^{-4}. Therefore change in k_j was more than 10^4 times greater than the linear strain perpendicular to the joints. This is comparable with the amplification reported by SNOW [3] and WITHERSPOON and GALE [1].

Some understanding of the dominating influence of joints can be gained by comparing equations (1) and (2), using reasonable estimates of appropriate η and m. Consider first jointed granite. From SNOW's study [13] of 30 damsites in predominantly crystalline rocks, mean values of aperture were 100 μm and porosity 10^{-5}. If we assume flow through intact granite occurs through pores, pore porosity might be 3×10^{-3} and pore width about 1 μm [6]. Then joint permeability, k_j would be about 10^6 times permeability through the joint-free granite. Under stress both η and m decrease. The change in m is proportional to joint length [19], and since joint length is already 10^3 or more greater than crack or pore length, stress effects should be vastly more pronounced for joints, as observed.

For rocks like sandstone, where η of 10^{-1} and m of 100 to 1000 μm might be more appropriate, flow through joints would be subordinate to flow through matrix.

3. *Future Work*

There is a clear need here both for more experiments, and for theories which will quantitatively predict variations in permeability such as shown in Fig. 1. Among the intact rocks, behavior of materials other than granite should be investigated; as we show elsewhere in this volume, granite is somewhat anomalous among the crystalline rocks. The relative increase in porosity due to dilatancy is much greater in quartzites and dunites, for example. There, stress effects on k should be even more pronounced.

The effect of stress cycling also needs to be investigated, particularly for the more porous materials. One would suspect that with pronounced compaction on the first cycle, stress effects in subsequent cycles may change, perhaps approaching the behavior of originally less porous rocks. Cycling effects have been explored for granite [5] and sandstone [7]; the changes for one or two cycles were small.

One difficulty is apparent in any attempt to quantitatively predict flow behavior under stress using relationships such as equation (1). Although porosity at stress and pressure can be determined, crack dimensions in general cannot. In one study velocity measurements made under stress were used to assess crack shape under stress [20]. This required many assumptions and gave at best averaged values. Some method needs to be devised to measure crack parameters directly while under stress.

There may be even greater difficulties predicting stress effects in jointed rocks. Witherspoon and Gale [1] and Snow [21] review many of the complications apparent from field and laboratory observations and suggest that, at scales larger than a meter, there is large variation in behavior of individual joints and important differences from smaller scale fractures. The fact that large joints do not close completely under stress [15, 16] is just one example of the complications which may have to be considered. Many *in situ* measurements in a variety of rocks may be required to generally predict flow in jointed media in large-scale geologic situations.

Acknowledgments

This study was supported by a grant from the Chevron Oil Field Research Company. J. B. Walsh and D. Norton suggested a number of improvements in the manuscript. P. Witherspoon, C. Scholz, J. D. Byerlee, and D. Norton generously supplied unpublished results.

References

[1] Witherspoon, P. A. and Gale, J. E. (1977), *Mechanical and hydraulic properties of rocks related to induced seismicity*, Eng. Geol. *11*, 23.

[2] De Wiest, R. J. M. (ed.), *Flow Through Porous Media*, Academic Press, New York 1969.

[3] Snow, D. T. (1968), *Fracture deformation and changes of permeability and storage upon changes of fluid pressure*, Colorado School of Mines Quarterly *63*, 201.

[4] Norton, D. and Knapp, R. (1977), *Transport phenomena in hydrothermal systems: the nature of porosity*, Am. J. Sci., *277*, 913.

[5] Zoback, M. D. and Byerlee, J. D. (1975a), *The effect of microcrack dilatancy on the permeability of Westerly granite*, J. Geophys. Res. *80*, 752.

[6] BRACE, W. F. (1977), *Permeability from resistivity and pore shape*, J. Geophys. Res. *82*, 3343.

[7] MORDECAI, M. and MORRIS, L. H., *An investigation into the changes of permeability occurring in a sandstone when failed under triaxial stress conditions*, in *Dynamic Rock Mechanics* (12th Sympos. Rock Mechanics, Rolla, Mo., 1970), ed. George B. Clark, Chap. 11, Port City Press, Inc., Baltimore 1971, 221.

[8] ZOBACK, M. D. and BYERLEE, J. D. (1976), *A note on the deformational and fluid flow behavior of crushed granite*, Int. J. Rock Mech. Min. Sci. *13*, 291.

[9] ZOBACK, M. D. and BYERLEE, J. D. (1976), *Effect of high-pressure deformation on permeability of Ottawa sand*, Amer. Assoc. of Petrol. Geol. Bull. *60*, 1531.

[10] WILHELMI, B. and SOMERTON, W. H. (1967), *Measurement of pore and elastic properties of rocks under triaxial stress*, Soc. Petrol. Engrs. J. TPTE-A, 283.

[11] ZOBACK, M. D. and BYERLEE, J. D. (1975b), *Permeability and effective stress*, Amer. Assoc. of Petrol. Geol. Bull. *59*, 154.

[12] BRACE, W. F., *Pore pressure in geophysics* (1972), AGU Monograph No. 16, Amer. Geophys. Un., Washington, D.C., 265.

[13] SNOW, D. T. (1968), *Rock fracture spacings, openings and porosities*, J. Soil Mech. Foundations Div., Proc., A.S.C.E. *94*, 73

[14] SOMERTON, W. H., SOYLEMEZOGLU, I. M. and DUDLEY, R. C. (1975), *Effect of stress on the permeability of coal*, Int. J. Rock Mech. Min. Sci. *12*, 129

[15] PRATT, H. R., BLACK, A. D., BRACE, W. F. and SWOLFS, H. (1977), *Elastic and transport properties of an in situ jointed granite*, Int. J. Rock Mech. Min. Sci. *14*, 35.

[16] GALE, J. E. (1975), *A numerical field and laboratory study of flow in rocks with deformable fractures*, PhD thesis, Univ. of Calif., Berkeley, 255 pp.

[17] BRACE, W. F., WALSH, J. B. and FRANGOS, W. T. (1968), *Permeability of granite under high pressure*, J. Geophys. Res. *73*, 2225.

[18] CHILDS, E. C., *Introduction to Physical Basis of Soil–Water Phenomena*, Wiley, New York, 493 pp.

[19] WALSH, J. B. (1965), *The effect of cracks on the compressibility of rocks*, J. Geophys. Res. *70*, 399.

[20] HADLEY, K. (1976), *Comparison of calculated and observed crack densities and seismic velocities in Westerly granite*, J. Geophys. Res. *81*, 3484.

[21] SNOW, D. T. (1972), *Fundamentals and in situ determination of permeability*, Proc. ISRM Sympos., Stuttgart, Germany, Genl. Rpt. Theme 1, 6 pp.

(Received 11th November 1977)