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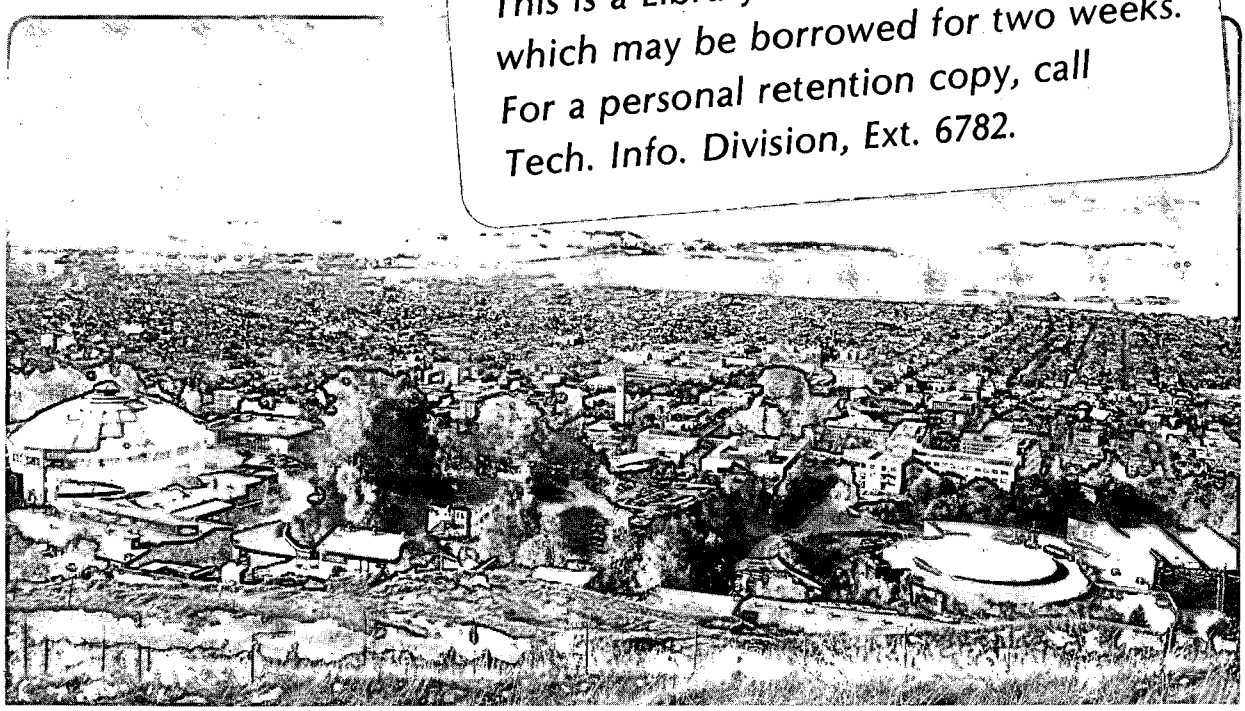

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STRENGTH AND PERMEABILITY OF AN ULTRA-LARGE SPECIMEN OF GRANITIC ROCK

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ABSTRACT

Laboratory tests were conducted to measure the mechanical and transport properties of a 1 m diameter by 2 m high specimen of jointed granitic rock. Uniaxial loading was applied and radial permeability tests were made at various stress levels. Ultimate strength of the specimen was estimated prior to loading by testing small 52 mm diameter cores with similar fracture patterns. It was found that deformabilities of the large and small specimens were similar; however, the uniaxial strength of the large core was about 10 percent of that predicted. Although the large core contained a complex joint system, its overall permeability was dominated by a single open fracture normal to the axis. Using a simple parallel-plate analog, changes in the equivalent single-fracture aperture under load were significantly less than closures measured by means of LVDTs situated across the main fracture.

INTRODUCTION

Despite the well-documented scale effect observed in the mechanical properties of rock masses (Heuze, 1980), relatively few large-dimensioned specimens have been used in rock mechanics experimentation. Several in-situ block tests have successfully measured the mechanical and transport properties of naturally fractured rock (e.g., Pratt, et al., 1977; Hardin, et al., 1982), and a limited number of samples of 1 m^3 or greater have been tested in the laboratory (e.g., Singh and Huck, 1972; Witherspoon, et al., 1977). For the latter work, specimens have been relatively homogeneous and unfractured, as opposed to in-situ block test sites specially chosen for their natural fractures or other heterogeneities. This paper describes a laboratory test to measure the strength and permeability of 1 m diameter by 2 m high specimen of highly fractured rock. While not intended to specifically address the issue of scale effects, the results provide an example of strength reduction with specimen size. More importantly, the test demonstrates the complexity of behavior that may be observed in large fractured rock samples when fractures are instrumented independently from the intact rock.

SAMPLE PREPARATION

The core sample was recovered from a depth of 360 m in granitic rock from the Stripa Mine in Sweden, the site of the Swedish-American Cooperative Program on Radioactive Waste Storage (Witherspoon and Degerman, 1978). Excavation was accomplished by drilling a circular pattern of overlapping holes around the periphery, during which time the rock was held in compression by a rock bolt through the central axis (see Andersson and Halen, 1978). After shipping to the laboratory, the specimen was prepared for testing by capping with reinforced concrete, as shown in Fig. 1. The axial compression was maintained throughout the excavation, shipping, and preparation stages, and removed only prior to testing.

The purpose of testing the core was to provide correlative data for other in-situ hydrologic and rock mechanics experiments at Stripa. With this in mind, the sample was selected such that several continuous natural fractures, labeled A, B, and C in Fig. 2, were oriented nearly perpendicular to the core axis. Another set of less continuous fractures (D, E, and F) were steeply inclined to the core axis. Filling minerals in the joints were predominantly chlorite and sericite with lesser amounts of epidote, calcite, and other minerals. Except for the principal discontinuities, most fractures appeared to be well healed. A preliminary series of low-pressure falling-head (0.3-0.4 Pa) injection tests on the unstressed core indicated that fracture B accounted for about ninety percent of the overall permeability, with fracture D contributing most of the remaining ten percent.

Shear strength of the inclined fractures was an important concern, since integrity of the core was to be maintained during uniaxial loading. Thus in order to estimate the ultimate strength of the large core, a series of triaxial compression tests were performed on small (52 mm diameter) samples containing similar inclined, strongly healed joints. Results indicated that an elastic modulus of about 55 GPa and an unconfined compressive strength of 60 to 70 MPa could be expected for the large core (Thorpe, et al., 1980). As will be discussed later, its strength fell far short of this estimate.

TEST PROCEDURE

The specimen was tested in the large triaxial testing machine located at the University of California's Richmond Field Station (Becker, et al., 1972). This equipment is shown in Figure 3 with the triaxial vessel being closed over the rock specimen. The test program took the form of a modified unconfined compressive strength test in which the axial loading, at a rate of 0.5 MPa/min, was interrupted and held constant at several stages. Permeability tests were performed at each constant load stage by injecting water into (divergent flow) and withdrawing water from (convergent flow) a borehole drilled through the axis of the core. The test configuration is shown schematically in Figure 4. To ensure saturation of the sample and to keep air in solution, the triaxial vessel was filled with water at a pressure of 1,400 kPa throughout the test. Linear variable differential transformers (LVDTs) and strain gauges were mounted on the specimen to measure overall axial deformation, circumferential strain at mid-height, deformation of the principal fractures, and strains in the intact rock. This instrumentation is shown in Figure 1 and the locations are shown in Figure 2.

TEST RESULTS AND DISCUSSION

Mechanical

The general load-displacement response is summarized in Fig. 5, which plots axial strains against the applied axial stress. The data are from three LVDT's (Nos. 19, 20 and 21 in Fig. 2) that measured the displacements between points 1.3 m

apart at the top and bottom of the specimen. Assuming that plane sections through the core remained planar, axial strain at the center of the core was calculated from these readings and is shown as the solid curve in Fig. 5. The curves exhibit typical nonlinear form at low stress levels, plus a number of more complex features. Creep deformation occurred when the axial stress was held constant during permeability testing, the magnitude increasing with successively higher stress levels. The failure kinematics involved some tilting of the sample combined with shearing along discrete joints. Because of this, the assumption of maintaining planar cross-sections was probably negated during failure; therefore, the apparent upward movement calculated for the center at the peak stress is considered fictitious. During failure new fractures were developed through previously intact rock, and pre-existing healed joints were opened, as shown in Fig. 2. A maximum stress of 7.4 MPa was attained at 0.06% strain before generalized failure. Although this peak stress is much lower than our predicted strength (70-100 MPa), the tangent modulus prior to failure was 52 GPa, which is similar to that obtained from the small diameter samples mentioned above.

As shown in Fig. 2, the core was instrumented in such a way that the overall deformation could be approximately decomposed into the separate contributions of major discontinuities and the intact, and presumably elastic, rock matrix. Axial closures for the three subhorizontal fractures (A, B, and C in Fig. 2) are plotted versus axial stress in Fig. 6. Each was calculated as the average of three LVDT readings at points spaced equidistant around the fracture. Individual LVDT readings along a given fracture were often substantially different, however, indicating nonuniform closure of the fracture.

Fracture D was the principal inclined joint that failed, and LVDTs 3, 7, and 8 monitored its vertical and horizontal movement. Shear and normal displacements that were resolved from the data are plotted in Fig. 7. Deformation at constant stress levels (steps in the loading curve) indicated that creep displacement along fracture D occurred under loads considerably less than that which caused generalized failure.

Permeability

A total of 12 divergent and convergent flow tests were performed at five different load stages. Results are shown by Fig. 8 in the form of overall flow rates versus differential head. Although the data are sparse, a nearly linear relationship appears to exist between flow rate and head for tests at several axial stress levels. This suggests that Darcy flow is generally applicable; however, the slight deviations from linearity probably are indicative of some turbulence in the flow.

Assuming that the overall permeability of the core can be attributed entirely to flow through fracture B (see Fig. 2), the equivalent single-fracture hyudraulic conductivity, K_f, is

$$k_f = \left[\frac{(Q/\Delta h)^2 \; (\ln r_2/r_1)^2}{(12\mu/\rho_f g) \; (2\pi)^2}\right]^{1/3}, \qquad (1)$$

where Q is the overall flow rate, Δh is the head, μ is the dynamic viscosity, ρ_f is the fluid density, g is the acceleration of gravity, and r_1 and r_2 are the radii of the inner and outer flow boundaries (Witherspoon, et al., 1977). Values of K_f for the data in Fig. 8 are plotted in Fig. 9, which also presents some previously published results from conductivity tests on large samples of crystalline rock containing single continuous fractures. The present data are several orders of magnitude greater, which emphasizes the large variability in conductivity that can be expected for natural fractures.

The hydraulic conductivity for a parallel-plate fracture model is defined by (Gale, 1975, among others)

$$k_f = \frac{\rho_f g}{12\mu} (2b)^2 \qquad (2)$$

Equivalent single-fracture apertures (2b) computed from the overall conductivities in Fig. 9 are presented in Table 1 and compared with the measured deformation of fracture B (Fig. 6). The maximum change in theoretical aperture was about 0.16 mm, whereas the corresponding measured closure of this fracture was 0.24 mm. This discrepancy would be even greater if the change in conductivity due to closures of several other fractures, notably C and D (Figs. 6 and 7), were considered. Observation of measured aperture changes exceeding theoretical values is consistent with results reported by Hardin, et al., (1982), who reasoned that such discrepancy is due to the effects of joint roughness and tortuosity of the flow path. This explanation seems to apply in the present case, since flow along each of the major fractures in the Stripa core was observed to be extremely discontinuous at exit points on the rock surface (Thorpe, et al., 1980).

CONCLUSIONS

The lengthy process of retrieving, preparing, and testing a large-volume specimen of jointed rock is difficult and expansive. Moreover, when its properties are dominated by the interactions of a complex system of fractures, the benefits of such tests should be carefully weighed before the work is undertaken. Although valuable experience was obtained from this particular test, an unambiguous analysis of coupled mechanical and hydraulic behavior would have required much more extensive instrumentation than was practicable.

Nevertheless, some general findings are noteworthy. First, the test demonstrated that large specimens can be much weaker than small ones due to the higher likelihood of weak, continuous fractures being present. However, since natural fractures in the large core were partially healed, particularly those which opened upon failure, there was little reduction in stiffness over that which was measured for smaller cores. Permeability tests on the large core indicated that measured closure of the major fractures was greater than the equivalent aperture change calculated by assuming flow through a single parallel-plate fracture.

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Table 1. Theoretical and Measured Aperture Changes

Axial Stress (MPa)	Average Measured k_f (cm/sec)	Calculated Equivalent Aperture (mm)	Calculated Aperture Closure (mm)	Measured Closure, Fract. B (mm)
0	14.64	0.27	0	0
0.85	6.19	0.17	0.10	0.13
2.89	3.59	0.13	0.14	0.20
5.56	2.79	0.12	0.16	0.24
7.40*	7.67*	0.19*	0.08*	0.26

*After sample failure.

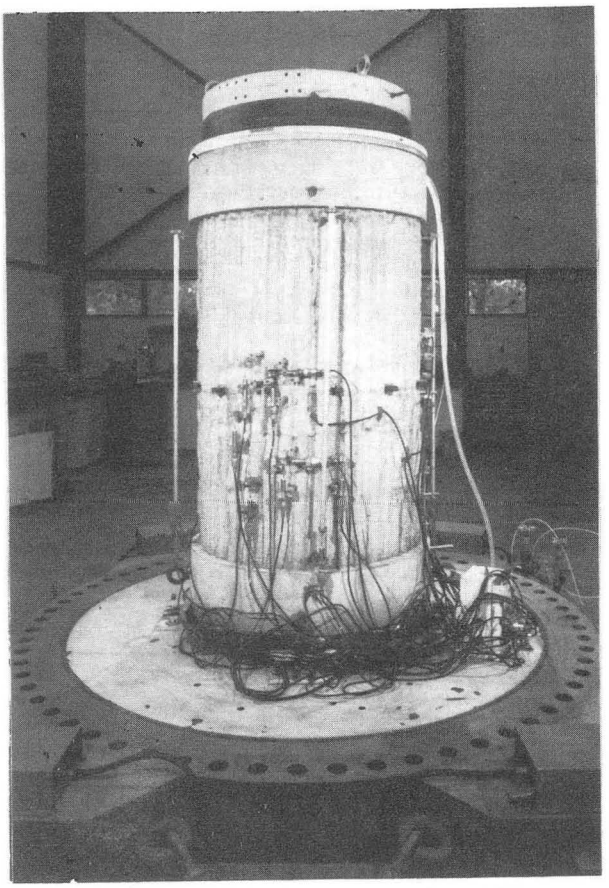

Fig. 1. Instrumented core, showing LVDTs, concrete end caps, loading plates, and base of pressure vessel. Core height is approximately 2m.

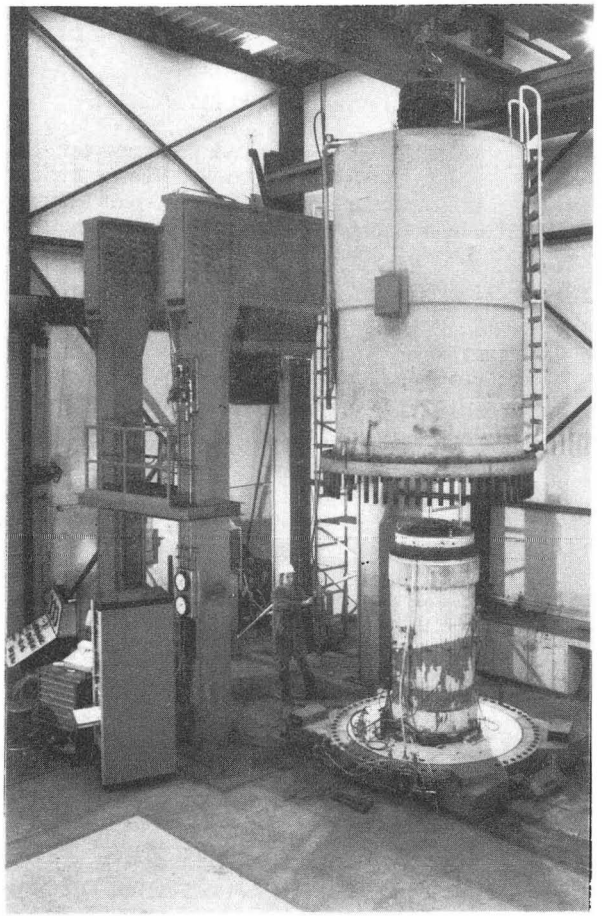

Fig. 3. Triaxial test facility at U.C. Berkeley.

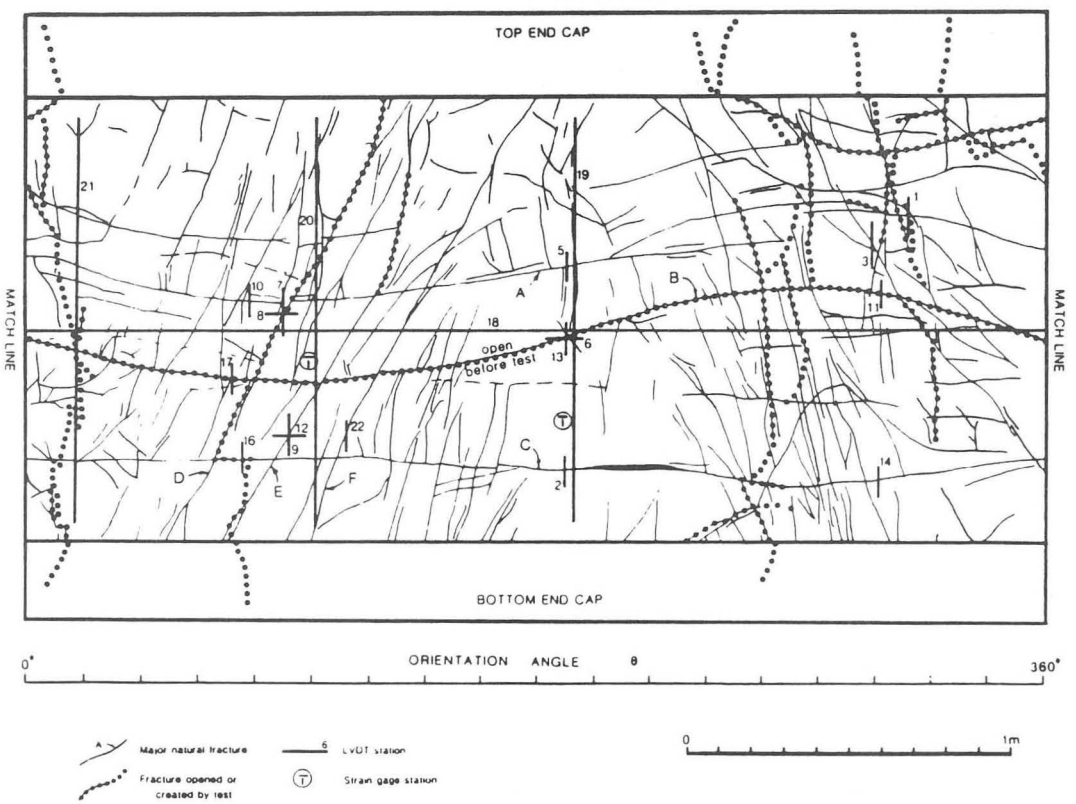

Fig. 2. Post-test fracture map of core, showing locations of LVDTs, strain gages, and opened fractures. Major continuous fractures are labeled A through F.

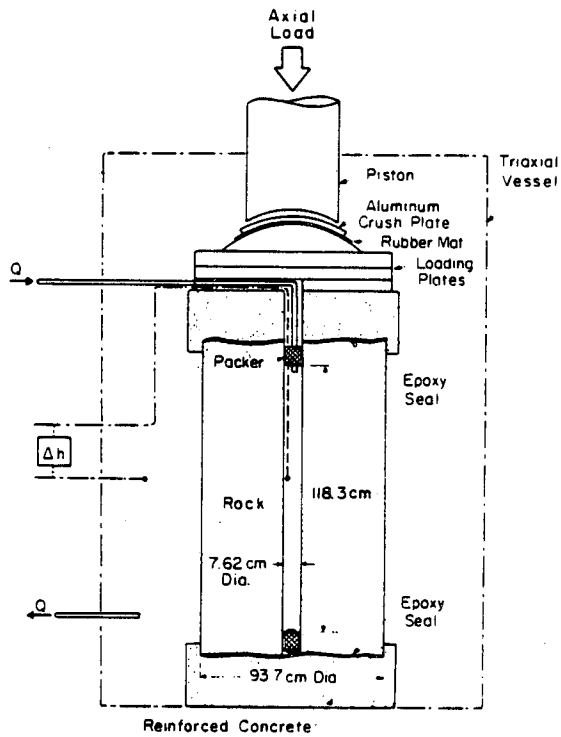

Fig. 4. Schematic of test arrangement.

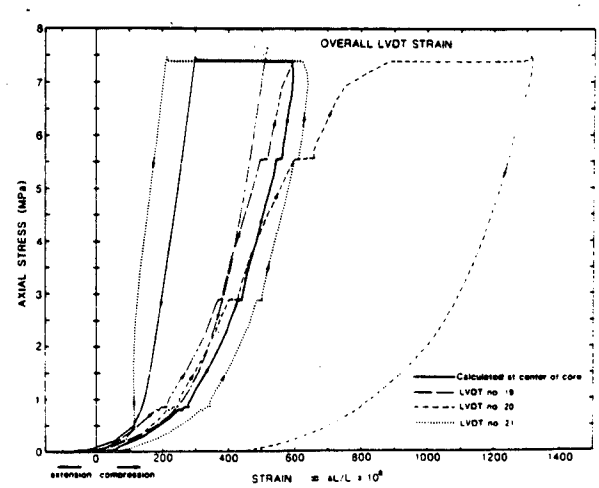

Fig. 5. Stress-strain response calculated from 1.3 m axial LVDT records. Solid line represents strain calculated for axis of core.

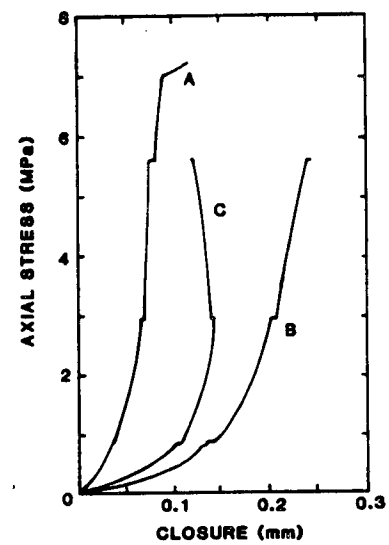

Fig. 6. Average normal displacements on the three subhorizontal fractures A, B, and C.

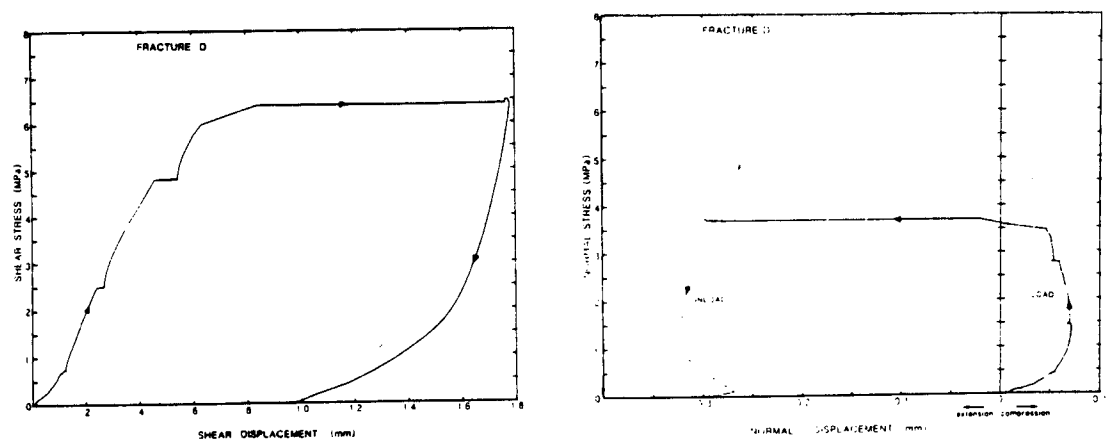

Fig. 7. Average shear and normal displacements on inclined fracture D.

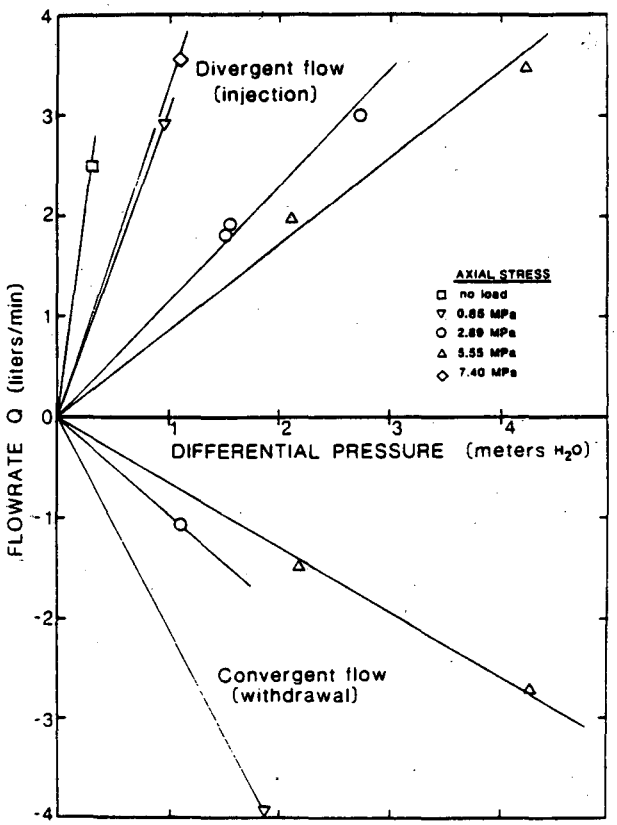

Fig. 8. Measured overall flowrates versus injection or withdrawal head.

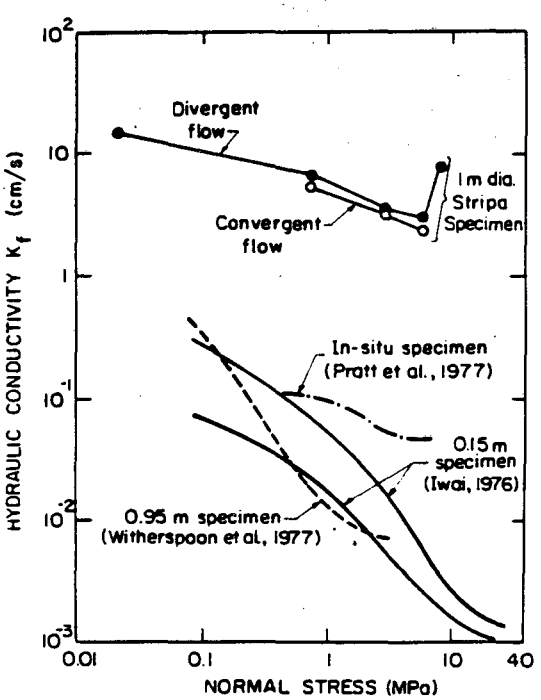

Fig. 9. Equivalent single-fracture hydraulic conductivity for Stripa core compared with previous results.

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