ROCK DAMAGE INDUCED BY DRILLING: AN EXPERIMENTAL ASSESSMENT OF POTENTIAL LEAKAGE AROUND BOREHOLE SEALS

by

S.P. Mathis and J.J.K. Daemen

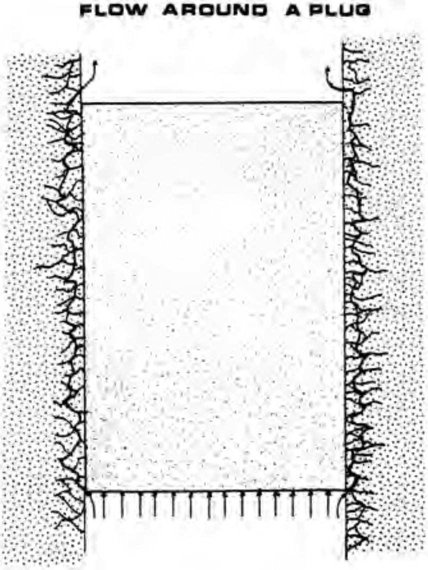
Department of Mining and Geological Engineering
University of Arizona
Tucson, AZ 85721

INTRODUCTION

The effective isolation of toxic or radioactive waste below ground requires that migration to the biosphere of unacceptable quantities of contaminants be eliminated. To accomplish this task, all shafts leading to repositories, repository chambers, exploratory boreholes and disposal boreholes used for waste injection must be sealed (1,2,3). It is the purpose of our study at the University of Arizona, which is funded by the U.S. Nuclear Regulatory Commission, to evaluate the effectiveness of various borehole sealing techniques. As part of this study an evaluation is being made of the amount of cracking (damage) induced in the borehole wall by the drilling operation. The study of the damaged zone is of importance since it must be determined whether or not this zone should be considered as a flow path around the plug (2,3,4)(Fig. 1).

The study deals exclusively with the evaluation of the physical characteristics of the damaged zone created while drilling small diameter percussion and diamond holes in granitic rocks, Leatherwood Quartz diorite, and Catalina Granite. The drilling methods were chosen because they represent extremes of energy input to the rock, percussion drilling being the most energetic and diamond the least energetic of all common drilling techniques. Granitic rocks were chosen for two reasons:

1) They are being considered as host rocks for nuclear waste repositories (2,5,6).
2) Suitable rock types were located near enough to the University of Arizona to cause no complication in the collection of samples and the performance of field drilling operations.



FLOW AROUND A PLUG

Fig. 1. Sketch of a potential flow path within the damage zone. Experimental results obtained suggest that the interconnecting network of cracks sketched is unlikely to develop in practice.

The testing techniques used to evaluate damage zone characteristics are based primarily on visual inspection of the zone and the evaluation of the rock strength within the damage zone.

LABORATORY TESTING

Sample Collection

The samples tested in this study are either two-inch diameter cores with a 1/2-inch center hole or six-inch diameter cores with a 1 1/2-inch center hole of Leatherwood Quartz diorite or Catalina Granite. The two-inch diameter cores were prepared by drilling blocks of rock in the Rock Mechanics Laboratory at the University of Arizona with an electric drill press fitted with a diamond bit or with a Milwaukee electric hammer, Model 5351, commonly used in construction. The six-inch diameter cores were retrieved by field drilling operations with a Joy 12B diamond coring rig and a Gardner-Denver 83 jackleg percussion drill. Holes of approximately 1 1/2 inches were drilled by percussion and by diamond drilling, then overcored with a 6-inch diameter diamond core bit. Variations in rock properties were randomized by alternating between diamond and percussion drilled 1/2 inch holes spatially around a rock block, and alternating between 2 foot diamond and percussion drilled lengths down hole for the field drilled samples. This procedure should minimize or eliminate the effect of variation both horizontally and with depth.

Preliminary Fluid Flow Measurements

The initial experiments performed were aimed at obtaining a direct measurement of the influence of the damaged zone on radial flow from or to a borehole. For this purpose a falling head radial permeameter was constructed, to test samples of 2-inch diameter, 4-inch length, with a 1/2-inch coaxial hole (Fig. 2). Samples were tested under a head of approximately 10 ft. The results of these measurements were inconclusive. The low driving pressure resulted in very low flow rates, which were so small as to make the results meaningless with respect to the experimental error. Nevertheless, the experiments confirmed that it would be very difficult to obtain direct measurements of the flow through the damaged zone. This confims that the damaged zone probably is not of major significance with respect to sealing effectiveness. It also was a major argument for going to indirect tests, easier to perform and possibly more sensitive.

Fluorescent Penetrating Dyes

The principle behind the use of fluorescent dyes is that the dye will enter cracks in the rock and highlight them under blacklight illumination. The testing sequence is as follows:

1) Cut core into disks by use of a diamond rock saw.
2) Spray penetrant onto surface of rock disk.
3) Let stand for the experimentally determined penetration time.[a]
4) Remove all excess penetrant from the surface with "cleaner-remover" compound.
5) Spray a thin film of "developer" onto the disk to bring penetrant trapped in cracks to the rock surface, thus highlighting the cracks.
6) Photograph the prepared rock sample.

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[a] The experimentally determined penetration time is that time which will allow maximum penetration of cracks without beginning to sature rock pores. It is usually on the order of 1-3 minutes

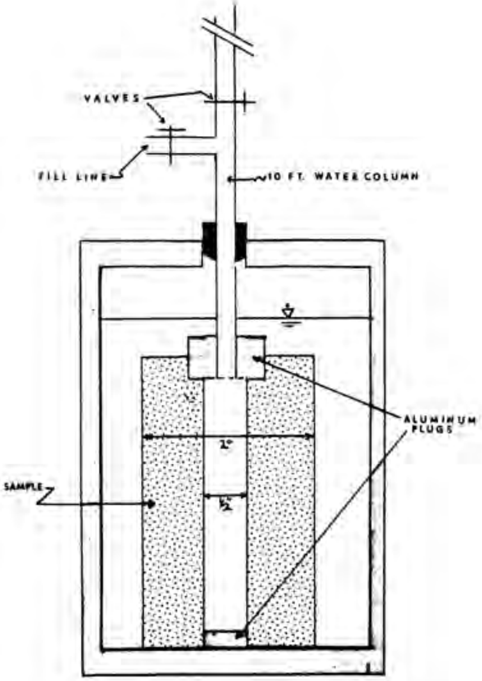


Fig. 2. Cutaway of falling head radial permeameter.

All of the above steps are to be performed under blacklight illumination except cutting the rock and spraying on the "developer". In a darkened room, experience has shown that the developer can best be seen under red light.

This test allows direct viewing of the damage zone which appears as a bright band surrounding the hole (Fig. 3).

Ring Tension Test

The ring tension test is designed to measure the tensile strength of rock disks with a small center hole (7). The tensile strength is measured at the center hole boundary (i.e. within the damage zone - a very attractive characteristic of this test for our study). A lower tensile strength in this area is an indicator of weaker rock and therefore more damage.

Fig. 3. Sample of fine grained Catalina Granite treated with penetrating dye. Note the damage zone, enhanced by the dye, particularly visible on the upper (in photograph) periphery of the hole. The above 6-inch diameter disk contains an overcored 1 1/2-inch percussion drilled hole, with a frequently observed pentagonal shape.

The test is performed by diametrically loading a rock disk to failure with a hydraulic loading device (Fig. 4). The center hole acts to concentrate the tensile stresses and therefore causes tensile failure to initiate at the points where the loaded dimaeter crosses the center hole boundary. This is the point of maximum stress concentration. After failure the tensile strength may be calculated by any one of several formulas. Since only relative tensile strength values are sought, consistent use of any of the available formulas that takes into account inner and outer disk radius, disk thickness and center hole eccentricity will be acceptable to use for comparison purposes.

Petrographic Microscope Inspection

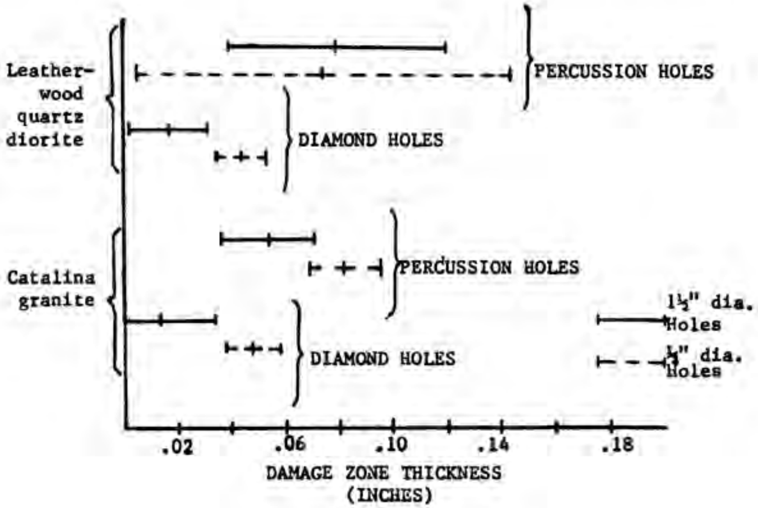
The study of the borehole wall with a petrographic microscope serves to directly illustrate the geometry and density of cracking within the damage zone. Samples are cut from various locations along the hole (perpendicular to the hole, along the length of the hole and at the hole bottom) and then ground in oil to form thin sections. The thin sections are observed under a microscope and photographed to yield information concerning the geometry, location , and density of cracking.

Fig. 4. Test set-up for ring tension test.

RESULTS OF TESTING

To date, fluorescent dye results have been obtained for the Leatherwood Quartz diorite and the fine-grained phase of the Catalina Granite, with the ring test yielding results for all three rocks (the Leatherwood and both the fine and coarse phases of the Catalina Granite). However, since only a very few rings were available for the Leatherwood due to the poor quality of core obtained from the field, interpretation of results is questionable. Therefore, the ring test results for the Leatherwood Quartz diorite have not been included here. A complete listing of results is given in (8). Petrographic microscope studies have been conducted for the Leatherwood Quartz diorite only.

The following plots (Fig. 5) show a summary of results from the fluorescent dye test performed on samples with 1/2-inch holes and 1 1/2-inch holes (approximately 10 samples of each rock type - hole type combination). Figure 5 also shows a summary of the results from the ring tension test performed on samples with 1 1/2-inch holes (approximately 15 samples of each rock type - hole type combination). The results are represented as the means with bars indicating one standard deviation. Observations



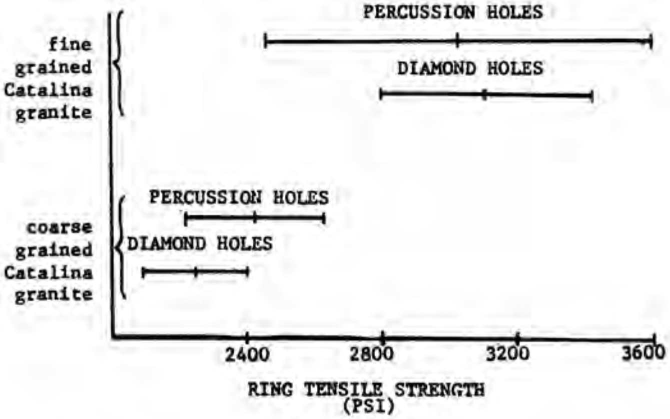


Fig. 5. Results of fluorescent dye (top) and ring tension tests. Means ± one standard deviation are shown.

made during the petrographic microscope study are recorded on a series of photographs not included herein; however, these may be found in (8) along with the listing of all other test results such as those from the ring test performed on samples with 1/2-inch holes.

CONCLUSIONS

The results from the fluorescent dye testing indicate that even though the width of the damage zone is small (on the order of a few hundredths of an inch), there is a noticeable difference in the width of the zone surrounding diamond and percussion drilled holes. Percussion drilling induces a greater depth of damage than does diamond drilling. The fluorescent dyes also illustrate that the damage zone thickness does not increase with increasing hole diameter. When comparing damage around a 1/2 inch hole with the damage around a 1 1/2 inch diameter hole, it can be seen that the amount of induced damage is slightly greater around the 1/2 inch holes or it can be considered the same since the difference is relatively little. This implies that the degree of induced damage may be independent of hole diameter.

The results from the ring test support the conclusion that the damage zone is small. The overlap of test results indicates that there is not a large enough amount of rock damaged to alter the intact ring tensile strength of the rock.

The results of the petrographic microscope study indicate that the geometry of cracking is random. No trends can be noticed that could lead to the conclusion that cracking is typically radial or concentric. Another observation from the microscope study is that noticeable cracking is primarily restricted to within grains, and interconnection of cracks across grains is limited.

The results obtained to date indicate some very important facts concerning the damage zone caused by drilling. It appears that the damage zone need not be considered a major flow path to be separated from flow along the plug-rock interface. The amount of rock affected by damage is quite small and the cracking within the damage zone shows little interconnection. Both of these facts severely limit the flow through this zone.

ONGOING WORK

At present all three of the above mentioned testing procedures are continuing. In addition, radial permeameter testing is being conducted to obtain information on relative plug performance within the diamond and percussion drilled holes. The procedure for performing these tests is modelled after that discussed by South (9) and is as follows:

1) Obtain a 12-inch length of field drilled core (6-inch diameter with 1 1/2 inch center hole).

2) Grind ends smooth and epoxy circumference of cylinder.

3) Saturate sample with de-aired, deionized water.

4) Place a 4 inch cement plug midway in sample by pouring cement mixed by American Petroleum Institute Specifications (10) onto a rubber stopper located 4 inches from hole base.

5) Allow cement plug to cure submerged for a period of time in excess of two weeks.

6) Place sample in radial permeameter and subject it to 3000 psi axial and 2800 psi confining pressure.

7) Inject water above plug at a pressure of 1500 psi and collect water beneath plug at atmospheric pressure

8) Monitor flow for a minimum of six hours.

9) Change water injection pressure and rerun test.

10) Remove sample and replace with a prepared sample of same rock type with the other hole type.

11) Repeat test.

Figure 6 shows a sketch of the testing set-up.

The above stated procedure will give information concerning the relative ease of plugging diamond and percussion drilled holes for a given rock type. To obtain information concerning different rock types, additional tests must be performed.

Along with the laboratory studies being conducted, theoretical evaluation of the amount of damage to be expected around a borehole is being performed. This study is involved with first evaluating the cutting mechanism of the drills in question and extending this to obtain approximations of the forces exerted on the rock during drilling. These forces are then used as input to a finite element program and the stresses generated near the bit are calculated. The mesh used to model the drill hole - bit system can be seen in Fig. 7. The elements used are axisymmetric and a vertical confining pressure is used to simulate overburden pressure. Percussion drilling is simulated by inputting a single time varying pulse along the symmetry axis, while the diamond drilling process is modelled with static vertical and tangential forces being imposed away from the axis of symmetry. Once the stress distribution during drilling has been calculated, a simple failure criteria will be imposed on the rock to estimate to what distance away from the borehole wall cracking is likely.

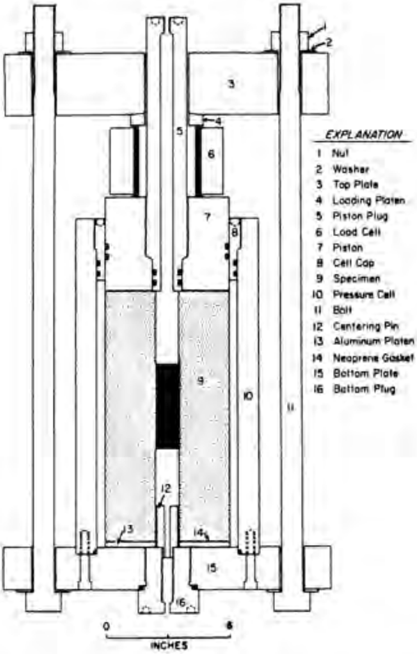


Fig. 6. Cutaway of permeameter test cell. Water is injected through piston plug (from 9).

Neither the permeameter study nor the finite element modelling have progressed far enough to have yielded results at this time. To date, the permeameter study is at the sample preparation stage while the finite element study has proceeded to such a degree that the method of inputting data has been checked with a known solution and the method for reducing results has been finalized.

ACKNOWLEDGEMENT

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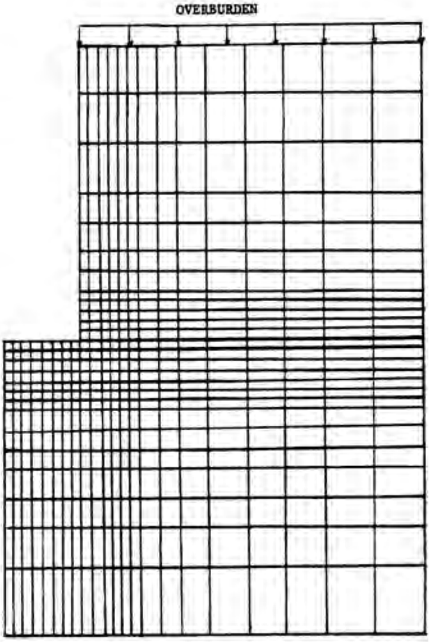

Fig. 7. Simplified representation of mesh to be used in finite element model. Actual mesh is made up of 522 axisymmetric elements, and represents an area of 5 1/2 inches x 7 inches.

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