INITIAL RESULTS OF TUFF BOREHOLE SEALING EXPERIMENTS

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ABSTRACT

Laboratory and field experiments are in progress to determine the performance that can be expected of cementitious and of earthen (bentonite) seals when emplaced in welded tuff.

Laboratory testing includes materials characterization testing, radial permeameter testing of cementitious borehole plugs emplaced in welded tuff cylinders, flow testing of bentonite and of bentonite/crushed tuff plugs, axial strength of cementitious borehole plugs emplaced in welded tuff, and fracture grouting experiments. Experimental work is performed in Apache Leap tuff, a formation exposed in east-central Arizona. Mineralogical, chemical, hydrological and mechanical characterization shows reasonable similarity between the Apache Leap tuff and the Topopah Spring tuff, the proposed Yucca Mountain repository host formation. The main conclusion from the mechanical characterization testing is that the tested tuff, not unexpectedly, is an extremely heterogeneous rock, with highly variable properties. A second notable observation is the extremely low saturated hydraulic conductivity of intact welded tuff, notwithstanding its very high porosity.

Mixtures of bentonite and crushed tuff show that samples containing 25 or 35 percent bentonite (by weight) have permeabilities of the same order of magnitude as similarly prepared and emplaced samples consisting of bentonite only. Permeability is noticeably pressure-dependent.

Short-term bond strengths of cementitious seals emplaced in tuff cylinders are moderately high, in the range of 3 to 8 MPa, with considerable variability. Results indicate a marked decrease in strength with increasing plug (or borehole) diameter. A pronounced strength loss occurs at 90°C, but not at 70°C.

INTRODUCTION

Shafts, ramps, drifts, and boreholes that penetrate the geological barrier surrounding an HLW (High Level Radioactive Waste) repository probably will have to be sealed. Sealing will prevent excessive flow of water and gas along such openings which, without sealing, form low resistance preferential flowpaths through the rock mass. Given the uncertainty about fluid flow circulations within rock masses, particularly when enhanced by a changing thermal driving force, it must be deemed prudent to assure that adequate sealing technology will be available to preclude flows that might prevent a repository from meeting regulatory performance requirements.

This paper presents an overview of ongoing research conducted at the University of Arizona supported by the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC). The objectives of the research include experimental evaluation of sealing technology, developing independent technical information in support of NRC reviews of U.S. Department of Energy (DOE) license applications, and identifying potential problem areas, i.e. anticipatory identification of technical issues that might hamper or delay repository licensing decisions.

The investigation is focused on evaluating proposed sealing methods for an eventual HLW repository at Yucca Mountain, Nevada. A repository at this site would be placed in an unsaturated volcanic ash flow tuff formation with relatively high porosity, at some distance above the water table. Heat generated by the emplaced waste is expected to boil off water in the host rock close to the waste. This water will condense at some distance from the waste, possibly leading to local saturation. Similarly, thermally driven airflows will develop. Both water and air are potential radionuclide carriers. All fluid flow patterns will change with time. In light of the fact that it probably will be some time before reasonable assurance and scientific consensus is reached about potential radionuclide migration, it is prudent to provide barriers within some of the most obvious potential flowpaths. Exploratory boreholes that penetrate the host formation within the contours significantly affected by thermally driven flows and that are deep enough to penetrate or come close to the water table are prime candidates for forming preferential water flowpaths. All excavations or openings, particularly those leading directly to the surface, such as ramps, shafts and holes drilled from the surface, could facilitate both water and gas flow to the surface, and water inflow towards the repository. All excavations or openings constitute preferential flowpaths for gas

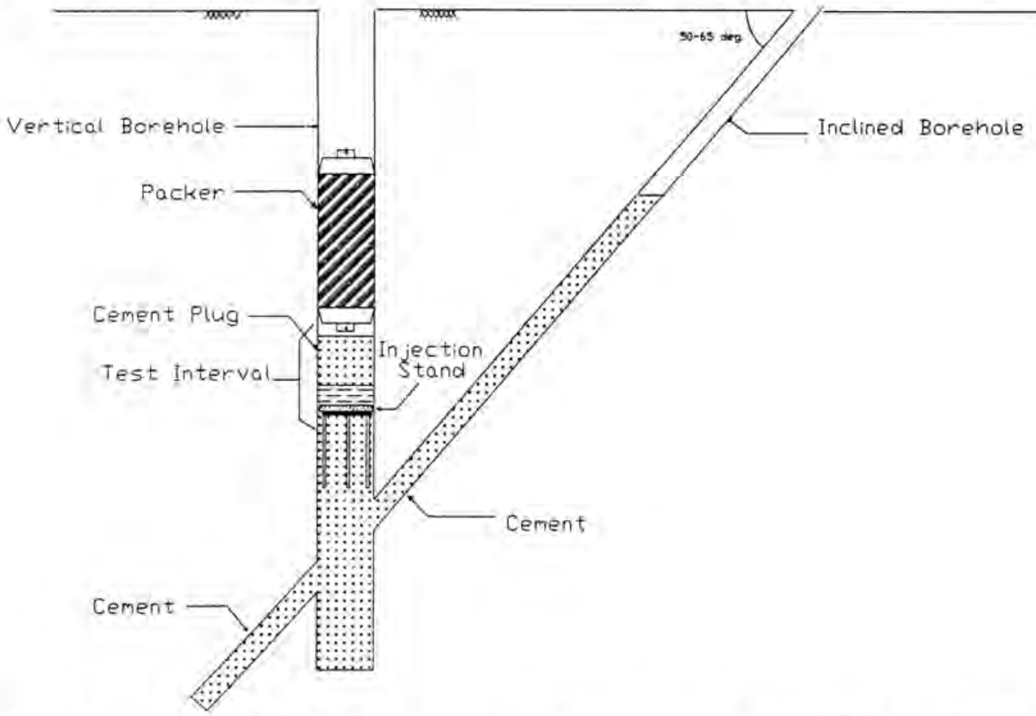

Fig. 1. Field arrangement for borehole plug testing. A cement plug is installed in a vertical 150 mm diameter borehole. An injection stand with four tubes leading to the surface through the inclined hole has been emplaced below the plug to be tested, allowing various combinations of pressurizing above and below the plug to be tested. The bottom sections of both holes have been backfilled with cement in order to minimize water flow.

circulation. Depending on local saturation conditions, they may or may not form preferential water flowpaths.

SEALING INVESTIGATIONS

The seal performance evaluations in progress include testing of the two types of seals most likely to be used for repository sealing: cementitious seals and earthen (bentonitic) seals. To simulate a testing environment reasonably similar to what may be anticipated at Yucca Mountain, many tests are conducted on seal materials emplaced in samples of Apache Leap tuff. The samples are prepared from the densely welded horizon of the brown unit of the Apache Leap tuff, a tuff fairly similar to the densely welded Topopah Spring tuff in terms of composition, and hydrological and mechanical properties (1). In-situ testing is conducted in an Apache Leap outcrop east of Superior, Arizona, where also samples are collected for laboratory testing.

Bentonitic sealing materials are prepared with a commercial well-sealing grade Wyoming bentonite, American Colloid c/s granular. Cementitious sealants are prepared with Dowell-Schlumberger Self-Stress II, a Portland cement to which expansive and fluidizing agents are added.

Field Testing

Field testing consists of long-term in-situ flow testing of borehole seals emplaced in welded tuff. One in-situ test is in progress on a cement plug. A second field test is in the final preparation stage. The layout of the field test configuration is shown in Fig. 1 (2). Vertical 150 mm diameter holes are cored to a depth between 6 and 8 m. Angled 57 mm diameter holes are cored to intersect the vertical holes at about 1 m above the bottom of the vertical hole. The core is logged, the hole walls are videologged, and the hydraulic conductivity of the holes is determined by packer testing. A location free or relatively free of fractures and of low hydraulic conductivity is selected for plug emplacement. The intersecting hole below the plug provides access to the bottom of the plug, thus providing considerably more testing flexibility than when access is available to only one side of a plug. After the instrumentation below the plug is installed, the lower sections of both holes are filled with cement to reduce water losses. Steady state flow testing has been started on one plug. *Initial results indicate* a very tight hydraulic bond between seal and host rock, with a system hydraulic conductivity probably of the same order of magnitude as that of intact welded Apache Leap tuff (10^{-9} to 10^{-12} cm/s). Steady-state testing will be followed by transient (pulse) testing and by tracer testing.

Laboratory Testing

Laboratory testing consists of testing hydraulic sealing performance of cementitious and of earthen plugs, a primary performance requirement, as well as strength testing.

Flow Testing Of Cement Borehole Plugs

Neat cement grout is emplaced in hollow tuff cylinders. Cylinders nominally are 15 cm in diameter, 30 cm long, and have a coaxial hole of 2.5 cm diameter. A 2.5 cm long cement plug is emplaced near the center of the hole (Fig. 2). A typical test sequence proceeds by first testing a cylinder with a rock bridge left in place (i.e. coaxial holes are cored from both ends of the cylinders, leaving an intact rock section of about 2.5 cm long. The cylinder is emplaced in a radial permeameter (Fig. 2). Axial and lateral stresses are applied to the cylinder. Flow testing is conducted by injecting water into the top hole and collecting outflow in the bottom hole. Flow testing is performed for a range of axial and lateral stresses, to determine the sensitivity of the hydraulic conductivity of the rock to the stress field. Determination of the hydraulic conductivity is performed both on the basis of simplifying analytical solutions and by means of axisymmetric finite element flow simulations.

Upon completion of testing on the rock bridge, the rock bridge is cored out (while the cylinder remains pressurized). A cement (or, as planned for future tests, an earthen) seal is emplaced. The test series is repeated. A relative determination of the seal performance, i.e. a comparison of the seal hydraulic conductivity with that of the rock is possible based directly on the flow rates. A more detailed determination of seal hydraulic properties requires bounding analytical or comprehensive numerical analyses (3).

Initial testing has been complicated considerably by the extremely low hydraulic conductivity of the rock tested (probably 10^{-12} cm/s), resulting in flows and flowrates near, if not below, the resolution limit of the test equipment. As a result, even minute leaks can significantly affect test results.

Flow Testing Of Earthen Borehole Plugs

Bentonite is widely considered to be a promising candidate for repository sealing, because of its longevity in nature, low hydraulic conductivity, sorptive properties, and healing capacity. Testing in progress, described in more detail in a companion paper (4), and in a technical report to be prepared (5), focuses on the sealing performance that might be expected from mixtures of crushed tuff and bentonite. Supporting work includes measurements of the hydraulic conductivity of bentonite itself, as a function of pressure gradients and temperature, and determination of water content. Closely related and discussed briefly later is an investigation of fracture sealing with bentonite slurries.

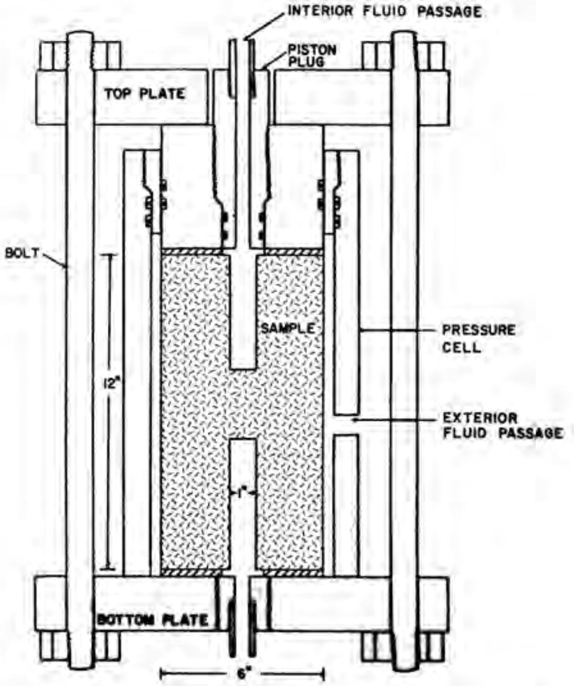

Fig. 2. Radial permeameter. A rock sample with coaxial holes cored from each end is placed in the pressure cell, and loaded axially in between the top and bottom plates by means of bolts. Lateral fluid pressure can be applied through the exterior fluid passage. Fluid can be injected into the top and collected from the bottom, or vice versa.

Early results of testing of compacted samples consisting of crushed tuff and 25 or 35% bentonite confirm that such combinations can provide a hydraulic conductivity of the same order of magnitude as that of seals constructed of the same type of bentonite only. A primary focus of the investigation is to determine the conditions under which bentonite displaces or flows through the pore space in between the crushed tuff particles. Under certain pressures or hydraulic gradients, bentonite flows into relatively small (in our experiments, 2.25 mm circular hole) openings in the wall of the seal container. Such a bentonite flow may be beneficial, because it may assist in sealing openings in the host rock in which a seal is emplaced. An excessive bentonite loss from the seal would detract from sealing performance of the seal itself. Long-term performance predictions of seals containing bentonite may need to address the question of bentonite loss over time, e.g. as influenced by pore space, size and connectivity in the host rock, by driving forces, and by the rheological flow characteristics of the bentonite.

An additional potential problem is the relatively high hydraulic conductivity measured in the transverse direction of compacted bentonite and crushed tuff seals. All indications are that this high transverse conductivity is due to inadequate bonding between sequentially emplaced and compacted seal layers. Transverse hydraulic conductivity may be of particular concern in a repository environment, where thermally driven flows are likely to be multidirectional as a function of time. Pressure gradients and flow directions will change, as a minimum as a result of heating and cooling.

In sum, hydraulic conductivity measurements for seals constructed by compacting crushed tuff and bentonite confirm that engineering excellent seals is possible, but that conditions under which severe performance deterioration may occur need to be identified, and taken into account in seal design.

Bond Strength Testing Of Cementitious Borehole Plugs

Because of the tightness of the hydraulic bond between seals of interest for repository sealing and the surrounding host rock, measurements of seal hydraulic conductivity require lengthy testing. A large number of variables, ranging from an infinite variety of seal compositions and host environmental conditions (temperature, stress, pressure gradient, permeant and rock chemistry) combine to preclude obtaining statistically significant results for a comprehensive representative set of conditions. Flow testing, for all practical purposes, is and will be limited to a relatively limited number of conditions.

Mechanical bond strength testing can be conducted in a small fraction of the time needed for hydraulic testing. As such, it forms an attractive alternative test method for characterizing seal performance. While it has been assumed or implied that mechanical bond strength is an acceptable alternate to hydraulic bond testing, the evidence for such a substitution is largely judgmental and circumstantial. The mechanical bond strength is a significant seal performance parameter in its own right, in that the interfacial strength between a plug and a host rock determines the load that can be taken by a plug without risking dislodging the plug (6,7,8).

The mechanical bond strength is determined by means of push-out testing (Fig. 3). Neat cement grout plugs are emplaced in hollow tuff cylinders. After curing, the bond strength is tested by loading the plug until failure occurs. Variables investigated include plug diameter, plug length, temperature, and degree of saturation of the host tuff in which the plug is emplaced. The existence of size effects on bond strength has been suspected to exist for some time (9). Results obtained here have allowed a clear definition of such size effects (Fig. 4). While it would be highly desirable to complement the results obtained so far with tests on significantly larger plugs, even the size relation as defined so far should be of considerable help in extrapolating design bond strength for plugs in larger openings such as shafts and

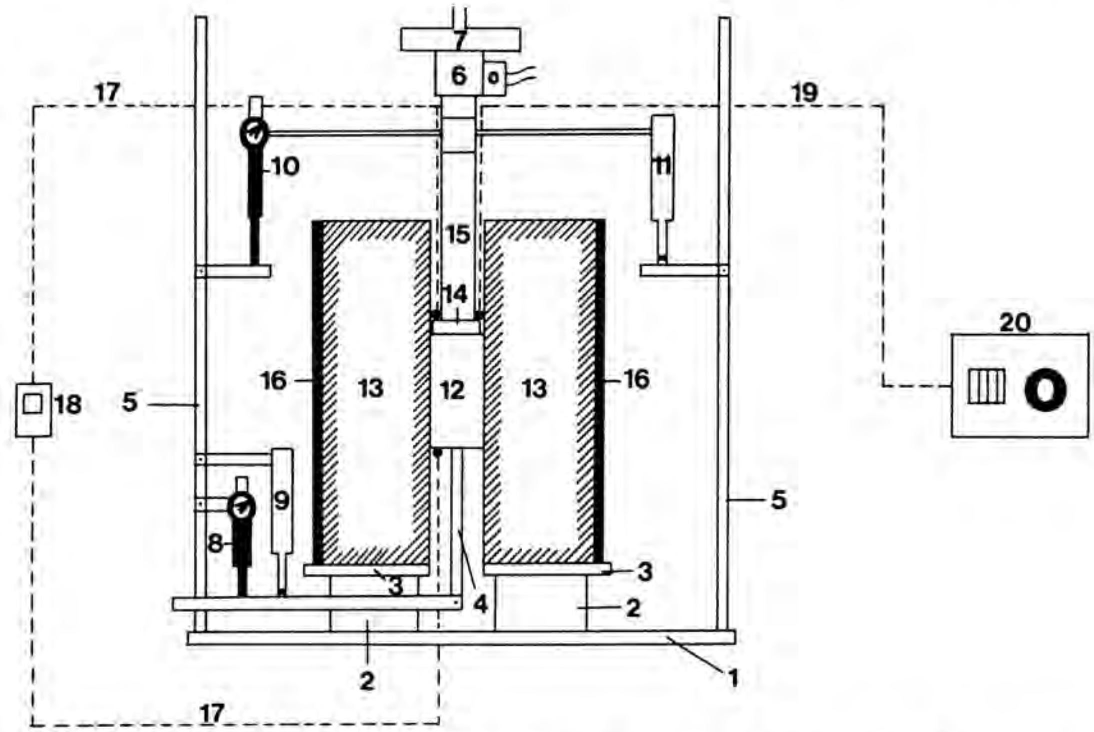

Fig. 3. Push-out test arrangement. Cement plug (12) is placed in tuff cylinder (13). An axial load is applied to the plug through steel plate (14). Redundant displacement monitoring is performed for top and bottom of the plug (10, 11, 4, 17).

drifts. Insufficient evidence presently is available with regard to the influence of saturation effects to draw firm conclusions. Preliminary results, however, strongly suggest that a noticeably lower strength may exist along the interface of plugs emplaced in tuff with a water content significantly less than that required for full saturation. The strength loss is not nearly as severe as for plugs tested previously under extreme drying conditions (10). A limited number of tests performed to date, marginally sufficient to allow statistically valid conclusions, suggest a modest strengthening effect for temperatures up to about 45° to 65°C, and a substantial strength loss at 90°C.

The highly nonuniform distribution of shear stresses along the interface is difficult to measure either directly or indirectly, and greatly complicates the interpretation, comparison, and, in particular, extrapolation of bond strength measurements. Preliminary theoretical approaches to provide a rational approach for such extrapolations are give in (8).

Fracture Sealing

Fractures in the host rock surrounding seals frequently form preferential flowpaths that allow by-pass flow around seals. For that reason, it is common practice to grout the rock in which underground dams are emplaced.

Fracture sealing studies are in progress on cementitious grouts and bentonitic grouts. Both grout types are being characterized in several ways. The risk of water loss is measured by means of bleeding tests, and the rheological properties, e.g. yield stress, cohesion and viscosity, are determined as a function of composition, particularly water content.

Fracture grouting is being studied in two different ways, first by testing the sealing effectiveness of grouting natural and artificial fractures in rock, and second by grouting studies on models of fractures in which grouting processes can be studied in more detail. For rock fracture grouting investigations, the initial fracture characterization consists of detailed mapping of the fracture roughness (Fig. 5), and of determining the hydraulic conductivity and the equivalent aperture of the fracture as a function of normal stress. Hydraulic testing is repeated after grouting. Early results confirm previous observations (11) that extreme care must be taken in interpreting changes in hydraulic conductivity resulting from grouting measured through the injection hole as indicators of the quality of grouting achieved. Orders of

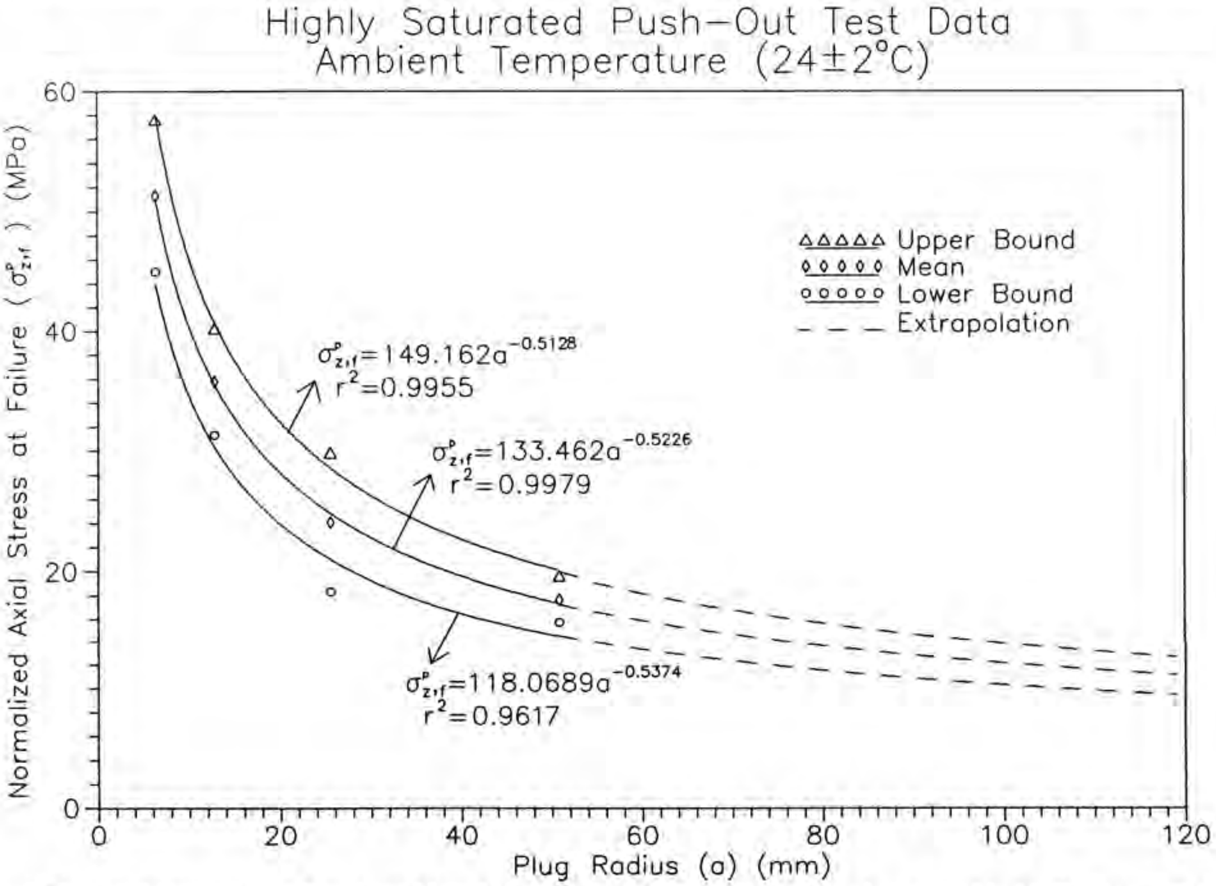

Fig. 4. Push-out strength as a function of borehole radius. Self-Stress II cement plugs in welded tuff. (From (8).)

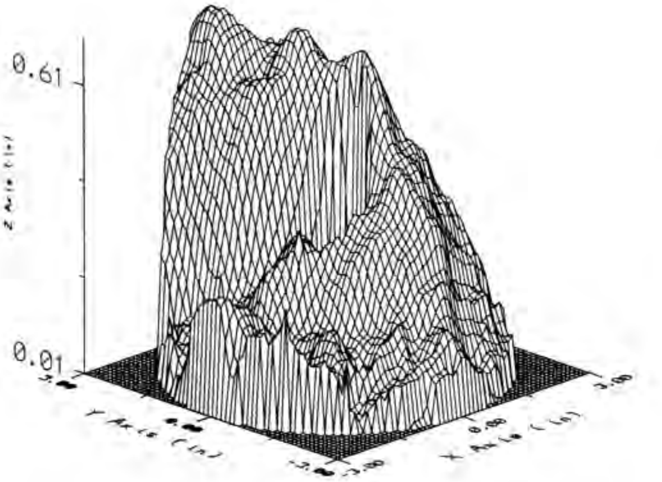

Fig. 5. Surface profile of a natural fracture across a 15 cm (6 in) diameter welded tuff core.

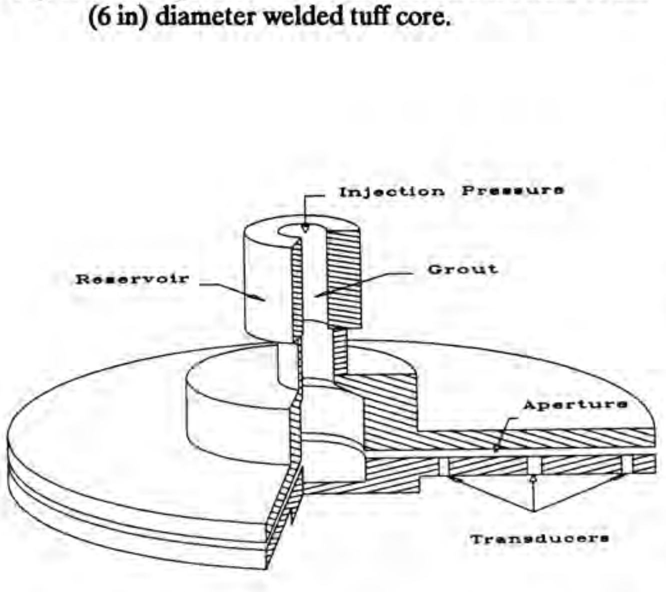

Fig. 6. Simulated fracture grouting model. Two parallel plates are clamped together around the edges with a ring of bolts (not shown). Central injection hole is used for flow testing and grouting. Pressure transducers monitor pressure distribution along one radius.

magnitude changes in hydraulic conductivity can result from grout emplacement directly around the injection hole. Minor emplacement, blocking a few channels, i.e. a minute fraction of the fracture area, can suffice to drastically reduce the permeability, as measured from the injection hole, without significantly reducing the permeability of the fracture itself. Severe bleeding, filtering or water loss has been observed during injections into very fine fractures of conventional cementitious grouts of Portland cement containing a few percent of bentonite (12).

Continuing fracture grouting studies will include grouting with microfine cement, in which particle sizes are much smaller than in conventional cement, and identification of preferential flow and grout paths. The latter will be determined by visual inspection and recording, and will be compared to flow channels calculated from the detailed maps of the joint geometry.

Bentonite slurry grouting of fracture models (Fig. 6) is conducted for a range of injection pressures and apertures. The objectives of these experiments include an experimental verification of he predictability of grout injection, e.g. as a function of injection pressure, aperture, and grout properties. Continuing experiments will include investigations of the hydraulic conductivity of grouted fractures and of the erosion resistance of the grout in the fractures.

Early observations during, and especially after, bentonite slurry injection into simulated fracture models reveal a complex grout distribution, for the extremely thin "fractures" grouted to date. Injection proceeds after a breakthrough pressure is reached. This breakthrough pressure presumably is related to the normal force applied to the parallel plates by the edge bolts, and to the stiffness of the plates. The applied edge forces simulate an in-situ (normal) stress, the plate stiffness a rock mass stiffness. Upon release of the injection pressure, grout flows backwards towards the injection hole occurs, presumably due to the rebound of the plates. For models left in air, a slow development of air channels takes place from the outside edges towards the center hole. These early model observations strongly suggest the complex sequence of events that may take place during the grouting of fractures in rock under stress. Further investigations are aimed at clarifying the mechanics and parameters that influence ultimate grout distribution and sealing effectiveness.

SUMMARY AND CONCLUSIONS

A brief overview is given of a research project on sealing of boreholes in progress at the University of Arizona for the U.S. Nuclear Regulatory Commission. Details of the studies and of the results are provided in technical reports to the Commission.

Field testing of one cement borehole plug is in progress, and indicates excellent hydraulic bonding with the host tuff. A second test installation is in the final preparation stages.

Laboratory flow testing of cementitious and of bentonitic materials is conducted for seals emplaced in tuff, steel and PVC permeameters. Testing of seals constructed of mixtures of crushed tuff and bentonite confirms that such seals can be designed and emplaced such as to give a hydraulic conductivity similar to that of bentonite only. Seals as constructed to date have preferential transverse flowpaths along the contact planes between layers. Bentonite flow through the bulk pore space in between the crushed tuff particles, and into openings in the host wall has been observed under some (high) pressure gradients.

Push-out testing of cementitious plugs emplaced in welded tuff has made it possible to define a relation between bond strength and plug size. Although confirmation in the larger size ranges would be highly desirable, this relation will allow a more realistic assessment of friction plug designs than has hitherto been possible.

Fracture grouting investigations are in the early stages, but have confirmed some characteristic complexities, e.g. the need for extreme care in interpretation of flow tests performed in grout injection holes in terms of fracture sealing effectiveness, and complexity of ultimate (long term) grout distribution along fractures on which external stresses act.

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