LABORATORY ASSESSMENT OF THE EFFECT OF DRYING ON THE PERFORMANCE OF CEMENT BOREHOLE PLUGS

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ABSTRACT

Boreholes and other manmade penetrations in the vicinity of underground nuclear waste repositories must be sealed to prevent rapid migration of radionuclide-contaminated water to the biosphere. Tests have been conducted to assess the performance of cement borehole plugs in granite. Steady state flow tests show the permeability of intact granite to be in the order of 1E-08 darcy. The permeability of saturated cement plugs is a degree of magnitude lower, i.e. 1E-09 darcy. Cement plug performance is significantly impaired when plugs dry; however, partial performance recovery occurs upon resaturation. The permeabilities of cement plugs after drying periods of three and seven months at room temperature are 1E-05 darcy and 1E-03 darcy, respectively. For oven-dried cement plugs, the permeability increases to 1E-06 darcy after five days of drying at a temperature of 90°C.

INTRODUCTION

The disposal of high-level nuclear wastes (HLW) in underground geologic repositories creates the risk of radionuclide release through manmade penetrations in the rock mass. One of the most likely ways by which radionuclides may return to the surface is by means of ground water transport. Manmade penetrations such as an open borehole in the vicinity of a geologic HLW repository clearly compromise the integrity of surrounding rock in slowing down the waste migration. All such penetrations must be sealed reliably in order to prevent rapid migration of radionuclide-contaminated water to the biosphere.

Concern about these manmade penetrations and their potential influence in the isolation performance of rock masses surrounding the repositories has been expressed in a number of basic reviews on underground HLW disposal (1,2,3,4,5,6,7,8,9,10,11). Although borehole plugging has been performed for decades by the oil and gas industry, few measured data are currently available regarding its effectiveness.

The research program reported herein addresses the sealing of boreholes, as a form of manmade penetrations, using cement plugs. More specifically, the objective is to assess the performance of model cement borehole plugs in granite, and their plugging effectiveness, under saturated and dried conditions, the latter being plug conditions in locations above the ground water table, or in locations near a HLW repository where waste heat drives water away during the initial period of storage. Cement is used in this study because, together with clay, it is the most likely candidate for plug material. This paper describes the laboratory experiments performed, equipment, procedures, and their results.

EXPERIMENTAL PROCEDURES

Sample Preparation

Cylindrical granite samples, approximately 300 mm long by 150 mm diameter with a 25 mm coaxial borehole, are used for this study. The boreholes are either drilled all the way through, or drilled from each end, leaving a rock bridge in the middle. In the former case, expansive cement, provided by Dowell, is used as plug material. The cement is composed of Ideal Type A cement (Tijeras Canyon), 50% distilled water, 10% D53 (an expansive agent), and 1% D65 (a dispersant); all percentages are weight percent with respect to cement. Mixing is performed according to the American Petroleum Institute Specifications, API Standards No. RP-10B.(12) The cement plugs are placed in the middle third of the boreholes and cured underwater for at least eight days. Three of the cement plugged samples were left to dry in room temperature and humidity for several months following the curing period. Four other samples had their cement plugs maintained underwater after the curing period until testing started. One of the latter was oven dried after flow testing was completed.

Granite samples used for these experiments were obtained from the Charcoal Black Quarry, St. Cloud, Minnesota. The rock is petrographically a quartz monzonite, with 68% feldspar, 18% quartz, 6% biotite, and 6% hornblende.

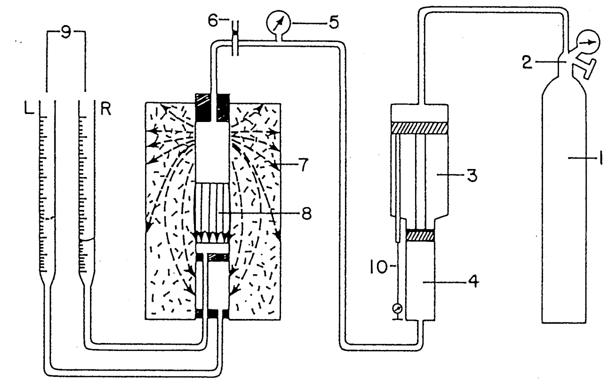
Steady State Flow Testing

To establish steady state flow through the plug, water is injected at a constant pressure to the top hole of the unconfined rock sample. Outflow is collected at the bottom hole and measured using pipettes. Various injection pressures, up to 4 MPa, are used in the flow test.

Two gas-over-water pressure intensifiers and three hydraulic accumulators are used to maintain constant injection pressure; therefore, five samples can be flow-tested at the same time. Both pressure intensifiers and hydraulic accumulators are driven by high pressure nitrogen gas. The lay-out of the steady state flow testing is shown in Figure 1.

EXPERIMENTAL RESULTS

Flow testing by injecting water to the center hole of an unconfined sample applies very severe stress conditions at the plug-rock interface. At the same time it induces a high tangential tensile stress in the rock. The rock has a density of 2.70 ± 0.01 g/cm^3, a Young's modulus, E, of 56.53 E03 ± 6.07 E03



1. Nitrogen gas tank.
2. Pressure regulator.
3. Low pressure/gas cylinder of pressure intensifer.
4. High pressure/water cylinder of pressure intensifer.
5. Water injection pressure gauge.
6. Rotameter (flowmeter).
7. Rock sample.
8. Borehole plug.
9. Measuring pipets for outflow collection.
10. Dial gauge for piston displacement measurement.

Fig. 1. The lay-out of the steady state flow testing. The outflow collection system collects separately the one-dimensional flow through the plug and plug rock interface in the right (R) pipette, and peripheral flow through the rock around the plug in the left (L) pipette.

MPa, a Poisson's ratio of 0.19 ± 0.05, and an unconfined compressive strength of 123.31 ± 44.18 MPa. One sample was hydraulically fractured at an injection pressure of 7 MPa. The mechanical properties of the cement are 6.89 E03 MPa for Young's modulus and 0.16 for Poisson's ratio, and 24 MPa for uniaxial compressive strength.

To represent the results of the flow test, outflow is plotted against time to obtain the flow rate for the corresponding injection pressure. By applying curve fitting based on the least square method, linear regression was found to give the best fit of the data, with the coefficients of determination r^2 closest to one. Figure 2 shows a typical flow vs. time plot of a sample with dry cement plug, with a 95% confidence band around the line of best fit. A dye injection test has revealed that for a dry cement plug, most of the flow passes through the plug-rock interface, as indicated by the dye traces along the interface.

The flow rate through the rock bridge/cement plug and plug-rock interface can be used to determine the permeability constant, K, of the medium, using Darcy's law (13) for one-dimensional flow:

$$K = \frac{Q\ L}{(h_2 - h_1)A} \qquad (1)$$

where K = permeability
Q = flow rate
L = plug length
A = plug cross sectional area
$h_2 - h_1$ = water head differential

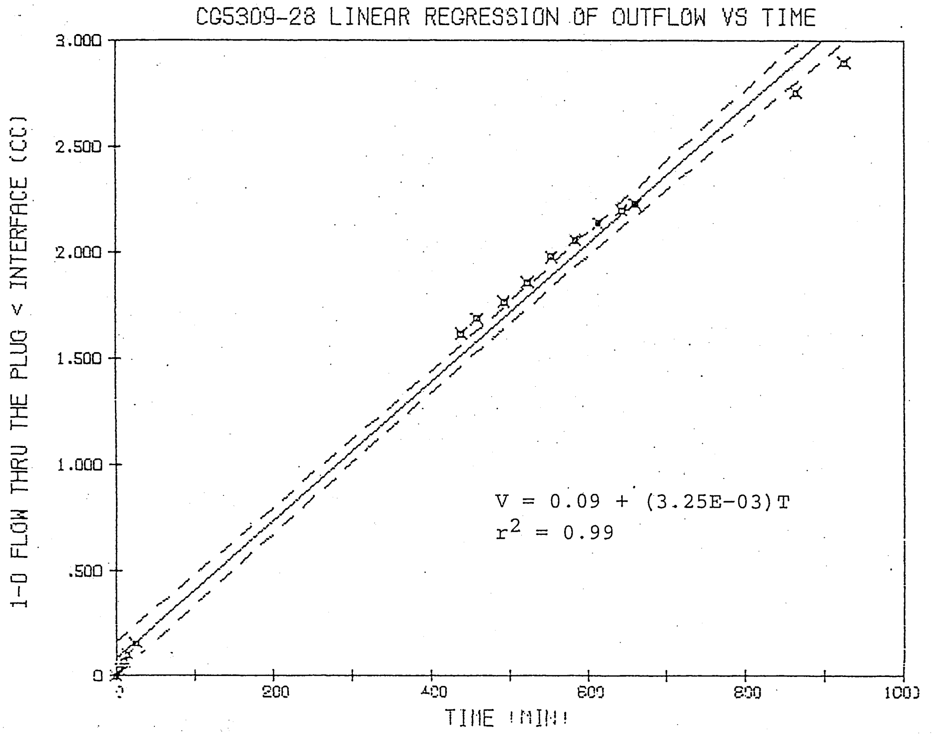


Fig. 2. Typical linear regression plot which gives the best fit for outflow, V, vs. time, T, with a 95% confidence band around the regression line. The plot shown is for a dry cement plug, where the plug-rock interface opened up as a result of drying and caused a high flow rate of 3.25 E-03 cm^3/min at an injection pressure of 1.3 MPa.

and the unit of K is cm/s or darcy (1 darcy = 9.68 E-04 cm/s).

Rock Bridge

Tests conducted on a Charcoal granite sample with a rock bridge in the middle give the value of permeability coefficient, K, of 1E-08 to 3E-08 darcy for injection pressures from 1 MPa to 4 MPa. This is in the same order of magnitude as the results obtained by South for Charcoal granite (14). The permeability remains nearly constant in the range of injection pressures used, indicating that the effect of opening and closing of microcracks and fractures due to different stress distribution is relatively small. The reduction of rock bridge length, L, from 11 cm to 10 cm at the later stage of testing also does not affect the permeability because of the correspondingly higher flow rate.

Figures 3 and 4 show the trend for permeability of Charcoal granite, as well as the permeabilities of the cement plug which is discussed in the next sections.

Saturated Cement Plug

Series of tests on Charcoal granite plugged with saturated cement give K values of 1E-09 to 7E-09 darcy. The results for two samples are plotted in Figs. 3 and 4, and they give all indications that saturated cement plugs perform better than Charcoal granite in preventing flow.

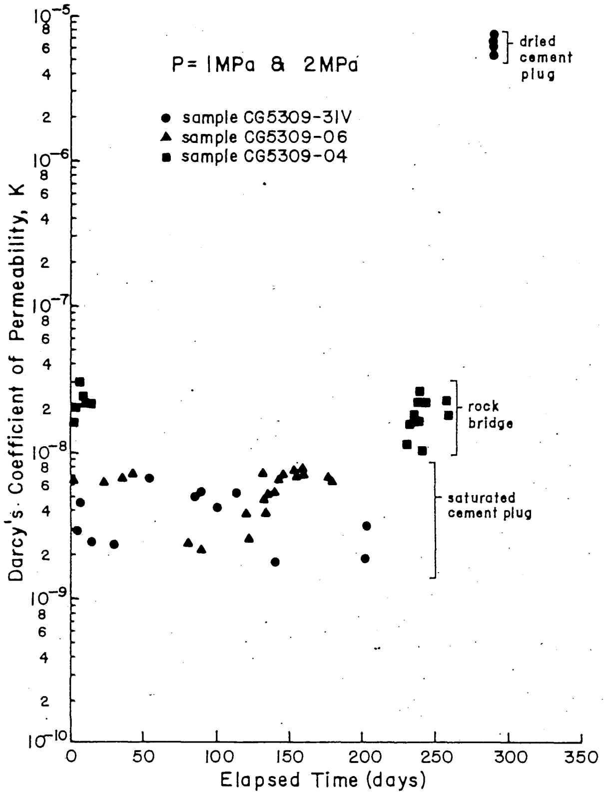


Fig. 3. Darcy's coefficient of permeability, K, vs. elapsed time for granite rock bridge, saturated cement plug, and oven dried cement plug, at injection pressure of 1MPa & 2MPa. Permeability of saturated cement is an order of magnitude lower than granite, but it increases by three orders of magnitude after drying.

Dye injection testing was performed on both samples and one of them (CG5309-06) was sawed in half lengthwise after six weeks of dye testing. The red dye clearly penetrated uniformly 2 cm into the plug, but the interface is still intact and was not acting as a preferential flow path. The dye-penetrated top portion of the cement plug is not the soft zone of laitance since that was already removed by grinding prior to testing.

The reduction of the plug length from 10 cm to 4 cm of sample CG5309-31V to increase the observed flow rate in the course of flow testing also does not change the permeability. This sample was oven dried later on to observe its effect as compared to drying in room temperature.

Dry Cement Plug

Following the test on saturated cement plugs, one of the samples (CG5309-31V) was put into a drying oven at 90°C for five days. As Figs. 3 and 4 show, its permeability increased by three orders of magnitude, to 7 E-06 darcy. This is caused by shrinkage and possibly cracking of expansive cement when it is dehydrated, which results in interface opening.

The same phenomena are observed in three other samples with saturated cement plugs that were dried in

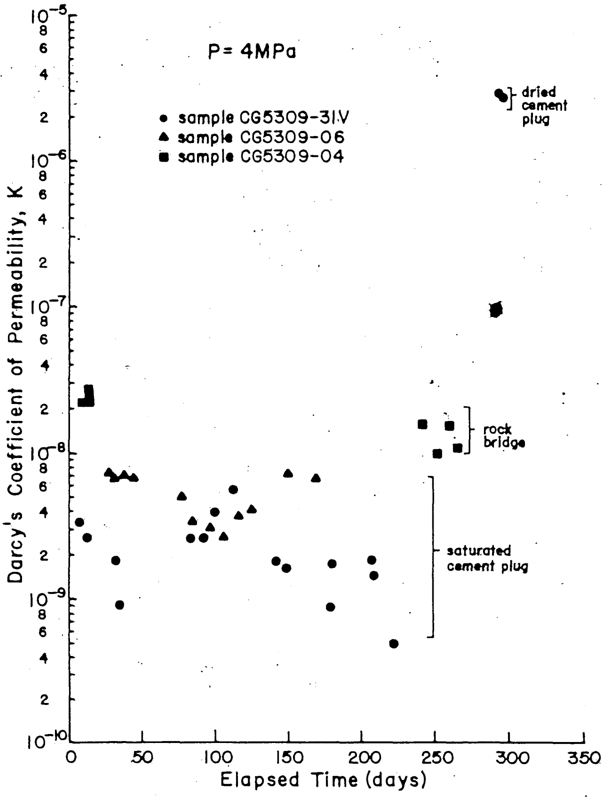


Fig. 4. Darcy's coefficient of permeability, K, vs. elapsed time for granite rock bridge, saturated cement plug, and oven dried cement plug, at injection pressure of 4 MPa. Note the similarity to Fig.3.

room temperature for longer period of time. The results for two are given in Figs. 5 and 6. Figure 5 shows the high plug permeability immediately after a three month drying period. Under the influence of the water flowing through it, the plug permeability rapidly decreases and levels off at 1E-07 darcy. This illustrates the partial recovery of plug performance upon rehydration because of cement reexpansion which closes the interface. However, the permeability is still two orders of magnitude higher than that of saturated cement plugs, even after six months of rehydration.

Figure 6 gives the permeabilities after seven months of drying, showing even higher permeabilities. Plug performance degradation due to drying has continued over the test period. To obtain the flow pattern in the dry plug, red dye was injected for six weeks and the sample was cut in half lengthwise afterwards. The effect of drying is clearly shown by the traces of dye color along the full length of both interfaces, while the cement plug itself was not penetrated. In addition, two large cracks in the cement extend from the right to the left interface. These cracks appear to be very similar to the transverse cracks that have been observed in many cement plugs when they are exposed to laboratory air for a few days to weeks subsequent to slicing upon completion of various tests. These cracks also have been penetrated by the dye and thus acted as additional preferential paths for the flow.

As with the other sample, the permeability decreases quickly and then levels off, indicating partial performance recovery of the cement upon rehydration. However, it is obvious that at K of 3E-05 darcy after six months of rehydration, it is very unlikely that the dried cement plug will ever regain its plugging effectiveness prior to drying.

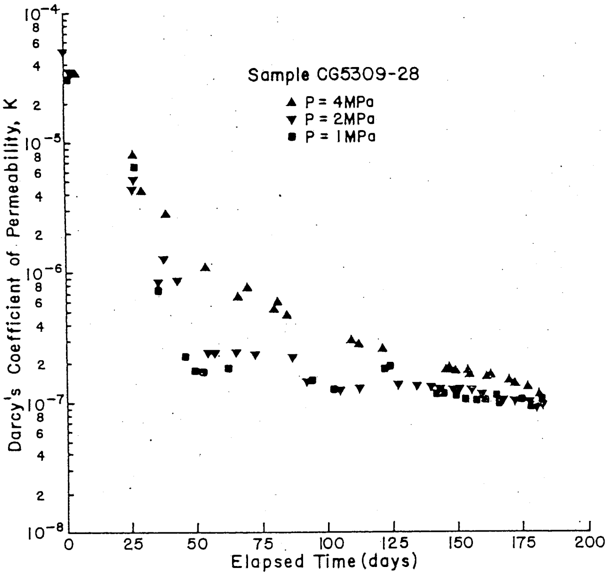


Fig. 5. K vs. elapsed time of a cement plug dried for three months at room temperature prior to testing. The high permeability at the beginning is caused by cracking at the plug-rock interface as a result of drying, which facilitates the high flow. The permeability drops quickly upon rehydration of the plug, but the plug performance is never fully recovered.

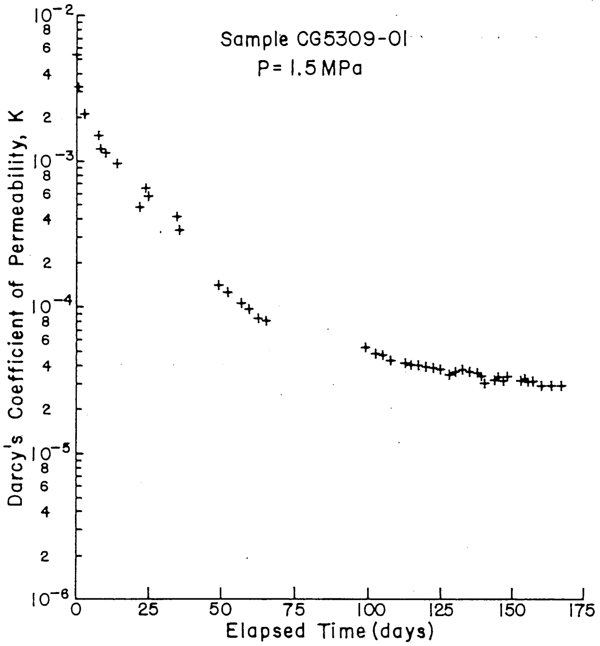


Fig. 6. K vs. elapsed time of a cement plug dried for seven months at room temperature prior to testing. The same pattern as in Fig. 5 is observed here, but the permeability is two orders of magnitude higher due to more severe cracking in the interface and additional cracking in the cement as a result of the longer drying time.

Similar observations on cement plug drying from the point of view of permeability and axial interface strength have been done (14,15). The data presented in this paper are part of ongoing work to study the response of borehole plugs to dynamic loading (16).

Summary and Conclusions

Direct experimental comparisons have been made of the sealing performance of cement plugs that remain saturated with that of plugs that have been allowed to dry out. Drying of the plugs results in an increase of hydraulic conductivity by several orders of magnitude. This appears to be due primarily to shrinkage of the plug and the consequent development of a separation between the plug and the surrounding rock. Upon resaturation of the plug, the sealing performance is recovered partially.

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