PERFORMANCE OF BENTONITE/CRUSHED ROCK BOREHOLE PLUGS

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ABSTRACT

A mixture of crushed rock and bentonite is being considered as backfill and sealant for high-level nuclear waste repositories. Many variables affect the hydraulic conductivity of such a mixture, including the size and shape of the rock particles, method of mixing, water content and density of the clay, and the weight ratio of rock to clay. Mixtures of crushed basalt and bentonite have been tested to determine the relative effects of these variables. Two types of permeameters are used, 20 cm diameter stainless steel permeameters and 10 cm diameter clear PVC permeameters. Plugs are installed as a single lift or in many lifts; the water content of the clay ranged from air-dry (in most cases) to as high as 200%. Preliminary results show that a mixture of 75% crushed basalt and 25% bentonite has a hydraulic conductivity between 1×10^{-9} cm/s and 2.5×10^{-8} cm/s. In some cases, preferential flow paths have developed (possibly as a result of the montmorillonite washing out of the crushed rock matrix), giving hydraulic conductivities as high as 1×10^{-4} cm/s. Other ratios of rock to clay have similar bimodal results. The probability of failure is decreased by including a higher percentage of clay, crushing the rock finer, and evenly mixing the crushed rock and clay.

INTRODUCTION

All penetrations of an underground waste repository formation must be properly sealed. Bentonite alone has been considered as a sealant material because of its desirable swelling and self-healing characteristics, low permeability, sorptive qualities, and longevity in nature (e.g. 1). However, high quality bentonite might not be available in sufficient quantities to be used by itself as a sealing and backfill material in a large repository. In addition, the large volume of rock, mined during construction of the repository, must be disposed of. Thus, a sealing and backfill mixture of crushed rock and bentonite is being considered as a partial solution to both problems (e.g. 2).

A suitable composition for the backfill of tunnels and shafts of repositories must fulfill several requirements. The requirements listed by Nilsson (3) are low permeability, low compressibility, small average pore size (to prevent montmorillonite from migrating), and some swelling potential. Additional backfill requirements suggested by Dixon, Gray, and Thomas (4) include the ability to maintain integrity in a hot, possibly saline environment, and thermal conductivity similar to that of the host rock.

According to Dixon et al (4), several advantages are gained by adding crushed rock to the clay. The addition of crushed rock increases the achievable compacted density, does not change (or decrease) the swelling pressures developed by the clay, decreases the shrinkage potential, increases thermal conductivity, and increases the bearing capacity of the backfill, thus minimizing creep or settlement.

It is possible that the addition of crushed rock to bentonite would change (either increase or decrease) the hydraulic conductivity of the backfill. This research project was designed to study the hydraulic conductivity of a mixture of crushed rock and bentonite. Twenty plugs were installed, varying different parameters. The hydraulic conductivities of the plugs were determined.

BENTONITE

The bentonite used is American Colloid C/S (for Clear Seal) Granular. This product contains a large percentage of sodium montmorillonite, valued for its low hydraulic conductivity and dispersive qualities. In most cases, it was used as shipped, in a powder form with a water content of about 10%. The properties of C/S Granular are well known from a recent testing program by Sawyer and Daemen (5).

CRUSHED ROCK

Source of the Crushed Rock

The rock used in this project (Fig. 1) is basalt from the Columbia Plateau, near Hanford, Washington. Boulders were collected at two sites: Sentinel Gap, north of the Hanford Site; and Wallula Gap, on the Oregon-Washington border.

The basalts are from the Pomona flow of the Saddle Mountains basalt, the Frenchman Spring or maybe the Roza flow of the Wanapum basalts, and a flow from the Grande Ronde basalts. The rock is believed fairly typical of the waste rock available should a high-level nuclear waste repository be placed at the Hanford site.

Rock Preparation

The crushed rock (Fig. 1) was prepared from boulders through which 5 to 13 cm diameter holes had

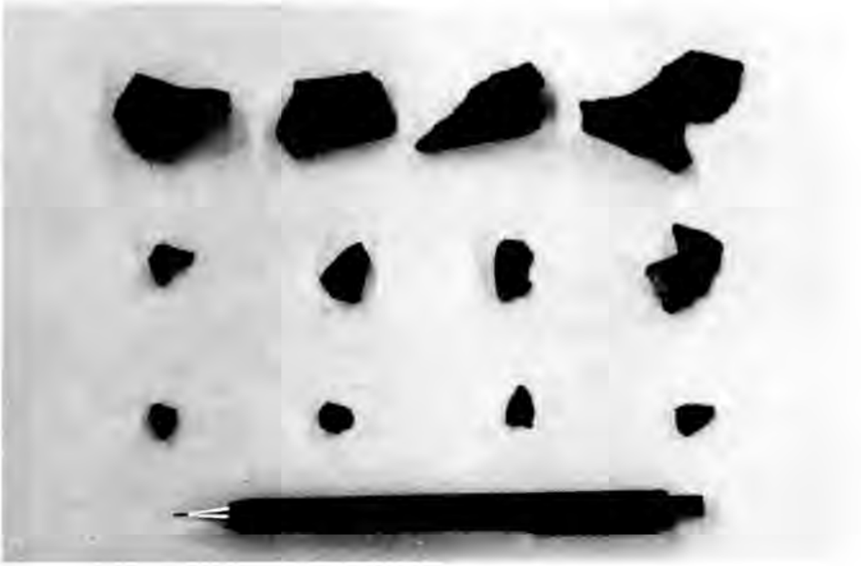

Fig. 1. Examples of crushed basalt particles.

been cored. A sledge hammer was used to break down the boulders into basalt pieces that fit into the crusher (maximum dimension = 20 cm). The rocks were initially run through a jaw crusher and thereafter through an adjustable roller crusher.

Basalt crushing produces a significant powder fraction. Two opposing viewpoints exist with respect to the use of the finer fractions. In general, smaller particles produce lower hydraulic conductivities. Larger particles react less with groundwater and with bentonite.

A smaller particle size produces a more homogeneous mixture. The voids between rock fragments are smaller, decreasing the possibility of having large voids not filled with clay. For low and medium level waste isolation the smaller particles are considered beneficial: researchers in Finland concluded that an optimum crushed rock for their purposes consists of 29% "ground rock" from a ball mill, with the remaining 71% crushed in a "conventional rock crusher" (6).

The possibility exists that the rock and clay will degrade chemically during the long time that a high-level repository will need to isolate waste. If the basalt and bentonite interact chemically, the greater surface area of the powder would make it far more active than pebble- or even sand-sized particles. Preliminary studies have shown that basalt and bentonite are stable at up to 300°C for short periods of time, so this may be an unnecessary fear (7) For these reasons, both types of aggregate (with fines left in and fines taken out) were tested.

Two varieties of crushed rock were prepared. For the first, the rock was sieved through a 5 cm siever between each crushing. Only the stones that did not pass the sieve were crushed again. All particles small enough to pass through a #16 sieve were removed. The second type of crushed rock was passed through a #4 sieve. Again, only the aggregate not passing through the sieve was rerun through the crusher. All particles smaller than the #4 sieve were left in; none of the fines were taken out.

Particle Shape

The shape of the rock particles can affect the compaction of the mixture, and, indirectly, the permeability. Powers (8) suggested qualitative descriptions using the terms very angular, angular, sub angular, sub rounded, rounded, and well rounded. The crushed basalt would be classified as very angular (Fig. 1).

The nonspherical, angular particle shape produced by basalt crushing should be a factor in the design of the backfill for a high-level waste repository in basalt. An extremely angular and/or nonspherical rock shape will stack more loosely than a rounded, spherical shape. This reduces the bulk density of the mixture and increases its porosity. For a given ratio of rock to clay, a non-spherical grain shape might therefore be expected to have a higher hydraulic conductivity than would a spherical shape.

PERMEAMETER DESIGN

Stainless Steel Permeameters

Four stainless steel permeameters were constructed by the Central Machine Shop at the University of Arizona (Fig. 2). The permeameters have a 10 cm inside diameter and are 20 cm long. This large diameter allowed aggregate of up to 2.5 cm in diameter to be tested, without any single clast dominating flow.

When testing the hydraulic conductivity of a pure bentonite borehole plug, high inflow pressures are necessary to get measurable outflow in a reasonable length of time. Therefore, the stainless steel permeameter inflow systems were originally designed to provide pressures of up to 1.4 MPa by a hand pump or a gas-over-water pump. However, after initial testing of three of the larger plugs (with rock/clay percentages of 65/35, 75/25, and 95/5), it became obvious

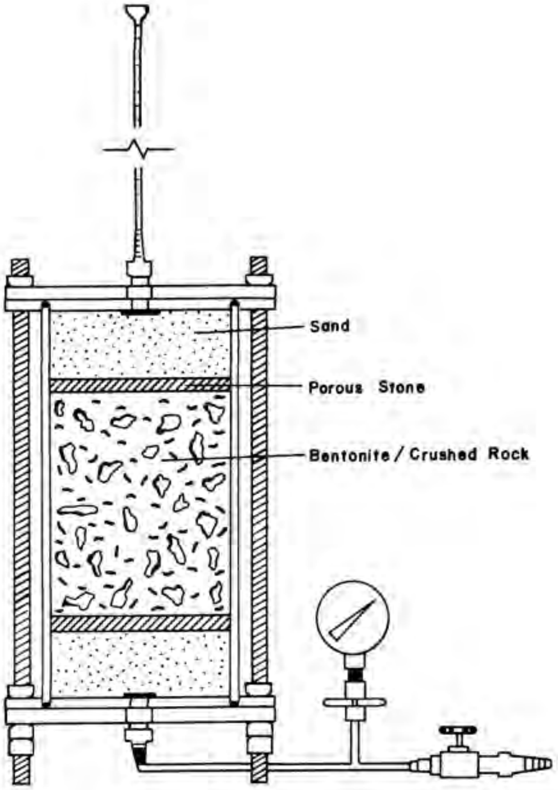

Fig. 2. Schematic of a stainless steel permeameter.

that the higher pressures were unnecessary, and even detrimental. Initial flow rates (at inflow pressures of 0.21 to 0.35 MPa) were high enough to wash the montmorillonite out of the rock matrix. Thereafter, inflow pressure for all plugs was provided by a water head of up to three meters.

PVC Permeameters

Fifteen 10 cm inside diameter clear PVC (polyvinyl chloride) permeameters were constructed. A 1/4 inch NPT (National Pipe Thread) to 1/4 inch Swagelok compression fitting is glued and screwed into both end caps. The lower cap is glued onto a 30 cm or 45 cm section of clear PVC pipe, the plug is installed, and the upper cap is glued onto the pipe (Fig. 3). This results in a simple, watertight permeameter suitable for low-pressure (up to 0.35 MPa) tests. Gluing the caps on is most suitable for tests of great duration; however, the permeameter may only be used once.

Inflow water pressure was provided by a head of water from 30 cm to 365 cm, depending on the hydraulic conductivity of the individual plugs. Total volumetric flow into the plug and out of the plug was measured in 9 ml pipettes, calibrated to 0.1 ml.

PLUG INSTALLATION

Percentage of Clay

An optimum range must exist for the weight percentage of bentonite in a backfill mixture. If no clay is included, the permeability will be as high as that of a sand or gravel. Conversely, if 100% bentonite is used, then the cost savings and other benefits of adding crushed rock will not be realized.

The weight percentage of bentonite tested by others varies from 50% (4) to as little as 3% (6) The percentages of bentonite used in this project were 35%, 25%, 15% and 5%.

Installation Methods

The tunnels and shafts of a repository may be backfilled in layers (or lifts) and compacted with a plate vibrator. In one scheme, the upper portion of the tunnel, where space is too restricted to use the plate vibrator, is backfilled by blowing in the crushed rock/bentonite with a modified shotcrete machine (3) Boreholes could be filled by pouring similar mixtures in them.

Ideally, laboratory testing should mimic the intended installation procedure used in the full-scale repository. However, care must be taken to insure that the plugs have a uniform texture and composition. Inconsistencies within the plug can greatly affect its performance.

Several methods of application were tested, including thin, distinct, alternating lifts of rock and clay. In other cases, the rock and clay for each lift was mixed together before being poured into the permeameters. For a few plugs, the rock and clay were mixed and poured as a single lift. The water content of the clay varied from air-dry (5% to 10% by weight) for most of the plugs, to extremely wet (100 to 200%).

Swelling was restricted for the majority of the plugs by sand and/or porous stones at the top and bottom. A few were free to swell at the top of the plug, supported on the bottom by porous stones. A plug that is not free to swell mimics a static deep

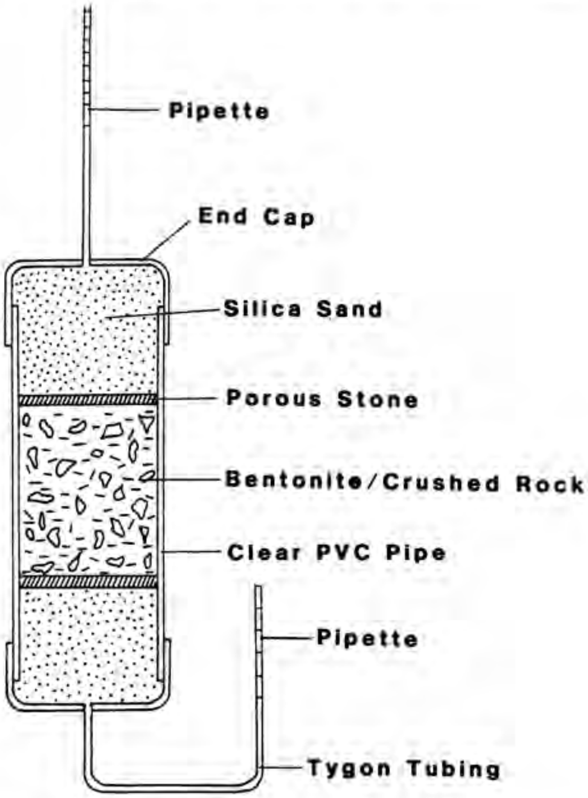

Fig. 3. Schematic of a PVC permeameter with the "double pipette system" (for injection and collection of water) attached.

underground installation best. On the other hand, in the event of tectonic movement, a backfill that has some swelling potential may be preferable. It is desirable to know what hydraulic conductivity to expect in the latter case.

It is not clear which type of restriction is the best. Paper filters were not used because of the possibility of degradation or breakdown during the long testing period. A porous stone or sintered brass filter is commonly used to support other types of soils during permeability testing, but small amounts of clay could clog a porous stone. In this case, the permeability test would measure the hydraulic conductivity of the clogged stone, and not that of the plug itself.

Using a clean sand, with no other filter, is not ideal either. Sodium montmorillonite is a dispersive clay, and under very low hydraulic gradients will wash out of the rock matrix and through the sand. In this case the hydraulic conductivity of the plug increases. For these reasons, porous stones, sintered brass plates, and sand alone were all used and compared.

VOIDS IN A ROCK/CLAY MIXTURE

The hydraulic conductivity of a soil is usually related to its porosity. The less dense a soil, the more space is available for flow. Because the crushed basalt has a very angular, nonspherical shape, it does not stack tightly. It is desirable to know the pore space within particular plugs.

Free Air Voids

When a borehole plug is built in the laboratory, the sum of the rock volume and the clay bulk volume (which includes substantial amounts of air) is less than the total plug volume. It can be assumed, then, that the volume unaccounted for remains in the plug as open pockets of air. If connected, these pockets become open channels through which fluids can flow freely.

The rock volume is calculated by dividing the rock mass in the plug by the density of basalt (3.01 g/cm^3, as measured in a pycnometer).

$$V(\text{rock}) = M(\text{rock})/D(\text{basalt}) = M(\text{rock})/3.01 \quad (1)$$

It is assumed that the effective rock porosity is close to zero. Although there may be voids within the rock, the assumption is made that the clay will not be able to swell into them.

Conversely, there is air trapped within the clay. Therefore, the volume of clay is computed by dividing the dry mass of clay by the dry bulk density (1.14 g/cm^3)

$$V(\text{clay}) = M(\text{clay})/D(\text{bulk, clay}) = M(\text{clay})/1.14 \quad (2)$$

These two volumes are then subtracted from the total plug volume to find the free air volume,

$$V(\text{free air}) = V(\text{plug}) - [V(\text{rock}) - V(\text{clay})] \quad (3)$$

The free air volume is plotted in Fig. 4 as a percent of the total plug volume.

Void Ratios

The void ratio of a borehole plug is computed by dividing the volume of voids by the volume of solids. The volume of clay solids is found by

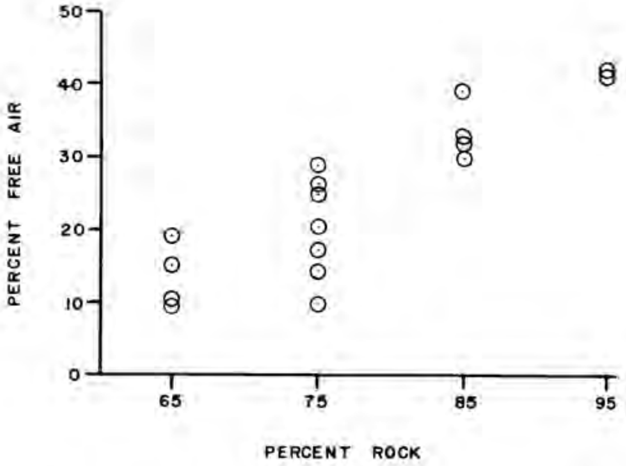

Fig. 4. Percent free air plotted versus percent rock.

dividing the mass of clay by the particle density of clay (2.6 g/cm^3). This volume is less than the bulk clay volume (V(clay)).

$$V(\text{solids, clay}) = M(\text{clay})/D(\text{solids, clay}) = M(\text{clay})/2.6 \quad (4)$$

The basalt volume is found by Equation 1. The volume of voids is found by subtracting the volume of solids from the total plug volume.

$$V(\text{voids}) = V(\text{plug}) - [V(\text{solids, rock}) + V(\text{solids, clay})] \quad (5)$$

The void ratios of the plugs, at all rock/clay ratios (from 65%/35% to 95%/5%), scatter from e = 0.5 to e = 1.0 (see Fig. 5). Since the void ratios of all the plugs are similar, one might infer that the sealing performance of all rock/clay mixtures would be similar. However, it is not the total void ratio of the plug that counts, but rather the void ratio of the clay within the rock matrix.

If it is assumed that the rock particles will not swell, while the bentonite clay swells uniformly into all the free air voids, then the eventual void ratio

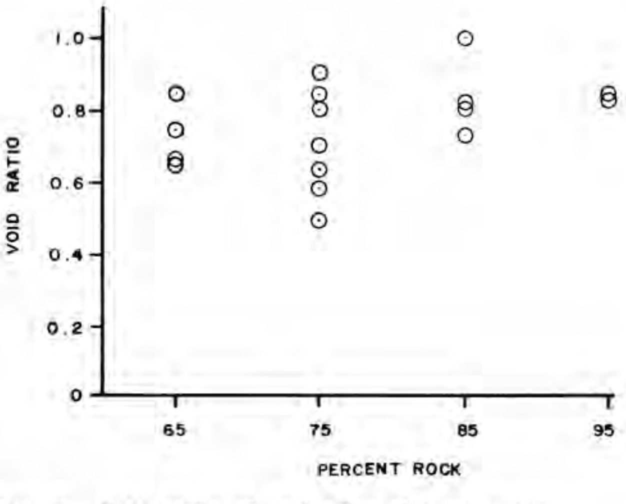

Fig. 5. Void ratio of each plug plotted versus percent rock.

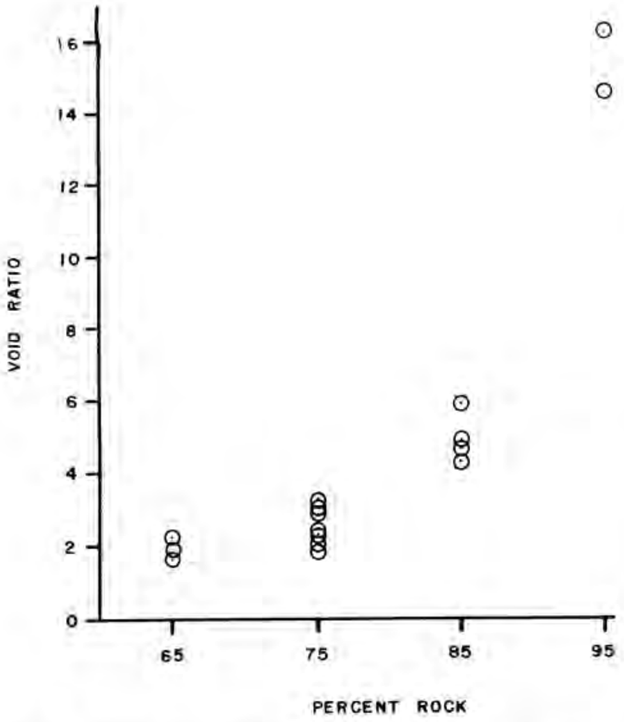

Fig. 6. Void ratio of the clay alone plotted versus percent rock. It is assumed that the clay swells uniformly into all voids.

of the clay can be calculated. This is done by dividing the total void volume (Eq. 5) by the volume of the clay solids.

$$e(clay) = V(voids)/V(clay) \qquad (6)$$

The void ratio of the clay is plotted in Fig. 6. The maximum void ratio of the clay ranges from 2.2 for 65% rock/35% clay up to more than 16 for 95% rock/5% clay.

Summary of Voids

The mixtures containing the finely ground aggregate (powder) had more free air than the mixtures containing only coarse aggregate. However, their free air pockets were much smaller and more widely dispersed, so that their sealing performance was at least as good as that of a coarse rock/clay mixture.

The void ratios of the clay alone (assuming the clay swells into the free air pockets) are similar for the 65/35 and 75/25 mixtures. The performance of plugs containing these ratios was similar.

PERMEABILITY TESTING

Permeability tests were performed on twenty plugs. Variables studied include ratios of rock to clay, size of rock aggregate, installation methods, and water content. The majority of the plugs were restricted at the top and bottom by sand and/or porous stones. A few were allowed to swell at the top.

The flow in and out of the plugs was monitored for periods ranging from weeks to months. The hydraulic conductivity was calculated daily and a weighted average computed.

Test Calculation

Some of the plugs were tested using a standard falling head test. The remainder of the permeability calculations were performed using a double pipette system (Fig. 3). Inflow water pressure is provided by a head of water falling in a pipette. The flow out is collected and measured in a pipette of the same diameter. The test is similar to a falling head test, except that the rising head must be accounted for.

Several assumptions are made when calculating the hydraulic conductivity. The calculations assume that Darcy's law is valid: water flow is linearly proportional to head (or energy) loss and inversely proportional to the plug length. The bentonite/rock mixture is assumed to be saturated. The commonly used permeability calculations (constant head and falling head) assume that flow into the plug is equal to the flow out. Because the validity of any one calculation is unknown, the hydraulic conductivity, K, has been calculated for each test in three ways:

(1) constant head calculation based on flow in,
(2) constant head calculation based on flow out,
(3) a modified falling head test.

The results are compared to find a range of possible values of hydraulic conductivities.

The hydraulic conductivity can be calculated for the double pipette systems using an equation based on the volume that flows into the plug:

$$K(in) = Q(in)L/h(average)At \qquad (7)$$

where $h(average)$ = average head difference $= (h_1 + h_2)/2$
$Q(in)$ = volume in
A = plug area
t = test time

Similarly, the hydraulic conductivity based on flow out can be calculated:

$$K(out) = Q(out)L/h(average)At \qquad (8)$$

where $Q(out)$ = volume out.

The modified falling head equation must take into account a rising head in the lower pipette. The equation given by Williams and Daemen (9) is:

$$K = \frac{aL}{2At} \ln\left(\frac{h_1}{h_2}\right) \qquad (9)$$

where a = cross-sectional area of the pipette
L = plug length
h_1, h_2 = beginning and ending differences in head.

SUMMARY OF RESULTS

A summary of average hydraulic conductivities for each plug may be found in Table I. Where possible, the hydraulic conductivity was calculated at approximately sixty days after installation, so that the results could be compared on an equal time basis.

The results are bimodal. The plugs had either very high or very low hydraulic conductivities. The very high conductivities represent plug failures.

TABLE I

Summary of Results

Plug	Days since Installation	Percent Rock	K(average) (cm/s)
SS 1	87	75	1.77×10^{-4}
SS 2	79	95	1.54×10^{-3}
SS 3	60	65	1.45×10^{-9}
SS 4	92	85	1.05×10^{-3}
PVC 1	74	75	1.11×10^{-9}
PVC 2	76	75	2.46×10^{-9}
PVC 3	58	75	1.06×10^{-8}
PVC 4	66	75	1.56×10^{-8}
PVC 5	77	75	5.96×10^{-4}
PVC 6	57	75	8.66×10^{-9}
PVC 7	66	65	4.98×10^{-10}
PVC 8	57	85	1.98×10^{-7}
PVC 9	91	95	3.85×10^{-4}
PVC 10	61	65	6.97×10^{-9}
PVC 11	61	75	5.07×10^{-9}
PVC 12	82	85	1.08×10^{-4}
SS 5	28	75	6.93×10^{-8}
PVC 15	57	65	1.12×10^{-8}
PVC 16	57	75	9.37×10^{-9}
PVC 17	57	85	3.29×10^{-8}

Of the twenty plugs tested, fourteen would be classified (according to Lambe and Whitman (10)) as "practically impermeable" (from 10^{-7} to as low as 10^{-10} cm/s). Eight would be classified as having "low" permeability (from 10^{-3} down to 10^{-4}) (Table II). Previous tests showed that, when unconfined, this particular bentonite (C/S Granular) has a hydraulic conductivity of approximately 10^{-9} cm/s (10).

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

There appears to be a correlation between the percentage of bentonite in the plug and the probability of not having a massive failure of some type. It appears that the addition of crushed rock has little effect on the permeability of the plug, unless there is so little clay in the plug that the water has an unobstructed path through the rock matrix.

TABLE II

Bimodal Distribution of Results

	K, cm s	
Percent Clay	10^{-4} to 10^{-3}	10^{-10} to 10^{-7}
35	-	4
25	2	8
15	2	2
5	2	-

There are several ways to avoid having a failure of the plug. The most important method is to include a larger percentage of clay. With the coarsely crushed rock (particles as large as 2.5 cm) the backfill should contain at least 25% bentonite.

Some type of compaction is necessary, especially if the clay has been allowed to swell. If the rock and clay is blown in, similar to shotcrete, the clay should be as dry and dense as possible. When moistened, the clay could then swell into any voids.

The crushed rock and bentonite should be mixed as thoroughly as possible. Voids within the rock matrix that are not filled with clay are possible channels for water flow.

Crushing the rock finer, so that the voids between rock particles are smaller, decreases the probability of failure. A more uniform, smaller grain size distribution, perhaps of sand size particles alone, might be a better choice for the crushed rock.

Future research efforts should focus on specific sizes of crushed rock, percentages of clay used, and emplacement methods that are similar to those that would be used in an actual repository. The results from this effort show that there is either total failure (high flow rates) or no failure at all (extremely low flow rates). Many more plugs should be tested, so that the results may be interpreted statistically.

Full-scale emplacement methods should be studied more thoroughly, especially methods of plugging boreholes and filling the upper portions of tunnels, where compaction equipment cannot readily be used.

The effects of wetting/drying cycles should be studied in greater detail. A bentonite/crushed borehole plug as a whole should shrink less than a pure bentonite plug. However, it is possible that, when dried, channels would open up within a bentonite/crushed rock plug that would allow the water to flow freely for some time before the clay rehydrates.

Mixtures should be tested using other types of crushed rock. It is possible that a rock type other than basalt, with a more spherical crushed shape, would give better results. This may have some bearing on the eventual emplacement in a high level nuclear waste repository.

In summary, a bentonite/crushed backfill mixture needs to be carefully engineered so that the bentonite does not wash out of the crushed rock matrix. When properly mixed and applied, bentonite and crushed basalt can have a hydraulic conductivity similar to that of pure bentonite.

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