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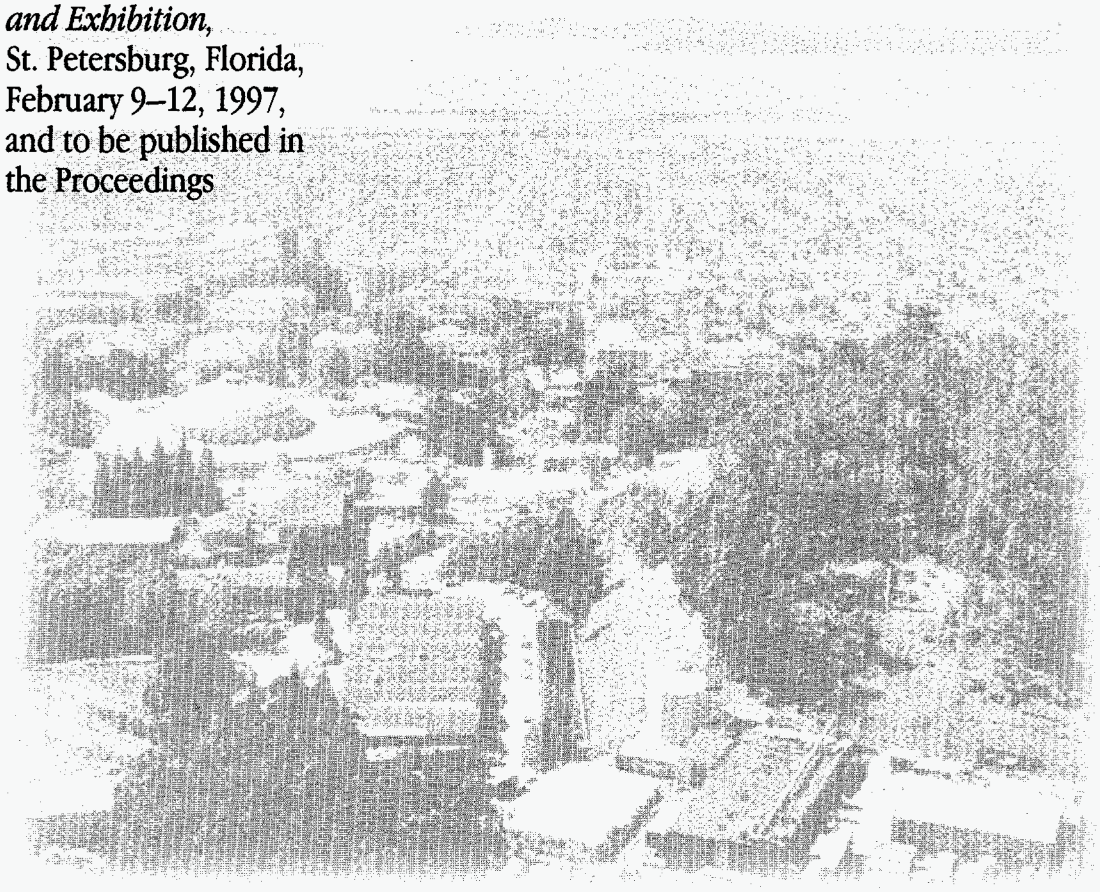

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INTRODUCTION

Landfill design requires a low permeability closure cap as well as a low permeability liner. The Savannah River Site, in South Carolina, has approximately 85 acres of mixed waste landfills covered with compacted kaolin clay. Maintaining low permeability of the clay cap requires both that the permeability of the compacted clay itself remain low and that the integrity of the barrier be maintained. Barrier breaches typically result from penetration by roots or animals, and especially cracks caused by uneven settling or desiccation.

In this study, clay layers, 0.81 m in diameter and 7.6 cm thick, were compacted in 7 lysimeters to simulate closure caps. The hydraulic conductivity of each layer was measured, and the compacted clay layers (CCL's) were cracked by drying. Then various repair techniques were applied and the effectiveness of each repair was assessed by remeasuring the hydraulic conductivity. Finally the repaired CCL was again dried and measured to determine how the repair responded to the conditions that caused the original failure. For a full report of this investigation see Persoff et al. (1996).

Six repair techniques have been tested, four of which involve the use of injectable barrier liquids colloidal silica (CS) and polysiloxane (PSX) described below: (i) covering the crack with a bentonite geosynthetic clay liner (GCL), (ii) recompaction of new kaolinite at STD+3 moisture content joined to existing kaolinite that had dried and shrunk, (iii) direct injection of colloidal silica to a crack, (iv) injection of colloidal silica (CS) to wells in an overlying sand layer, (v) direct injection of polysiloxane to a crack, and (vi) , injection of polysiloxane (PSX) to wells in an overlying soil layer .

EXPERIMENTAL

Compacting Kaolin Layers in Lysimeters

The lysimeter design is shown in Figure 1. Each lysimeter consists of two concentric cylinders of 0.6-cm thick gray polyvinyl chloride (PVC), hot-air-welded to a base of 1.2-cm PVC. The inner cylinder divides the flow area beneath the compacted clay layer (CCL) into a 5-cm wide annulus at the outer wall and a 71-cm diameter central region, which are drained separately. During the experiments, however, there was evidence that flow from the edge of the lysimeter can flow to the central drain and vice versa.

The CCL's were constructed from Barden AG-1 kaolin (Kentucky-Tennessee Clay Co., Langley SC). This clay was received powdered at 1% moisture. Its Liquid and plastic limits (ASTM D-4318) were 83 % and 37 % respectively, and its maximum dry density under standard Proctor compaction (ASTM D-698) was 1370 kg/m^3, with an optimum water content of 29.5 %. A sample compacted at 32.5% water (i.e., 3 % wet of optimum, STD+3) had a hydraulic conductivity (ASTM D-5084) of 4.7 x10^{-8} cm/sec.

Kaolin at STD+3 was compacted in each lysimeter in three lifts to form a 7.6-cm-thick (3 inch) CCL. Each lift was compacted with 1047 blows of a Modified Proctor compaction hammer, which was 2.7 times standard compactive effort to compensate for the lack of wall confinement when compacting in the wide lysimeters. Between lifts the surface was scarified to ensure good bonding.

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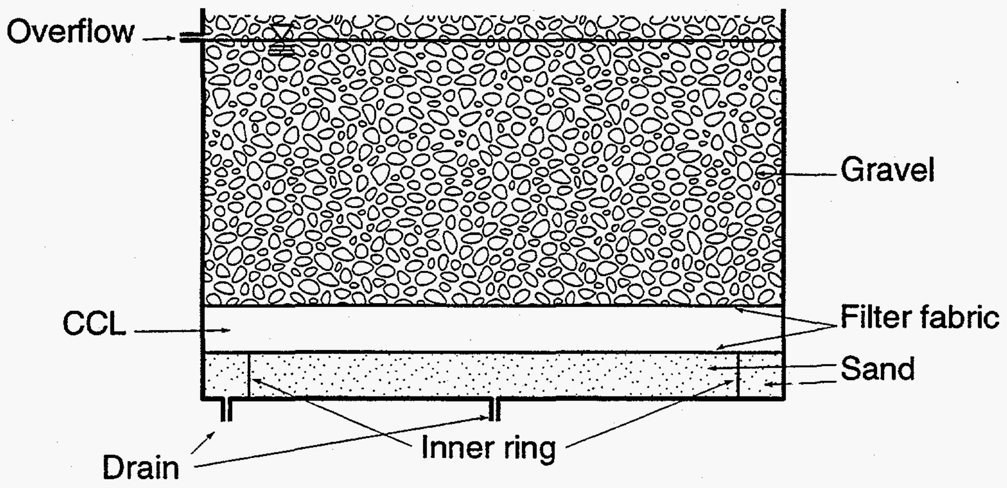

Figure 1. Lysimeter with CCL over sand drainage layer. Flow rates through central and edge drains were measured under constant hydraulic head.

After compaction, the dry density and the moisture content of the compacted clay was checked by taking 1-inch diameter plugs from the compacted clay, weighing, drying, and reweighing. Holes left by removal of plugs were repaired by compaction of additional kaolin into the holes, using a miniature compaction hammer. Similar sampling and recompaction was done several times on each CCL to monitor changes in moisture content and dry density as the kaolin dried.

To measure the hydraulic conductivity, a layer of filter fabric was placed over the CCL, and then 36 cm of gravel was placed over the filter fabric to prevent the CCL from swelling during the test. Water was then maintained at a depth of 36 cm, to give a hydraulic gradient of 4.67. Flow was collected in tared Erlenmeyer flasks. Although the inner ring was supposed to isolate flow from the edge and central areas of the lysimeter, flow usually issued only from either the center or edge drain. This suggested that the filter fabric between the sand and kaolin layers conducted flow across the dividing ring. The hydraulic conductivities of the CCL's in the various lysimeters ranged between $3x10^{-8}$ and $8x10^{-8}$ cm/sec, values that compare favorably with the value measured on a sample of the same clay compacted by ASTM D-698 and flow tested by ASTM D-5084.

Drying and Fracture Formation

Following the measurement of as-built hydraulic conductivity of the CCL's, dry air was flowed over their surfaces to dry them. Although in the field drying clay cracks as it shrinks, this behavior was not reproduced in the laboratory. Instead, the CCL's tended to shrink as a unit, gapping away from the walls of the lysimeter rather than cracking. Various techniques were implemented to prevent annular gapping and encourage formation of tension cracks. Tension cracks were successfully produced by aiming a heat gun at a line. These cracks tended to reclose as water diffused from wetter parts of the clay layer, but after sufficient drying they remained open.

After the cracks were established by drying, they were widened to 2 to 4 mm by driving a mason's chisel into each end of the crack and twisting it. During dry back, measurements were made of dry density, moisture content, and areal shrinkage . Data for CCL 6, which are typical for all are shown in Figure 2. Normalized area, which indicates shrinkage, was estimated from gap measurements.

CONDUCTIVITY OF CRACKED CCLs

The hydraulic conductivity of the cracked CCL's was measured to provide a baseline against which to assess the effectiveness of repairs. Measurement of the hydraulic conductivity of the cracked CCL was complicated by two factors: the annular gap between the perimeter of the shrunken CCL and the lysimeter wall, and the tendency of kaolin to swell and reseal itself under ponded water. Before measuring the hydraulic conductivity of a cracked CCL, bentonite paste (1.6 mL water per g of bentonite) was packed into the annular gap. The dry kaolin took water from the bentonite

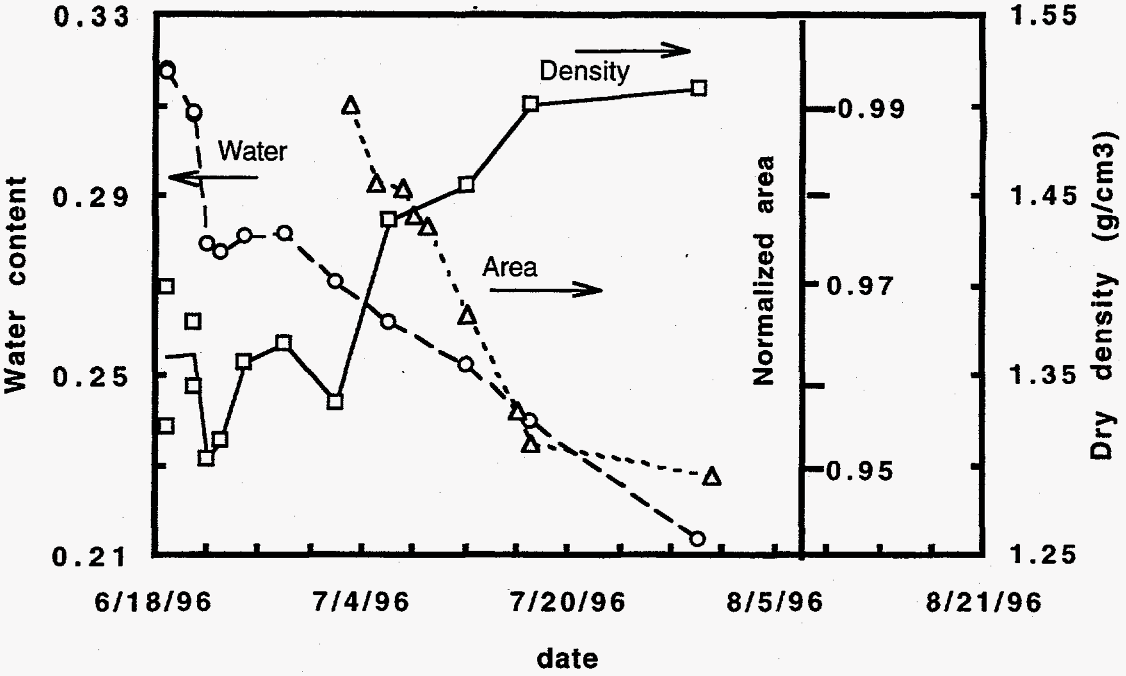

Figure 2 Water content (left axis), dry density and normalized area (right axes)during dry back of CCL 6.

paste, causing it to shrink. The bentonite paste was repacked immediately before starting hydraulic conductivity measurements, but some time was required (generally two days) before it swelled in place sufficiently to stop the flow of water.

Four measurements were made of the hydraulic conductivity of cracked CCL's. Although essentially all the flow in these measurements was through the crack, results are expressed as equivalent conductivity of the entire cracked CCL. Details of these measurements are presented elsewhere (Persoff and Moridis 1996). These measurements showed that the initial hydraulic conductivity of the cracked CCL was greater than 1x10-4 cm/sec but decreased rapidly because of kaolin. If the crack was not propped open it sealed completely (no detectable flow) within 2 days, while if the crack was propped open by filling it with sand (same as used for base layer), the hydraulic conductivity of the cracked CCL decreased to about $1x10^{-5}$ cm/sec.

Testing the repaired clay caps required that they be subjected to a hydraulic head. If the cracks were not sand-propped, this would cause the crack to self-heal and give a false indication of success. Therefore, to ensure that a measurement of low hydraulic conductivity of a repaired clay cap could be attributed to the repair and not to swelling of the kaolin, all cracks were sand-propped before the repair techniques were tested. Although the crack in CCL 2 did self-heal after two days under ponded water, such self healing is not likely to occur In the field. A CCL is generally overlain by a drainage layer of coarse material that prevents the formation of ponded water; also the coarse material enters cracks and prevents them from closing upon rewetting (Caldwell and Reith, 1993).

TESTING THE REPAIR TECHNIQUES

The results of the tests with six repair techniques are summarized in Table 1. All techniques were effective in restoring the hydraulic conductivity of cracked clay caps below the generally accepted standard of 10^{-7} cm/sec except for injection of PSX through soil, which failed because the

Table 1. Hydraulic conductivity of CCLs as built and after repai

Lysimeter	2	3	4	5	6	7
K as built (cm/sec)	3.7E-8	2.7E-8	2.7E-8	5.7E-8	no flow	–
K after crack (cm/sec)	nm [b]	1.6E-4	7.7E-5	1.9 E-5	nm [b]	–
repair technique	CS direct to crack	CS through wells in coarse sand	GCL	PSX through wells in JN soil	PSX direct to crack	Recompaction of new kaolin
K after repair (cm/sec)	9.1E-8	no flow , 90 days	2.1E-8	6.0E-6 [a]	5.4E-8	2.3E-8
results of redrying	crack reopened at surface; K=4.3E-8	[b]	new crack, increased K to 1E-6 cm/sec		Not tested	[b]
re-repair			additional patch			
K after repair (cm/sec)			no flow , 20 days			
results of redrying	[b]		new crack, increased K not measured			
re-repair			additional patch			
K after repair (cm/sec)			8.8E-9			

[a] incomplete coverage of crack [b] test still in progress

capillary forces prevented much of the injected PSX from draining down to the clay surface and flowing to cover the crack.

Fracture Covered With GCL (Lysimeter #4)

Lysimeter 4 was repaired by application of Claymax R Bentonite Geosynthetic Clay Liner (GCL) (CETCO, Arlington Heights, IL). A patch of GCL was cut to overlap the entire fracture by 10 cm on both sides and fit closely with the wall. Since the hydraulic conductivity of the cracked CCL had just been measured, the bentonite paste in the annular gap was still watertight, so when hydraulic conductivity was measured, there was no flow from the edge. Flow from the center drain indicated that the repair was successful.

Lysimeter 4 was then redried by flowing a stream of dry air over it. A shallow (1 mm) secondary crack was observed extending out from under the GCL, and presumably connecting with the main crack. Hydraulic conductivity measurement showed that the new crack was carrying flow to the original crack under the GCL, resulting in a permeability (averaged over the entire area) of about 10^{-6} cm/sec, gradually decreasing. The overburden was then removed and a second GCL patch was applied, covering the new crack and overlapping the first patch. Overburden and water head were applied, and the second patch reduced the flow rate to zero. After ten days the test was discontinued with no flow having been observed. A third redrying produced similar results, with new crack formation, and a third repair reduced the hydraulic conductivity to 8.8x10-9 cm/sec.

Excavation of Cracks and Recompaction of New Kaolin (Lysimeter #7)

When cracks are detected, either during construction or in service, the cracked material can be removed and new material recompacted in its place. This is the baseline technology against which the other technologies are to be compared. During the construction of the existing clay caps at SRS, some material dried and cracked and was removed, and new material was joined to it. Thus, this repair technique has actually been implemented in the field. The repair technique consists of compacting new material next to, and joining it to existing compacted material. The desired result is that the "seam" between the two materials is as tight as the bulk material; and that the seam not constitute a zone of weakness during drying that may occur after construction.

Recompaction of new clay can only succeed if the existing clay is sufficiently plastic to deform when the new clay is joined to it. Observations made in the other lysimeters showed that even 21% water is too dry to accept much compactive effort. It was desired that the clay to be repaired have dried and shrunk sufficiently to develop a significant crack, and yet still be plastic enough to repair. The lysimeter was divided in half by a temporary wall, and new Barden AG-1 kaolin at STD +3 was compacted in half of the lysimeter. This half-CCL was allowed to dry until it was judged by feel to be near the lower limit of water content necessary for successful joining of new clay. The water content was 28.4%. The CCL has also shrunk to 98.2% of its original area; this would constitute a significant crack. The temporary wall was removed, and clay was removed from the vertical surface of the existing clay to leave an oblique surface with a slope of 1 vertical to 2 horizontal. Water was sprayed on the oblique surface and it was scarified, and new material was compacted to fill the lysimeter. No problems with cracking of the existing clay cap were noted. The hydraulic conductivity was measured at $2.3\text{x}10^{-8}$ cm/sec,. indicating a successful repair. Following the flow test, after several weeks under ponded water, the repair was not visible. The laboratory test is continuing with drying of the CCL, to see whether the seam behaves differently from the bulk compacted clay. Presumably when this technique was used in the field, no problem was observed due to inadequate plasticity of the existing clay. Therefore the available evidence confirms that this repair technique was satisfactory.

The Viscous Barrier Liquids

Viscous barrier liquids are low-viscosity grouts that can be injected into soils to gel or solidify in place, blocking water flow. The two types of liquids tested here were selected for low initial viscosity, controllable gel time, effective pore blocking, and non-toxicity. See Moridis et al, (1993, 1995) or Persoff et al. (1994, 1995) for more information about the barrier liquids .

The colloidal silica was NP-5880 (Eka-Nobel, Marietta GA). This is an alumina-modified colloidal silica that typically contains 25% by weight silica, and 0.4% by weight Na_2O; its viscosity is 7 cP, pH 6.5, and density 1.17 g/cm^3. The nominal particle size is 8 nm. This colloid is made to gel by mixing 1 part by volume of CaCl2 brine with 5 parts colloid. The brine concentration controls the gel time. For direct-to-crack injection, 0.32 *M* $CaCl_2$ brine was used, which gels to a solid in 2 hr, and for through-sand injection 0.28 *M* $CaCl_2$ which takes twice as long to gel.

The polysiloxane was Dow-Corning 2-7154-PSX-10, with catalyst Syl-Off 4000. (Dow-Corning, Midland MI). This has an initial viscosity of 10 cP. It was used with 3% catalyst by weight, which gives a gel time of 1 hr.

For injection of gelling liquid to succeed as a repair technique, the liquid must (i) flow to the crack through the overburden (clay-sand or drainage layer), (ii) drain into the crack, (iii)gel in the crack before it drains down out of the crack, and (iv) be effective in sealing once it has gelled in the crack. In order to isolate these events, the testing of gelling liquids was conducted in two parts: First, the ability of the gelled liquid to seal the crack was tested by injecting the liquids directly to the crack. Second, the liquids were injected through wells into a layer of overburden, through which they flowed over and into the crack.

Direct PSX Injection Into Fracture (Lysimeter #6)

Bentonite powder was poured into the annular gap at the wall, and followed by packed-in bentonite paste. Sand was poured and packed into the fracture and the barrier liquid was applied to the crack with a pipette. Several 100-g batches of PSX were mixed and applied to the crack, saturating the crack, and allowed to gel. Because this CCL had been dried to a lowest water content of all the CCL's, much of the PSX was imbibed by the kaolin. A total of 700 grams of PSX were applied, until the crack refused to take any more PSX. An additional 200 grams were used to fill large divots formed when the crack was spread by rotating a chisel.

Initially there was a fast flow of water, which was recognized as typical of leakage through the bentonite paste. This flow issued from center drain as well as from the edge drain; however since it was turbid it was interpreted as flow through the bentonite powder. After two days the flow at the center stopped completely and a slow flow continued through the edge drain. In Table 1 this flow rate is interpreted as leakage through the repaired CCL.

Direct CS Injection Into Fractures (Lysimeter #2)

Colloidal silica was applied to CCL 2 in a similar manner as PSX had been to Lysimeter 6. After a total of 470 mL of CS grout had been applied in six injections, the crack would not accept any more. As in Lysimeter 6, there was initially fast flow of turbid water (equivalent to a hydraulic conductivity K of 1×10^{-5} cm/sec) through both drains; after the bentonite swelled a slow flow continued through the center drain, indicating a final hydraulic conductivity of 9.1×10^{-8} cm/sec.

CS Injection Into Sand Overburden (Lysimeter #3)

A practical advantage of injecting gelling grouts through overburden (sand or soil) is that the overburden need not be removed and replaced. In this case the liquid can be injected into a well or trench and must flow downward to the CCL and laterally to the crack, and then drain into the crack. In the field, the crack location may not be known, but generally the CCL is sloped, which will aid the grout in finding the crack.

To test this method of application in the laboratory, the crack was packed with sand to prevent it from self-healing and 15 cm of coarse sand, simulating the actual drainage layer overlying the some of the clay caps at the Savannah River Site was placed over the CCL. Two wells, perforated only in the bottom inch, were located 22 cm from each side of the crack as shown in Figure 3.

The electrical conductivity of CS grout was used to monitor its flow from the well to the crack. Twenty pairs of wires, used as resistivity sensors were arrayed over the surface of the CCL as shown in Figure 3. Sensors 10 through 16 trace out the crack. After this photograph was taken, the coarse sand was placed over the entire CCL, and two 2100 mL grout injections were made from a Mariotte bottle on successive days, first through the north well (between sensors 1 and 2) and then through the south well. The advance of grout through the coarse sand overburden is shown by the decrease in resistance as grout contacted each probe in Figure 4. No outflow was detected during 100 days. Complete flow blockage indicates either that the grout flowed into the crack and sealed it or that a complete layer of grouted sand was formed above the CCL. This lysimeter is now being dried for further testing.

PSX Injection Into Soil Overburden (Lysimeter #5)

This test was done in a similar manner to the preceding test, except a local clay-sand soil was used instead of coarse sand, lightly compacted to a dry density of 1.44 g/cm^3. Following the second injection of PSX, the soil was covered by filter fabric and gravel overburden, and the hydraulic conductivity of the repaired CCL was measured. The flow rate indicated a hydraulic conductivity of 6.0×10^{-6} cm/sec, which is lower by a factor of 3 than the hydraulic conductivity of the sand-packed fracture, but well above the target value for repaired CCL. To diagnose the cause of failure, the soil was mucked out by hand to reveal the grouted plumes, which were in the form of symmetrical mounds. The injected PSX grout spread over the surface of the CCL but did not completely cover the crack, leaving the ends of the crack exposed.

Analysis of numerical simulations of the injection showed that the great majority of grout injected into JN soil was taken up into pore space by capillarity, and did not contribute either to filling the crack or to forming an impermeable zone above the crack. The amount of PSX injected was sufficient to cover the CCL to a depth of 1 cm. If a greater volume of liquid had been injected, greater spreading and saturation of the grout would have resulted, and the design criterion (1×10^{-7} cm/sec) might have been met.

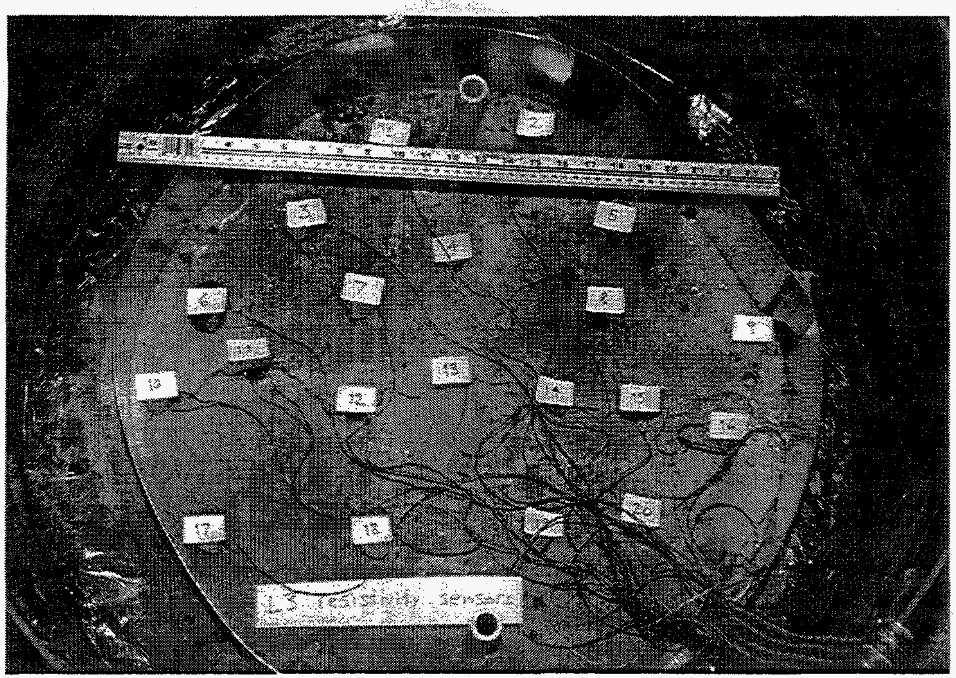

Figure 3. Resistivity sensors and wells arrayed on CCL 3 before covering with coarse sand.

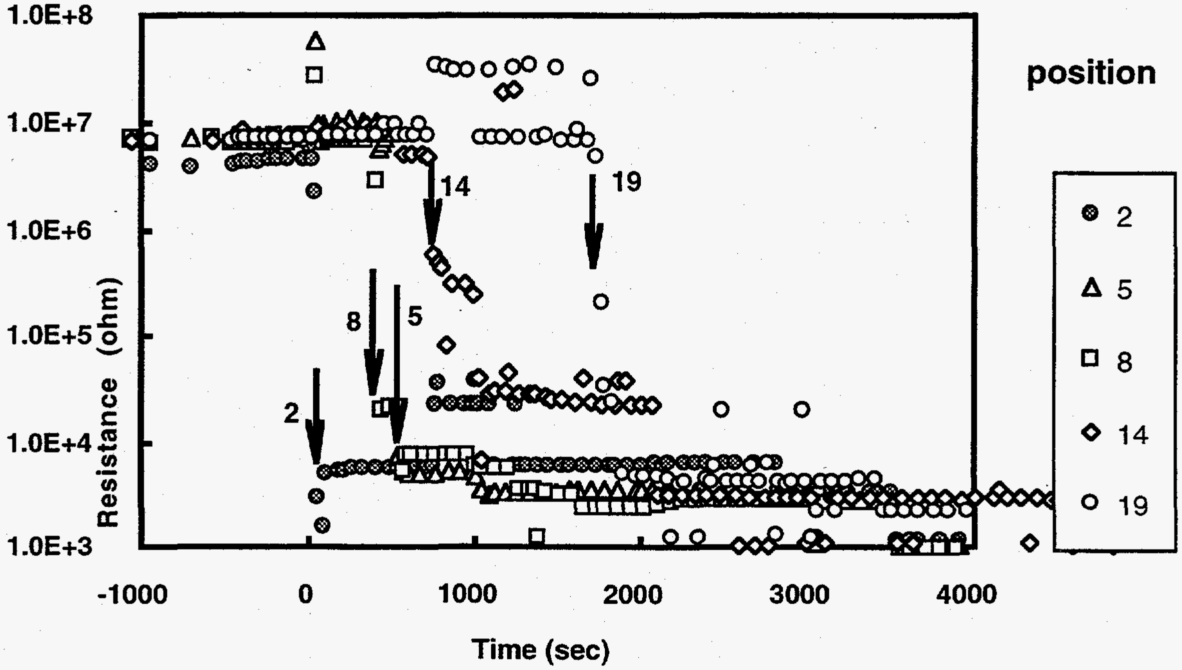

Figure 4. Resistivity measurements showing time of grout arrival at stations 2, 5, 8, 14, and 19.

CONCLUSIONS

The observations support the following conclusions:

(1) Covering a crack with a GCL effectively prevents water from entering the crack, but does not fill the crack. Additional cracks that connect with the repaired crack can therefore bypass the repair.
(2) Either colloidal silica or polysiloxane, if injected or drained into a crack in compacted clay, seals the crack effectively.
(3) Colloidal silica can be injected into a sand drainage layer and flow into a crack and seal it.
(4) Electrical resistivity measurement is an effective technique for tracking the penetration of colloidal silica grout.

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