

USBM Contract HO144061

FINAL REPORT
DEVELOPMENT OF A FLY ASH-CEMENT
MINE SEALING SYSTEM

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USBM CONTRACT REPORT HO144061

March, 1975

DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
WASHINGTON, D. C.

Bureau of Mines Open File Report 26-76

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BIBLIOGRAPHIC DATA SHEET	1. Report No. BuMines OFR 26-76	2.	3. Recipient's Accession No.
	4. Title and Subtitle Development of a Fly Ash-Cement Mine Sealing System		5. Report Date March 1975
7. Author(s) Kenneth R. Maser, Robert E. Wallhagen, and John Dieckmann		6. Performing Organization Code	
9. Performing Organization Name and Address Foster Miller Associates, Inc. 135 Second Avenue Waltham, MA 02154		8. Performing Organization Rept. No.	
12. Sponsoring Agency Name and Address Office of Assistant Director--Mining Bureau of Mines U.S. Department of the Interior Washington, DC 20241		10. Project/Task/Work Unit No.	
15. Supplementary Notes Approved for release by Director, Bureau of Mines, February 6, 1976.		11. Contract/ Grant No. H0144061	
16. Abstracts This report describes the development of a system which modifies an existing fly ash-foam remote mine sealing technique to make it capable of impounding water in a fire zone. Laboratory-scale determinations were made of the capillarity, permeability, shrinkage, and shear strength of various mixtures of fly ash, bentonite, limestone, and cement. Leakage tests (1/4-scale) indicated that shrinkage in fly ash-cement mixtures always result in leakage, whereas fly ash-bentonite mixtures were impervious to water. Large-scale leakage tests with a 15-foot water head showed that a 1:1 fly ash-bentonite bulk seal with a 2-inch top layer of 1:1 fly ash-Huron cement is the optimum combination for a water-tight seal; a froth foam topping is suitable for providing an air-tight seal. A water leakage rate of about 1.5 gpm is predicted for the optimum combination of the above sealants in a typical mine with a 15-foot water head. Guidelines are given for determining the quantities of materials required for constructing a mine seal.		13. Type of Report & Period Covered Contract research, FY 1976	
17. Key Words and Document Analysis. 17a. Descriptors Mining Sealing Mine fires Cements Flyash Foam		14. Sponsoring Agency Code	
17b. Identifiers/Open-Ended Terms		15. Supplementary Notes Approved for release by Director, Bureau of Mines, February 6, 1976.	
17c. COSATI Field/Group 08I, 11A		16. Abstracts This report describes the development of a system which modifies an existing fly ash-foam remote mine sealing technique to make it capable of impounding water in a fire zone. Laboratory-scale determinations were made of the capillarity, permeability, shrinkage, and shear strength of various mixtures of fly ash, bentonite, limestone, and cement. Leakage tests (1/4-scale) indicated that shrinkage in fly ash-cement mixtures always result in leakage, whereas fly ash-bentonite mixtures were impervious to water. Large-scale leakage tests with a 15-foot water head showed that a 1:1 fly ash-bentonite bulk seal with a 2-inch top layer of 1:1 fly ash-Huron cement is the optimum combination for a water-tight seal; a froth foam topping is suitable for providing an air-tight seal. A water leakage rate of about 1.5 gpm is predicted for the optimum combination of the above sealants in a typical mine with a 15-foot water head. Guidelines are given for determining the quantities of materials required for constructing a mine seal.	
18. Distribution Statement Release unlimited by NTIS.		19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages
		20. Security Class (This Page) UNCLASSIFIED	

FOREWORD

This report was prepared by Foster-Miller Associates, Inc., Waltham, Massachusetts under USBM Contract No. H0144061. The contract was initiated under the Coal Mine Health and Safety Program. It was administered under the technical direction of PM & SRC with Messrs. Donald Mitchell and Joseph Kuchta acting as technical project officers. Mr. Joseph Herickes was the contract administrator for the Bureau of Mines.

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Summary

This report describes the development of a system which modifies an existing fly ash-foam remote mine sealing technique to make it capable of impounding water in a fire zone. The modification involves blending equal quantities of fly ash and bentonite to form the bulk of the seal, and blending a thin layer of fly ash and Huron Regulated Set Portland Cement (RSPC) as a coating. The modification replaces the pure fly ash approach, but continues to use a froth foam topping to complete the seal. The modified material system is implemented with minimal complexity by adapting a "Y" connector to the existing delivery system. Each bulk hauler (fly ash and bentonite, or RSPC) will pump into one leg of the "Y", and the blending will be controlled by two pinch valves.

The development effort has involved an evaluation of potential material systems by using small sample, quarter scale, and full head tests. The small sample tests measured the basic properties of a large number of selected material combinations. Property measurements included capillarity, permeability, shrinkage, and shear strength. As a result of these tests, particular combinations of fly ash-bentonite and fly ash-cement were selected for scale model testing in a 1/4 scale test facility. These tests simulated, in a scaled manner, the water rise and total head which would be experienced by a seal. The tests indicated that shrinkage in the fly ash-cement combination would always result in leakage; whereas, fly ash-bentonite mixes were impervious to water.

The weak zone of the fly ash-bentonite seal was identified as the interface between that mixture and the froth foam topping. A full head test was designed to evaluate that interface under simulated full scale conditions, and the resulting evaluation lead to the development of the final fly ash-Huron RSPC coating. The results of the full head test suggested that the seal would leak at about 5 gpm when subjected to a full head of 15'. This is well below tolerable leakage rates for inundation of a fire zone.

1. Introduction

This report is submitted in fulfillment of the requirements of USBM Contract No. H0144061, "Development of Fly Ash-Cement Mine Sealing System." It is a technical report which summarizes the results of laboratory testing and system development. The results presented in this report are to be incorporated as an amendment to the "Operations Manual for Extinguishing Coal Mine Fires by Remote Sealing, Vol. I"; as described under Section 1.2 of Contract No. H0122046.

1.1 Background

Although continuing efforts at improved mine safety are minimizing the causes of coal mine fires, the chance of serious mine fires is still a reality. Whenever this occurs and can not be extinguished quickly by men nearby, the fire area must be sealed off. This can be done by constructing air-tight stoppings in the mine passages leading to the fire zone. It is desirable, of course, to isolate the fire zone in such a way that normal operations can be resumed in the remainder of the mine as soon as possible.

Construction of fire zone seals by workmen in the mine, is a very hazardous operation. With an active fire in a coal mine, the possibility of explosions is very real. Because of this, considerable effort has been directed towards developing a system which can remotely seal off mine passages from the ground surface.^{(1,2)*} This has been attempted by pumping any one of a number of materials through a bore-hole into the passage. The most recent advances in the development of such a remote sealing system have been made by Foster-Miller Associates under USBM Contract No. H0122046. A full description of the operation of that system and its development can be found in the final reports for that contract.⁽³⁾

*Numbers in parentheses refer to references listed in the Bibliography.

Even if successful seals are created around the fire zone, it may be weeks to months before the mine can be reopened. Oxygen continues to feed the fire due to the expanse of the sealed area, and due to leakage through fissures in the rock and coal. Attempts to reduce this time have been made by introducing inert gas, and by water inundation. This latter approach has been attempted with some degree of success in the Nemeocolin⁽⁴⁾ and Somerset⁽⁵⁾ Mine fires. In these cases, the water was impounded by dams that were built from within the mine. For a remote sealing operation, inundation requires that the remotely placed seals be capable of impounding millions of gallons of water at pressures which reflect the difference in mine elevation within the sealed, or flooded zone.

Early in the development of the fly ash remote sealing technique⁽²⁾ it was suspected that the fly ash seal alone could serve adequately as a dam for water impoundment, but further examination indicated that it was inadequate due to excessive shrinkage upon wetting.⁽³⁾ Another technique for remote construction of a water dam in a mine employs gravel and a slurry,⁽⁶⁾ but this technique requires 7 accurately placed boreholes per seal, and this would not be feasible for a mine deeper than 50'.

Although the fly ash sealing technique, in its most recent state of development, was not capable of water impoundment, preliminary tests had indicated that the addition of rapid set cement to the pneumatically delivered dry fly ash would cause it to harden shortly after wetting. In a 1/4 scale test, this behavior, which was enhanced by capillary action, appeared to produce a water-tight seal.⁽³⁾

It was with this stimulus that the work described herein was undertaken. Basically, the goal was to modify the existing fly ash technique with some additive which would make the resulting seal water-tight. The development effort is described in the ensuing chapters.

1.2 System Requirements

The requirements for the water-tight mine seal can be summarized as follows:

- (a) The system must interface with the fly ash remote sealing technique which has already been developed.
- (b) The emplaced seal must withstand both the water-rise rates that would be experienced during a fire fighting operation, and the ultimate head which would develop due to elevation differences in the sealed zone.
- (c) The seal should be such that recovery operations are minimized.

These requirements are elaborated below.

1.2.1 Interfacing with Fly Ash Remote Seal System

The existing fly ash remote sealing system involves the pneumatic injection of fly ash into a borehole which intersects the passage to be sealed. Figure 1 shows a schematic of the surface delivery setup. The proper formation of the seal requires the fly ash to be delivered in the dry state. This implies that any additive to the pumped fly ash must be in a dry powder form, capable of being introduced into the fluidized flow.

1.2.2 In-Mine Conditions

Each sealing situation will differ from the next. The sealed area will depend on the size of the fire zone and surface accessibility for boreholes. The ability to flood the area will depend on the availability of water, both on the surface and underground.

1-4

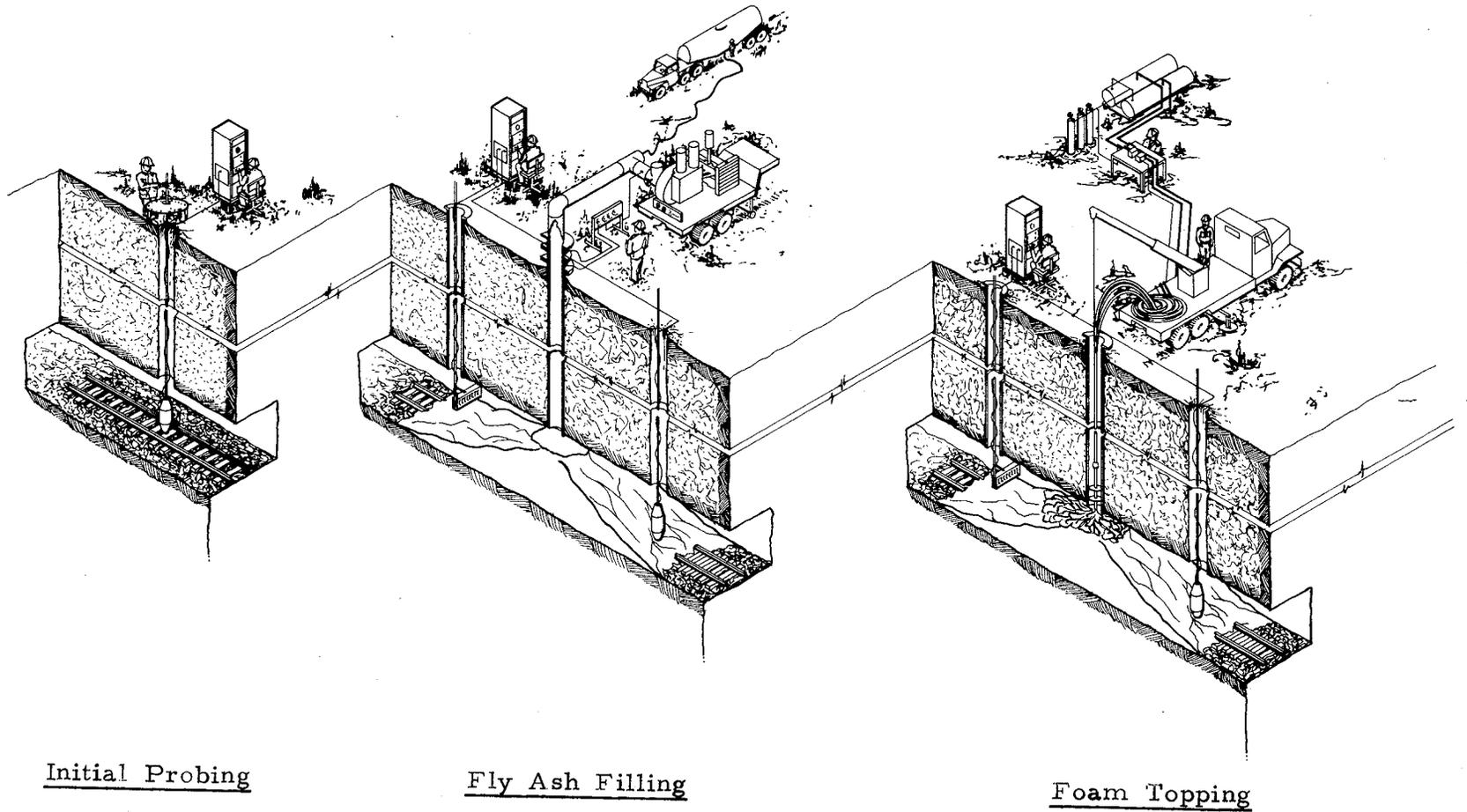


Figure 1. Remote Mine Sealing System

We are concerned with two parameters - the rate of water rise and the total head. We can estimate these parameters by considering a hypothetical fire zone, 300' x 800', as shown in Figure 2. If entries are 100' on center, and 20' wide, then the sealed area equals the total area minus the pillar area, or 86,400 sq. ft. The sealed area will be flooded through boreholes, where the maximum water flow is calculated as

$$\begin{aligned}
 \text{Flow/Borehole} &= 7.5 \frac{\pi d^2}{4} v \text{ (gpm)} & v &= \text{discharge velocity} \\
 &= 7.5 \frac{\pi d^2}{4} \sqrt{2 gh} & d &= \text{borehole diameter} \\
 & & g &= 32 \text{ ft/sec}^2 \\
 &= 47 d^2 \sqrt{h} \text{ (gpm)} & h &= \text{depth of borehole}
 \end{aligned}$$

Boreholes used in remote sealing are 6" in diameter. For a 400' borehole

$$\begin{aligned}
 \text{Flow/Borehole} &= 47 \times \frac{1}{2}^2 \times \sqrt{400} \\
 &= 236 \text{ gpm}
 \end{aligned}$$

In our hypothetical case, we shall assume that we are using two boreholes to capacity, and hence we are filling a 86,400 sq. ft. area at the rate of 472 gpm. The rate of water rise is calculated as

$$\begin{aligned}
 R &= \frac{472 \text{ gal}}{\text{min}} \times \frac{1 \text{ cu. ft}}{7.5 \text{ gal.}} \times \frac{1}{86,400 \text{ sq. ft.}} \times \frac{12 \text{ in.}}{\text{ft}} \times \frac{60 \text{ min.}}{\text{hour}} \\
 &= 0.52 \text{ in. /hour}
 \end{aligned}$$

For different cases, this number will vary, but for most reasonable estimates it should range from 0.1 to 2.0 in. /hour.

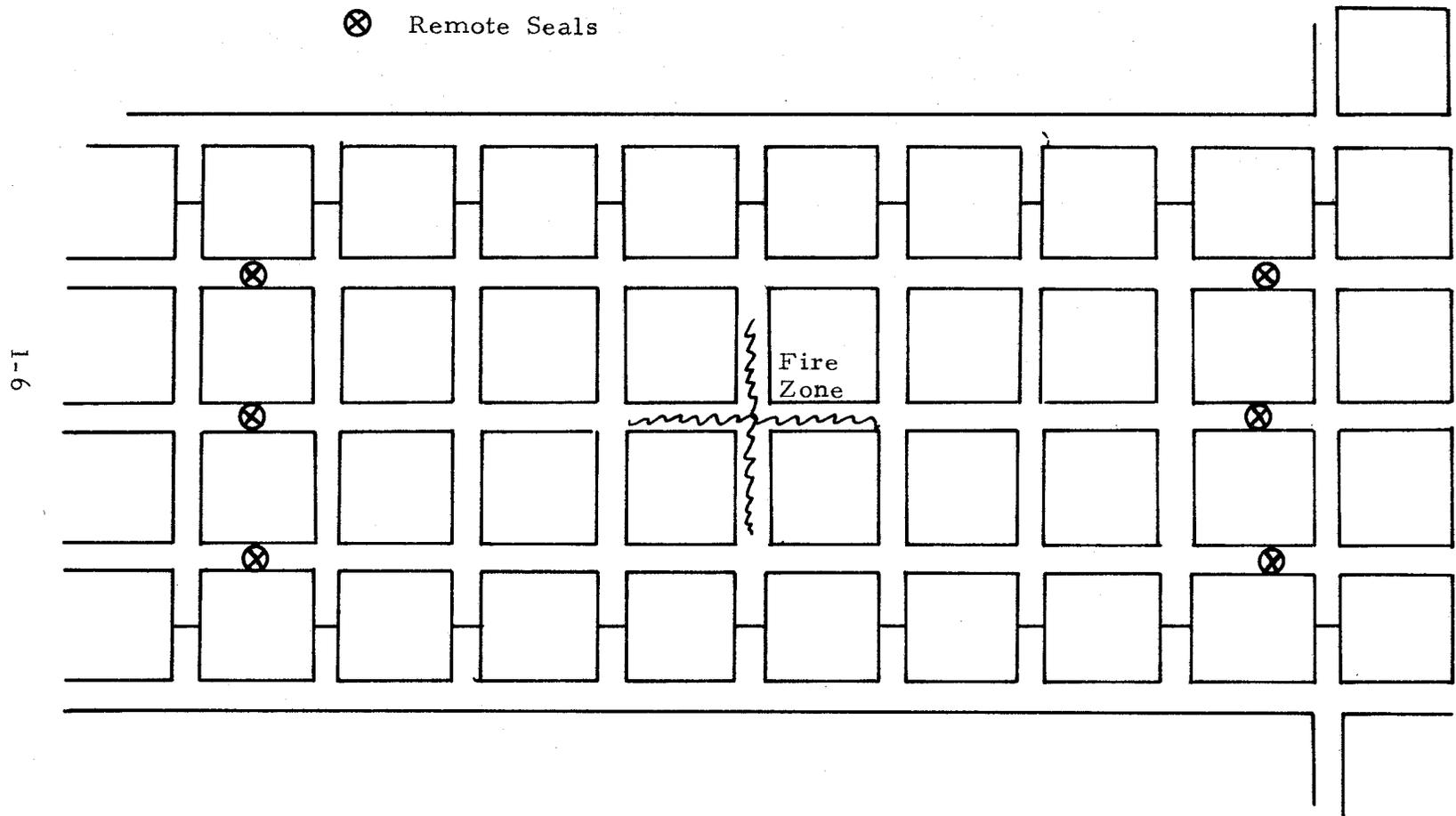


Figure 2. Possible Configuration of Sealed Area

The maximum total head to be experienced by any one seal will depend on the elevation difference between the mine floor at that seal and the maximum height of water. This can roughly be related to the slope of the coal seam and the extent of the flooded area. If we assume that we have a 6' seam at a 1% slope, our hypothetical example would yield

$$\begin{aligned} \text{Head} &= \sqrt{300^2 + 800^2} \times 0.01 + 6 \\ &= 14.55 \text{ ft.} \end{aligned}$$

or 8.55' above the passage roof. Since there is no way of fixing what this value will be in a general case, we have assumed, based upon the Nemecolin experience and reasonable examples such as the above, that the proposed seal be capable of holding a total head (from the floor) of 15 feet.

1.3 Scope of Work

The effort described in this report is divided into three categories:

1. Small sample tests
2. Scaled tests
3. Full head test.

A review of anticipated seal failure modes, and potential additive materials, is presented in Section 2. The small sample tests, used to determine the engineering properties of the various fly ash-additive mixtures, are described along with their results in Section 3. The results of these tests were used to select potential sealing systems, and these were evaluated using quarter scale simulation. A description of those tests and their results is presented in Section 4. The critical zone of

the sealing system, i.e., the interface between the top of the pneumatically emplaced seal and the frothed foam, was identified from these tests. This interface was tested under full height conditions as described in Section 5. The final sealing system, along with mixing and metering hardware, is described in Section 6.

2. Basic Considerations

Before discussing the details of the experimental program, we shall first review the potential failure modes of the sealing system, and we shall investigate potential additive materials which could preclude the occurrence of such failures.

2.1 Seal Behavior

The sealing system which we are seeking is physically similar to an earth dam, with two principal exceptions.

1. The mine seal must support a head above its own height, and it must seal a top interface.
2. We are concerned with transients which occur during filling as well as steady state phenomena.

Figure 3 indicates the transient condition of the mine seal during filling. The indicated water level is rising at a steady rate of somewhere between 0.1 and 1.0 inches per hour. The capillary head of the fly ash mixture causes the wetted zone in the seal to extend to a height above the height of the water. The total extent of the wetted zone depends on the capillary head, but is primarily a function of the permeability of the fly ash mixture and the head of the water. Theoretically, the entire flow history, and ultimate steady state flow net, can be computed given the geometry of the seal, the capillary head and permeability of the fly ash, and the rate of water rise. The usefulness of such an exercise will not be clear until some consideration is given to potential failure modes. We do know, however, that the density of the pneumatically emplaced material varies considerably throughout the

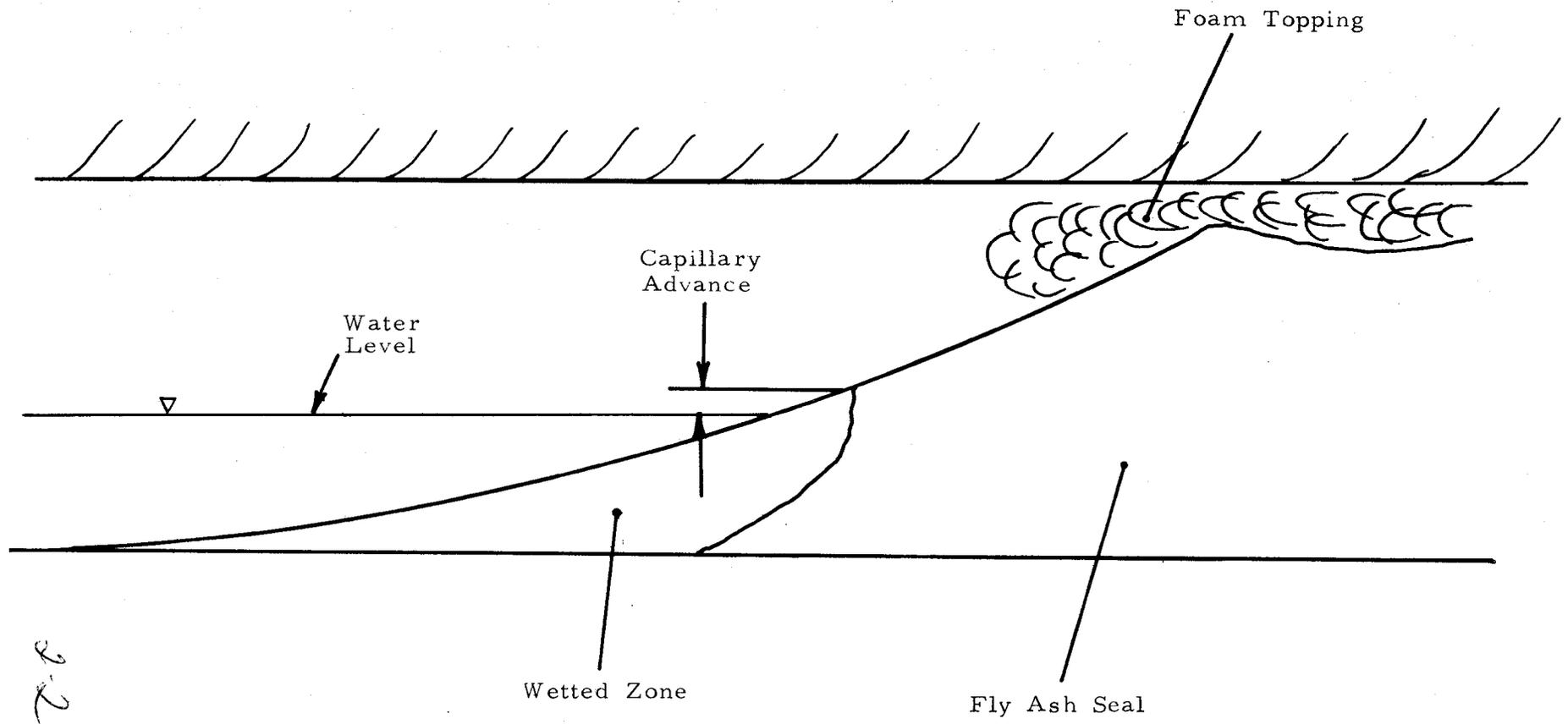


Figure 3. Upstream End of a Fly Ash Mine Seal Subject to Rising Water

seal, ranging from very loose at the extremities to densely packed in the region near the borehole. This density variation would have to be quantified before any realistic numerical results could be obtained.

2.2 Potential Failure Modes

We shall consider two basic types of seals - one which has a permeability high enough so that water permeates the entire seal during its life, and one whose permeability is low enough that the wetted area is well within the upstream half of the seal.

For the first type, we must be concerned with failures at the downstream slope, where the seepage pressure is not balanced by externally applied pressure. Such failure types include:

1. Sloughing of the toe
2. Downstream slope instability
3. Piping

Sloughing of the toe occurs when the seepage pressure counteracts the internal friction of the material and causes localized collapse of the slope. A downstream slope instability would be sloughing on a grander scale, where a full circular failure would occur due to the loss of shear strength. Piping occurs due to erosion along a stream line beginning at the downstream slope or toe. Percolating water causes erosion, reducing the length of the stream line. This increases the hydraulic gradient, and the seepage pressure as well, causing the erosion to accelerate. This accelerated linear erosion results in a "pipe," which produces a sudden failure.

One upstream failure mode can be described as sloughing of the upstream face. The sloughing failure occurs when water permeates

through the dry fly ash at a rate such that the particles almost go into suspension, and the wetted particles start to flow, slough, or collapse from the positions where they were emplaced. This process continues until the water has washed its way completely through the seal. A shell failure occurs in the opposite extreme of permeability. If the material has a low permeability the water will rise up the surface, wetting only a thin layer. If hardening takes place this layer will form a shell. The remainder of the dam is only dry fly ash plus additive, supporting the full weight of the shell and water. If the dry dam material does not have the strength to hold the pressure of the impermeable layer and water, it will give way and the impermeable layer will split open allowing water through under pressure.

A failure mode peculiar to the mine seal occurs at the top. When the head level is above the height of the passage, the hydraulic gradient is greatest along the top of the seal. Hence erosion, and a possible blowout, is most likely to occur here. This possibility is enhanced if shrinkage or compaction occurs within the seal. This volume reduction may manifest itself as a gap at the top, where leakage and erosion will take place.

The final type of failure is a plug failure of the complete seal. This can occur when the upstream hydrostatic pressure is greater than either the sum of all the retaining shear forces at the floor, roof, and side walls, or the sum of the retaining shear forces in the dam material itself. In either case, total catastrophic failure would result.

2.3 Sealant Materials

From the discussion of failure modes the following important properties are identified for sealant materials.

1. High cohesive strength upon wetting.
2. Minimum, or no shrinkage.

3. Low permeability.

All of the downstream failure modes are the result of loss of shear strength. If we consider cementing type materials, the resulting hardening will prevent such failures. Cementing will also prevent erosion. Shrinkage upon wetting can be responsible for failures as well, and we should seek to use materials where this can be minimized, eliminated, or better yet, replaced by a volume expansion. Low permeability materials will confine the wetted area to the upstream zone, and hence eliminate potential downstream failure modes.

Two basic types of additive materials have been identified which could result in improved fly ash properties, resulting in water tight seals. These two basic types of additive are cements and clays.

Cements added to the fly ash result in a hardened, water impermeable seal, provided the cement has set and developed some strength before it has to support a significant water head. Desirable properties of a fly ash-cement mixture in the presence of water include a rapid rate of capillary water rise and a permeability such that the bulk of the seal is moistened as the water level rises behind the seal. A rapid rate of capillary water rise initiates the hardening of the seal before any actual water head must be withstood. Moistening the bulk of the seal results in the hardening of the bulk of the seal.

Certain types of clay, when added to fly ash, result in a significantly reduced permeability of the fly ash and in the maintainance of some wet cohesive strength. The water head is supported by the dry fly ash-clay mixture comprising the bulk of the seal. Desirable properties of fly ash-clay mixtures include low water permeability,

good wet cohesive strength, and increase in volume upon wetting. One principal advantage of a clay-type seal is that during recovery of the mine, it is much easier to remove than a hardened cement seal.

Table 1 presents a summary of the materials and material combinations whose addition to the fly ash would improve the seal's capacity to hold water. Primary additives include cement, clay, and lime, and secondary additives are typically set accelerators, which are added as a small percentage by weight of cement.

In evaluating potential material systems, we must weigh the advantages of multiple component systems (e.g., fly ash-cement, and sodium silicate) against the complexity of mixing and metering more than two components.

Additional consideration must be given to cost and availability of materials. In general, the primary costs associated with a mine sealing operation are associated with labor and equipment. Material costs should be minimized where possible, but not at the expense of increased complexity of equipment. Availability of the material is important in the scheduling of the sealing operation. Materials such as fly ash can be delivered practically on call, in an emergency situation. Bentonite, on the other hand, must be shipped by rail in advance of the sealing operation. If the sealing operation is properly planned, the shipping time should not present a problem, since there are many other preliminary operations which must take place before the seals are actually built.

2.4 Emplacement Techniques

When additives are mixed with fly ash to improve its properties as a seal, one would naturally expect that uniform mixing would be the most desirable approach. This might involve a storage hopper for the additive(s) and some kind of metered feed of the additive into the pneumatically conveyed fly ash. When one considers the

TABLE I
CANDIDATE MATERIALS FOR WATER TIGHT FLY ASH SEAL

Primary Additive	Estimated Amount Required, percent of fly ash by weight	Secondary Additive	Approximate Amount Required		Data on Primary Additive				Data on Secondary Additive			Effect of Combination	
			percent of primary	percent of fly ash	Availability	Form	Cost	Est. Cost /Ton Fly Ash	Availability	Form	Cost		Est. Cost /Ton Fly Ash
None	--	None	--	--	--	--	--	--	--	--	--	--	Slow pozzalanic hardening arising from the free lime in the fly ash
Portland Type I Cement	15 percent - 20 percent	None	--	--	Widely available provided in bulk or bag, locally available	Finely ground powder	Approx. \$30-\$35 per ton	\$4-\$8	--	--	--	--	Initial set 3-6 hours Final set 6-12 hours Hardens over course of days
Portland Type I Cement	15 percent - 20 percent	Calcium Aluminate Cement (Lumnite)	10 percent to 30 percent	1.5 percent to 6 percent					See Lumnite, below			\$2-8	Rapid or flash set, reduced final strength
Portland Type I Cement	15 percent - 20 percent	CaCl ₂	2 percent to 10 percent	.3 percent to 2 percent					On allocation, probably avail. within 3-4 weeks notice 100 lb bags	Flakes powder avail.	52/ net ton	\$1-5	Rapid or flash set depending on amount added
Portland Type I Cement	15 percent - 20 percent	NaHCO ₃ Baking Soda	2 percent	.3 percent to .4 percent					In short supply	Powder	195/ ton	\$4	Flash set
Portland Type I Cement	15 percent - 20 percent	Na ₂ CO ₃ (Soda Ash)	1 percent to 2 percent	.2 percent to .4 percent					On allocation, comes in 100 lb bags	Dry powder	160/ ton	\$1	Initial set within a few minutes
Portland Type I Cement	15 percent - 20 percent	Sodium Silicate	2 percent to 10 percent						Fairly widely avail. supplies currently short	Powder 100 mesh hollow spheres	220/ ton	\$1-5	Accelerated set, degree of acceleration unknown dry handling is difficult
Portland Type III Cement	15 percent - 20 percent	None	--	--	Widely available in bag or bulk	Finely ground powder	\$35-40/ ton approx	\$5-8	--	--	--	--	Initial set 1-3 hours Final set 3-6 hours Significant strength developed within one day
Huron Regulated Set Cement	10 percent - 20 percent	None	--	--	Shipped from Alpena, Mich. in 100 lb bags or in bulk hauler	Usual cement powder	\$50/ton F. O. B. Alpena \$25/ton delivery	\$7.50 - \$15.00	--	--	--	--	Will set over a period of minutes. Significant strength developed after one day
Lumnite (Calcium Aluminate Cement)	15 percent - 20 percent	None	--	--	Local dist. in most Appalachian Coal Mining areas packaged in 100 lb bags	Finely ground powder	Approx. \$140/ ton	\$15-30	--	--	--	--	Initial set approx. 4 hours Final set approx. 5 hours Rapid strength development after set
Bentonite (clay)	10 percent - 50 percent	None	--	--	Mined in Wyoming, Dakotas shipped by rail - delivery 2-3 weeks total	Finely ground powder	\$12.80/ ton F. O. B. Wyoming ~ \$30/ton shipping	\$15-50	--	--	--	--	Absorbs water and swells, becoming impermeable
Lime	10 percent - 25 percent	None	--	--	Inventories not maintained, but shipment is usually prompt. Widely avail.	Finely ground powder	\$13/ton in bulk F. O. B.	\$1.50 - \$4.00	--	--	--	--	Results are somewhat unpredictable and depend largely on the individual properties of the fly ash. For fly ash with good pozzolanic properties, initial set might occur within a few hours. Strength develops over a period of months.

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complexities of the field situation, however, there may be some distinct advantage in avoiding the uniform mixing requirements, and replacing it by some kind of layered approach.

Before discussing the merit of either the uniform or layered mine seal construction technique, it is beneficial to review the operation of the existing mine sealing system. A rough sketch of the overall sealing operation is shown in Figure 4. A sketch of the piping and instrumentation arrangement on the blower trailer is shown in Figure 5. The fly ash is pumped from the bulk haulage truck to the eductor on the blower trailer by the built in blower system on the bulk transport. The blower system on the bulk transport is typically capable of flows up to 300 cfm at pressures of 15 psi. The nature of the flow of fly ash from the bulk transport to the eductor is far from steady and uniform. In fact, it would be more accurately described as slug flow, where the flow alternately changes from mostly air and very little fly ash to a very dense slug of fly ash with only a little air.

It is evident that with such a highly random flow of fly ash, it is virtually impossible to meter an additive into the fly ash and achieve a uniform mixture. However, there is a built-in compensation for non-uniform mixtures entering the blower system. When the fly ash mixture reaches the mine passage it is distributed over the top of the growing mine seal in a uniform pattern. Because the mine seal surface is a very large area, time variations in mixture ratio result in a very thin layering effect which can reasonably be neglected when looking at the whole seal. For example, using 0.5 tons/minute as the delivery rate from the fly ash bulk transport and 60 lb/ft³ density; results in approximately 20 ft³/min of fly ash being deposited on the seal. With one quarter of a seal built in a 6- by 16-foot passage, this amounts to approximately 1/4 inch/minute seal growth.

Thus, in actual practice, the two emplacement techniques boil down to either finely layered mixes (approaching uniform mixing) or

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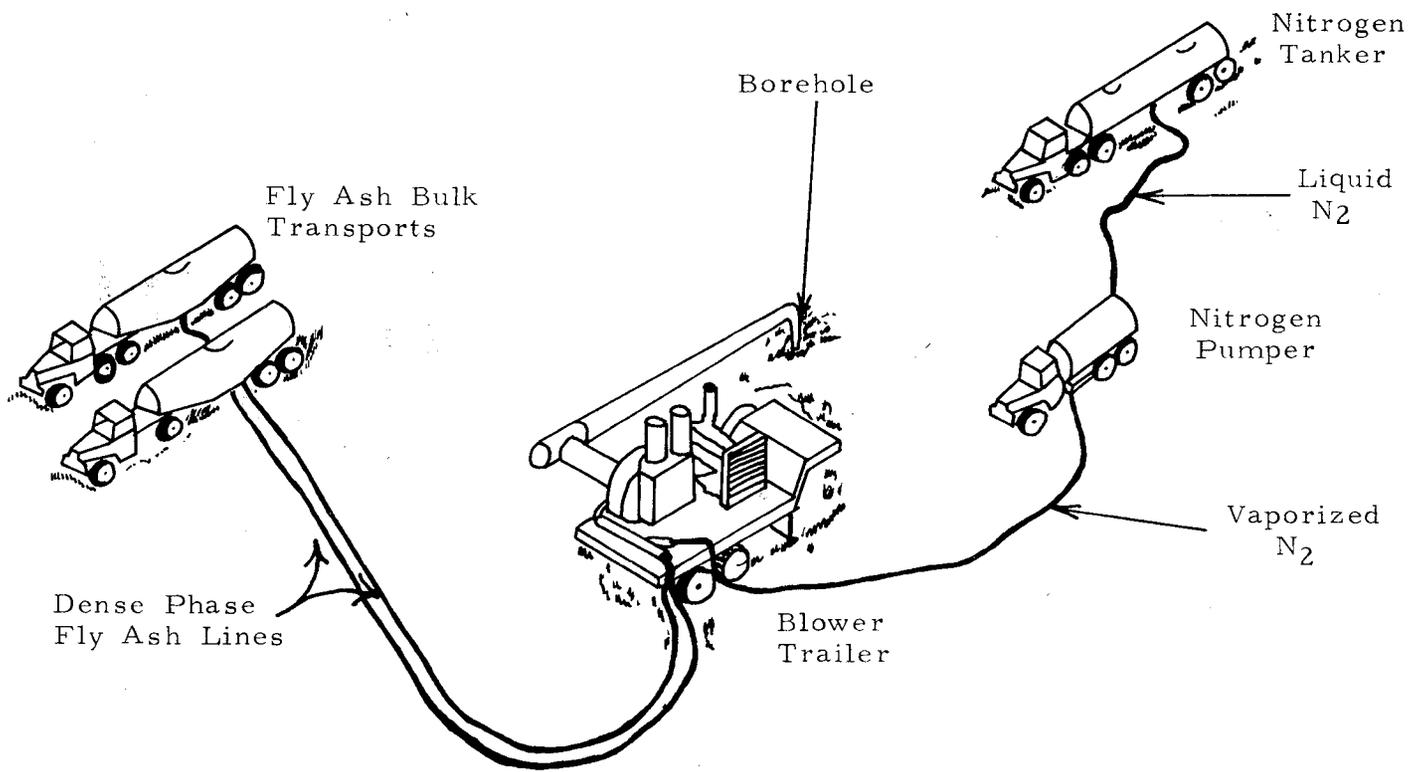


Figure 4. Overview Sketch of Remote Mine Sealing Operation

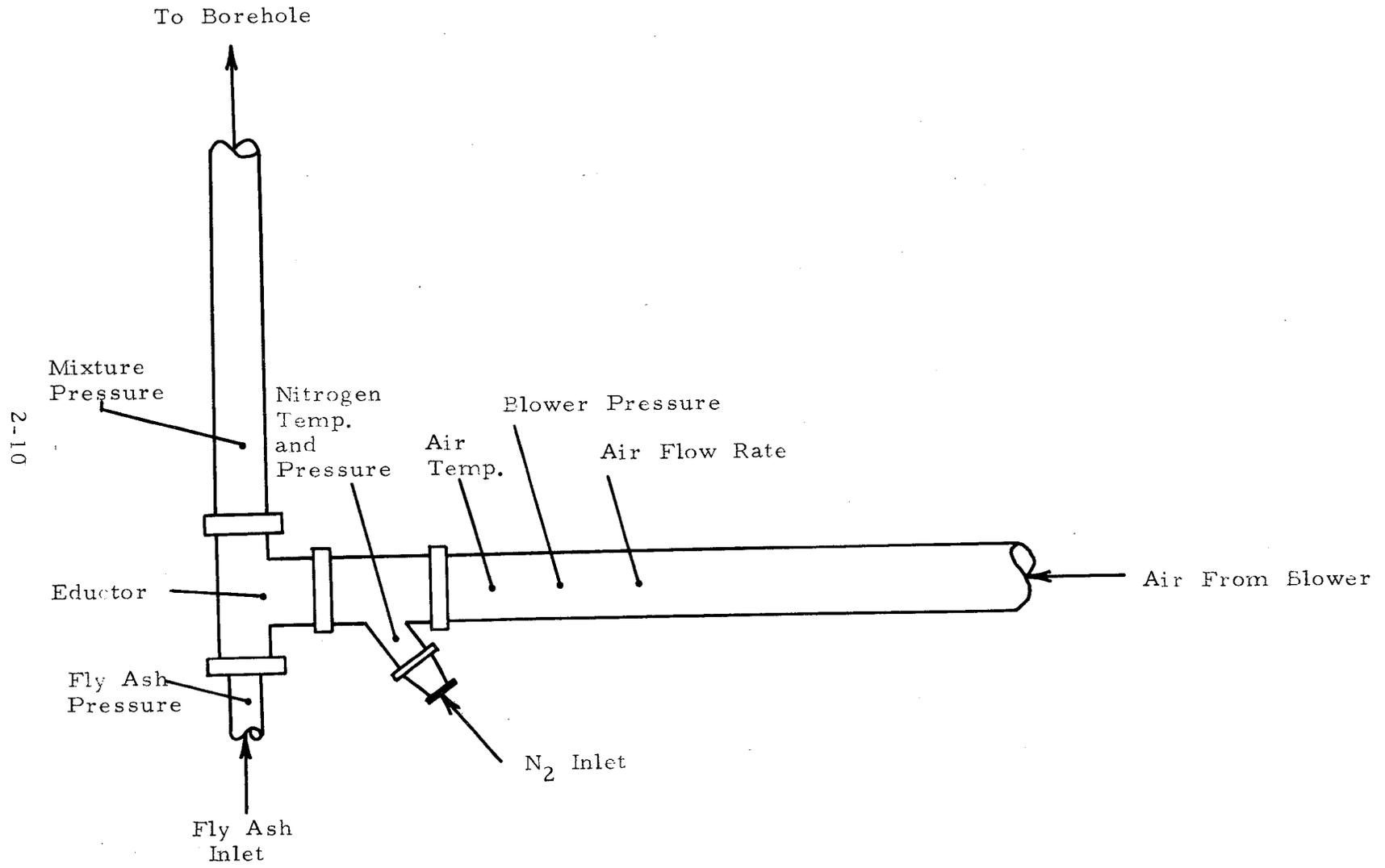


Figure 5. Piping and Instrument Sensor Layout

gross layering.

Layering is carried out by pumping off the fly ash and additive bulk haulers directly into the high volume air system, either alternatively or simultaneously. For example, a mixture of 1 part cement and 5 parts fly ash can be achieved by pumping off the cement bulk hauler for 8 minutes, followed by a full truck load of fly ash (assuming that it takes about 40 minutes to unload a cement truck). Metering a 1:5 mixture directly from the two trucks would be ideal, but in fact it is impossible to throttle the solids flow of a bulk hauler with any kind of control.

The effect of layering, or non-uniform mixing has been investigated in the test program and will be discussed in Section 4.9.

2.5 Test Program Objectives

The test program described in the next three sections was designed to:

1. Identify the most suitable materials for the water-tight fly ash seal.
2. Simulate the capability of the resulting pneumatically emplaced seal to retain a specified head of water.
3. Test the critical element of the seal under full head conditions.

The first aim was accomplished by conducting tests on small samples of various material combinations. In these tests, those engineering properties of the mixture which would determine its suitability were observed qualitatively, for comparison, and measured quantitatively

for subsequent analysis. The objective of the small sample tests was to both determine the properties of the candidate formulations, and to narrow down the field of interest for further testing.

The second objective, that of simulation, was achieved with quarter scale tests. The use of quarter scale tests was extremely successful in developing the characteristics of pneumatically placed fly ash,⁽³⁾ and similar success has been obtained in simulating the behavior of the water seal. The quarter scale tests permitted the simulation of the final candidate material systems, leading us to choose a "best" system, and alternative systems.

Short of complete full scale demonstration (**beyond the scope of this contract**), the best approach to full scale testing is to isolate the critical area or component of the system and subject a representation of that area to full scale conditions. The quarter scale tests identified that area as the top interface of the seal, and a full head test on a representation of that interface served to clarify the problem and to verify a successful solution.

Details of the test program are in the following sections.

3. Small Sample Tests

Considerations regarding the behavior of the fly ash water seal, and the potential modes of failure, as outlined in Section 2, suggest that potential seal materials be tested for the following properties.

- (a) Capillarity (tendency to absorb capillary water)
- (b) Permeability
- (c) Shrinkage upon wetting
- (d) Shear strength

Capillarity measures the tendency of the seal to absorb water in advance of the rising water level. Capillary advance tends to produce favorable effects. For those cementitious materials which "set" after wetting, the capillary water initiates setting before the water level reaches the material, thus minimizing failure problems at the upstream slope. Capillary wetting, in general, tends to be more favorable than water level saturation, since capillary forces tend to hold the material together.

Permeability is defined as the ratio of the seepage velocity to the hydraulic gradient. It is a measure of how quickly the water will percolate through the seal.

Shrinkage is the change of volume associated with wetting. Capillary forces tend to contract the loosely packed particles, and saturation causes densification due to particle rearrangement. In either case, the decrease in volume produces problems in a seal required to retain water.

The shear strength measures the resistance of the seal to a number of the failure modes discussed earlier.

3.1 Description of Tests

3.1.1 Test Equipment

The tests were conducted in the test fixture shown schematically in Figure 6. The 6" O.D. clear plexiglas tube and porous stone bottom together form a container which held the sample while allowing water to pass freely through the container bottom. The burette assembly, consisting of the plexiglas top and the burette was clamped on top of the 6" sample tube, providing a water tight chamber above the sample.

3.1.2 Sample Preparation

The samples were prepared in a manner that duplicated, as much as possible, pneumatically emplaced fly ash. This was accomplished by sifting the sample material into the sample tube.

The proportions of the sample were measured by weight, thoroughly mixed, and placed in the sample tube. The sample tube was weighed before and after the sample had been placed to determine the weight of sample actually emplaced. The height of the placed sample was measured, and the sample volume and density were calculated.

Before the capillary test was started, the burette assembly was clamped on top so the capillary and permeability test could proceed without requiring any further disturbance of the test fixture.

3.1.3 Capillary Tests

The rate of capillary water rise and the total capillary head were measured directly by placing a sample fly ash-additive mixture in the test fixture, wetting the bottom, and observing

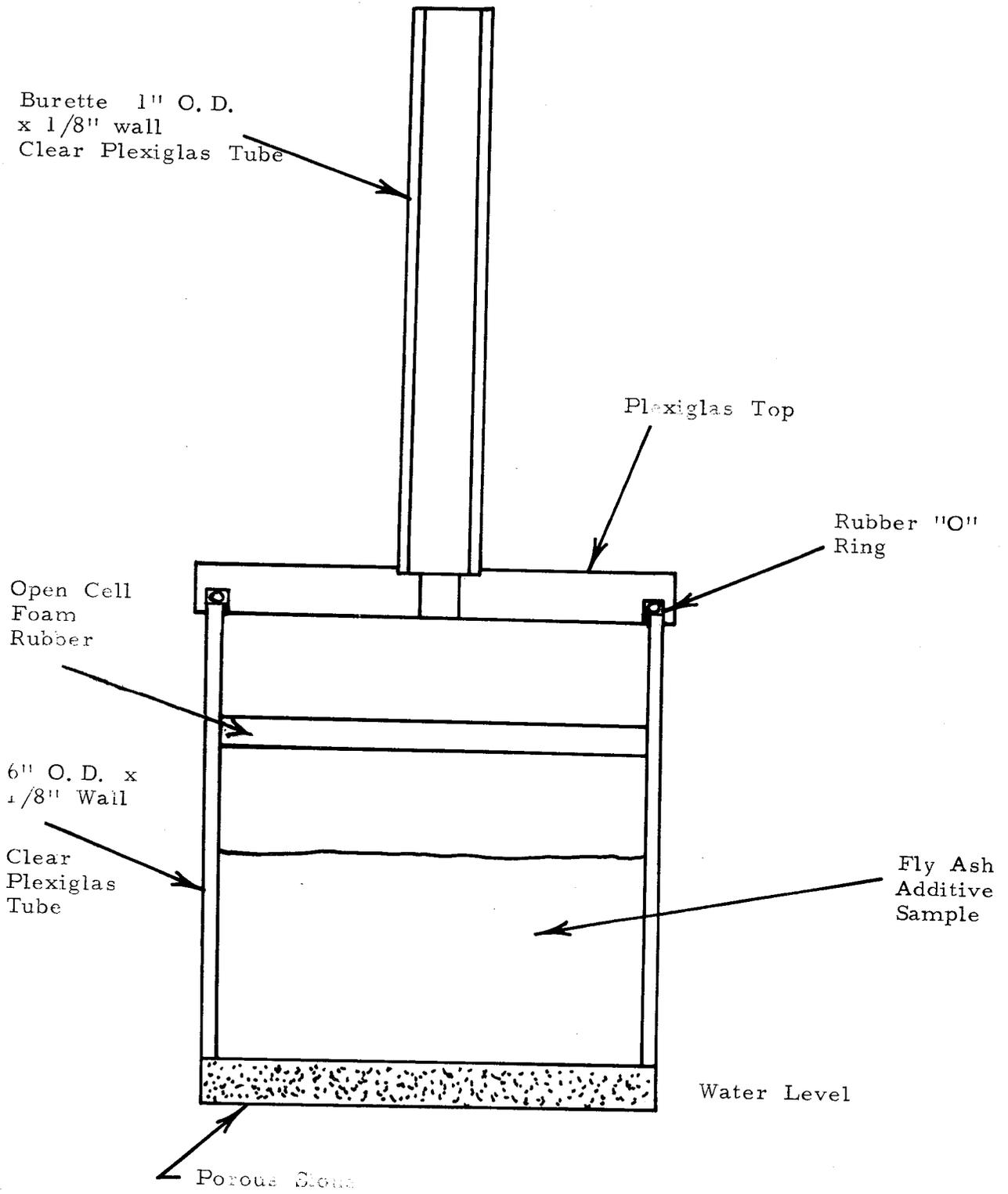


Figure 6. Small Sample Test Fixture

the height of the capillary water through the tube at regular time intervals until the sample was saturated. An estimate of the ultimate height of capillary rise was obtained by extrapolating the height-time curve for the sample.

The prepared sample as placed in the test fixture was lowered into a basin (Figure 7) until the porous stone was immersed. The height of the capillary water was measured periodically until the entire sample was saturated. The saturated sample was checked for the formation of cracks along the tube wall and the height of the saturated sample was measured to check for any settling of the sample due to the initial wetting with capillary water.

3.1.4 Permeability Test

Once the sample in the capillary test had been saturated with capillary water, its permeability was measured. This was accomplished using a falling head permeability test. In this type of permeability test, a column of water is placed above the sample and the rate of fall of the water level as the water seeps through the sample is measured. Since the height of the water level above the sample is equal to the hydraulic head acting on the sample and the rate of fall of the water level is directly related to the permeation velocity, a direct measure of the permeability of the sample was provided by the test.

The height of the sample was measured to check for further settling and compaction due to the water head.

3.1.5 Strength Tests

Immediately following completion of the permeability test, strength measurements were taken. For fly ash-clay samples several measurements were taken over the course of the day following a permeability test to determine if any degradation of cohesive strength

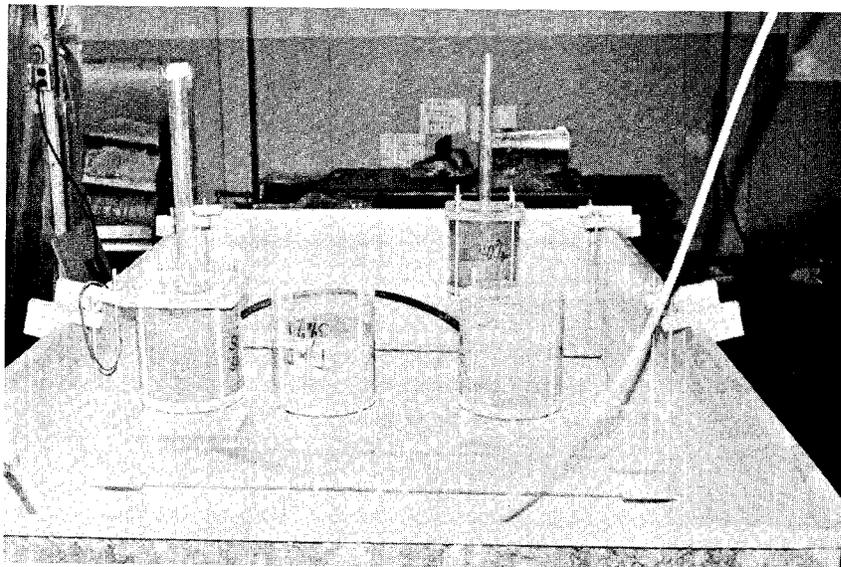


Figure 7. Small Sample Test Basin

had occurred. For fly ash-cement samples, strength measurements were taken at intervals appropriate for observation of setting and hardening of the sample.

Strength measurements were taken using the Torvane,^{*} an instrument designed to measure the in-situ shear strength of cohesive soils. The vanes are inserted into the sample and the Torvane is twisted slowly and evenly to the point of failure. The failure shear stress can then be read from the instrument dial. All tests were conducted at room temperatures, which varied between 60°F and 70°F.

3.2 Test Results

3.2.1 Plain Fly Ash

The properties of fly ash without any additive materials were measured to provide a basis for comparison with measurements taken on fly ash-additive mixtures. The measured values are listed below:

Capillary head	60 in.
Coefficient of permeability	0.0028 in./min.
Volume change on wetting	15% decrease
Wet cohesive shear strength	0.004 tons/ft ²

3.2.2 Fly Ash Bentonite Mixtures

One major finding from the small sample tests was the bentonite content required to reduce the permeability of the mixture to something considerably below that of plain fly ash. Up to about 20 percent bentonite, the mixture permeability did not differ much from that of plain fly ash. Between 20 and 30 percent, the permeability dropped considerably, and at 40 percent bentonite the permeability was reduced by a factor of 100. The data is shown in Figure 8.

*Made by Soiltest Inc., Chicago.

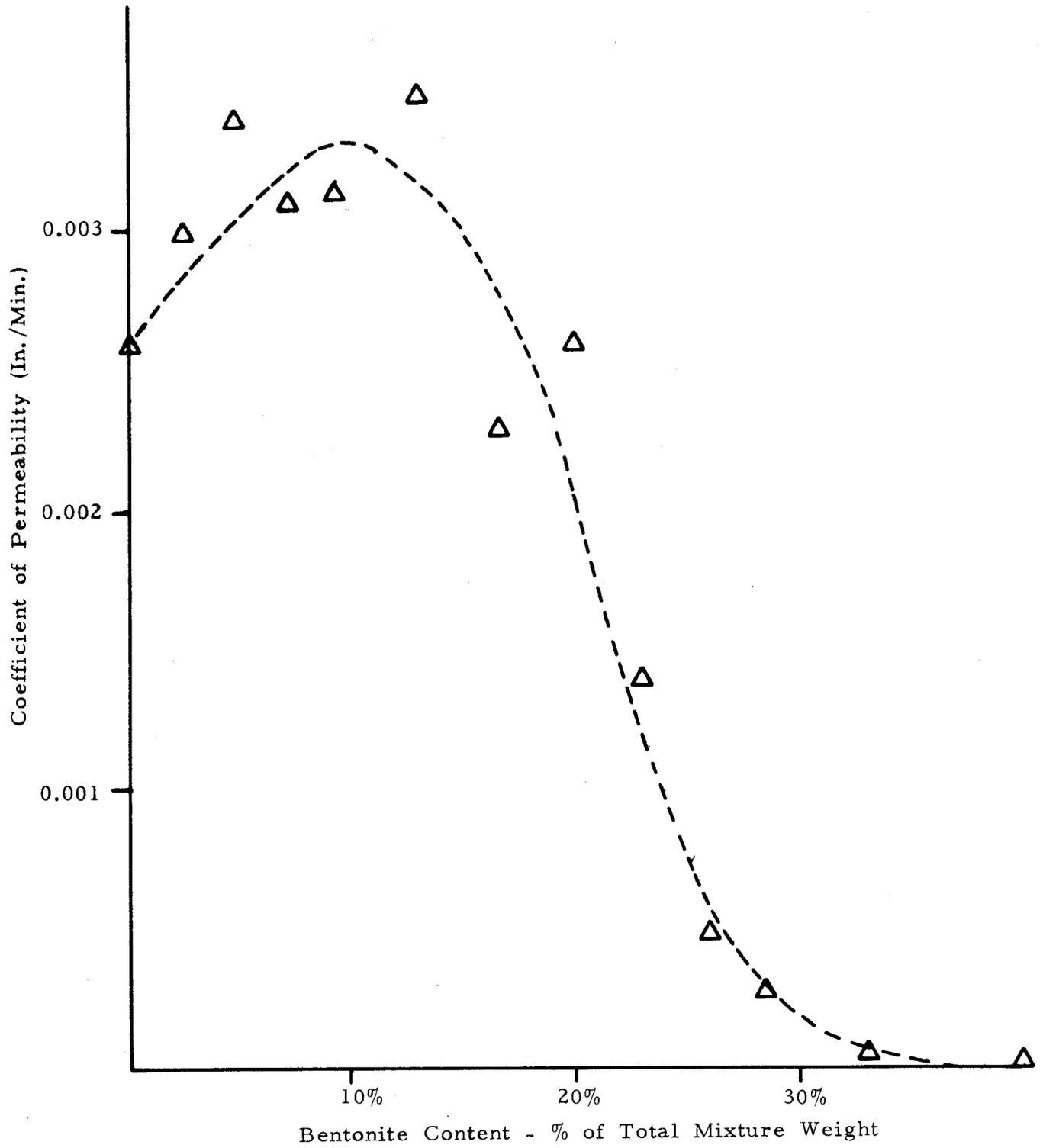


Figure 8. Permeability of Bentonite Fly Ash Mixes

Another important feature of the addition of bentonite is the volume change. Figure 9 presents laboratory data for percent volume change vs percentage of bentonite. As can be seen, the transition from shrinkage to swelling and from permeable to impermeable occur over the same range of concentrations.

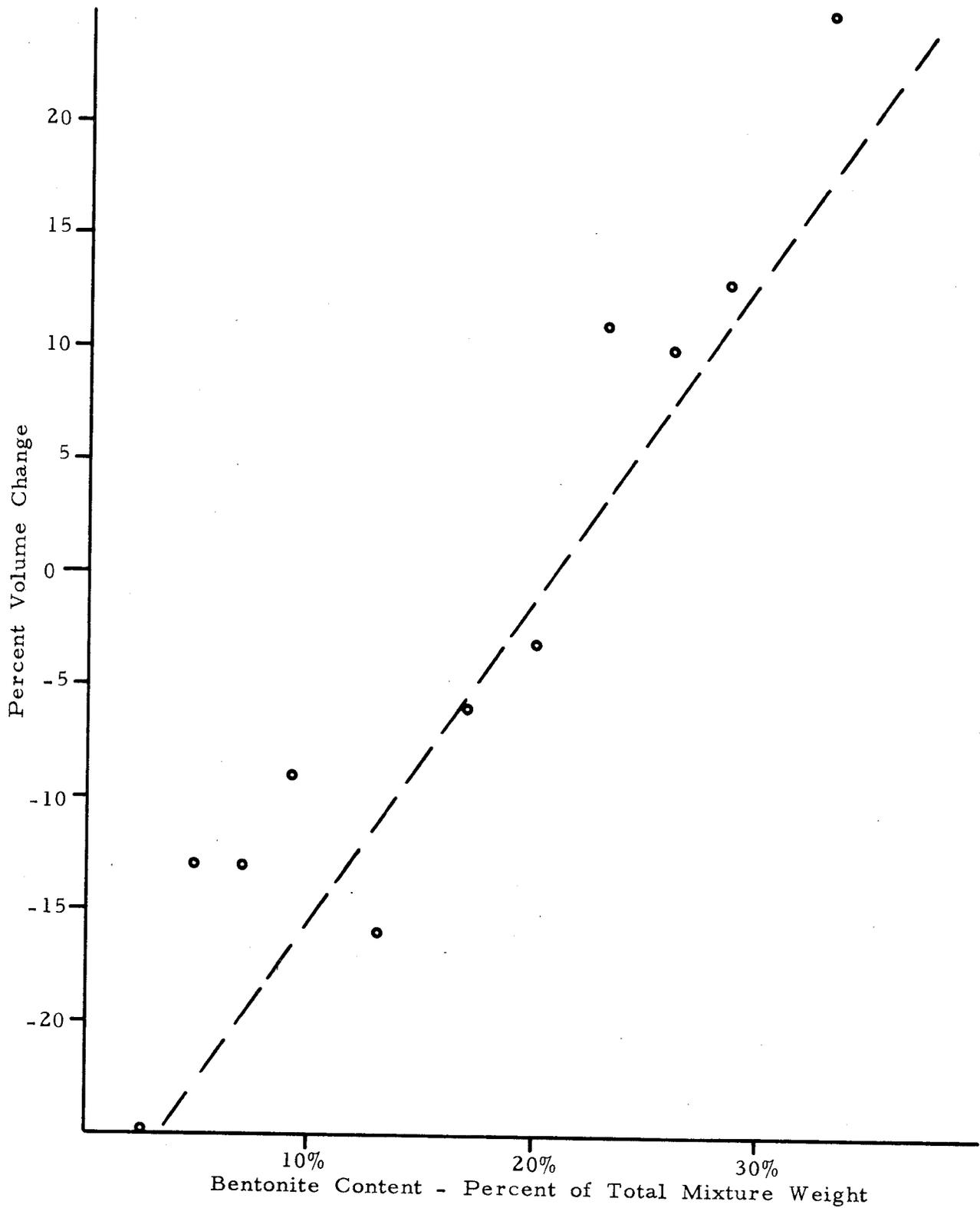
Observable capillary rise depended primarily on the permeability. In general, the low permeability associated with the bentonite reduces the capillary rise. The test data is shown in Figure 10.

The shear strength of the wet bentonite-fly ash mixture ranged from 0.004 to 0.01 tons/ft², with no particular trend. The data is shown in Figure 11.

3.2.3 Fly Ash-Cement Mixtures

Mixtures of fly ash and cement harden on wetting. In general, the hardened fly ash-cement mixture exhibits a somewhat lower permeability than plain fly ash; however, due to the shrinkage of the mixture and subsequent hardening, leakage paths permanently set in the bulk material, accounting for the major flow of water. Early wetting of the fly ash-cement mixture through capillary action is particularly desirable, initiating hardening in advance of the water flow induced by the rising water level, which would erode unhardened seal material. Two types of cements were considered as additive materials - Normal setting cements and flash setting cements. The normal cements tested included Type III Portland cement (high early strength) and Lumnite (Calcium Aluminate Cement). The flash setting cements tested included Huron Regulated Set Portland Cement, mixtures of Type III Portland cement and Lumnite, and Type III Portland cement with baking soda, NaHCO₃, as a set accelerator.

The results of the tests are summarized below:



Bentonite Content - Percent of Total Mixture Weight
 Figure 9. Volume Change in Bentonite-Fly Ash Mixes

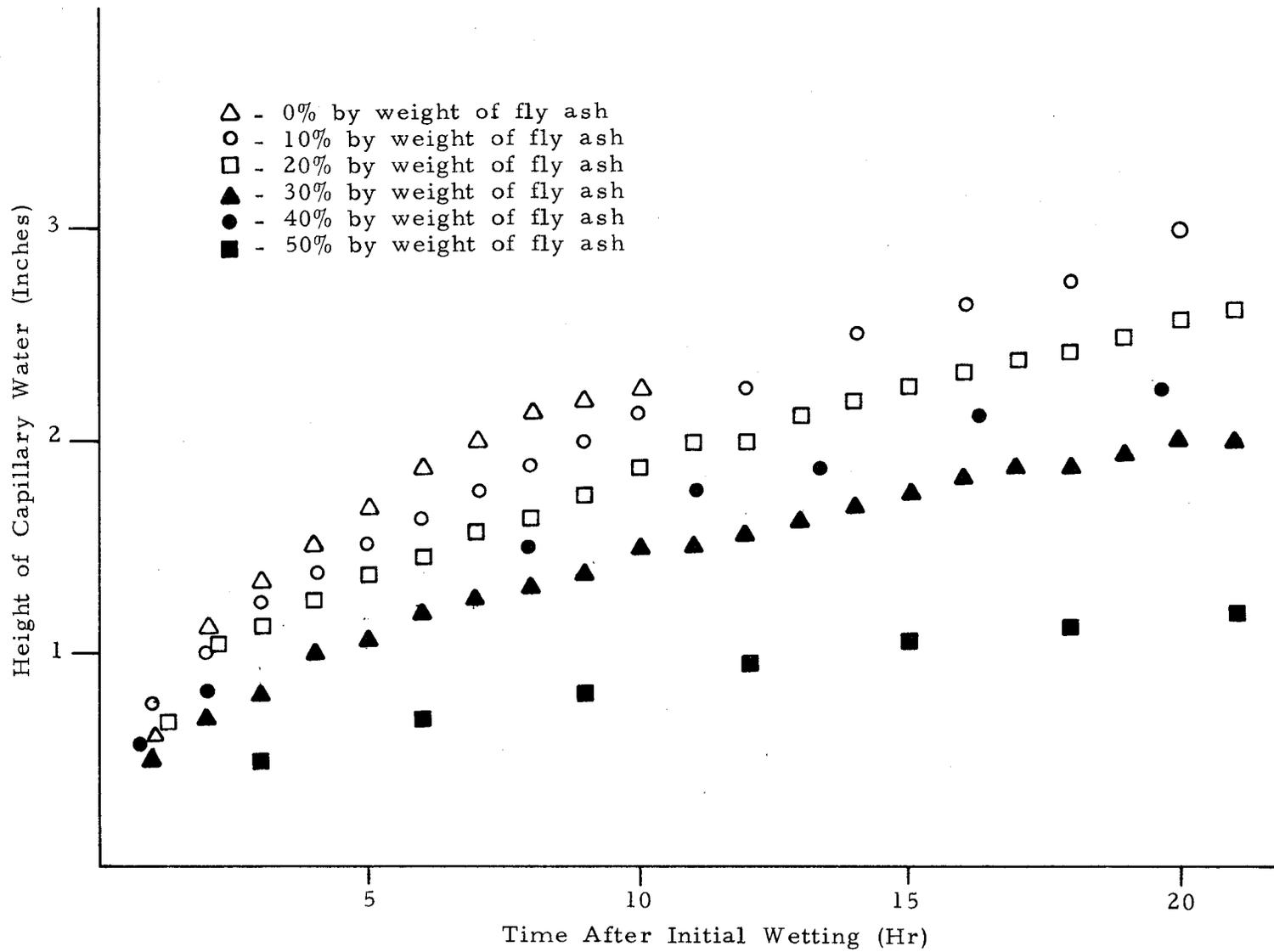


Figure 10. Capillary Rise Data for Bentonite Mixes

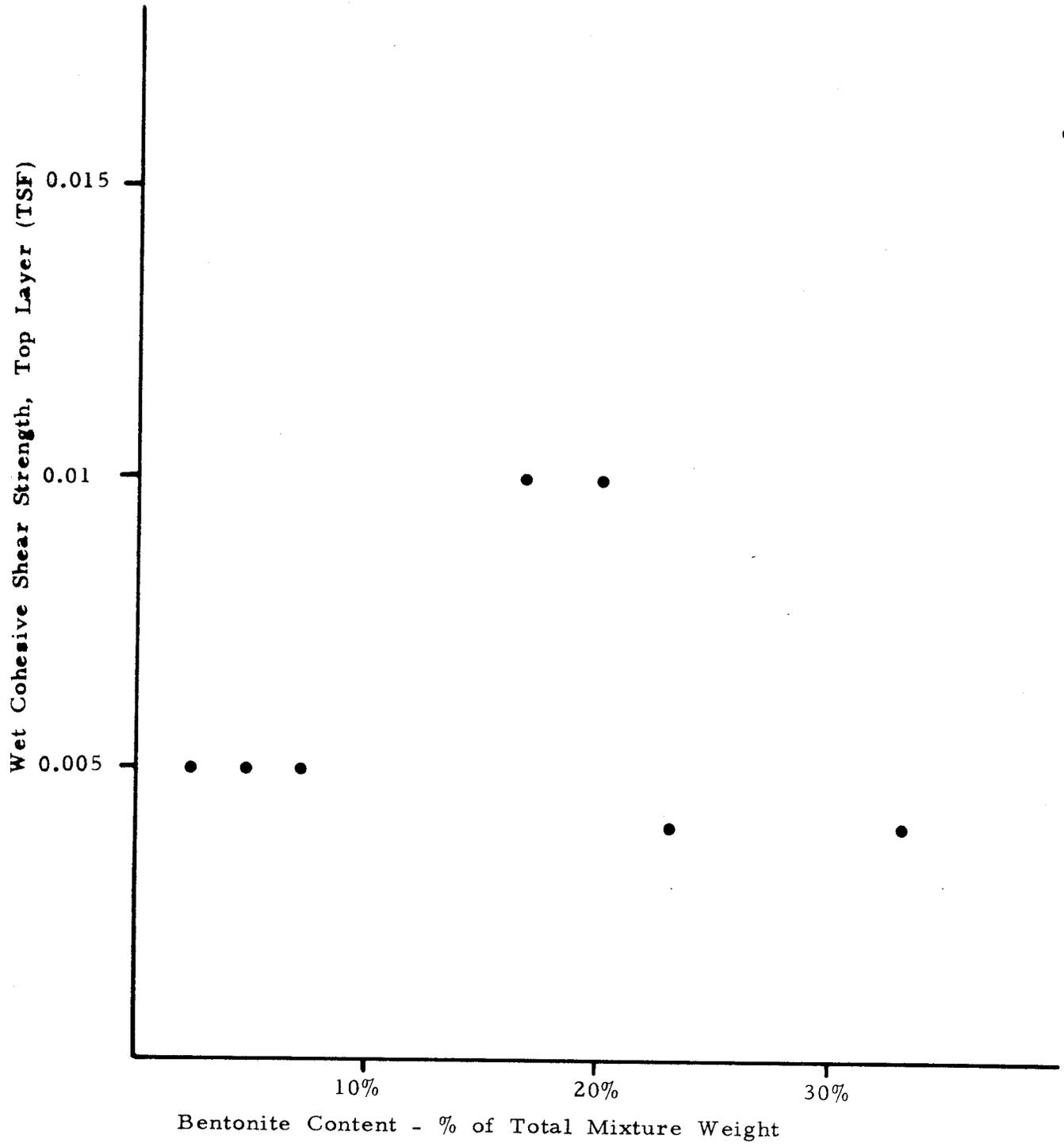


Figure 11. Shear Strength Data for Bentonite-Fly Ash Mixes

Capillarity

Capillary rise data, shown in Figure 12 covers mixtures of fly ash with Type III Portland cement, Lumnite, and Huron cement. The cement content had no significant effect on the capillary rise rate.

Figure 13 gives the volume change on wetting of mixtures of fly ash with Huron cement, Lumnite, or Type III Portland cement. All of the samples shrunk on wetting, with no clear relationship between type or content of cement and the percentage volume decrease.

Permeability

The measured coefficient of permeability for mixtures of fly ash with Type III Portland cement, Lumnite, and Huron cement are plotted in Figure 14. The permeability coefficients for fly ash-Lumnite and fly ash-Type III Portland cement mixtures are close to those of plain fly ash and did not change significantly over the course of several days. Fly ash-Huron cement samples, on the other hand, had quite high permeability coefficients immediately upon wetting, which decreased significantly after a day.

Shear Strength

Shear-strength vs time after wetting are plotted in Figures 15, 16, and 17 for fly ash-Portland Type III cement, fly ash-Huron cement, and fly ash-Portland Type III-Lumnite mixtures respectively. Fly ash-Lumnite mixtures failed to develop significantly more strength than plain fly ash, and hence were eliminated from further consideration. The quick setting cements - both Huron cement and the Portland cement-Lumnite mixtures - developed several times the strengths of equivalent Portland Type III mixes within the first minutes after wetting. Their ultimate strength values were also somewhat greater than equivalent Portland Type III mixes. Baking soda failed to produce any acceleration of set.

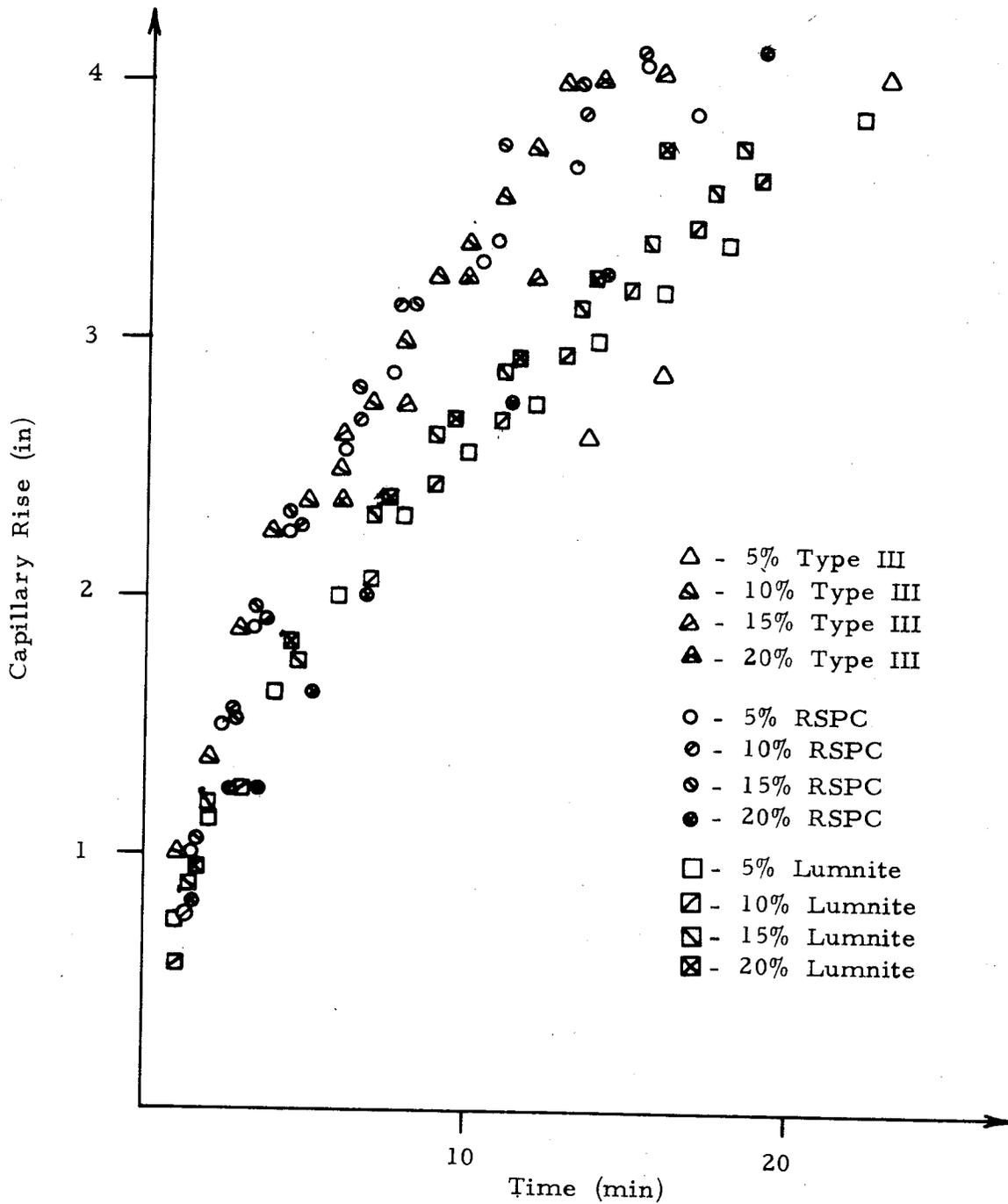


Figure 12. Capillary Rise Rate Data for Various Mixtures of Fly Ash with Portland Type III, Lumnite, and Huron Cement

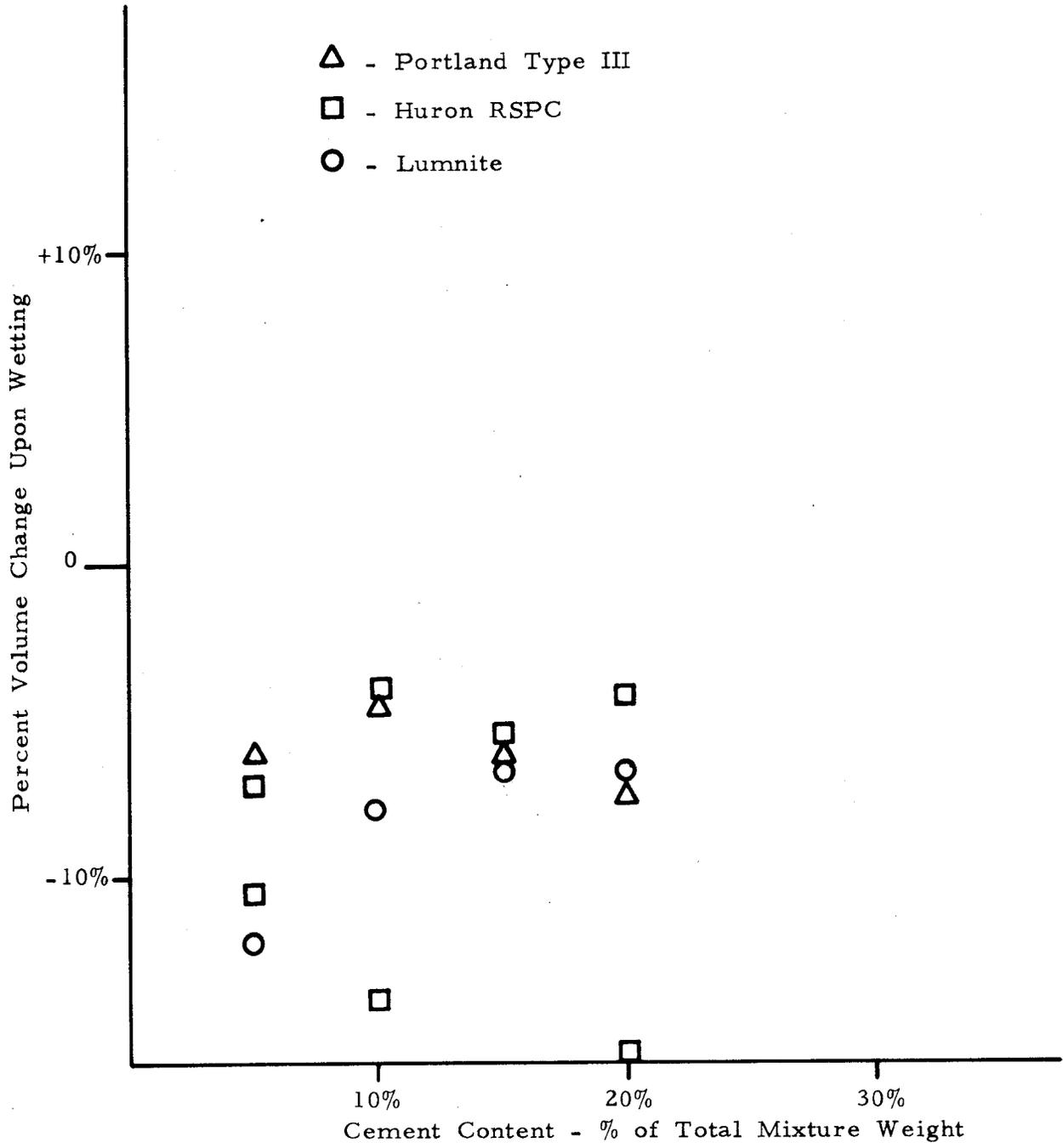


Figure 13. Volume Change for Fly Ash-Cement Mixes

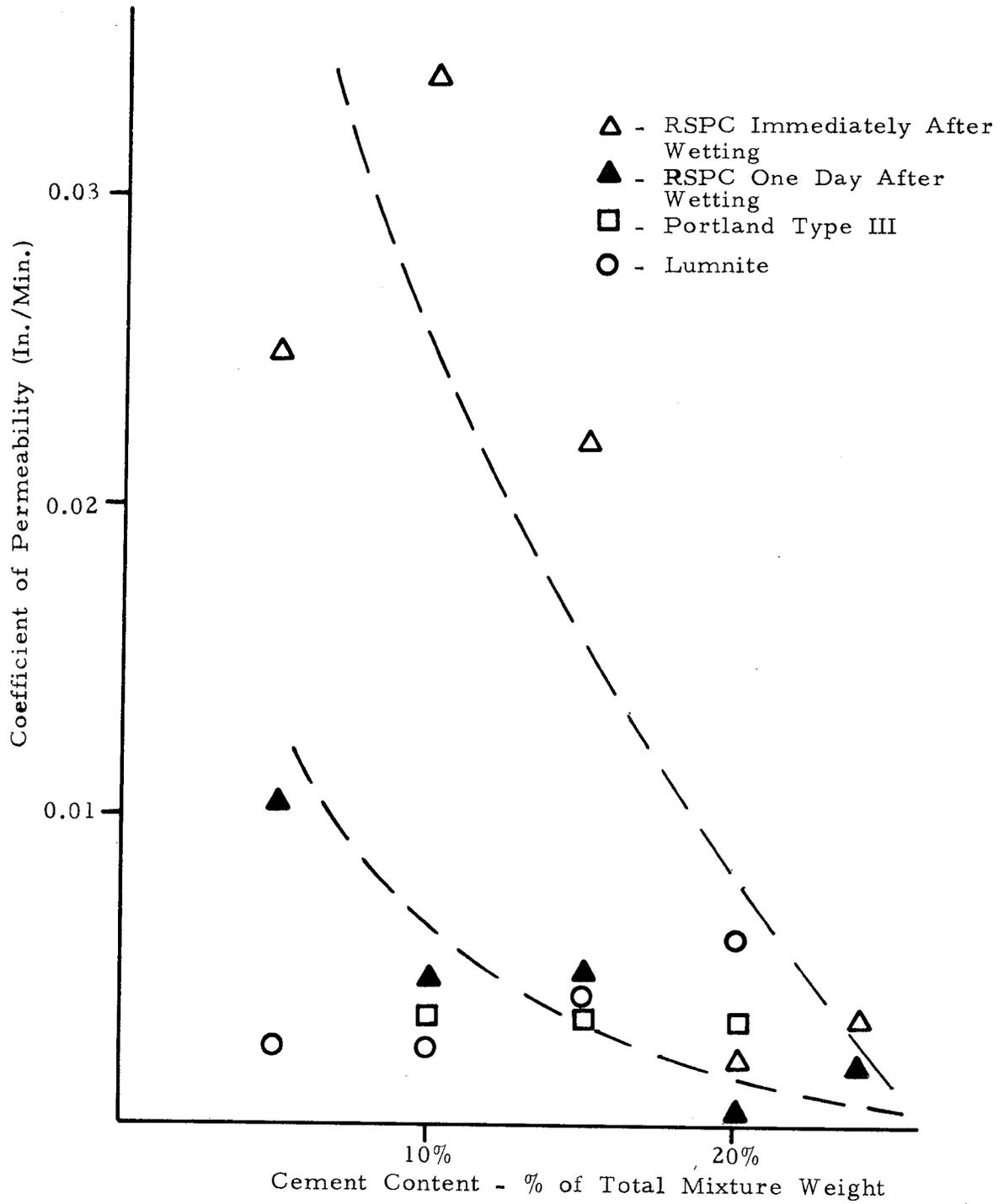


Figure 14. Permeability of Fly Ash-Cement Mixes

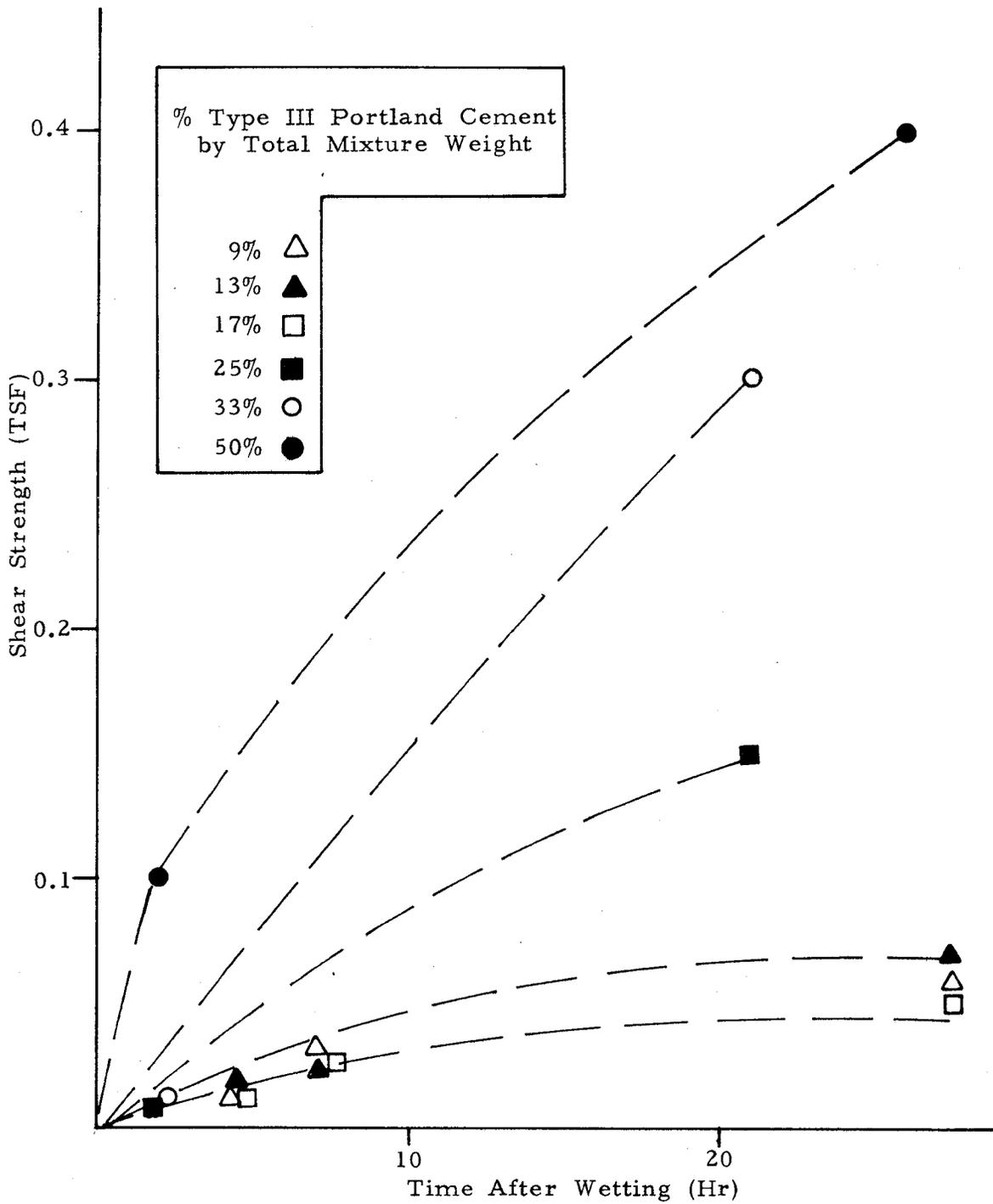


Figure 15. Strength vs Time for Fly Ash-Type III Portland Cement Mixtures

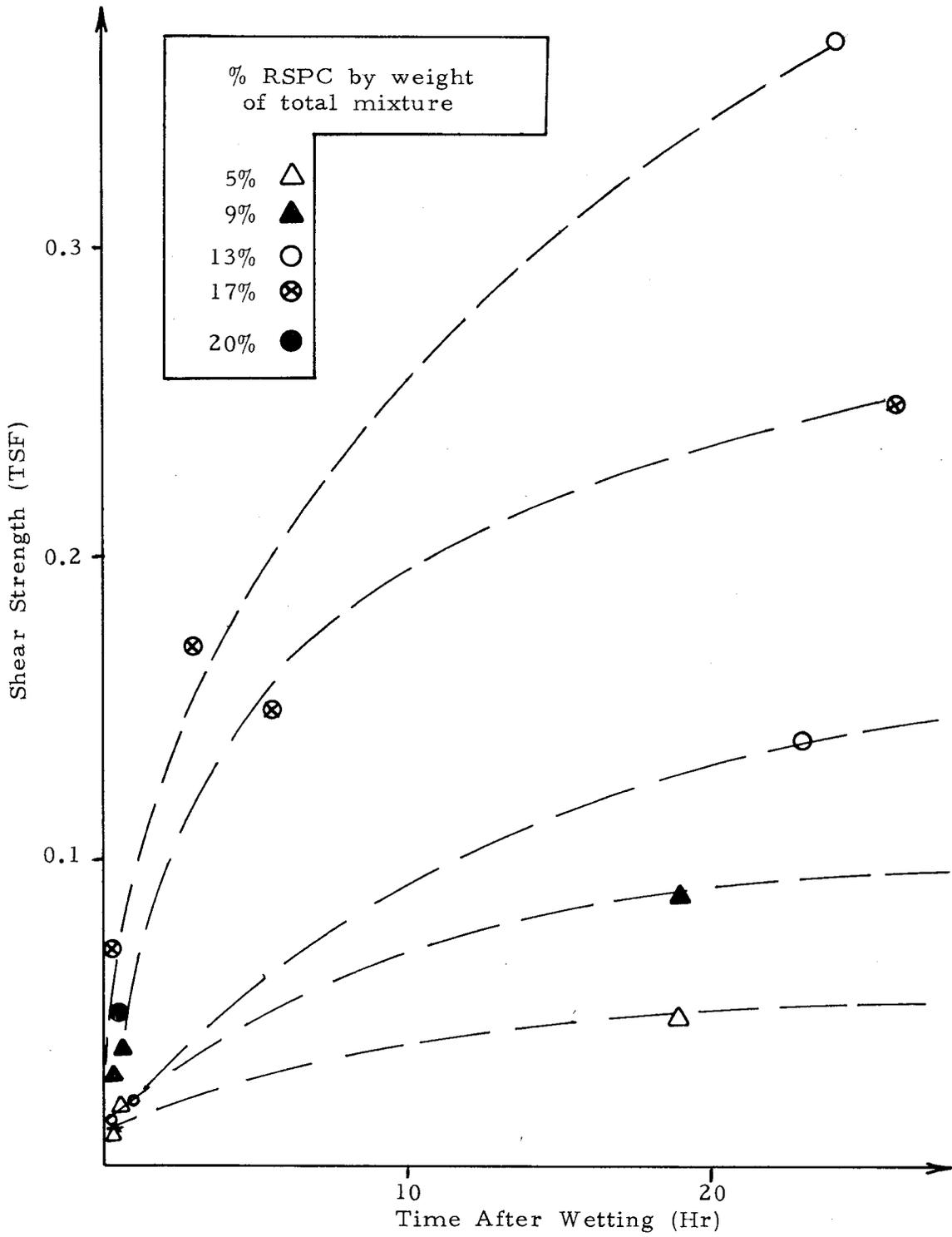


Figure 16. Strength vs Time for Fly Ash-Huron RSPC Mixtures

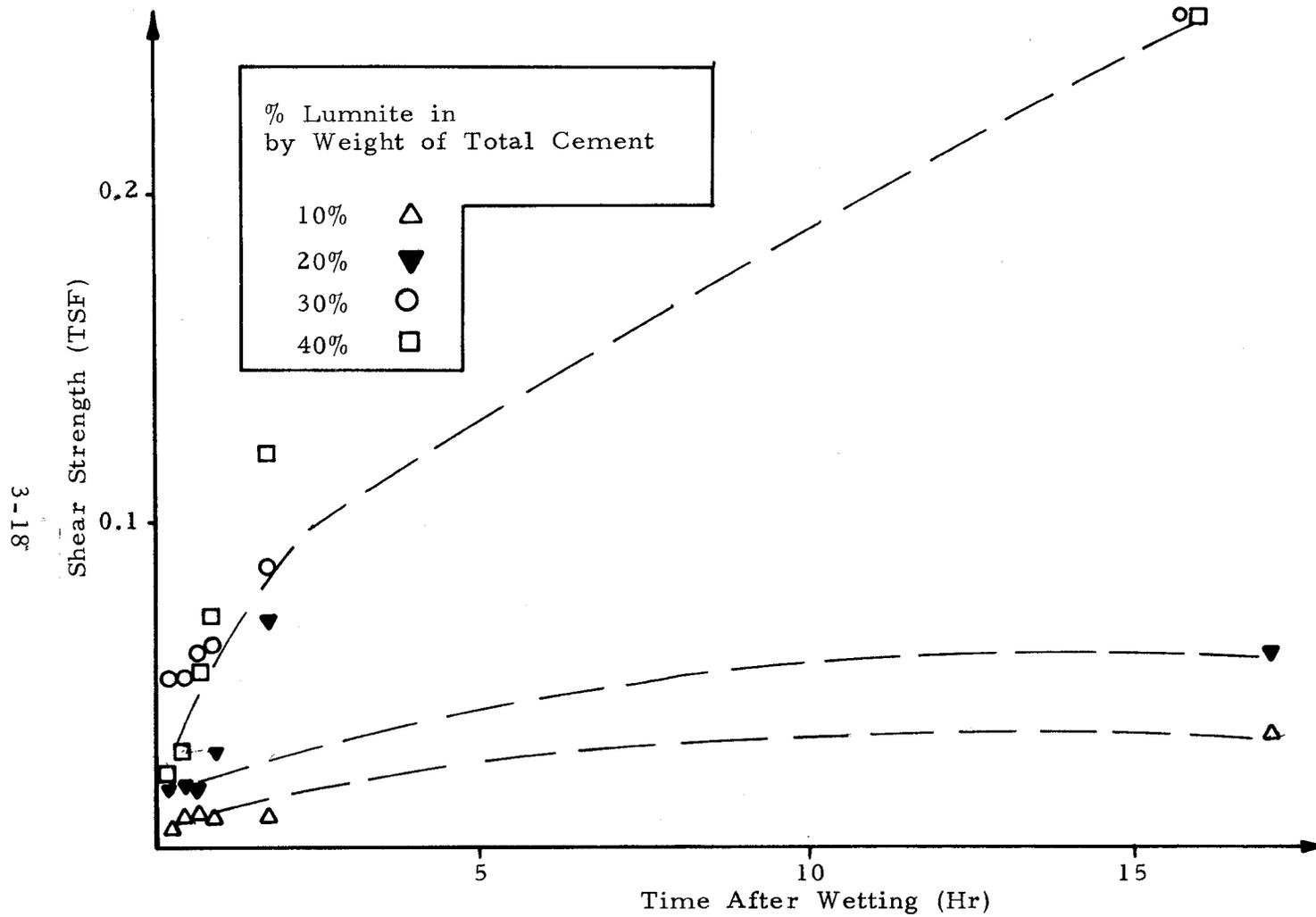


Figure 17. Strength vs Time for Fly Ash with 15% Type III Portland Cement - Lumnite Mixtures Added

3.3 Conclusions of Small Sample Test Program

The significant conclusions of the small sample test program can be summarized as follows:

1. All fly ash-cement mixtures exhibited shrinkage of between 5% and 10%. The addition of cement caused a reduction in the shrinkage from that which occurs for fly ash alone.
2. With the exception of some high initial permeability values with RSPC, the capillarity and permeability of fly ash is generally unaffected by the addition of cement.
3. Accelerated set is achieved most efficiently by mixing fly ash with Huron Regulated Set Portland cement.
4. Addition of 20% or more of bentonite with fly ash produces a mixture which expands upon wetting and which is highly impervious to water. Expansion and loss of permeability increase with increasing percentages of bentonite.

From these results we chose to confine our further investigations to mixtures involving the following components:

Fly ash-Portland Type III
Fly ash-Huron RSPC
Fly ash-bentonite.

Before proceeding, two items are worth mentioning. First, the water used in these tests was tap water. It is anticipated that, during the inundation of a mine, the water used will be from whatever source is available. If that source has an unusual chemical composition, such as a high acid content, some preliminary tests should be carried out with that water sample to verify that the appropriate setting and swelling reactions take place.

Secondly, test temperatures ranged from 60° to 70°F, which is similar to temperatures found in a mine. Fire conditions might increase this temperature, but we do not anticipate this rise (small, considering the total volume of water to be heated) to have any significant effects on the performance of the seal materials.

4. Scaled Testing

As indicated in Section 2, the behavior of a fly ash type seal subject to a rising water level is a complex phenomenon, involving capillarity, permeability, volume changes, and a number of possible failure modes. Since there are a number of possible approaches to the development of a pneumatically emplaced water tight seal, including different materials and emplacement techniques, a simple evaluation technique was required to represent the complex behavior involved. For this purpose, a 1/4 scale model program was developed. With this program we are able to accomplish the following goals:

Visualization

The scaled testing yields important visualization of the phenomena involved, and enabled the identification of the parameters of interest.

Failure Mode Identification

Through the scaled testing it becomes clear what failure mode or modes require the greatest attention.

Quantitative Evaluation

Some of the basic phenomena associated with behavior of the seal subjected to rising water level and fixed water head follow naturally from geometric scaling. Others can be made to scale by appropriate adjustment of parameters. In this manner the scale model represents a true model of the water seal quality. This is discussed in detail below.

4.1 Scaling Relationships

Before proceeding with a description of the scaled testing program, it is important to quantify some basic phenomena and to see how these phenomena can be represented in a scaled test. These phenomena are described below.

4.1.1 Geometry of Emplaced Seal

In a previous program,⁽³⁾ scaling relationships were developed for the geometry of a seal formed by the pneumatic emplacement of a dry powder. These relationships indicated that if there is uniform geometric scaling, λ , then a geometrically similar seal is produced when the inlet volume air flow is scaled as $\lambda^{5/2}$. This conclusion was verified by comparison of quarter scale pneumatic emplacement results with full scale in-mine tests.

4.1.2 Distance of Water Permeation

For simplicity, we shall assume the permeability to be one-dimensional (horizontal), and we shall neglect the capillary head effects. Referring to Figure 18, the increment of distance permeated can be expressed as

$$dx = v_s dt \quad (1)$$

where x is horizontal distance, t is time, and v_s is the seepage velocity. From Darcy's Law,⁽⁷⁾ the seepage velocity equals

$$v_s = \frac{k}{n} i = \frac{k}{n} \frac{H}{x} (t) \quad (2)$$

where i = hydraulic gradient

n = porosity

k = permeability

$H(t)$ = height of water level above a given point on the slope

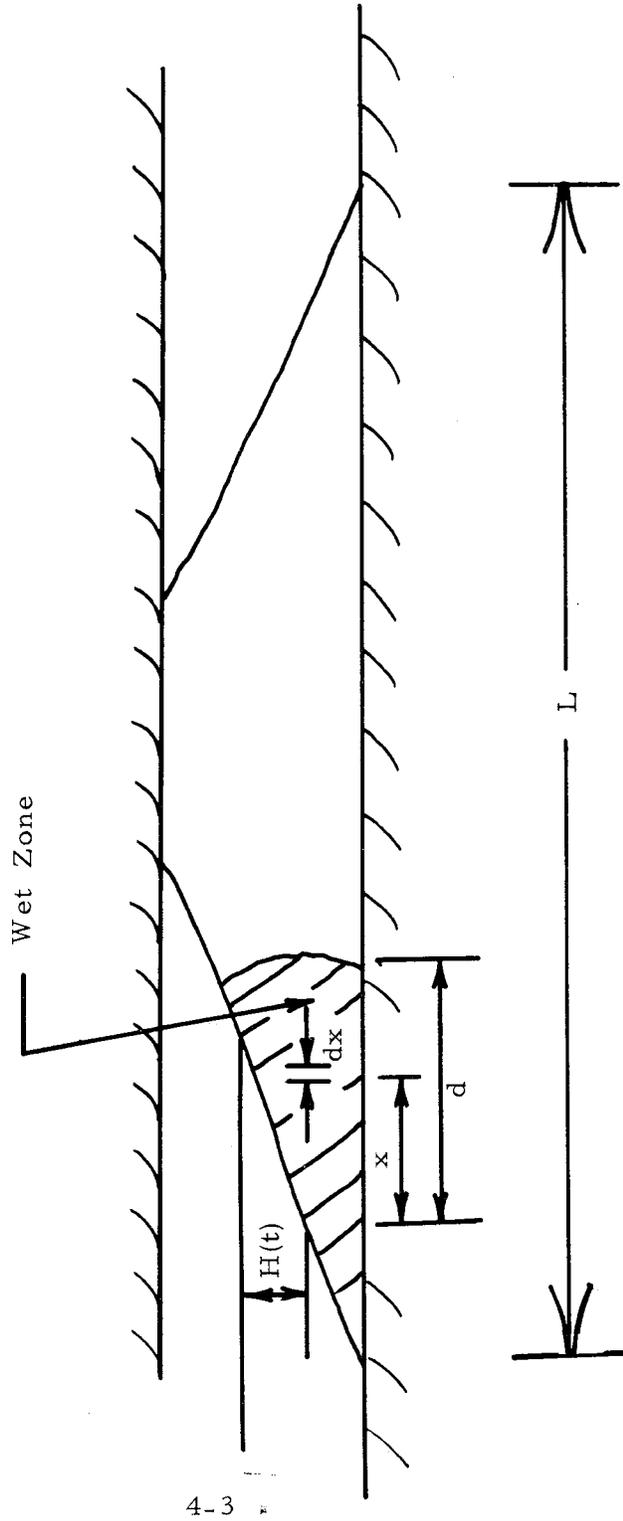


Figure 18. Sealing of Permeability

Substituting (2) into (1) we obtain

$$dx = \frac{k}{n} \frac{H}{x} (t) dt$$

or

$$x dx = \frac{k}{n} H(t) dt \quad (3)$$

We can distinguish two cases of interest: one, where the permeation of interest occurs while the water level is rising, and the other, where the permeation of interest occurs when the water level is fixed.

Case 1

$$\frac{dH}{dt} = \text{constant} = A$$

$$H = At$$

from (3),

$$\int_0^d x dx = \int_0^t \frac{kA}{n} t dt$$

$$d^2 = \frac{kA}{n} t^2$$

or

$$d = \sqrt{\frac{kA}{n}} t \quad (4)$$

Case 2

$$H = \text{constant} = H_o$$

$$\int_0^d x dx = \int_0^t \frac{k}{n} H_o dt$$

$$d^2 = \frac{2k H_o}{n} t \quad (5)$$

If we consider a non-dimensional permeation parameter $\frac{d}{L}$, and we recognize that k and n are approximately the same for both model (m) and prototype (p), then the following scaling relationships result.

Case 1

$$\frac{\left(\frac{d}{L}\right)_m}{\left(\frac{d}{L}\right)_p} = \sqrt{\frac{A_m}{A_p}} \frac{L_p}{L_m} \frac{t_m}{t_p} \quad (6)$$

Case 2

$$\frac{\left(\frac{d}{L}\right)_m}{\left(\frac{d}{L}\right)_p} = \sqrt{\frac{(H_o)_m}{(H_o)_p}} \frac{L_p}{L_m} \sqrt{\frac{t_m}{t_p}} \quad (7)$$

These lead to the following conclusions:

1. For $\frac{d}{L}$ to be the same for both quarter scale model and prototype, the rise rate A and the total head H_o must each be 1/16 of the full scale value.
2. For arbitrary values of A and H_o , the value of $\frac{d}{L}$ will be the same for both model and prototype when the model time (t_m) and the prototype time (t_p) have the following relationship:

Case 1

$$t_p = 4\sqrt{\frac{A_m}{A_p}} t_m$$

Case 2

$$t_p = 16 \frac{(H_o)_m}{(H_o)_p} t_m$$

3. For arbitrary values of A and H_o , at a fixed time, the relative permeation distance in the model, $(d/L)_m$ equals $4\sqrt{\frac{A_m}{A_p}}$ or $4\sqrt{\frac{(H_o)_m}{(H_o)_p}}$ times the relative distance in the prototype.

Conclusions 2 and 3 can be exemplified as follows. If we use a water rise rate in the quarter scale model that is equal to that which occurs in the full scale, then the permeation pattern that we see after 3 hours in the model is either what has occurred after 12 hours in the prototype, or is four times the extent that it would be in the prototype.

As noted earlier, the effect of capillary head has been neglected. This is an effect which is related to particle size, and hence can not be scaled. Qualitatively, we can say that the influence of capillarity is greater in the model than in the prototype, and has the effect of accelerating the permeation.

4.1.2 Plug Failure

There are two types of plug failures to consider - one in which the bulk of the seal is dry, and one in which it is wet. For the former, the shear strength is frictional, and dependent upon the height of the seal; for the latter, the shear strength is a combination of friction and cohesion.

The force tending to push the seal down the passage, expressed in dimensional terms is proportional to the water head and the seal frontal area,

$$F_p \sim (\gamma_w H)(L^2)$$

H = water head

L = seal dimension

γ_w = density of water

F_p = force applied

In the dry case, the resistance of the seal is proportional to the weight (γL^3), and the friction angle ($\tan \phi$); i.e.,

$$F_r = (\gamma L^3) \tan \phi$$

γ = density of seal material

Since the densities are roughly the same in model and prototype, and the friction angle is a constant, the ratio of resistance to applied force is

$$\frac{F_r}{F_p} \sim \frac{L}{H} \quad (8)$$

If scaling is such that the water head is scaled with the passage dimensions, then the scale model is an accurate model of plug failure of a dry seal.

In the wet case, cohesion forces accompany the frictional forces in producing the total resistance. In this case

$$F_r \sim L^2 c + \gamma L^3 \quad c = \text{cohesive strength} \quad (9)$$

and hence

$$\frac{F_r}{F_p} \sim \frac{c}{\gamma H} + \frac{L}{H} \quad (10)$$

This relationship implies that the cohesive part of the resistance to plug failure can not be modeled with scaled head.

4.1.3 Slope Failure

The factor of safety for slope failures (down stream slope) can be computed from sliding moments due to overburden and seepage pressure vs. the resisting moments from available shear strength. In dimensional terms

$$M_s \sim \gamma L^4 + p_s L^3 \quad \begin{array}{l} M_s = \text{sliding moment} \\ p_s = \text{seepage pressure} \end{array} \quad (11)$$

Resisting moments are a product of shear stress, area, and length, or

$$M_r \sim \tau L^3 \quad (12)$$

The shear strength, τ , can be divided into frictional and cohesion components.

$$\tau \sim \mu \gamma L + c \quad \mu = \text{coefficient of friction} \quad (13)$$

and the seepage pressure can be related to the hydraulic gradient as

$$p_s = \gamma_w \frac{H}{L} \quad \gamma_w = \text{density of water} \quad (14)$$

The factor of safety for slope stability becomes

$$F.S. = \frac{M_r}{M_s} \sim \frac{\mu \gamma L^4 + c L^3}{\gamma L^4 + \gamma_w H L^2} \quad (15)$$

The relationship implies that in general, the phenomenon can not be scaled. However, for specific cases, e.g., when frictional and gravity forces dominate seepage pressure and cohesion, the scale model provides an accurate representation.

4.1.4 Leakage

Leakage which occurs at the top of the seal is due either to an imperfect seal with pre-existing leakage paths, or to shrinkage of the seal upon wetting. Figure 19 shows the parameters which must be considered in scaling leakage. For pre-existing leakage paths, we shall assume the depth of the path to be proportional to the seal height. If the gap is due to uniform shrinkage throughout the seal, then the above is in fact the case; i.e.

$$d = \lambda h \quad (16)$$

where λ is the proportionality factor, or shrinkage constant. The total head H equals the velocity head plus the head loss along L , or

$$\frac{v^2}{2g} \left(1 + \frac{fL}{d} \right) = H \quad (17)$$

where f is the friction factor. Substituting (16) and (17), we obtain

$$\frac{v^2}{H} = \frac{2g}{\left(1 + \frac{fL}{\lambda h} \right)} \quad (18)$$

A quick Reynolds number check using some expected values of leakage gaps and flow rates indicates that the flow is in the turbulent regime. Consequently, f can be regarded as constant. Hence, from (18), for geometric scaling where L/h is constant in the model (m), and prototype (p)

$$\left(\frac{v^2}{H} \right)_m = \left(\frac{v^2}{H} \right)_p \quad (19)$$

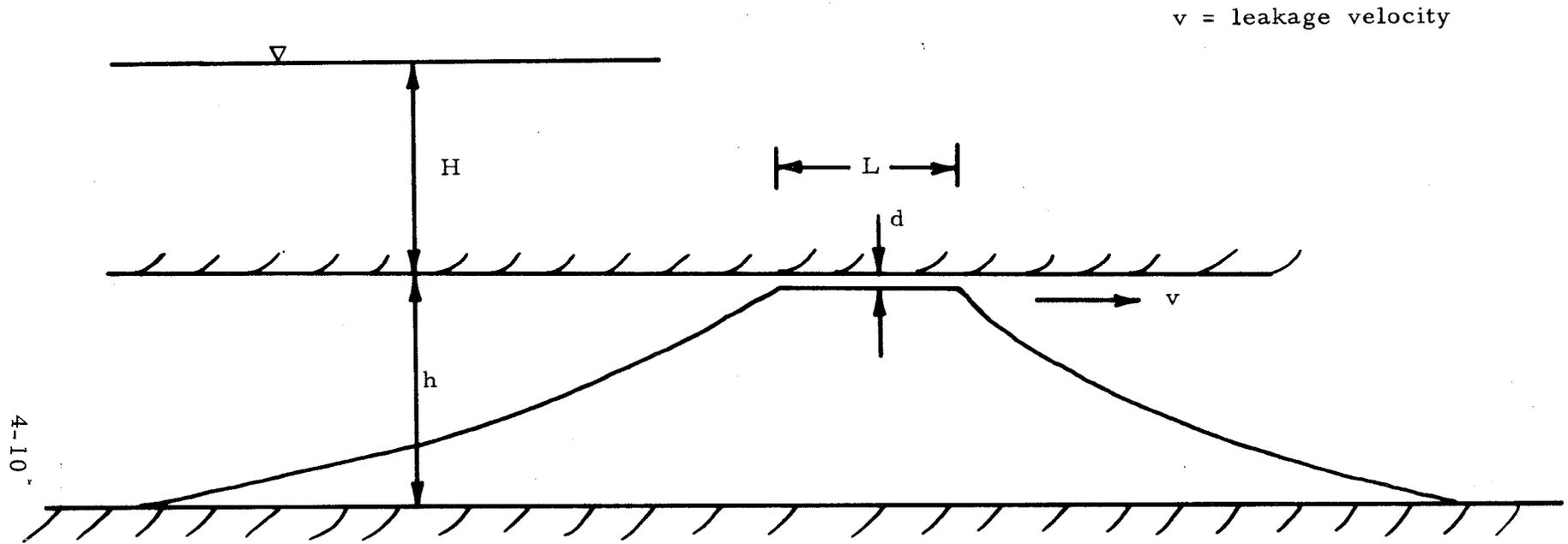


Figure 19. Model for Leakage at the Top of a Seal

Since we measure flow rates (q) rather than velocities, we must express (19) in these terms.

$$q = Av = Wdv = W\lambda hv$$

W = passage width

Therefore

$$\left(\frac{q^2}{h^2 W^2 H} \right)_m = \left(\frac{q^2}{h^2 W^2 H} \right)_p \quad (20)$$

or

$$q_p = \frac{h_p}{h_m} \frac{W_p}{W_m} \sqrt{\frac{H_p}{H_m}} q_m \quad (21)$$

For quarter scale modelling, this becomes

$$q_p = 16 \sqrt{\frac{H_p}{H_m}} q_m \quad (22)$$

This implies that if the head used in the model is 1/4 that of the prototype, then the leakage in the prototype can be expected to be 32 times that of the model.

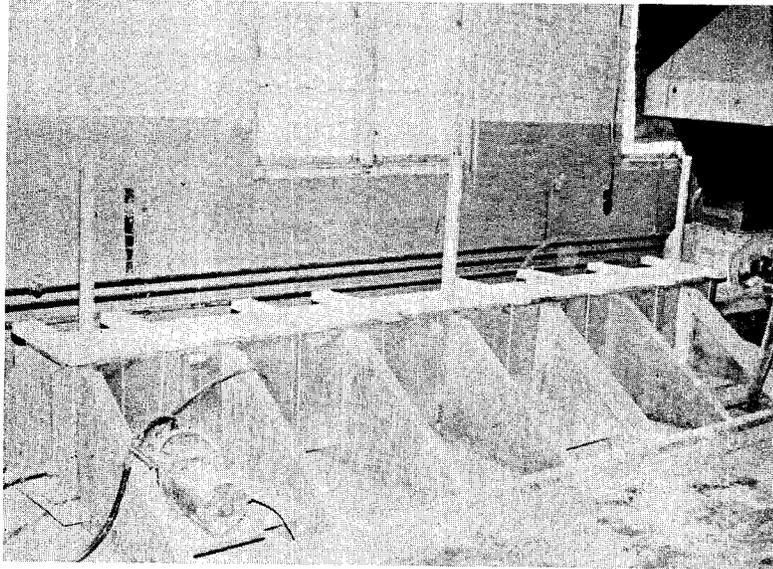
The preceding discussion has indicated that certain phenomena scale differently than others, and certain phenomena cannot be scaled at all. This background will facilitate our discussion of the results of the scaled testing program, and will give us a means by which some of these results can be extrapolated to full scale conditions.

4.2 Laboratory Facility

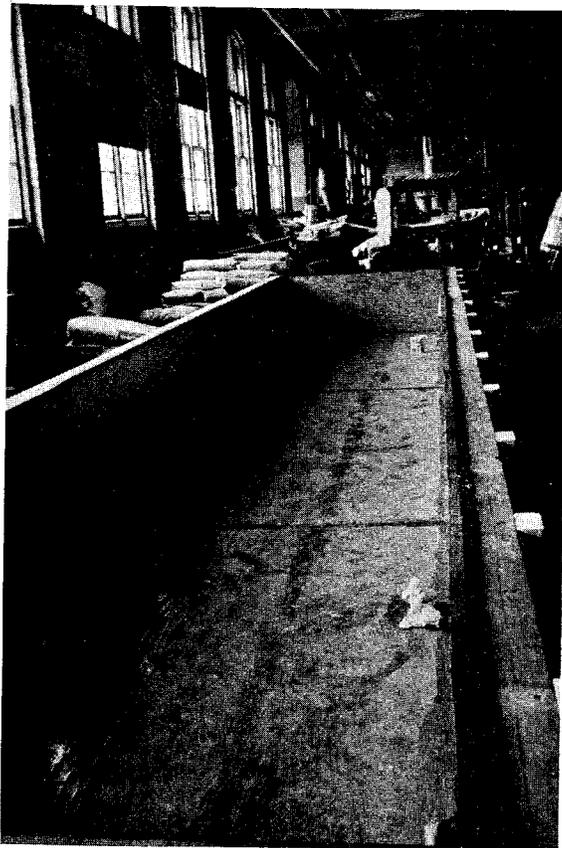
The scaled seal emplacement tests were performed using two different scaled passage mockups. The first of these, shown pictured in Figure 20, is a lucite trough with a cross-section 1 foot wide by 1-1/2 feet high. This geometry represents a 1 foot wide slice of a 1/4 scale passage. The trough is 12 feet long, is covered with a plywood cover, and is braced with wood buttresses to withstand the pressure forces. The cover has three pipes attached to it to simulate the three boreholes needed for emplacing the fly ash-additive seal. The center borehole or pipe is used to pneumatically pump in the fly ash mixture. The outside two pipes are used to exhaust the air that is used to transport the fly ash mixture.

The second passage mockup is functionally the same as the lucite trough, except that it has a realistic quarter-scale geometry. This passage, shown pictured in Figure 20b, is 4 feet wide by 1-1/2 feet high and 24 feet long. It is constructed entirely of plywood and framing except for lucite sheets along one side for viewing. The cover for the quarter-scale passage is in three pieces and has the same piping (borehole) arrangement as the lucite trough.

The fly ash and additive mixture is pneumatically transported to the scaled passages using a compressed shop air supply. A shut off valve, pressure regulator, and air flow meter are included in the air supply. The air controls are shown in Figure 21. The fly ash-additive mixture is introduced to the air stream through a rotary air lock solids feeder, shown in Figure 22. Fly ash and additive are mixed in the hopper and are fed by gravity into the rotating vanes of the airlock where the mixture is fluidized with air and transported to either passage mockup. The transport air is exhausted from the mockups through flexible hoses from the pipes at both ends of the mockup to a combined blower-filtration unit. The discharge from the blower-filtration unit is ducted outside the test facility.



(a) Lucite Trough Scaled Emplacement Passage



(b) Quarter Scale Emplacement Passage

Figure 20. Scaled Passage Mockups

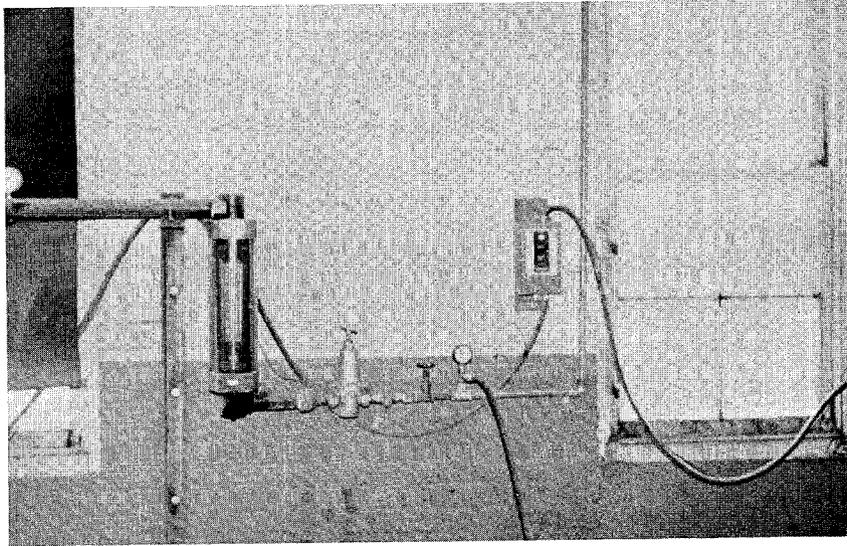


Figure 21. Air Meter and Controls for Pneumatic Transport System

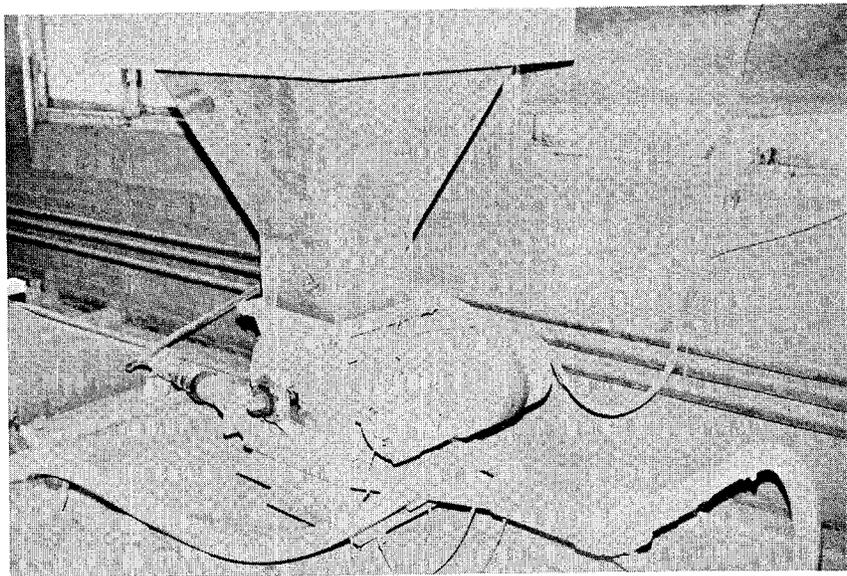


Figure 22. Rotary Airlock Solids Feeder with Dry Materials Hopper

The rising water level was controlled by the level controller shown in Figure 23.

This level controller provided a controlled water rise rate for tests in the full 1/4 scale and in the Lucite trough. An excess of water was continuously supplied to the barrel via a length of garden hose connected to the building water supply. The water level of the barrel and the trough was controlled by the level of the overflow hose inlet, since any water above the level of the overflow hose inlet was pumped out of the barrel by a self-priming centrifugal pump. The level of the overflow hose, and hence the water level of the barrel, was raised at the desired rate by winding up the support line around a pulley driven by a constant speed clock motor and a gear reductor.

4.3 Test Program Description

4.3.1 Lucite Trough Tests

The scaled test program was designed to make maximum use of the lucite trough. This was because of the considerable savings in cost due to the reduction in materials and preparation time associated with the smaller volume.

Fly ash mixtures were introduced into the lucite trough by pneumatic injection, to simulate the density distribution of an actual seal. In some cases the seal was entirely fly ash mixture - in others a foam topping was used.

Uniform mixtures of fly ash and either cement or bentonite were created by stirring the components with a spade in the hopper before pneumatic delivery.

Water was introduced at a rate of 1/2" to 2" per hour, and a maximum total head of 42" above the base of the trough was reached. The following observations were made.

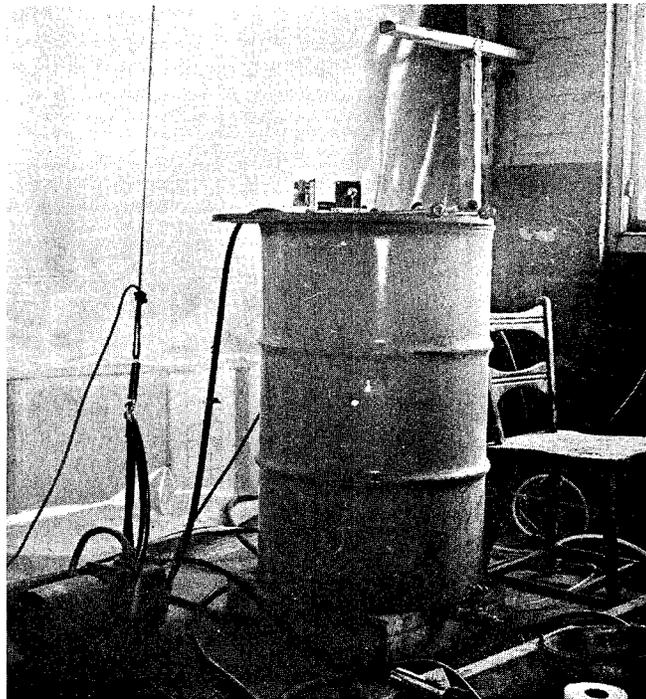
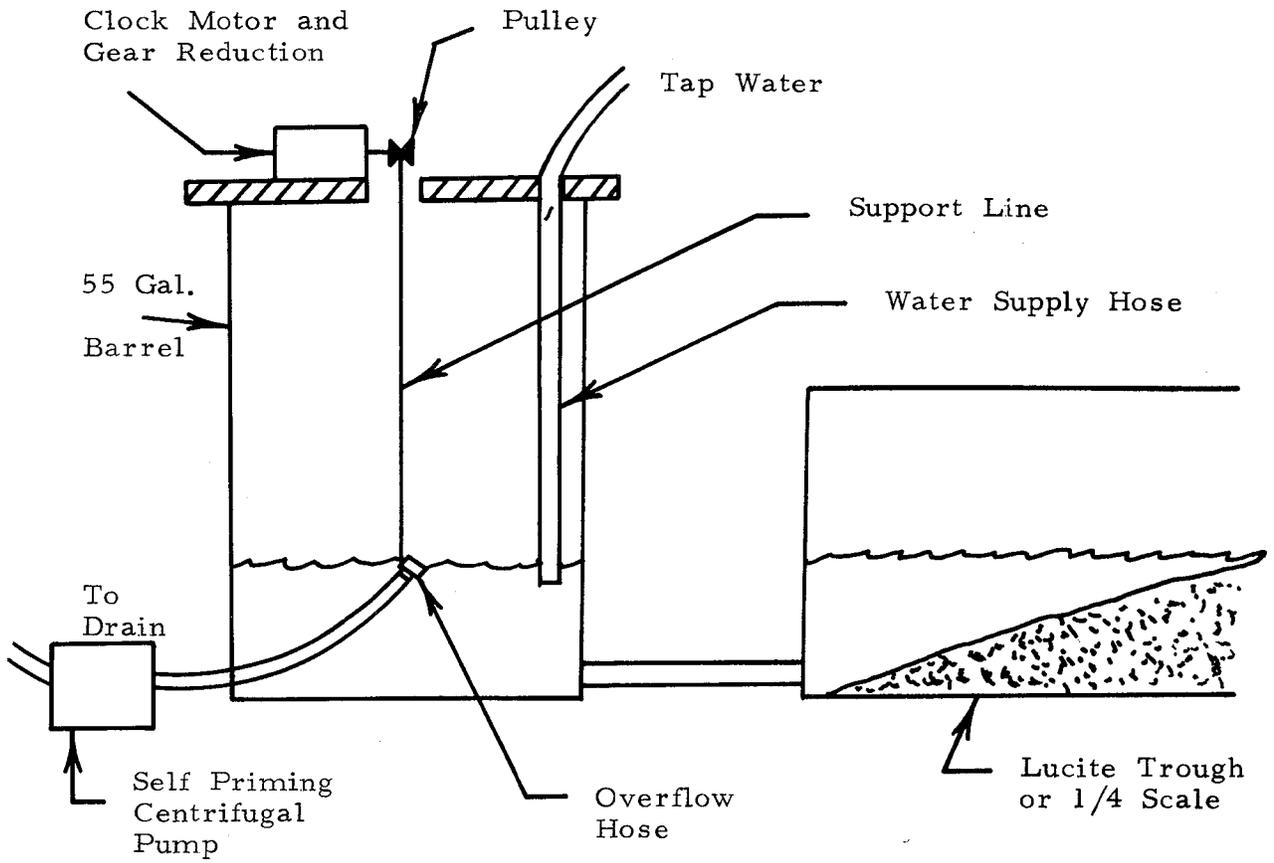


Figure 23. Level Controller

(1) Upstream Slope Behavior

Here the upstream slope of the scaled seal was viewed as a segment of a full scale seal. With this view local occurrences such as capillarity, shrinkage, and collapse, could be observed just as they would occur in a full scale seal.

(2) Water Permeation

The lucite trough enabled full visibility of the water permeation through the seal.

(3) Shrinkage

Local shrinkage cracks, as well as overall settlement of the seal, was observed, as well as the resulting percolation and leakage.

(4) Final Water Support

Ability to support head was observed in terms of leakage, erosion, and collapse.

4.3.2 Full Quarter Scale Tests

The full quarter scale passage was used to represent the three dimensional effects not modeled in the lucite trough. It was also used as a final scaled evaluation of the selected sealant system.

The fly ash mixture was emplaced pneumatically using the pneumatic delivery system described earlier. The foam topping was created by injection through the delivery hole in the passage top,

similar to the full scale technique, using an Autofroth* froth foam system.

The water was introduced using the same level control system as was used in the lucite trough.

One unique observation made during the full quarter scale tests was the geometry of the dry emplaced seal. It was of interest to investigate the influence of additives to the fly ash on crater formation and overall seal geometry. Other observations were similar to those made in the lucite trough.

4.4 Results of the Test Program

A summary of the test program is presented in Table 2. Testing was divided between cement and bentonite type seals, and various layering techniques were attempted. Results of the lucite trough tests showed that fly ash-bentonite seals were superior to fly ash-cement seals. Consequently the bentonite seals were selected for further evaluation in the full quarter-scale passage. The results of the individual tests are described below.

Test 1

The first test conducted in the lucite trough was a pure fly ash seal. The purpose of this test was to identify problems with the use of fly ash alone, and to suggest how they may be overcome by the use of additives. The water rise rate of 2" per hour may be considered realistic for upstream slope behavior, but somewhat excessive in terms of permeation rate through the seal. Consequently, the wetted zone in the seal progresses at a rate faster than would occur in the full scale.

* Trade name for froth foam system produced by Olin Chemical Co.

TABLE 2.
TEST SUMMARY

Lucite Trough

<u>Test No.</u>	<u>Materials</u>	<u>Water Rise</u>	<u>Comments</u>
1	Pure fly ash	2"/hr	No foam topping
2	40% Bentonite	1.5"/hr	No foam topping
3	17% Bentonite	1.5"/hr	No foam topping
4	25% Bentonite	1.5"/hr	No foam topping
5	50% Bentonite on top of a pure fly ash core	1.5"/hr	a. No foam b. Foam topping added
6	17% Portland Type III	1.5"/hr	Foam topping
7	50% Portland Type III over a pure fly ash core	1.5"/hr	Foam topping
8	Test 7 in four layers	0.5"/hr	Foam topping
9	17% Huron cement applied in thin layers	0.5"/hr	Foam topping

Full Quarter Scale

10	Pure fly ash (pneumatic emplacement test)	-	
11	50% Bentonite over a pure fly ash core	0.5"/hr	Foamed
12	50% Bentonite over a pure fly ash core	0.5"/hr	a. Foamed b. Re-foamed

Figure 24 illustrates the response of the seal during the early stages of water rise. Figure 24b indicates how the upstream slope would appear in an actual full scale test. Capillarity causes the water to permeate the fly ash 3 to 4 inches above the level of the rising water. The capillary forces cause the fly ash to shrink, as can be seen by the shrinkage cracks in both views, and by the separation of the seal from the wall in view b. The shrinkage is most pronounced on the sloped surface because here the fly ash is most loosely packed. View "a" shows that cracks are also occurring well within the seal.

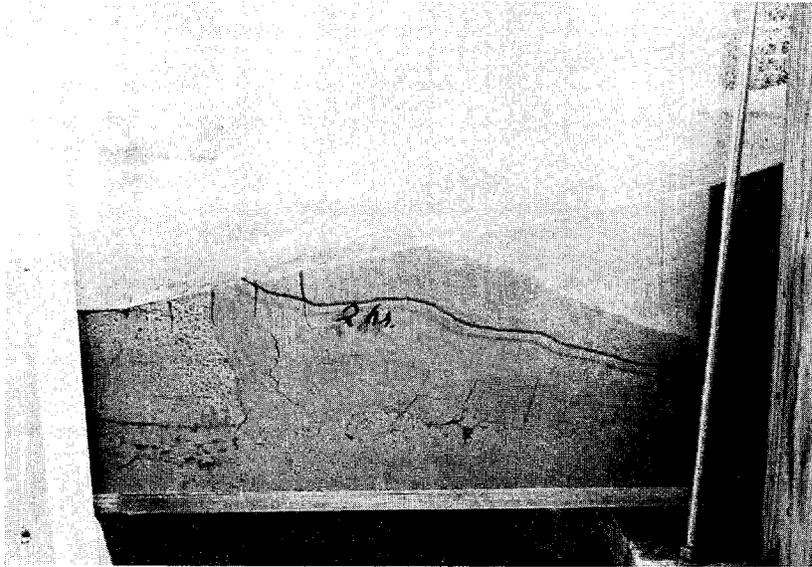
Figure 25 shows the permeation pattern after 17 hours at a head which was maintained constant, close to the top of the passage. Under these conditions, the permeation pattern should closely resemble that for the full scale. Shrinkage cracks have occurred throughout the entire seal.

The seal "failed" when a sufficient number of cracks connected to form a continuous leakage path from one side of the seal to the other. This path eroded until a large hole was formed, as shown in Figure 26. The outlet of the hole can be seen in the upper right hand corner of the trough in the photo. This failure occurred before the water level had reached the crest of the seal.

The failure of the pure fly ash seal indicated a need for a material additive which would either prevent shrinkage or prevent erosion. The use of bentonite and cement respectively serve these purposes.

Test 2

This test consisted of 40% bentonite by total weight. It was designed to illustrate the influence of impermeability on the seal performance. Figure 27 shows the seal response. Note from Figure 27a that only a thin layer of the mixture becomes wetted, and from Figure 27b that there is no noticeable capillary rise or shrinkage on the upstream slope.



(a) Side View



(b) View of the Upstream Slope

Figure 24. Pure Fly Ash Seal After 2+ Hours

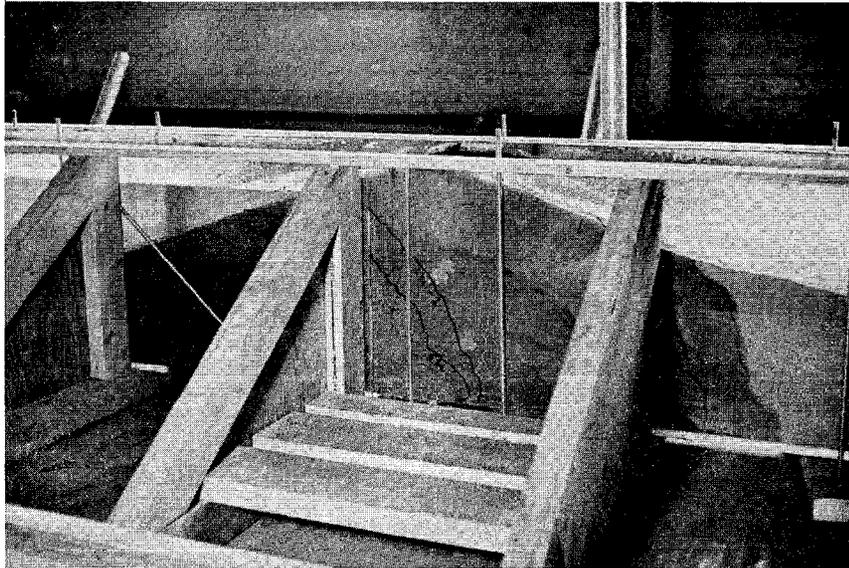
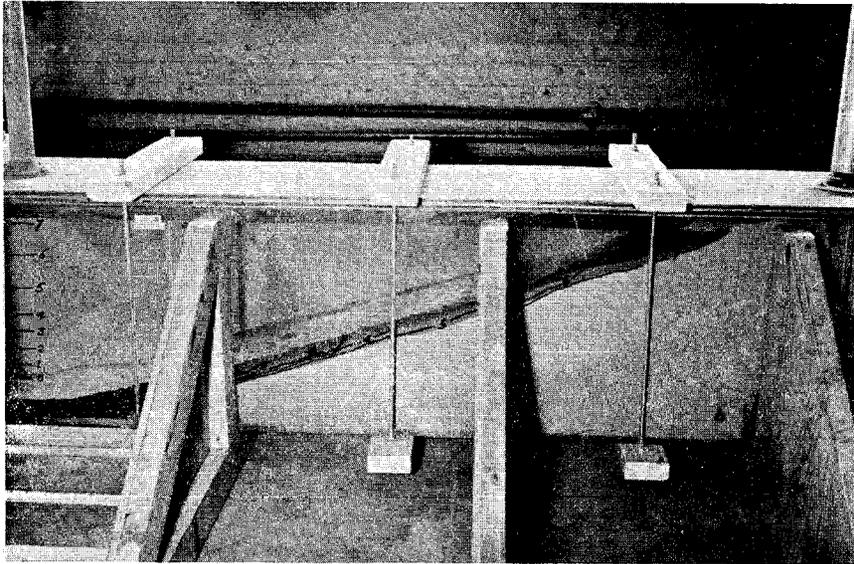


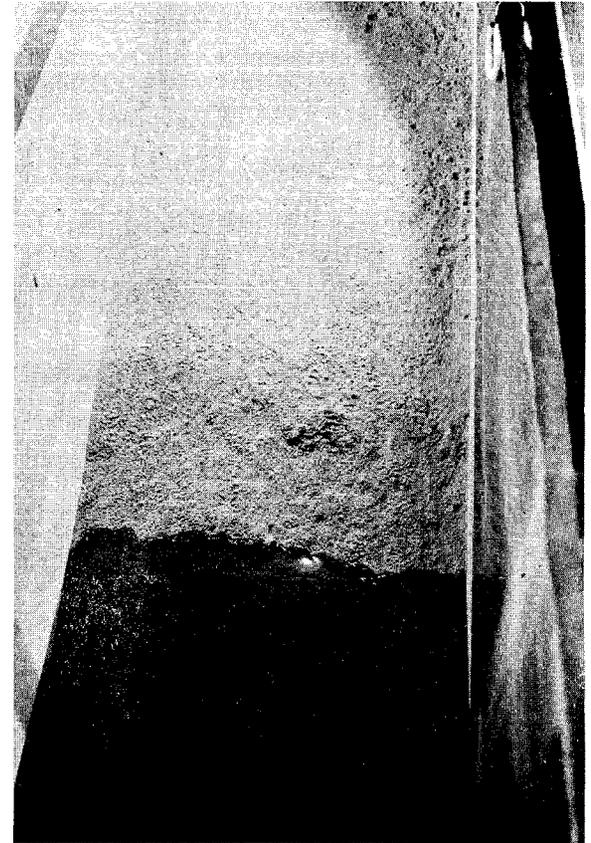
Figure 25. Permeation Pattern After 17 Hours at Constant Head



Figure 26. Failure Mode



(a) Side View



(b) View of Upstream Slope

Figure 27. Seal with 40% Bentonite

Upon raising the water level above the passage top, some leakage occurred at the top interface along the side edges, as shown in Figure 28. It was suspected that this was due to gaps which occurred during seal emplacement. Since this test does not accurately model the sealing at the roof, the top of the seal was touched up by hand, and the test was repeated. Figure 29 shows the top of the seal after a water rise of 10" above the passage top. Once again, small leakage paths developed at the top corners of the seal. Figure 30 shows the permeation pattern after holding water for 100 hours. Note that the bulk of the seal is still dry.

Test 3

Since bentonite is somewhat expensive, an attempt was made to determine a lower bound for the amount of bentonite required to produce a relatively impermeable, non-shrinking seal. The small sample tests indicated that the property transitions for the bentonite-fly ash mixtures began at about 20% bentonite, and hence this value was chosen for the test. Figure 31 illustrates the seal behavior during the early hours of the test. A small amount of capillary rise occurs, but shrinkage occurs as well (Figure 31a).

Shrinkage from the walls eventually accounted for the ultimate failure of the seal. When the seal was subjected to water head above the top of the passage, a leakage path developed along the wall due to the inward shrinkage of the seal (Figure 32). This progressed rapidly to the far end of the seal, and led to the ultimate failure of the seal (Figure 33).

Test 4

This test had two objectives: one to test an intermediate percentage of bentonite, and the other to evaluate a two layer seal. Since 40% bentonite had proven sufficiently impermeable, and 20% was



Figure 28. Initial Leakage Paths Due to Sealing Gaps at Passage Roof



Figure 29. Modified Seal Top After Being Subject to a Head 10'' Above the Passage Height

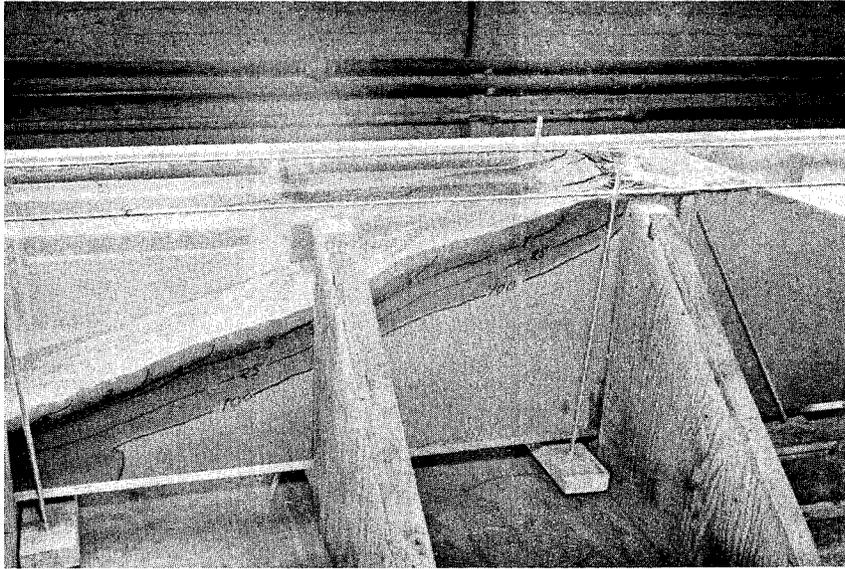
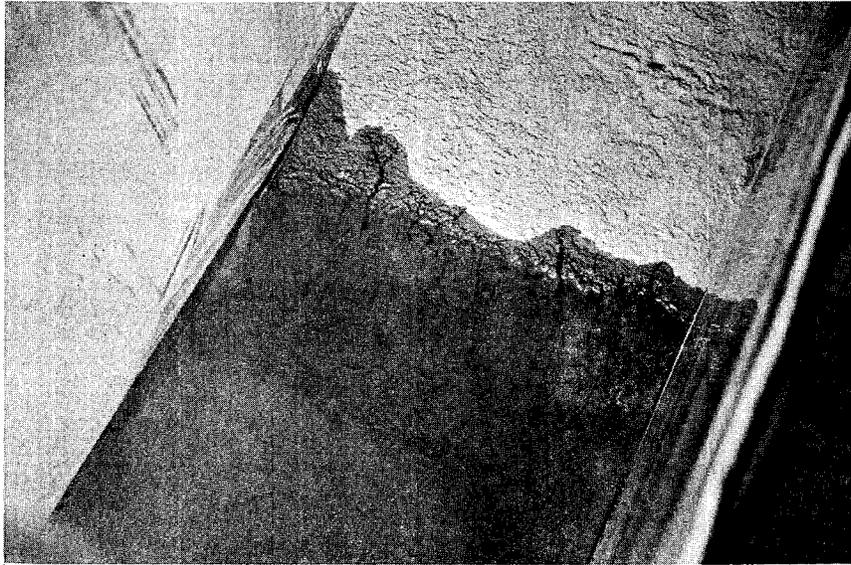
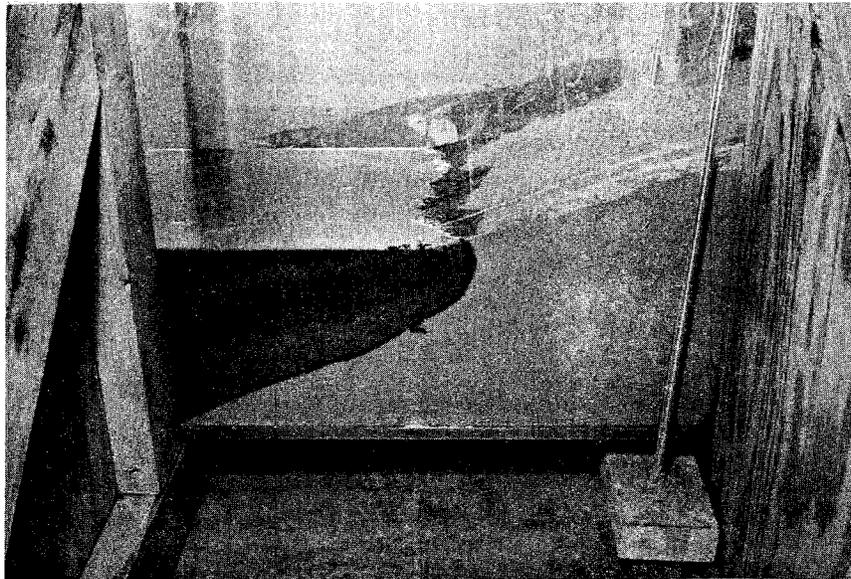


Figure 30. Permeation of 40% Bentonite Seal After 100 Hours



(a) Upstream Slope



(b) Side View

Figure 31. Seal with 20% Bentonite

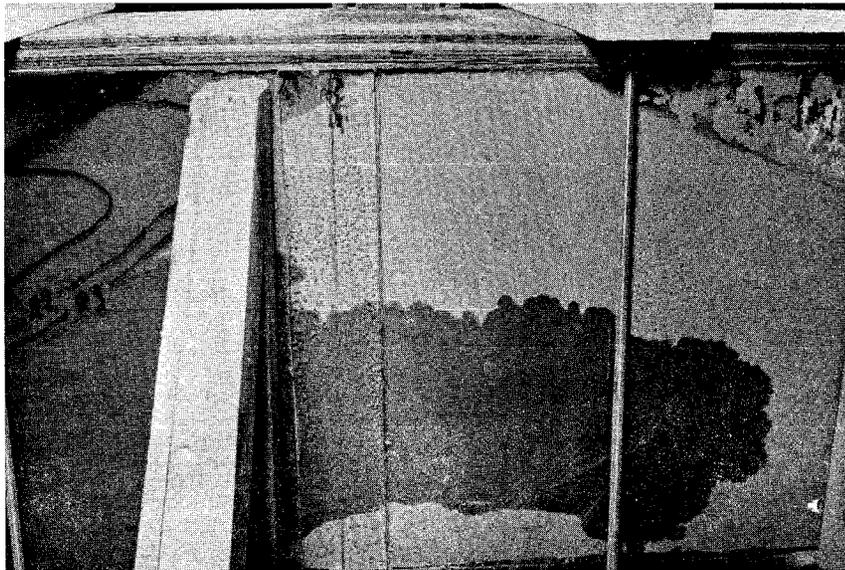


Figure 32. Rapid Development of a Leakage Path Through the Seal - 20% Bentonite

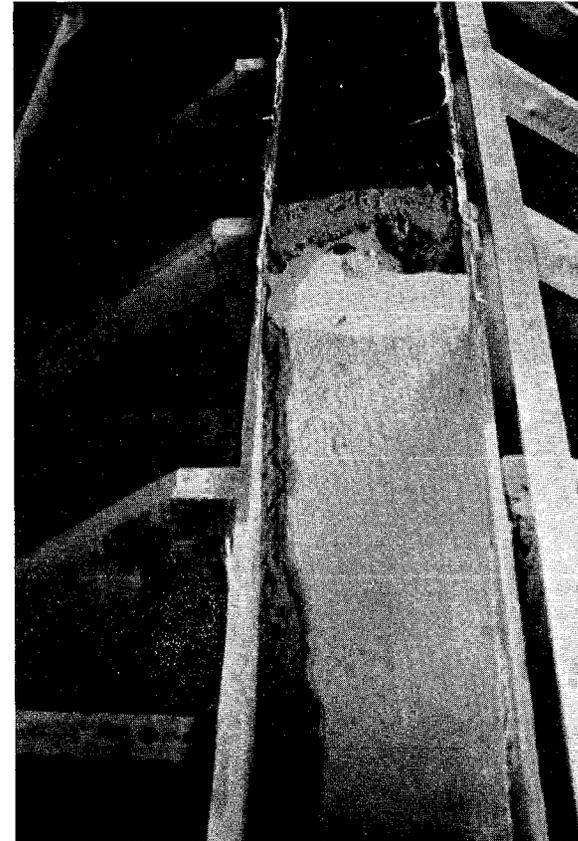


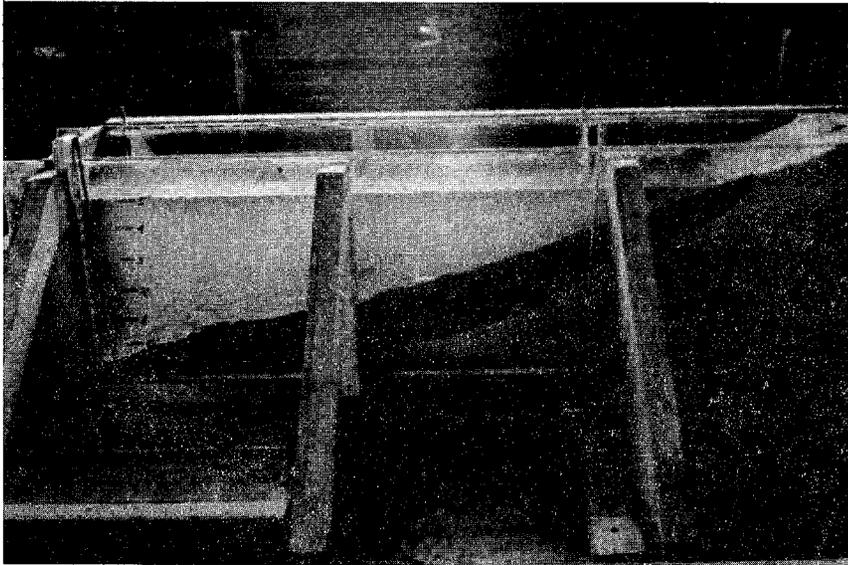
Figure 33. Final Failure - View of Downstream Slope (20% Bentonite)

insufficient due to shrinkage, a 25% mixture of bentonite and fly ash was used in this test. Since a sufficiently impermeable mixture of bentonite only causes wetting in a thin layer of the upstream surface, we experimented with a core of pure fly ash and a top layer of 25% bentonite mix. The "core" constituted 2/3 of the total weight of material.

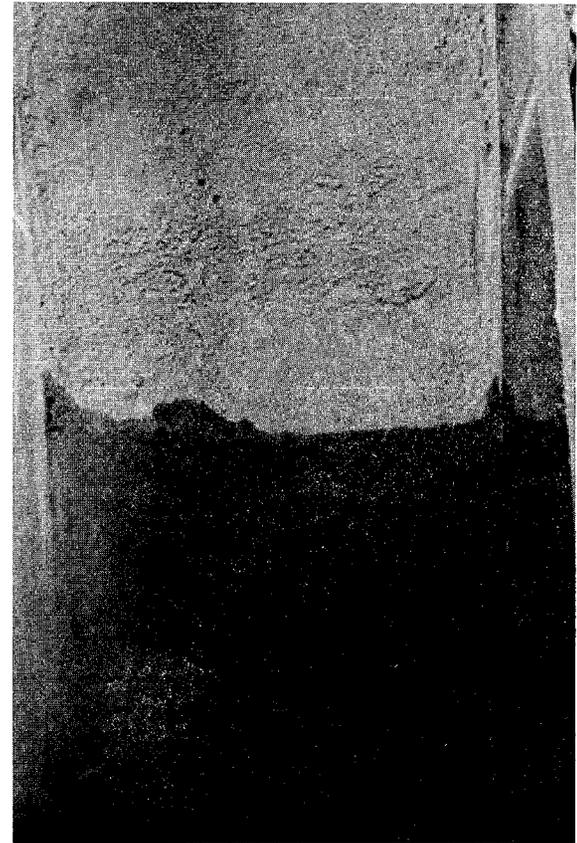
Figure 34 shows the geometry of the seal and its initial response during water rise. Although shrinkage does not occur, the 25% mix is not sufficiently impermeable to keep the water from seeping into the fly ash core (Figure 34b). Ultimately, when the water level rose above the height of the passage, leakage paths developed at the top corners of the seal (Figure 35). This may have been due partially to inadequate sealing at the top, and partially due to settlement of the top of the seal due to shrinkage of the fly ash core. The settlement of the wetted core is dramatically illustrated by the crack shown in Figure 36. In any event, the test concluded that the layered approach demanded a highly impermeable bentonite layer to guarantee that water would not permeate into the fly ash.

Test 5

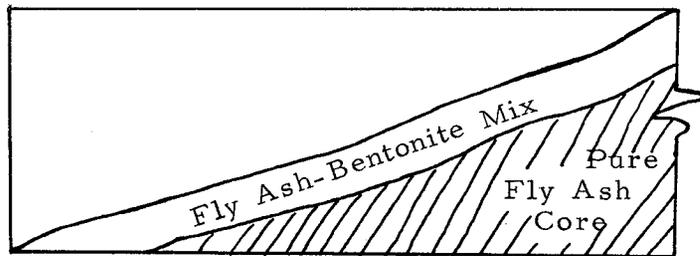
This was basically test 4 repeated with a 50% bentonite mix. Figure 37a shows the response of this seal to rising water. Note that the bentonite is quite impermeable and keeps the water away from the fly ash core. Note also, however, that the bentonite layer tapers from a maximum thickness at the top, to a minimum thickness at the bottom, as a result of the pneumatic emplacement. Consequently, at the upstream toe of the seal the bentonite layer was quite thin and water did permeate, to a limited degree, into the fly ash core (see dark area at the bottom left corner). The total head was raised to 34", or 16" above the passage top, at which point slight leakage developed along the top corner. Figure 37b shows the top of the seal after withstanding the head. The leakage occurred along the far side of the passage (top of photo). Once again, this leakage was believed to be due to our inability to create a perfect seal with the fly ash mixture alone.



(b) Side View During Water Rise



(c) Upstream Slope During Water Rise



(a) Emplacement Geometry

Figure 34. 25% Bentonite on a Pure Fly Ash Core

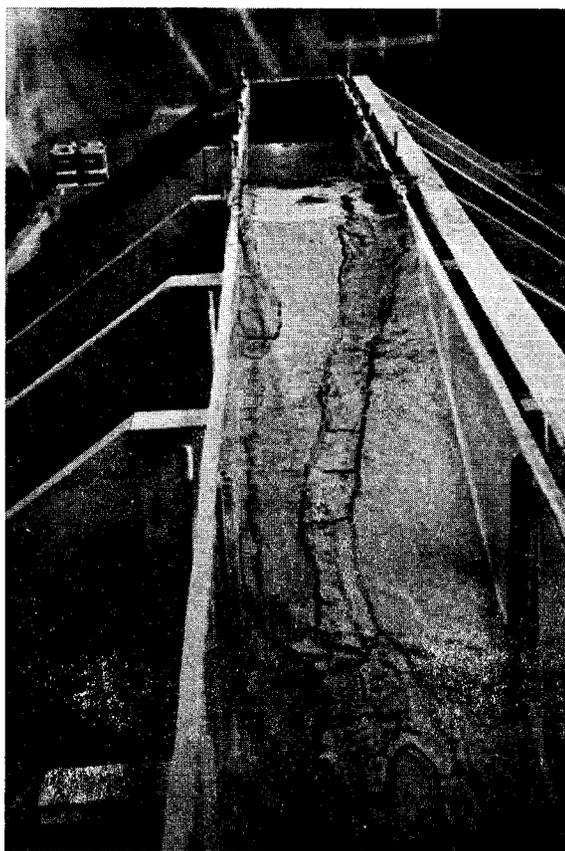
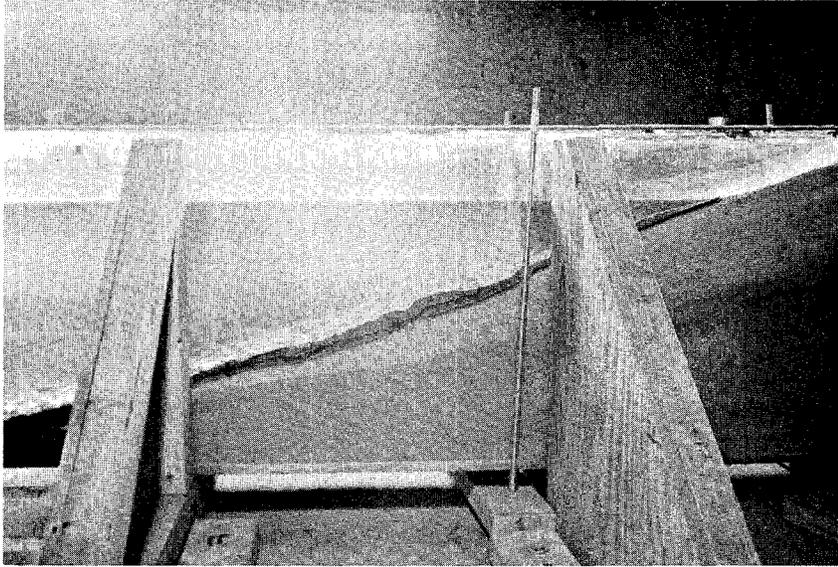


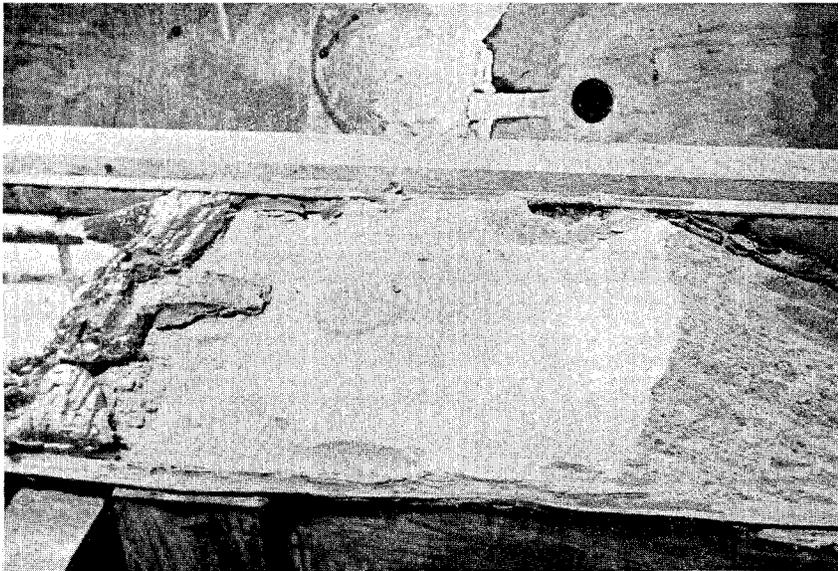
Figure 35. Failure Resulting from Leakage Paths at Top Interface



Figure 36. Shrinkage of Wetted Inner Fly Ash Core after Three Days



(a) During Water Rise



(b) After Head of 16" Above Passage Top

Figure 37. Two Layer Seal with 50% Bentonite Mix

A second test, using the same seal, was carried out with a froth foam topping. Since the seal itself was relatively impermeable, the lowering and raising of the water level, which had to be done to carry out this modification, had little effect on the seal as a whole.

Figure 38a shows the froth foam topping from the upstream end of the seal. The seal was once again subjected to 34" of total head. This produced slight leakage between the foam and the top of the seal. The head was maintained for six days, and the resulting permeation pattern is shown in Figure 38b. As shown at the left of the photo, the permeation into the fly ash core at the toe continued, but was considerably controlled by the bentonite layer, so that it did not proceed far enough to cause shrinkage damage.

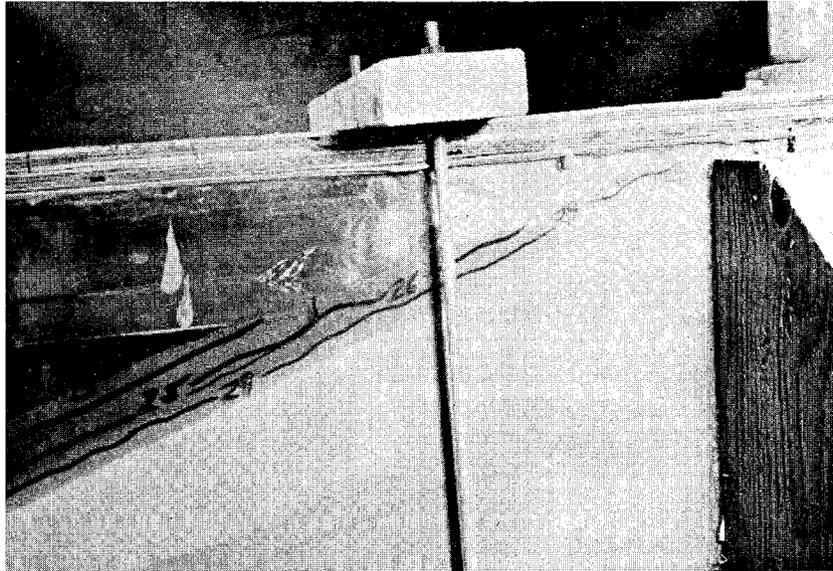
This system was considered to be a prime candidate for further evaluation.

Test 6

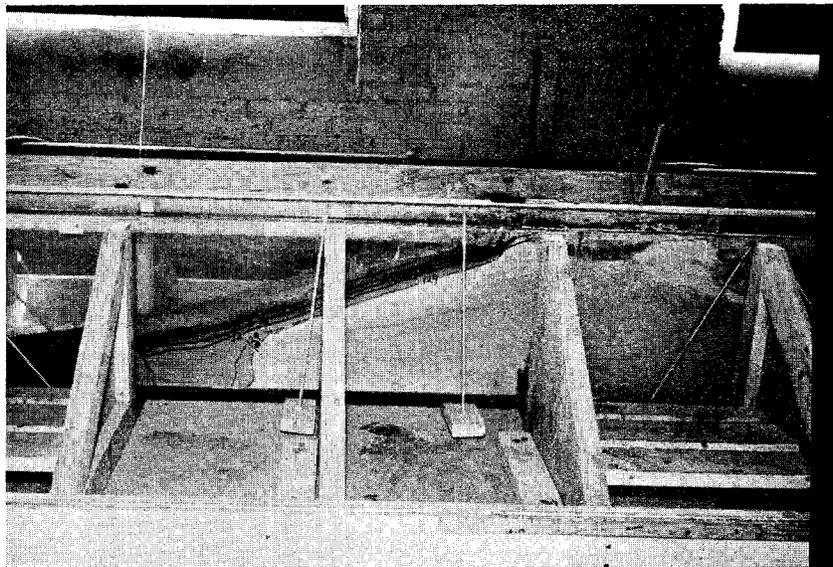
Test 6 was the first of the tests using Portland cement. Tests 6, 7, and 8 used Portland Type III cement in varying quantities and with different emplacement techniques. Test 9 used Huron Regulated Set Portland Cement (RSPC).

In Test 6, a uniform mixture of 17% Portland Type III cement was employed. Figure 39 shows the behavior of the seal during water rise. As indicated in the small sample tests, the permeability and capillarity of the fly ash-cement mix is similar to that for fly ash alone. Shrinkage cracks occur as well, but they are smaller than those which occurred for fly ash alone.

Figure 40 shows the behavior of the seal during the later stages of the test. The head was brought to a total of 24-1/2" after 10 hours, and no discernable leakage occurred. The test was allowed

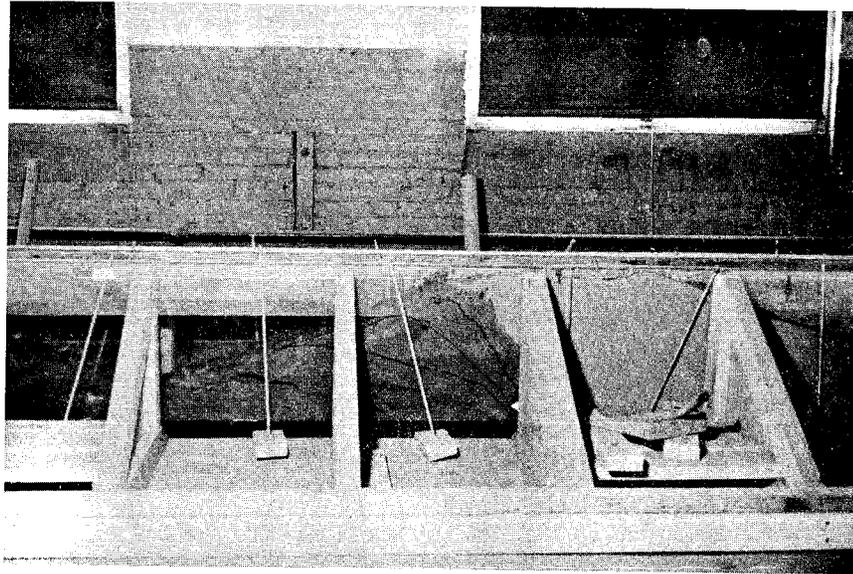


(a) Upstream Slope with Foam Topping

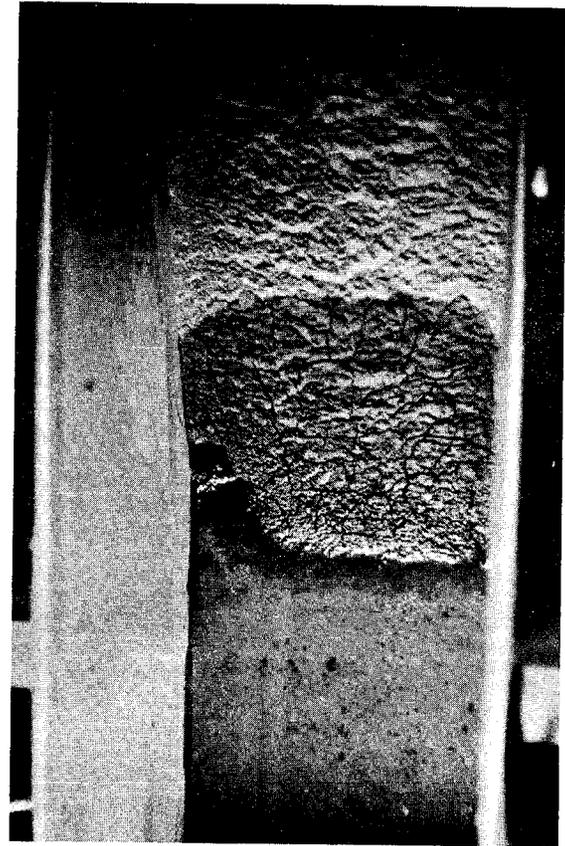


(b) Entire Seal Subjected to Water Head After 6 Days

Figure 38. Two Layer Seal with 50% Bentonite and a Froth Foam Topping

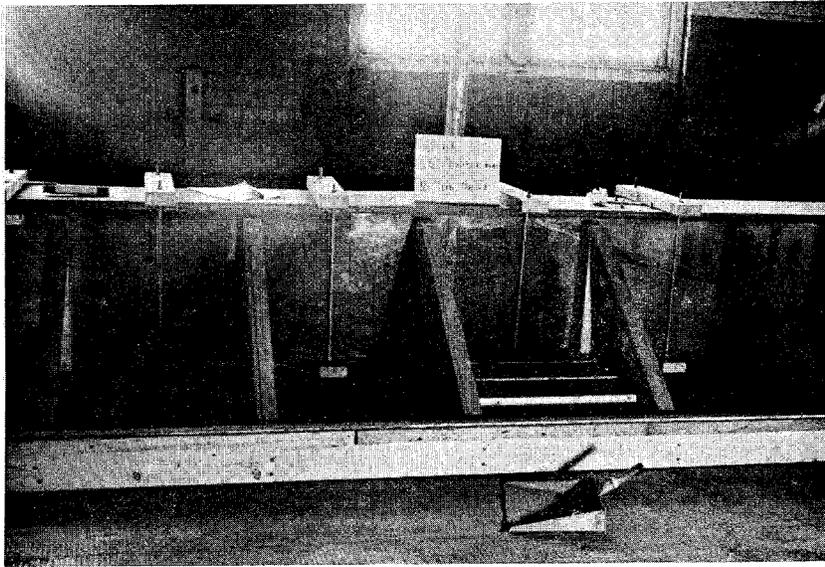


(a) Side View During Water Rise

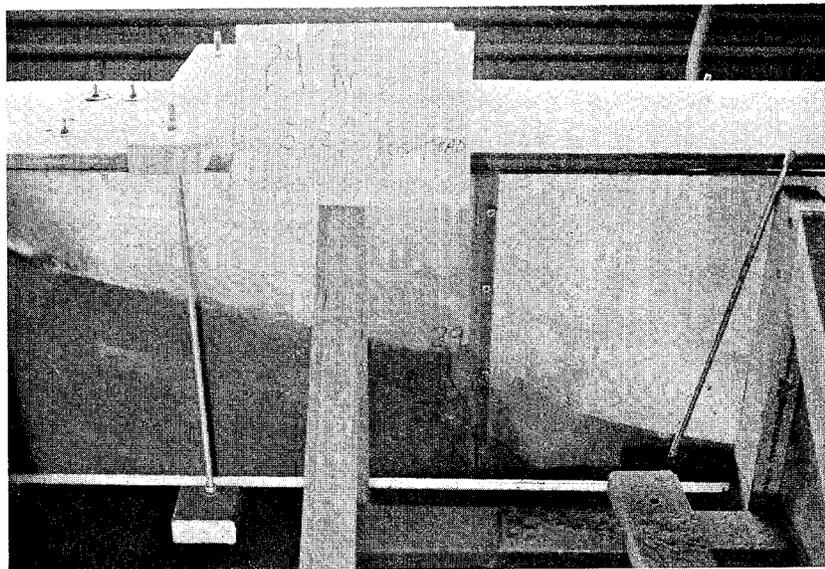


(b) View of Upstream Slope, Looking Down

Figure 39. Uniform Mix of 17% Portland Type III Cement



(a) After 10 Hours at 24-1/2" Total Head
(6-1/2" Above Top)



(b) After 29 Hours at 23-1/2" Total Head

Figure 40. 17% Portland Cement Seal - Later Stages

to stand overnight, during which time permeation progressed almost completely through the seal. The head was brought back up, and at 23-1/2", noticeable leakage did occur. This leakage could have occurred due to shrinkage which took place from the progressive permeation, or it could have been a manifestation of something which went unnoticed earlier due to absorption of water by dry material. In any event, subsequent attempts to raise the water head produced erosion and accelerated leakage, and hence the test was discontinued.

Tests 7 and 8

These tests had two goals in mind:

- Investigate the benefits of a higher Portland Type III concentration.
- Investigate emplacement methods for which the materials can be injected without premixing.

The higher cement ratio was attempted to eliminate the erosion which was observed in Test 6. The alternative emplacement methods involved layering, where material would be delivered at a 1:1, or 0:1 ratios. In this way, an intermediate storage silo and a metered feeder would not be required. The two components could either be pumped simultaneously or one at a time.

The first of these techniques (Test 7) involved a pure fly ash core covered with a 1:1 mixture of fly ash and Portland Type III cement (similar to Tests 4 and 5 with bentonite). Here, the pure fly ash core constituted 50% of the weight of the seal material. It was felt that although the fly ash core would get wet and shrink, the cement cover would harden and arch over it.

Figure 41 shows the initial stages of Test 7. The permeation pattern was quite similar to that for Test 6. The principal result of the test was that the fly ash-cement did harden and arch over the fly ash, but before it hardened some settlement occurred, and this produced leakage at the top (~ 2 gpm at 10" head). No erosion occurred, and this leakage rate held steady.

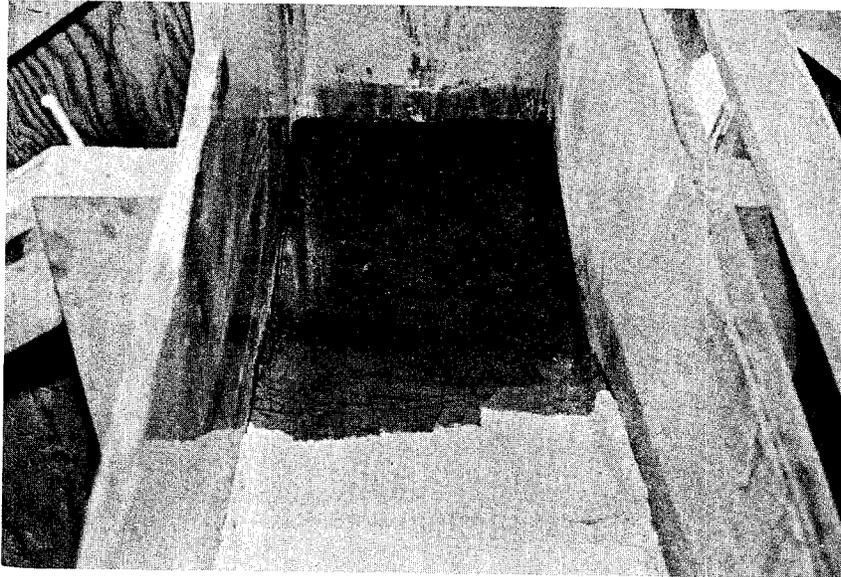
Test 8 considered a finer layering scheme, using 8 layers alternating between pure fly ash and 1:1 fly ash-Portland Type III. One other alteration which was made was the use of a lower rise rate (1/2"/hour). From a scaling point of view, this would yield a more realistic view of the permeation rates through the seal.

The results for Test 8 were essentially the same as those for Test 7; i.e., some shrinkage and about 2 gpm leakage at 6" head above the passage roof. Figure 42 shows the permeation. Due to the decrease in water rise rate, the contours are more vertically oriented, and the progress of the permeation is much slower, than that which occurred in the previous tests.

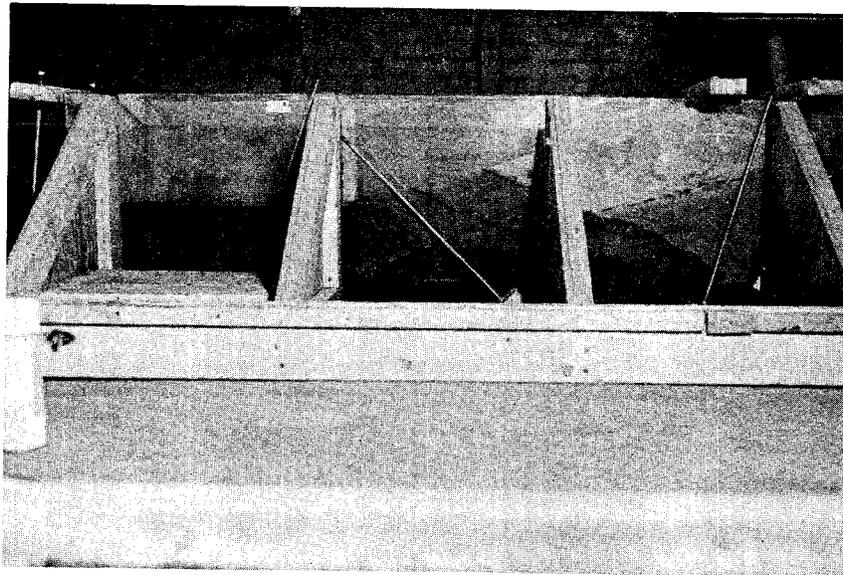
Test 9

A final attempt at an optimal cement seal was made using Huron RSPC. Small sample tests indicated that this cement, in relatively low percentages with fly ash, would set up within 5 minutes and would shrink less than other cement combinations. This test was designed using 17% RSPC. The emplacement was not in uniform mixing, but rather by delivering alternating layers of 50 lbs of fly ash and 10 lbs of RSPC. This would simulate a means by which the mixture could be pumped directly from two bulk haulers say, for example, 5 minutes of RSPC for each truck of fly ash.

The test is shown in Figure 43. As in Test 8, the slower, concave permeation contours are due to the slower water rise rate. The seal experienced little noticeable shrinkage, and was able to maintain a full 42" of total head with a leakage rate of 1/2 gpm.

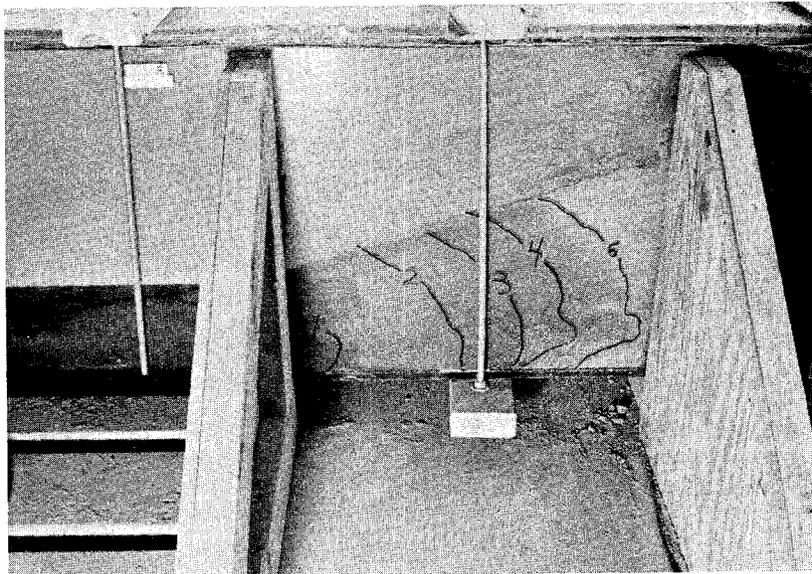


(a) Looking Down the Upstream Slope During Water Rise

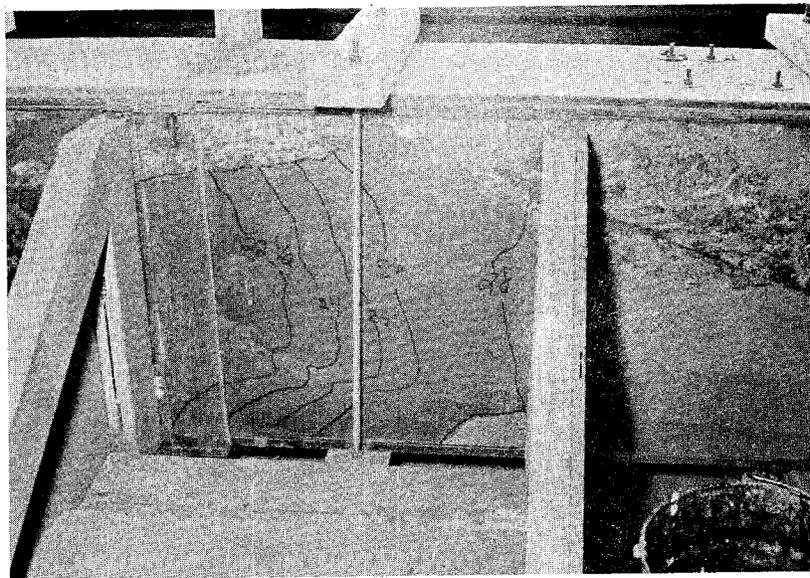


(b) Side View During Water Rise

Figure 41. Test No. 7 - 50 Percent Portland Type III
Mixture Over a Pure Fly Ash Core

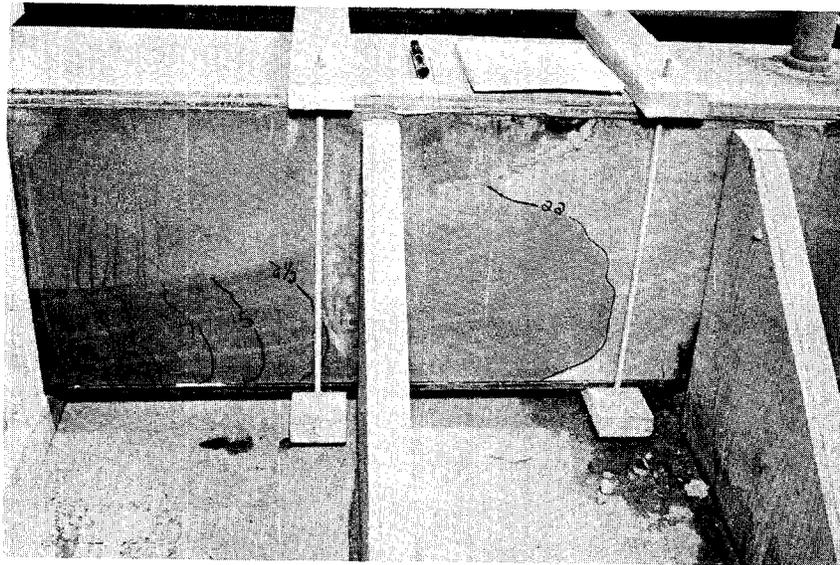


(a) Permeation During Early Stages

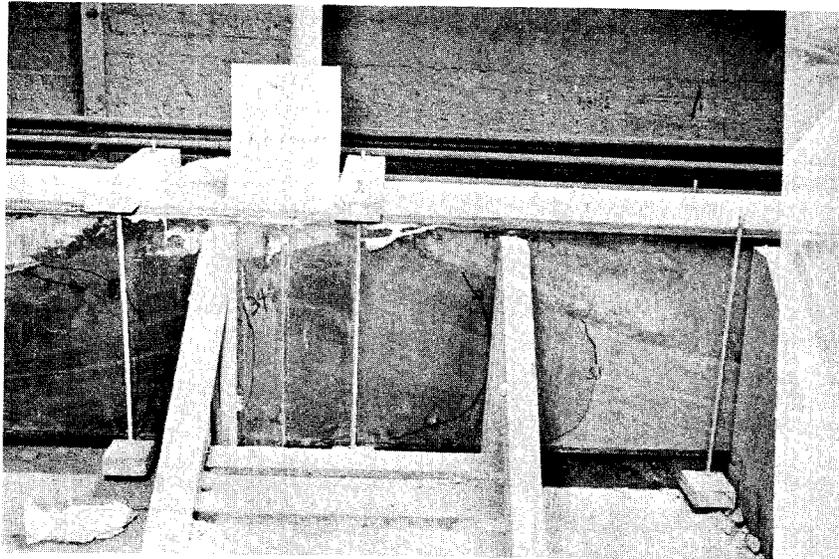


(b) Permeation Through the Seal During Support of Water Head

Figure 42. Test No. 8 with Eight Layers of 50% Portland Type III and Pure Fly Ash



(a) Permeation Patterns During Water Rise



(b) Seal with 42" Of Total Head

Figure 43. 17 Percent Huron Cement Seal

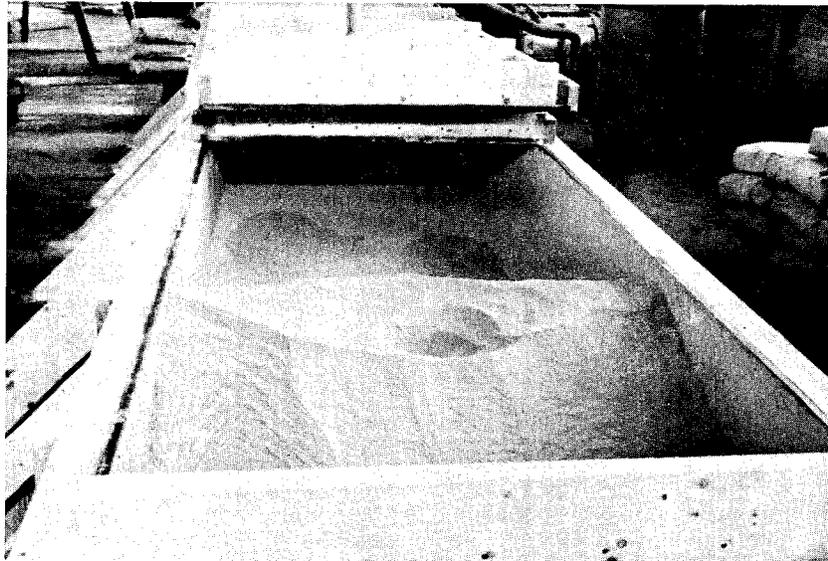
Test 10

This test was used as a reference for the influence of bentonite on the geometry of pneumatic emplacement. This test used fly ash alone, and produced the seal geometry shown in Figure 44a. The volume of material was four hoppers (see Figure 22), or about 2,000 lbs. The material was emplaced using an air flow of 80 cfm, which scales to a value of 2,560 cfm for a full scale operation.⁽³⁾ Figure 44b shows the same amount of material emplaced under the same conditions. Here, however, the second two hoppers were a 1:1 mixture of fly ash and bentonite (Test 12). Note that the crater is somewhat smaller and the slope angle is steeper. This is due to the higher friction angle of bentonite, as well as to its pneumatic transport characteristics. The platelet structure of the bentonite particles causes it to settle out more quickly, thus concentrating it near the borehole. This is seen again in the Test 11 description.

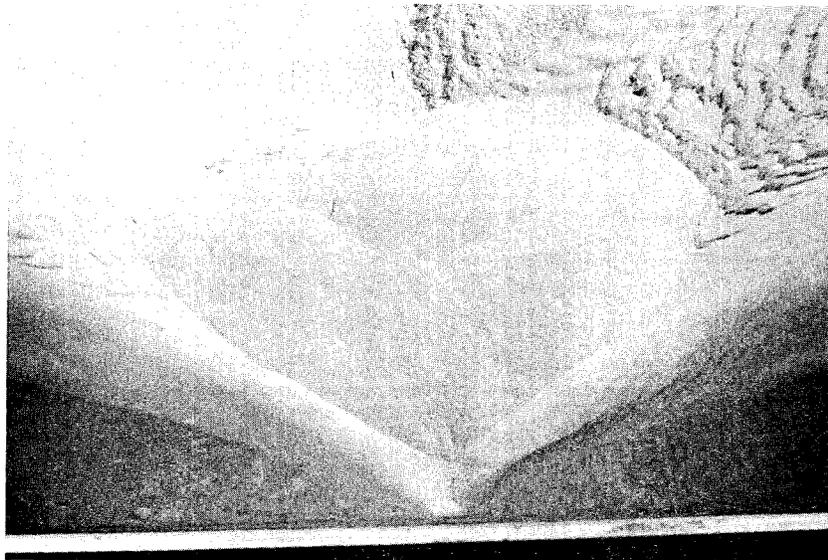
Test 11

Test 11 consisted of 2 hoppers of pure fly ash covered by 3 hoppers of a 1:1 fly ash-bentonite mix. Figure 45a shows the top of the seal with the passage lid removed. A near perfect seal was created at the roof of the passage. For water emplacement, however, we wished to use a foam topping. To allow space for the foam, a crater the width of the passage was hollowed out, and foam was injected through the fly ash injection pipe. An end view of the resulting seal is shown in Figure 45b.

Figure 46 shows a side view of the seal layering. Once again as noted in the Test 10 description, the placement of the bentonite mix pneumatically is different than that for fly ash alone. The bentonite has less of a tendency to be carried by air, and hence settles sooner, forming a tapered layer which is thick at the crest and thin at the toe.

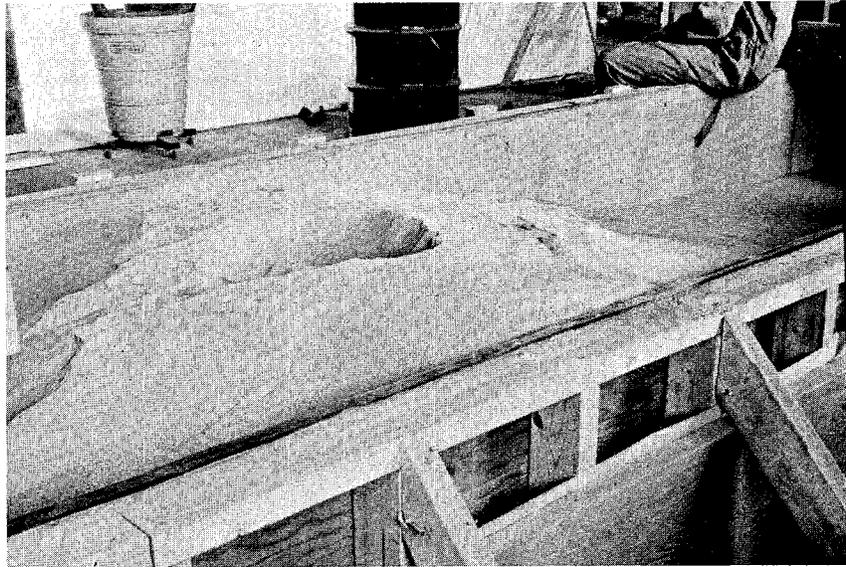


(a) Four Hoppers of Fly Ash

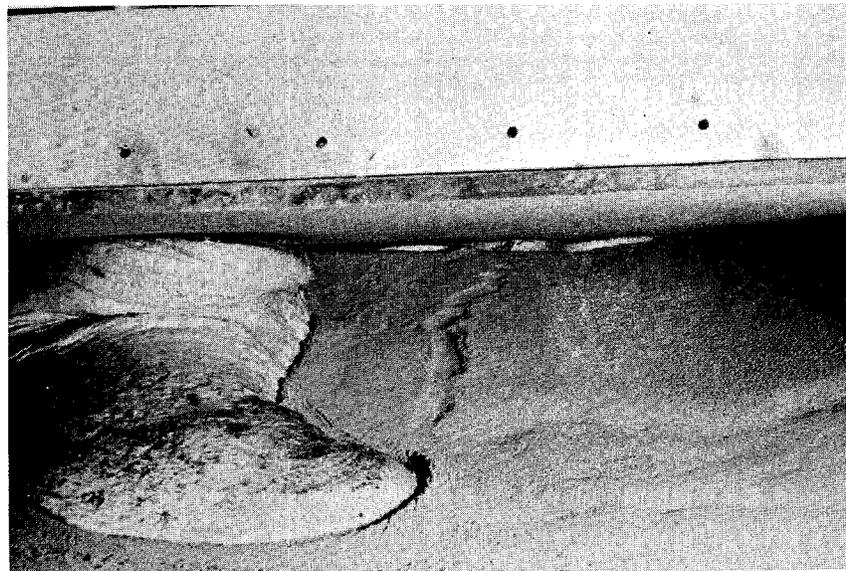


(b) Two Hoppers of Fly Ash and Two Hoppers of 1:1
Fly Ash Bentonite Mix

Figure 44. Comparison of Seal Geometries with and without
Bentonite



(a) Top of Seal



(b) End View of Seal After Foaming

Figure 45. Test 11 - Seal Characteristics

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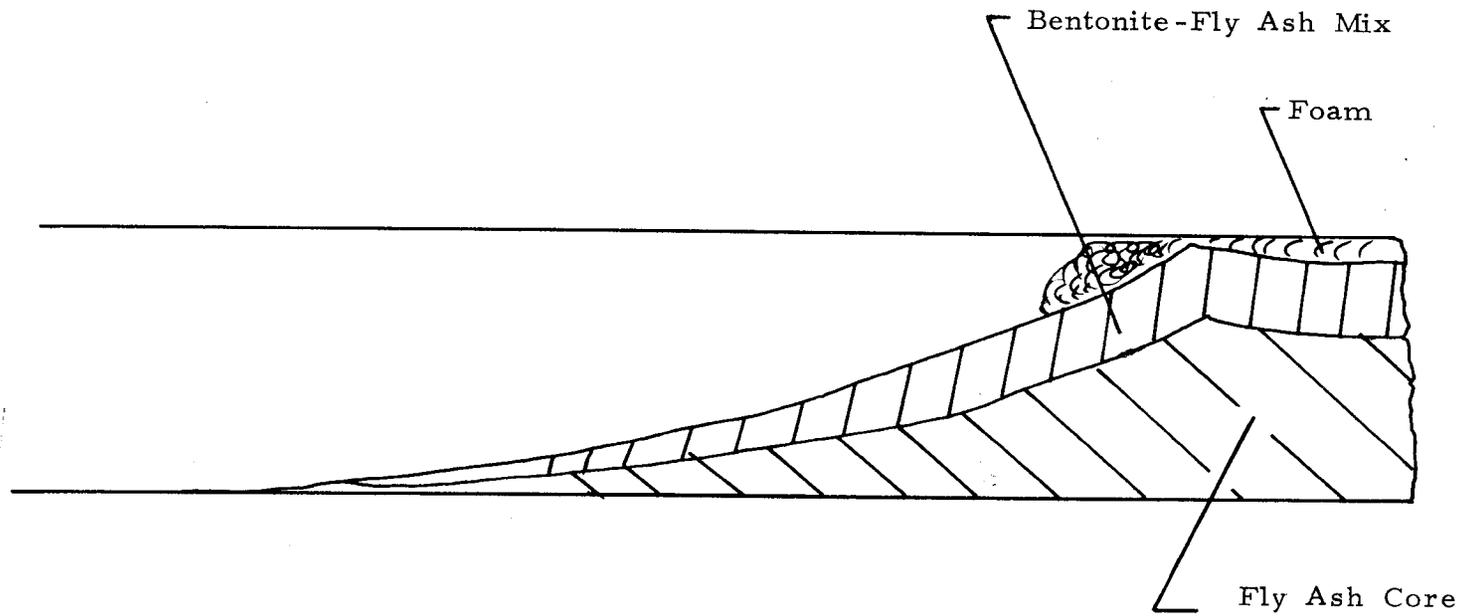


Figure 46. Side View of Test No. 11 Seal

This latter feature turned out to be the undoing of the seal, as illustrated in Figure 47. The bentonite layer was so thin and loosely packed at the upstream toe, that water permeated into the fly ash core. The thin bentonite layer broke down at several places early along the slope, and soon the permeation of water into the core progressed through the seal. This wetting of the fly ash core produced shrinkage and collapse, and soon it became evident that the seal would not hold. At this point, the test was discontinued.

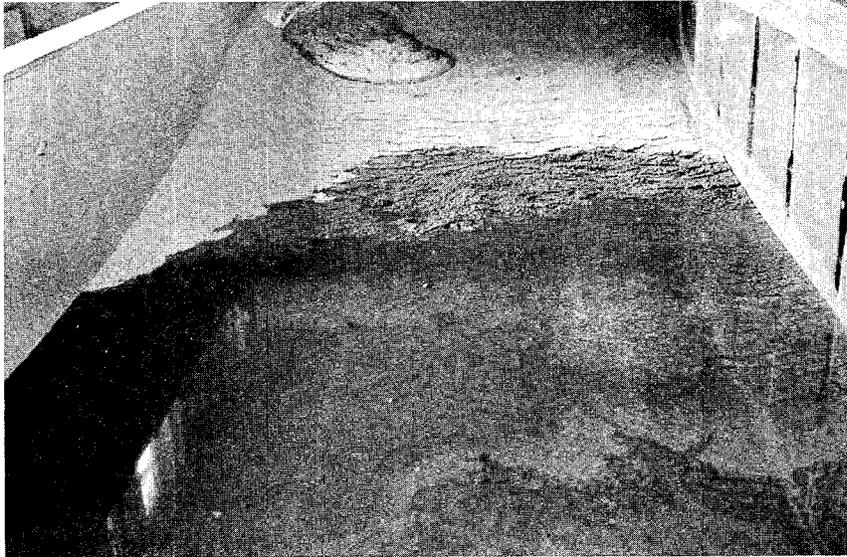
This type of failure was not previously encountered in the lucite trough because of the limited length of that trough. It was felt that this problem could be alleviated by thickening the bentonite layer at the toe. This could be accomplished by reducing the fly ash core.

Test 12a

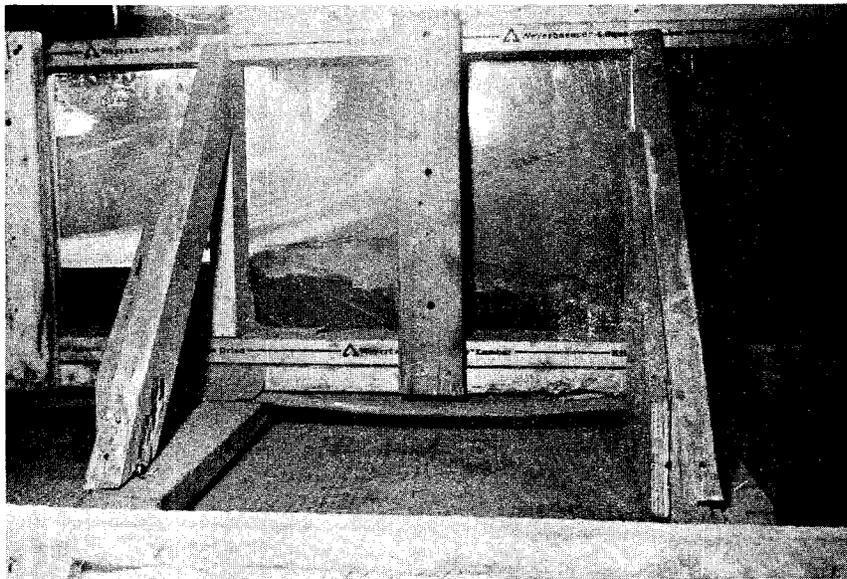
This test involved the use of 2 hoppers of fly ash and two hoppers of the 1:1 fly ash-bentonite mix. This had the effect of thickening the layer of bentonite mix. Figure 48a shows the rising water level from the side of the passage. The interface between the two layers can be seen clearly here. Once again the water passed through the thin bentonite layer at the toe, and permeated the fly ash core. This time, however, the leakage was controlled due to the swelling of the bentonite.

When the water level was raised above the passage roof, a leak developed under the foam topping, as shown in Figure 48b. This leak accelerated, and the water level could not be raised any further.

An examination of the failure, as shown in Figure 49 indicated that it was due to the nature of the foam topping. Although a complete seal was achieved using foam, part of the seal was on the downstream side of the crest. Consequently, where the water level reached the crest of the fly ash-bentonite pile, it quickly flowed over and washed down the far side of the seal. The head on the far side

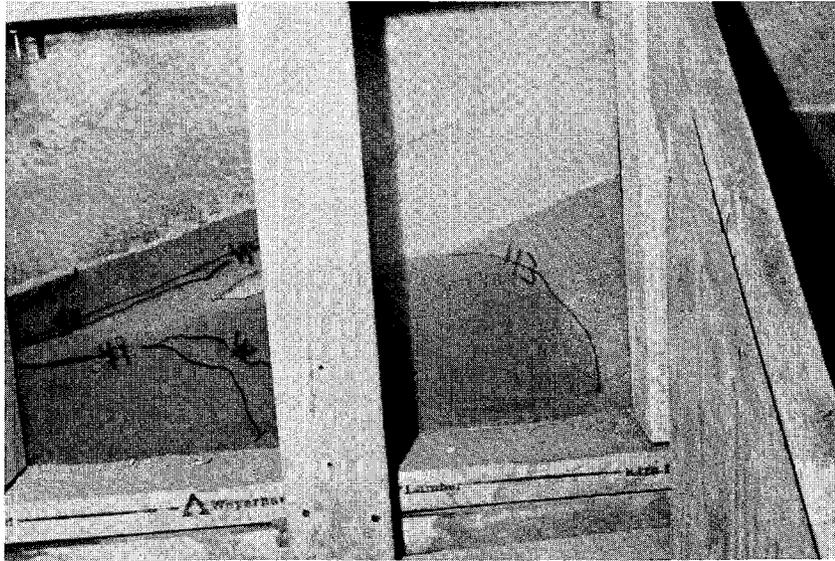


(a) View of Upstream Slope

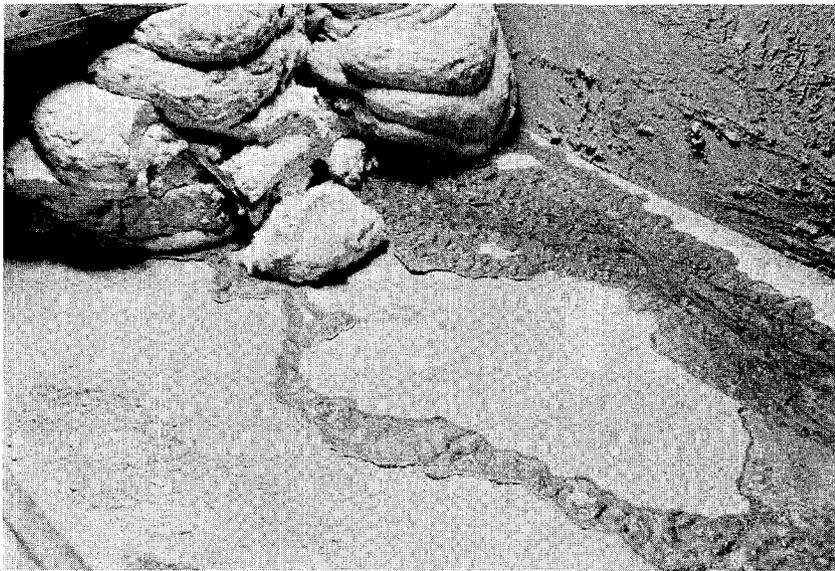


(b) Side View

Figure 47. Test 11 - Seal Behavior During Water Rise

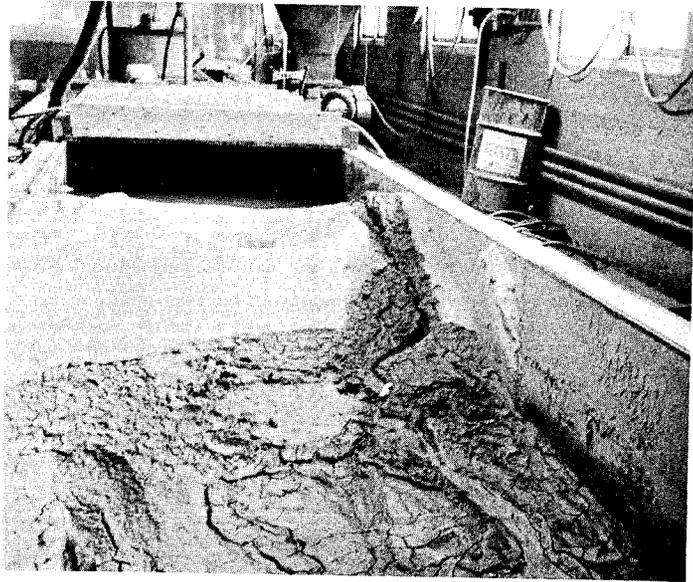
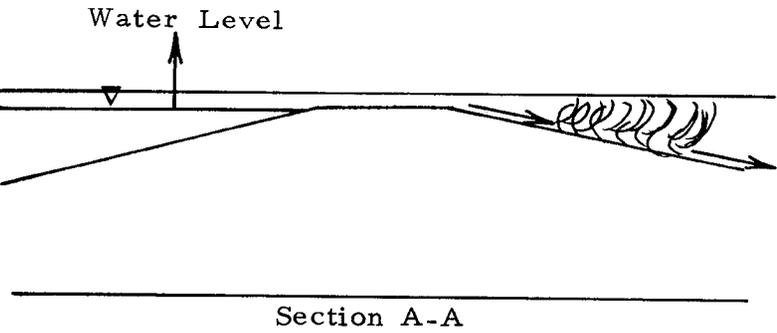
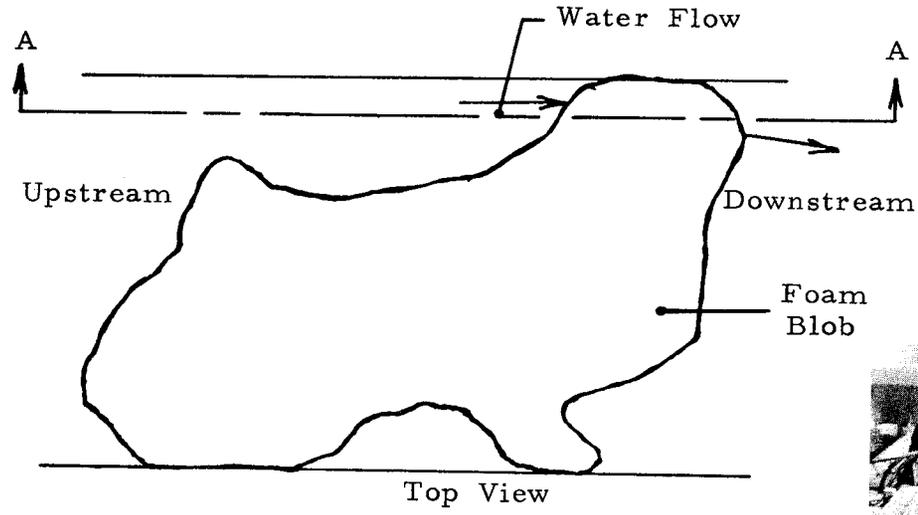


(a) Rising Water Level



(b) Leakage When Water Reached the Top of the Passage

Figure 48. Test 12



(a) Schematic of Foam Topping and Leakage Path

(b) Photo of Leakage Path with Foam Topping Removed

Figure 49.. Examination of Test 12 Failure

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quickly built up to equal that at the crest, and a leak developed. This appeared to be a serious shortcoming of the sealing system, since such foam topping geometries are likely to happen. The development of the final cement coating, described in Section 5, appears to have solved this problem.

Test 12b

This final test was a rerun of Test 12 with a more carefully placed foam topping. Since water permeation had been limited in extent, the same basic seal was reused, recapped with fly ash-bentonite and foam.

This seal was able to withstand 10" of head before leakage developed. The leakage did accelerate at higher heads, and the test was discontinued. Examination of the top of the seal indicated that the water either found or created a gap at the interface of the fly ash-bentonite layer and the foam, and here was where the leakage occurred.

4.5 Conclusions

Our conclusions from the scaled test program can be summarized as follows.

- (1) A pure fly ash seal is not capable of impounding water.
- (2) The critical area for both fly ash-cement and fly ash-bentonite seals is the interface between the top of the seal and the froth-foam topping.
- (3) Fly ash-cement seal always leak at the top due to shrinkage. The minimum leakage rate, which was 0.5 gpm for a 1' slice of a 1/4 scale model, scales to a value of 64 gpm for a full scale seal. Due to the hardening of the cement, the leakage remains stable and erosion does not take place.

Huron Regulated Set Portland cement is the most effective cement for producing seals, since it hardens rapidly and experiences the least amount of shrinkage.

One possible solution to the shrinkage problem is the injection of foam after the major portion of the seal was wetted. It would be necessary to monitor the water level, but this could be done through a seal checker borehole.

- (4) Fly ash-bentonite seals were capable of retaining head without leakage. Some leaked due to pre-existing gaps at the foam interface. Others leaked when high enough pressure caused a breakthrough at the foam interface. The leakage tended to accelerate due to erosion.

The top leakage and erosion problems can be alleviated using a thin coating of fly ash-cement over the bulk seal. This technique was investigated by a full head test described in the next section.

5. Full Head Test

5.1 Test Rationale and Description

The purpose of the full head test was to test those critical features of the water-tight seal which do not properly scale in the quarter scale testing.

As a result of our series of 1/4 scale tests we found that whenever leakage did occur in an otherwise intact seal, it took place between the fly ash and the roof, or when using foam, between the fly ash and the foam. In the case of fly ash-cement mixtures, we attributed this leakage to the overall shrinkage of the seal mass, which occurred upon wetting. In other cases when shrinkage did not occur, we were usually able to identify some area which was not properly sealed due to the experimental conditions, through which water was able to flow. Whether experimental conditions prevented perfect sealing or whether in fact the creation of a perfect seal is impossible with this method, our experience clearly indicates that the interface between the bulk seal material and the foam topping is the critical zone of the seal.

In the full head test described herein, a one foot wide by 12 ft long slice of the foam fly ash interface is subjected to a full head of water, developed gradually as in actual field conditions. The following questions are answered:

1. Does leakage occur?
2. How much leakage occurs?
3. Does leakage stabilize, self seal, or accelerate?

This slice is 18" high, containing approximately 12" of the fly ash mixture covered by 6" of foam. The full height fly ash pile is not necessary, based on the following reasoning.

1. The consolidation of the full pile under water pressure before leakage occurs produces a lateral translation of the upstream slope, which is not associated with leakage.

2. Once leakage does occur, it occurs in small rivulets. The water pressure in these rivulets compresses the dry material beneath, but this pressure varies inversely with depth. Thus a 5 psi (full head) pressure in a 1" wide rivulet decays to 0.5 psi at a depth of 12"^(8,p.377)
At this level of pressure, the consolidation of fly ash is negligible.⁽⁹⁾ In other words, all of the compressibility effects are taken up on the top foot of fly ash.

The test setup is shown in Figure 50. The same lucite trough was used, but was additionally reinforced at the upstream end to handle the extra pressure. The previous level controller was used to raise the water up to a 35" level (top of the barrel). Thereafter, the water level was raised manually and maintained automatically. The total head was 10' above the top of the seal.

5.2 Test Program and Results

The test program was oriented towards the fly ash-bentonite seal system. Two tests were conducted - one with 12" of fly ash-bentonite covered with 6" of foam, and one with 10" of fly ash-bentonite, 2" of Huron RSPC and fly ash, and 6" of foam. The tests are described below.

Test 1

This test involved bentonite-fly ash and foam. The water level was raised at about 2"/hour.

Slight leakage was observed at about 1' of positive head, and this accelerated until about 5' of positive head where the water level could no longer be maintained. The test was discontinued.

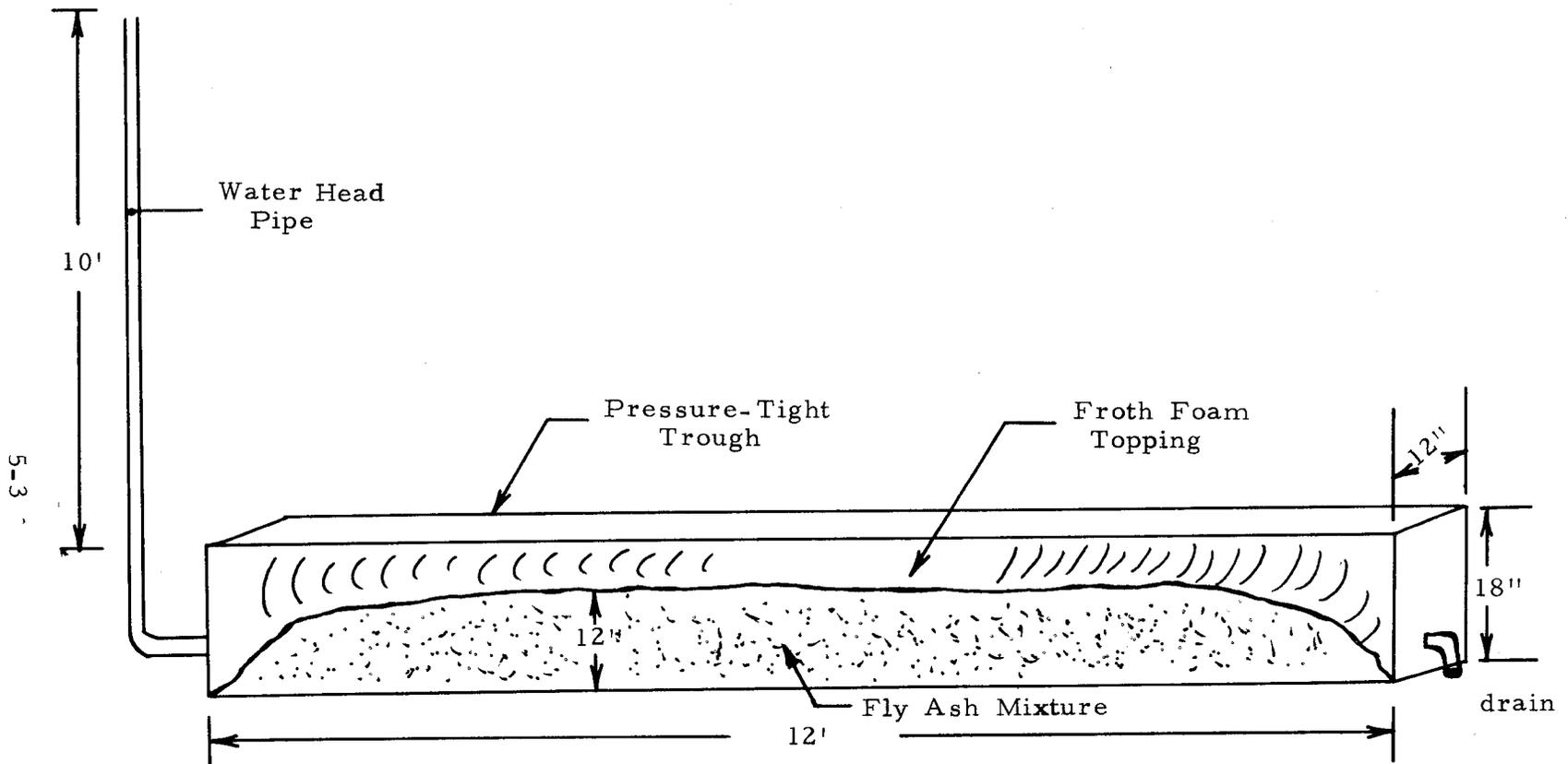


Figure 50. Schematic of Full Height Test

Subsequent examination of the foam fly ash interface indicated that there was a gap running lengthwise down the trough along which foam and fly ash did not meet. This gap was attributed to some problems which occurred in applying the foam. It is likely, however, that such gaps may occur in an actual mine sealing operation due to the "fingering" characteristics of the foam. Since bentonite does not offer much resistance to erosion, erosion takes place, preventing a maintenance of head above the crest of the seal.

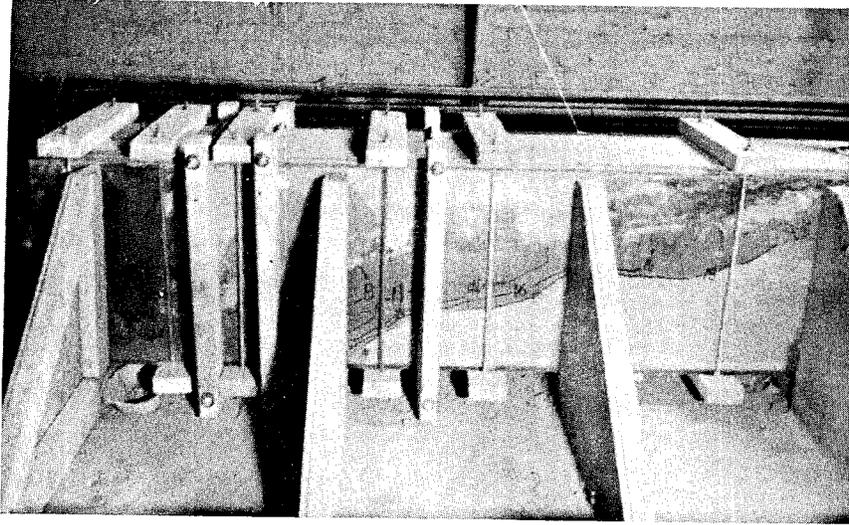
Test 2

Since we can not prevent the occurrence of preexisting leakage paths, we can attempt to minimize their influence by preventing erosion. This aim can be realized by making the final layer of the seal a mixture of fly ash and cement. If the layer is thin enough, shrinkage will not be important, yet erosion will be prevented. In addition, the full top of the bentonite seal will be wetted non-destructively through the highly permeable fly ash-cement mix. This wetting will cause a swelling which will help to close gaps.

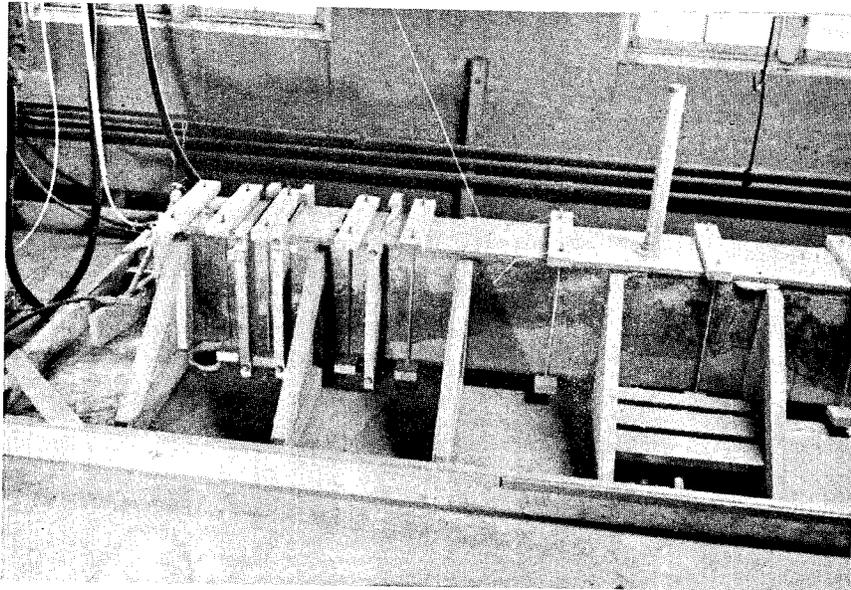
The method was tested using a 10" layer of 1:1 fly ash-bentonite mix topped with a two inch layer of 1:1 fly ash-Huron RSPC mix, which was in turn topped with 6" of foam.

Figure 51 shows the pattern of leakage during the first hours of water rise (at 2"/hour). Note that although the fly ash-bentonite mix remains impermeable, the fly ash-cement mix absorbs water through capillarity and forced permeation. At a total head of 34" the fly ash-cement layer was wetted for a length of 6', and at a total head of 50" the wet layer had proceeded completely to the downstream end. At this point a leakage measurement of 0.011 gpm was recorded.

Figure 52 summarizes the measurement of leakage vs head of water above the top of the trough. The leakage remained stable during a 24 hour measurement period. The water level was allowed to drop and remain stable



(a) After 18 Hours



(b) After 51 Hours

Figure 51. Full Head Test-Water Permeation Using 2" Layer of Huron RSPC and Fly Ash

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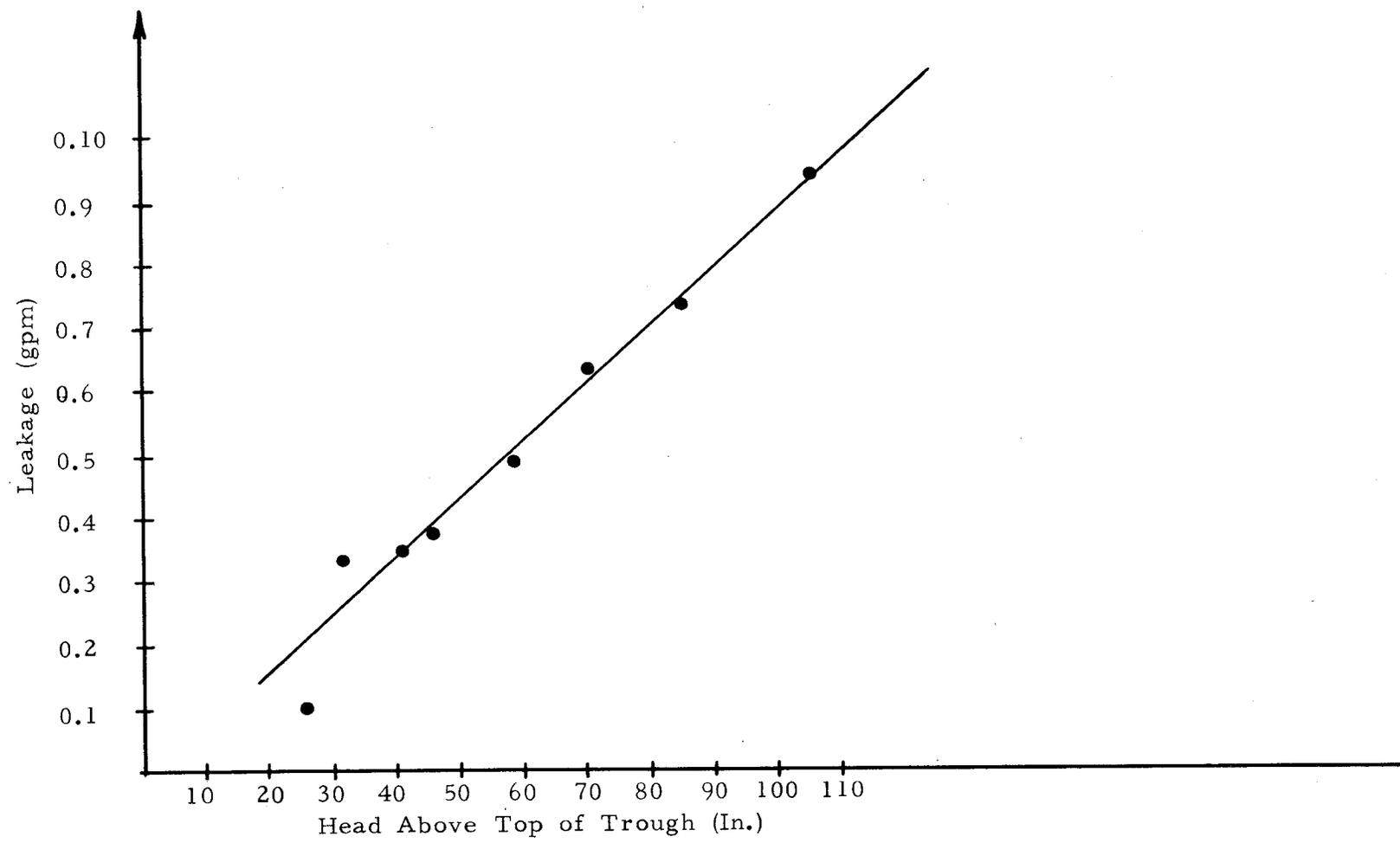


Figure 52. Head vs Flow Data - Full Head Test

over a two week period, after which the head was raised once again. This time to a height of 5 ft. The leakage rate increased to approximately 0.15 gpm. The gradual wetting of the bentonite mixture caused swelling and bulging of the flexible lucite walls. This created a gap between the bentonite and cement layers, and this gap was most likely the cause of the increased leakage. In actual practice, the rigid mine walls will force such swelling to grow vertically, sealing up leakage paths in the process.

The maximum pre-swelling leakage rate was 0.094 gpm. Assuming that this is a one foot slice of a 16 ft wide passage, then the total expected leakage would be $16 \times 0.094 = 1.5$ gpm. This compares to an expected value of 64 gpm for a complete fly ash-Huron cement seal (see Section 4.4, Test 9).

5.3 Test Program Conclusions

On the basis of our test program observations, we conclude that a 1:1 fly ash-bentonite bulk seal with a 2", 1:1 fly ash-Huron cement top layer is the optimum dry material combination for the development of a water-tight seal. The fly ash-bentonite mixture is not only impervious to water, but also expands upon wetting. The interface problems between the foam and the fly ash-bentonite are solved by the thin, rapid setting cement layer. This layer hardens to a "crust", preventing erosion, yet allowing a gradual wetting of the bentonite to maximize the positive influences of swelling.

Considering a typical 16' wide mine passage, the expected leakage of 1.5 gpm compares to a value of 64 gpm for the complete fly ash-Huron cement seal. This extrapolation is approximate in the sense that the seal-roof contact length varies from a maximum under the borehole to a minimum at the furthest extremity. This variation will depend on the location of the borehole with respect to the center of the passage. Our experiences with remote sealing have shown, however, that the minimum length of contact is about 10', and hence our test extrapolations are conservative.

In addition to leakage considerations, recovery problems associated with removing up to 200 tons of hardened cement are far greater than those associated with removal of the wet or dry bentonite.

The implementation of the selected system will be discussed in greater detail in the next section.

6. Final System Description

Aside from the major requirement of serving as a water seal, the principal aim in the development of the seal system was to make it simple to apply in the field. Our experience in remote sealing operations has indicated that complexities in equipment can not only be equated to cost, but can also interfere with the overall success of the operation.

In the development work described in the previous sections, we have focused on those systems, or techniques which involved either equal amounts of two components, or one component at a time. This was because such an approach adapts readily to the existing hardware with a simple "Y" connector. The final system which has been selected reflects this approach.

6.1 Material System

The final system consists of a 1:1 bentonite-fly ash mix topped with a 2" layer of 1:1 Huron RSPC-fly ash mix, which is in turn topped with froth urethane foam. Figure 53 shows a schematic of the final seal. The material quantities are calculated from the following relationship⁽³⁾

$$N = 0.00175 \text{ hw} \left(\frac{h}{\tan \theta} + w \right)$$

where

N = the total number of 20 ton bulk hauler truckloads

w = passage width

θ = seal slope $\sim 15^\circ$

h = seal height

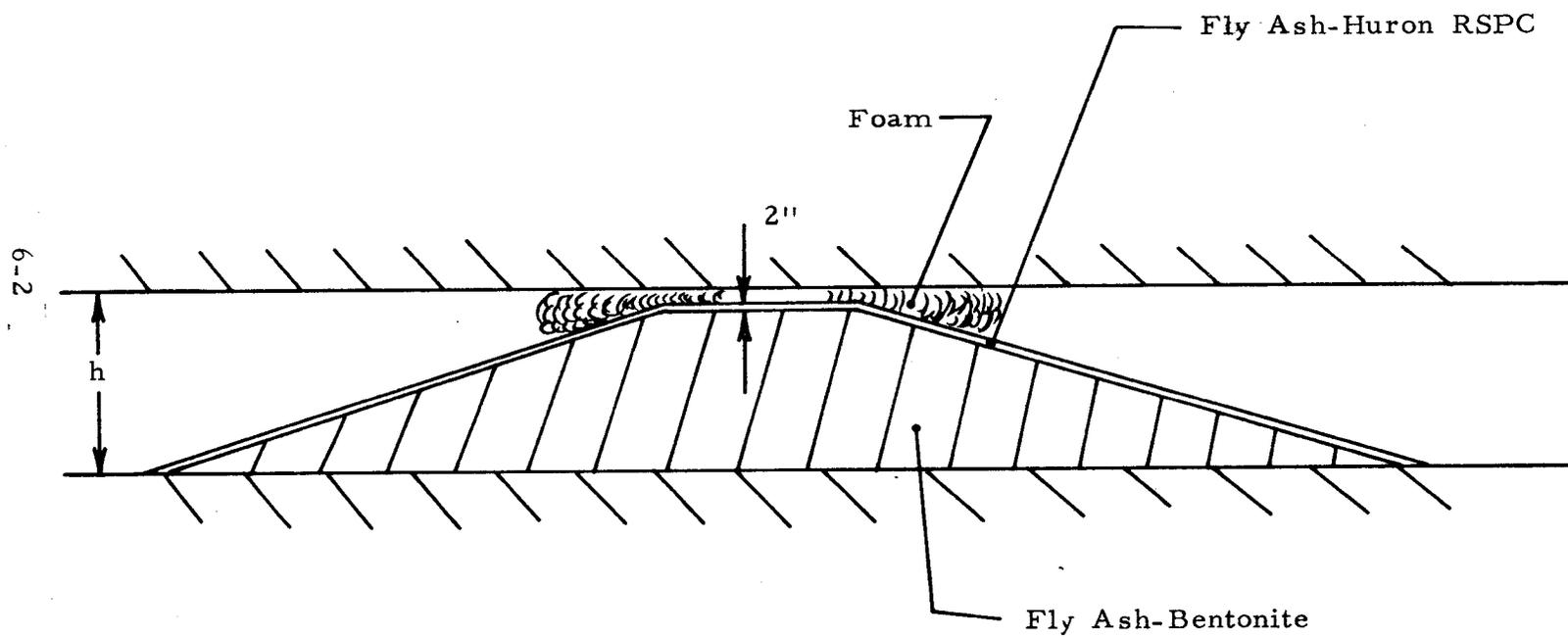


Figure 53. Schematic of Final Seal

In order to determine the quantity required for the thin cement layer, we compute $N(h') - N(h)$, where $h' - h = \Delta h =$ the thickness of the layer. This becomes

$$N' = N(h') - N(h) \approx 0.00175 \Delta h w \left(\frac{2h}{\tan \Theta} + w \right)$$

For a 6' seal in a 17' wide passage with a 2" cement-fly ash layer, we obtain

$$N = 7 \text{ truckloads}$$

$$N' = 0.3 \text{ truckloads}$$

In actual practice the seal would be emplaced as follows:

1. Deliver 4 truckloads each of bentonite and fly ash simultaneously.
2. Deliver approximately one quarter of a truck each of fly ash and Huron RSPC simultaneously. Estimate this quantity by timing the delivery as a percentage of total delivery time.

Quantities do not have to be precise, but care must be taken to insure that the bentonite and cement are properly incorporated into their respective final layers.

6.2 Hardware

Figure 54 shows a layout of the hardware required for creation of the water tight seal. The blower and eductor unit are a part of the currently existing sealing system. What has been added is a "Y" connector, and two pinch valves.

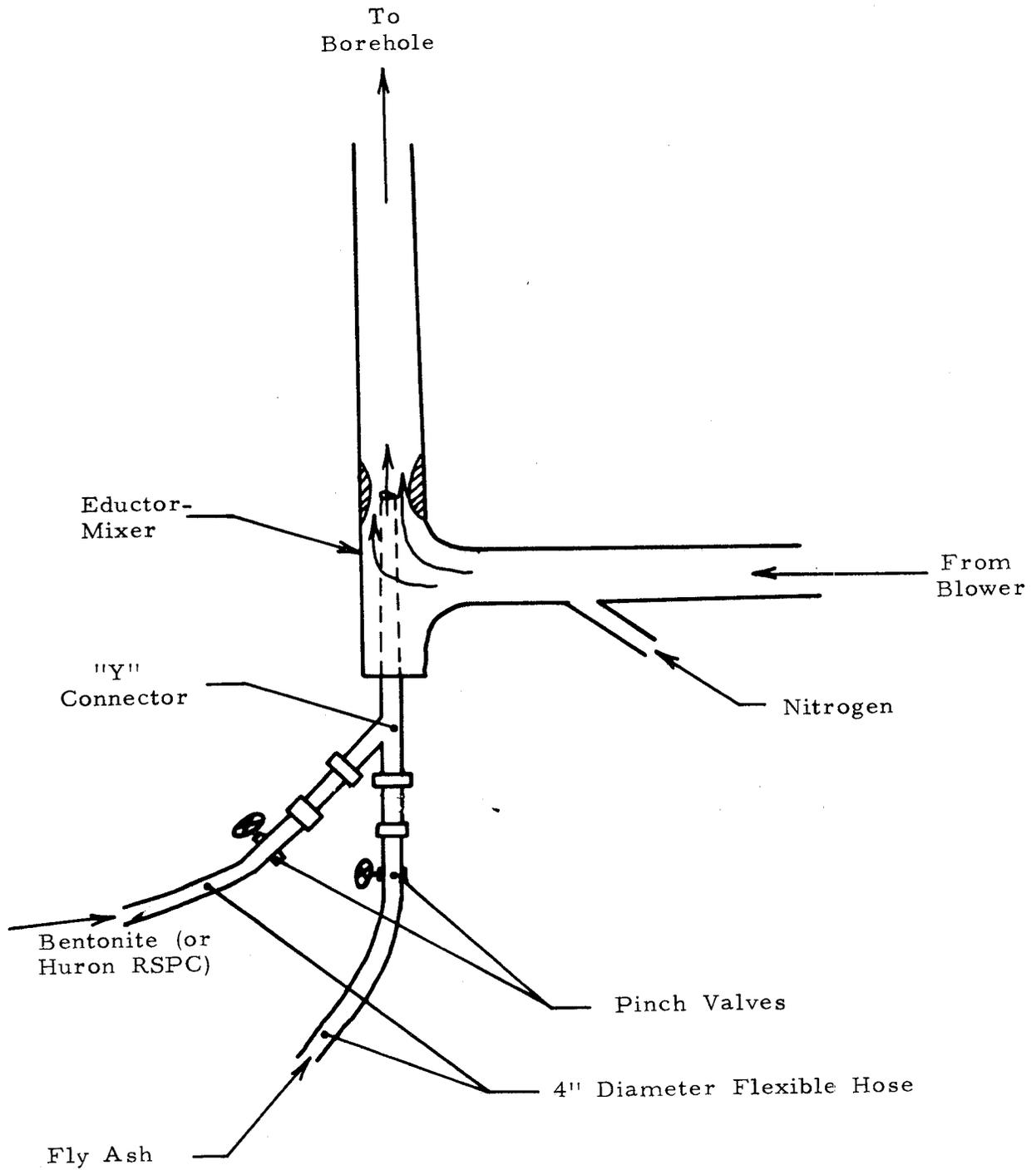


Figure 54. Layout of System Hardware

The "Y" connector simply blends the two flows coming out of the two bulk haulers. Ideally this would create a 1:1 mixture of the two components. In fact, due to differences in the flowing capacities of the two trucks, one truck will dominate the other, resulting in irregularities in the mixing. On the average, however, the mixing will be uniform.

Should one truck overpower the other truck in such a way that mixing is barely occurring, the pinch valve from that truck can be partially closed to increase the back pressure on that line. The experience of the operator and the total unloading times will dictate this type of judgement.

6.3 Logistics

The final system consists of four principal components: fly ash, bentonite, Huron RSPC, and foam. A description of the foam system has been presented in detail elsewhere and will not be repeated here.⁽³⁾ The field layout for the delivery of fly ash, bentonite, and RSPC is shown in Figure 55. It is basically the same as that for fly ash alone, except that one fly ash truck is replaced by the bentonite or cement truck.

Delivery of materials to the site is no problem with fly ash. It is trucked in from the closest coal fired power plant, which is usually within 100 miles. Bentonite and Huron RSPC, on the other hand, must be delivered from more distant places. Bentonite is shipped by rail from Wyoming in tank cars carrying 50 tons. By making rail connections to the mine coal cleaning plant, the bentonite tank cars can arrive fairly close to the mine site. From this point, the material can be loaded into bulk haulers and delivered to the sealing site, with fairly rapid turnaround on deliveries. It is important that the delivery of bentonite to the sealing site be continuous, and responsive to fairly short notice. This can be accomplished by having most of the bentonite delivered by rail before the sealing operation begins. Since there is a two to three week delivery time on the bentonite, and since the preliminary operations

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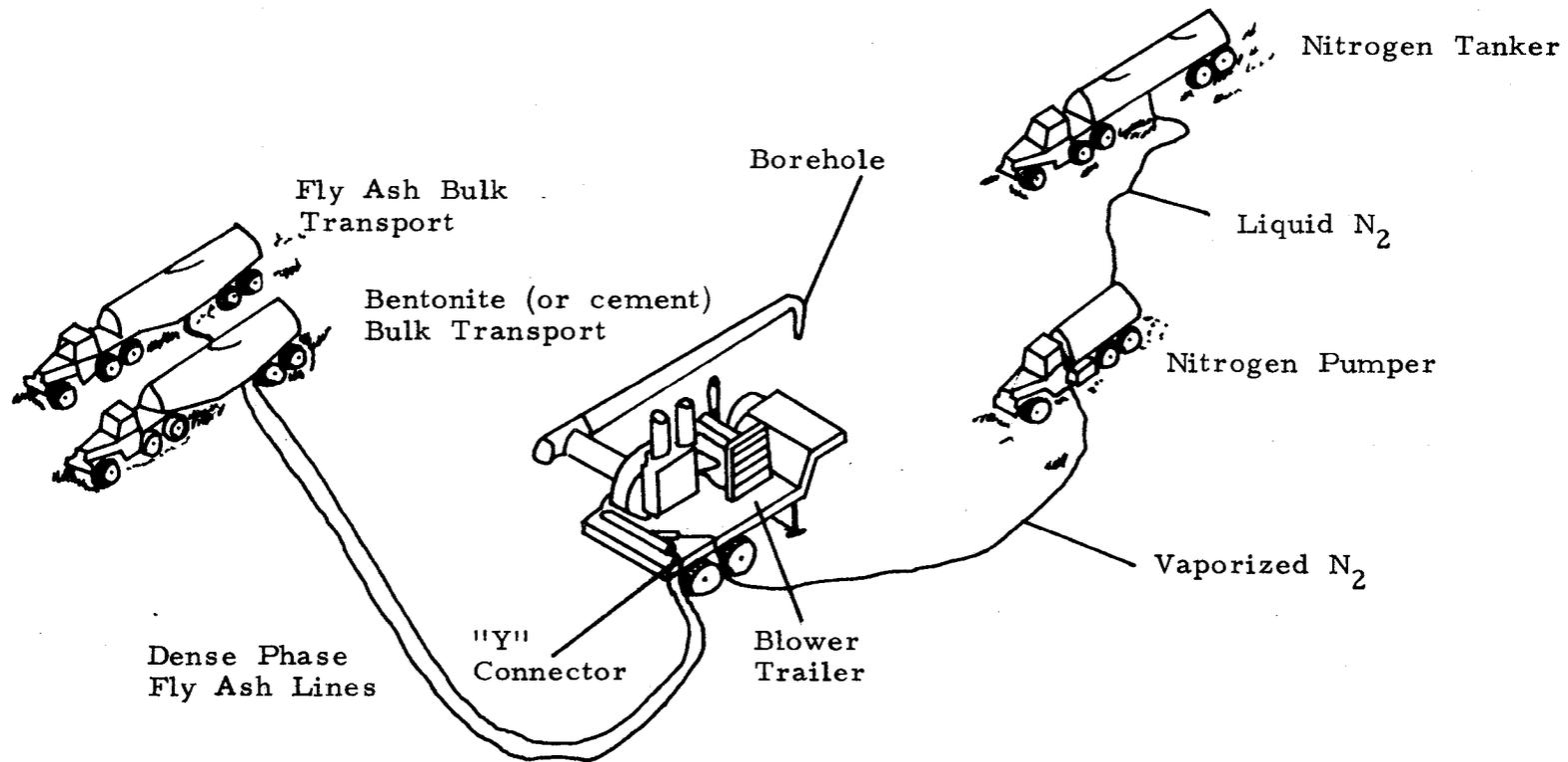


Figure 55. Field Layout of Final System

for remote sealing, such as surveying and borehole drilling, take at least that long, this presents no problem.

Huron RSPC is delivered from Alpena, Michigan. Since this is required in very small quantities (1 to 2 trucks for an entire sealing operation), it can be trucked in directly to the site from Alpena.

6.4 Cost

For a seal 6' high by 16' wide, the cost of materials at the site would break down as follows:

Fly ash - \$80/truck x 4 trucks = \$ 320

Bentonite - \$50/ton x 80 tons = \$4,000

Huron RSPC - \$75/ton x 5 tons = \$ 375

Total \$4,695/seal

This represents an additional expense of about \$4,000/seal over a pure fly ash technique. The expense may seem large, but one must consider the other expenditures involved. In a recent remote sealing operation at the Joanne Mine, six seals were constructed. The total cost for seal construction was approximately \$300,000. Using the example here, the additional cost for water-tight seals would have been \$24,000, a small percentage of the total. When one considers the fact that the mine may be reopened sooner due to the ability to flood the seal, the extra expense is well justified. The production of the Joanne Mine, which is a medium sized mine, is approximately 14,000 tons per week. Estimating a profitability of \$1.50/ton of coal, if the mine can be opened one week sooner, the savings pays the cost of the sealing materials.

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