1 of 1

Development of Fly Ash-Based Slope Protection Materials for Waste Disposal Ponds

Task 7.7 Topical Report

Charles J. Moretti

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February 1993

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**For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia**

**By
University of North Dakota
Energy and Environmental Research Center
Grand Forks, North Dakota**

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Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880**

**By
University of North Dakota
Energy and Environmental Research Center
P.O. Box 9018
Grand Forks, North Dakota 58202-9018**

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DEVELOPMENT OF FLY ASH-BASED SLOPE PROTECTION MATERIALS FOR WASTE DISPOSAL PONDS

1.0 INTRODUCTION

1.1 Generation of Coal Combustion Wastes

Coal-burning power plants produce large amounts of solid wastes. For example, a typical 1000-MW power plant using a dry-bottom, pulverized coal combustion process and burning a coal with an 8% ash content will produce about 167,000 tons of fly ash and 42,000 tons of bottom ash each year (EPRI, 1981). In addition to the ash, large amounts of spent scrubber solids may also be produced if lime- or limestone-based scrubbers are being used to remove sulfur dioxide from the combustion flue gas. Although the amount of scrubber waste produced at a particular plant will depend on a number of factors, usually it exceeds the amount of ash being produced.

Fly ash is generated when very small mineral inclusions are released from coal during combustion, entrained in the flue gas, and collected downstream from the combustor usually in either an electrostatic precipitator or a baghouse. Fly ash is composed of fine particles with diameters generally ranging between 0.1 and 0.001 mm. The specific chemical composition of fly ash particles will depend to a large extent on the mineral content of the coal being burned, but in general the particles contain high percentages of silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3) plus smaller percentages of other oxides, alkalies, and unburned carbon.

Bottom ash is generated when minerals released from the coal agglomerate to form large particles that fall to the bottom of the combustor and eventually drop into a collection hopper. Bottom ash has a gross chemical composition similar to fly ash, but its particles are much larger, with diameters generally ranging between 20 and 0.1 mm.

Scrubber wastes from lime- and limestone-based processes usually contain high percentages of calcium sulfate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and calcium sulfite ($\text{CaSO}_3 \cdot \frac{1}{2}\text{H}_2\text{O}$) resulting from chemical reactions between the sorbent and sulfur dioxide (SO_2) in the flue gas. Due to the differences among the various scrubbing processes, the spent scrubber waste may have a consistency ranging from a wet sludge to a dry powder.

1.2 Coal Combustion By-Product Utilization

Many utility companies which operate coal-fired power plants have developed programs to promote the sale of their solid wastes. When solid wastes are sold for various uses, they are usually referred to as coal combustion by-products. A strong economic incentive exists for companies to sell their combustion by-products, not only for the additional income, but also because significant savings may result due to the fact that any by-products that are sold will not require ultimate disposal.

Fly ash and bottom ash have been sold for various uses for many years. Fly ash is commonly added to concrete mixtures to replace about 25% of the portland cement, to increase pozzolanic reactions which occur as the concrete

sets up, and to reduce the amount of water required to produce a specific flow. These and other applications utilize about 14% of the fly ash produced in the United States. Bottom ash is commonly used for a wide range of uses such as blasting grit, construction fill material, and road and highway subbase construction material. These and other applications utilize about 25% of the bottom ash produced in the United States (EPRI, 1984). Scrubber wastes are utilized to a much lesser extent than fly ash or bottom ash; however, processes have been developed to utilize these materials for applications such as the manufacture of wallboard (Snow and others, 1987; Boone and others, 1987).

Fly ash and bottom ash have been used for some of the applications described above for over fifty years. However, the total amount of combustion by-products being sold for these "conventional" uses has not increased in recent years simply because related construction activities in the United States have not increased. In order to expand the sales of combustion by-products, utility companies and research organizations are seeking to develop new "nonconventional" uses for these materials. Some of these new applications include the use of fly ash and bottom ash mixtures for lining coal pile runoff ditches, the use of fly ash as a cover material for landfills (National Ash Association, 1973; Tchobanoglous and others, 1977), and the use of fly ash as a dust control cover for coal storage piles.

1.3 Development of By-Product-Based Slope Protection Materials

In order to develop a nonconventional, cost-effective use for coal combustion by-products, a research project was conducted to develop a by-product-based slope protection material for a 100-acre scrubber sludge disposal pond at the Sherburne County Power Plant (Sherco). The Sherco plant is located in Becker, Minnesota, and is operated by Northern States Power Company (NSP).

This project was conducted as a joint venture between NSP and the University of North Dakota Energy and Environmental Research Center (EERC). Joint venture matching funds were provided by the U.S. Department of Energy.

Figure 1 shows a cross section of the Sherco disposal pond. The pond has a two-foot-thick compacted clay liner covered by a seven-foot-thick layer of bottom ash. The purpose of the bottom ash is to create a buffer zone to

Figure 1. Section view of the Sherco scrubber sludge disposal pond.

protect the structural integrity of the clay liner. At the time that the pond was constructed, the lower one-third of the pond slope was covered with crushed granite riprap to protect the bottom ash from wave erosion. In 1989, when this research project was initiated, the water level in the pond had reached the top of the existing riprap, and additional protection was needed for the upper two thirds of the pond slope.

2.0 RESEARCH OBJECTIVES AND PROJECT ORGANIZATION

The technical objective of this research project was to formulate and evaluate the performance of slope protection materials produced from self-cementing coal combustion by-products. The desired material was to have sufficient durability and erosion resistance so that, when it was placed on the interior side slopes of the pond, it would protect the underlying bottom ash fill and clay liner from wave erosion for at least five years.

To minimize the cost of installing the slope protection material, some additional goals of the project were to develop a material that a) was self-cementing and thus would not require the addition of lime or cement, b) could be mixed in the field with a minimum of specialized equipment, and c) was available in a sufficiently high volume to allow uninterrupted placement once the construction process was started.

The slope protection research project was conducted in three phases. The first phase was a laboratory study performed in 1989 and 1990, the second phase involved small-scale field tests performed in the summer of 1990, and the third phase was a demonstration-scale field test performed in the summer of 1991.

The initial project task involved characterizing the elemental and mineral compositions of two candidate coal combustion by-products. Following the characterizations, the two by-products were separately blended with various amounts of water and, in some cases, bottom ash to produce about 30 different test mixtures. These mixtures had flow properties ranging from a thin grout to a relatively dry and compactible material similar to a roller-compacted concrete mix. The suitability of these mixtures for use as slope protection materials was evaluated in the laboratory by molding and curing specimens and then testing them for density, compressive strength, and durability.

For the second phase of the project, five slope protection materials were selected for the small-scale field tests based on the results of the preceding laboratory work. To perform the tests, a one-foot-thick slab of each material measuring 10 feet by 15 feet was placed on the slope of the scrubber sludge disposal pond. The purpose of these tests was to assess the in-field mixing and handling properties of the materials and their durability under ambient weathering conditions. Cost estimates were also done for placement of each of the five materials.

The third phase of the project involved selecting the most promising of the slope protection materials for a demonstration-scale field test. Since four of the materials had performed reasonably well in the small-scale field tests, the selection of one material for the demonstration-scale test was

based on estimated construction costs and the availability of the by-products. The demonstration-scale test was conducted by placing approximately 3300 tons of slope protection material in a 15-foot-wide strip around approximately three-quarters of the pond. The slope protection material was spread and compacted in a one-foot-thick lift.

3.0 MATERIALS AND METHODS

3.1 Preliminary Characterization

The two by-products that were considered for the development of a slope protection material were a spray dryer waste from combustion unit #3 at the Sherco Power Plant and a fly ash from combustion unit #8 at the Riverside Power Plant. Both plants are operated by NSP. The Sherco spray dryer waste was approximately a 50:50 mixture of subbituminous coal fly ash and reacted, lime-based spray dryer sorbent. The Riverside ash was a subbituminous coal fly ash produced from a cyclone-fired boiler. Both by-products displayed self-cementing behavior when mixed with water.

The by-products were characterized using the tests specified in ASTM C618 "Standard Specification for Fly Ash and Raw and Calcined Natural Pozzolan for Use as Mineral Admixture in Portland Cement Concrete."

3.2 Moisture Addition and Consistency Tests

After the by-products had been characterized, a series of tests were done to evaluate the effect of various moisture addition levels on the consistency, time of set, and unconfined compressive strength of the slope protection mixtures.

The wet-mix consistency of a slope protection mixture is important because it dictates how the material will be handled and placed on the pond slope. For each of the by-products, the consistencies of a compactible mix, a low-flow slurry, a high-flow slurry, and a pumpable grout were determined by sequentially increasing the amount of water added to the by-products. At low water addition levels, standard Proctor compaction tests using ASTM D698 were used to quantify the consistencies of the mixtures in terms of their compacted dry densities.

When the water addition level was raised to the point where the mixture would no longer support the compaction hammer used for the Proctor test, a concrete slump test was used following ASTM C143 to quantify the consistencies of the by-product mixtures in terms of inches of slump. Mixtures with low slumps (less than about three inches) were described as low-flow slurries. Low-flow slurries were expected to stay in place when poured onto the pond slope. Mixtures with high slumps (greater than about three inches) were described as high-flow slurries. High-flow slurries were expected to flow down the pond slope when poured onto the slope.

When the slump of the by-product mixtures exceeded about 10 inches, a standard flow cone test was used following ASTM C.939 to measure consistencies in terms of flow time. While no set cutoff point differentiates a slurry and a grout, a slurry should have enough body to produce a measurable slump, while

a grout should be thin enough to flow out of a standard flow cone in 10 to 40 seconds. The mixtures that were measured with a flow cone were described as grouts.

3.3 Strength and Time-of-Set Tests

Based on the results of the consistency tests, three water addition levels were selected to bracket each type of slope protection material (i.e., compactible, low-flow slurry, high-flow slurry, and grout). In order to evaluate the effect of adding bottom ash to the slope protection materials, the grout mixtures were prepared with and without the addition of bottom ash. Samples of the materials were prepared at each water addition level by either hand compacting or pouring the mixtures (as appropriate for the specific mix consistency) into 3-inch-diameter by 6-inch-long molds. Three samples were prepared at each water addition level. One sample was tested immediately for time of set using ASTM C191 (Vicat needle procedure). The other two samples were cured for 28 days at 70°F and then loaded to failure to determine unconfined compressive strength following ASTM C873.

The amount of time required for a by-product mixture to set up after it is mixed is an important consideration for selecting a workable slope protection material because if the material sets up too quickly it cannot be properly placed in the field. Unconfined compressive strength is also an important property because it indicates how durable the material will be under the various weather-related stresses encountered on the pond slope.

3.4 Laboratory Durability Tests

From the 60 different by-product mixtures that were tested for time of set and unconfined compressive strength, 8 were selected for follow-on durability tests. Four of these mixtures contained Sherco spray dryer waste and four contained Riverside fly ash. The purpose of the durability tests was to determine how well the materials would stand up to weather-related stresses in the field such as freeze-thaw cycles and wet-dry cycles. The durability tests performed on each of the eight by-product mixtures included 7-day unconfined compressive strength tests, 28-day splitting tensile strength tests, permeability tests, sulfate resistance tests, two types of freeze-thaw tests, and wet-dry tests. The methods used for these tests are listed in Table 1.

The four mixtures containing Sherco spray dryer waste were all either compactible or low-flow mixes, since it had been determined from the preceding strength tests that the Sherco high-flow and grout mixes did not have enough strength to serve as slope protection materials. Two of the selected Sherco mixtures contained bottom ash.

The four mixtures containing Riverside fly ash included compactible, low-flow, and high-flow mixes, since it had been determined from the preceding strength tests that the Riverside grout mixes did not have enough strength to serve as slope protection materials. Two of the selected Riverside mixtures contained bottom ash.

TABLE 1
Test Methods Used for the Slope Protection Durability Tests

Durability Test	Test Method
7-Day Unconfined Compressive Strength	ASTM D1633
28-Day Splitting Tensile Strength	ASTM C496
Permeability	Falling head test, specimen was confined with a rubber membrane in a pressurized chamber.
Sulfate Resistance	Specimens were placed in a sodium sulfate bath for 90 days and periodically examined for deterioration.
100-Cycle Freeze-Thaw	Specimens were placed in a freezing-and-thawing cabinet set on a 48-hour cycle, subjected to 100 cycles, and periodically examined for deterioration.
Soil Cement Freeze-Thaw	ASTM D560
Soil Cement Wet-Dry	ASTM D559

Based on the initial results of the durability tests which indicated that neither of the selected Riverside mixes containing bottom ash had sufficient durability to serve as slope protection materials, one additional material was selected for testing. This was a mixture of Riverside fly ash and bottom ash having a relatively low slump (2.25 inches). This mix was included because the amount of Riverside fly ash available for construction of the slope protection layer was limited. Therefore, it was necessary to develop at least one durable Riverside mix which contained bottom ash as a replacement for some of the fly ash. Since the next phase of the project had been scheduled to start shortly, an abbreviated set of durability tests was performed on the additional Riverside mix.

3.5 Small-Scale Field Tests

The results of the laboratory durability tests were used to select several slope protection materials for small-scale field tests. Of the nine materials previously tested in the laboratory durability tests, five were judged to have sufficient strength, freeze-thaw durability, and wet-dry durability to warrant follow-on field testing. Thus the following slope protection mixes were selected for small-scale field testing:

- Mix 1 - A mixture of 25% Riverside fly ash and 75% bottom ash. This mix had a consistency suitable for roller compaction on the pond slope.
- Mix 2 - A mixture of 25% Riverside fly ash and 75% bottom ash. This mix had a consistency similar to a low-slump concrete so that it could be placed and leveled on the pond slope without roller compaction.
- Mix 3 - 100% Riverside fly ash. This mix had a consistency suitable for roller compaction on the pond slope.
- Mix 4 - 100% Riverside fly ash. This mix had a consistency suitable for gravity-flow slurry placement from the top of the pond slope.
- Mix 5 - 100% Sherco spray dryer waste. This mix was to have a consistency suitable for roller compaction on the pond slope.

A 1-foot-thick test slab measuring approximately 10 feet by 15 feet was constructed for four of the slope protection mixes described above. These slabs were placed on the slope of the scrubber waste disposal pond at the Sherco plant in July of 1990. The initial moisture addition levels selected for the various mixes were based on the results of the consistency tests conducted in the laboratory. However, these moisture levels had to be adjusted slightly in the field to achieve the desired consistencies for field placement. The moisture contents of the field mixes were checked by oven drying the samples and then measuring the weight loss.

The compactible materials that contained Riverside fly ash were produced with a concrete mixing truck. This truck was equipped with separate bins to hold the fly ash and bottom ash, and it was able to accurately proportion the mix ingredients at the test site. The only problem encountered with this type of truck was that it could not produce the compactible Riverside fly ash mixture (Mix 3 described above) fast enough to allow the material to be properly placed. This particular mix was found to set up about 20 minutes after it was mixed with water, and there was just not enough time to mix the material and transport it to the slope before it hardened.

It should be noted that the compactible Riverside fly ash mix set up much faster in the field than was expected from the time-of-set tests performed in the laboratory. This difference in set time may have been due to the fact that the temperature in the field was about 10°F higher than the temperature in the laboratory.

The compactible Sherco material (Mix 5) was obtained from the batch mixers that are routinely used at the Sherco plant to condition their unit #3 spray dryer waste. The flowable Riverside fly ash (Mix 4) was mixed with a venturi-type jet mixer at the top of the pond slope and allowed to flow down the slope by gravity.

The strength developed in various slope protection materials was determined by cutting 4-inch-diameter core samples from each slab after the

materials had cured in the field for about 2½ months. The cores were then trimmed and tested for unconfined compressive strength in the laboratory.

3.6 Cost Analysis

Construction engineers from NSP developed cost estimates for the five slope protection materials selected for the small-scale field tests. The principal factors considered for these estimates were material transportation costs, mixing costs, and placement costs. Avoided disposal costs for the by-products were not included in these estimates. The cost savings associated with using the by-product-based slope protection materials was demonstrated by ranking the costs of the various mixes and then comparing their costs to the cost of using conventional crushed granite riprap to protect the pond slope.

3.7 Demonstration-Scale Field Test

The final phase of this research was a demonstration-scale field test of the by-product-based slope protection material. From the four mixes used for the small-scale field tests, one was selected for the demonstration-scale test. Since most of the materials had performed reasonably well in the small-scale tests, the selection of a material for the demonstration-scale test was primarily based on estimated construction costs and the projected availability of the by-product.

The mix selected was Sherco spray dryer waste with a moisture content of 26% of dry weight. This particular mix was a relatively dry, nonflowing material which could be compacted to within 5% of its maximum Proctor density using a moderate compactive effort. A major reason for selecting this mix was that large quantities of the spray dryer waste are produced at the Sherco plant. This meant that the construction activities required for the test could proceed continuously without having to wait for more waste to be produced.

The slope protection layer constructed for the demonstration-scale test was placed in a fifteen-foot-wide strip starting at the water line of the Sherco sludge disposal pond. The pond had 3:1 (run:rise) side slopes. The slope protection layer was about 1-foot-thick and extended approximately 6000 feet around three sides of the 100-acre pond. The layer was keyed into the slope with a toe trench that was dug just above the water line. The slope section below the water line was already protected with crushed granite riprap placed over a geotextile membrane.

The Sherco spray dryer waste used to construct the slope protection layer was originally collected in a baghouse and stored in a silo until it was conditioned by mixing it with water. After conditioning, the waste was loaded onto a truck and transported to the ash disposal site at the Sherco plant. At the disposal site, the material was stockpiled, reloaded onto smaller trucks, and then transported to the construction site. The material was transferred to smaller trucks because the large trucks normally used to transport the spray dryer waste from the storage silos to the disposal site were too large to conveniently use the access road at the pond.

Since the spray dryer waste was already moist when it was delivered to the disposal site, it was decided that the material should be transferred to

the pond within about 1 hour. If the material was not transferred in 1 hour, it was to be discarded. This was done to ensure that the material would set up properly when it was placed on the pond slope. It should be pointed out, however, that when the construction activities were going on it was difficult to keep track of how long the waste actually sat at the disposal site before it was transferred to the pond.

When the waste arrived at the pond, it was dumped in a pile on the access road at the top of the slope. A water truck was positioned next to the pile, and the material was sprayed with water to increase its moisture content from about 19% (as-received) to about 26% of dry weight. The material was then picked up with a front-end loader and carried down the pond slope to the construction area.

In order to control the amount of water being added to the waste, its moisture content was tested about every 30 minutes. It was important to be able to get the results of the moisture determinations quickly, so that the water addition could be adjusted if necessary. To do this, a test method was developed to determine the moisture content in the field in about 10 minutes.

The method commonly used for measuring moisture contents of soil-like materials is done with a drying oven set at 110°C and takes at least several hours to perform. The method that was developed for the slope protection material used a microwave oven to dry the sample in 6 minutes. The accuracy of the microwave method was checked in the laboratory by comparing results from split samples tested with both a drying oven and a microwave oven. In repeated tests, the moisture contents determined with the two methods were within 1 wt% of each other.

After the slope protection material was placed on the slope, a bulldozer spread it in a 1-foot-thick lift and compacted the material with its tracks. The original construction plan called for additional compaction of the material with a smooth-drum steel roller, but it was found to be a slow and difficult process to use the roller on the 3:1 slope (run:rise). Also, the compacted material tended to stick to the roller, producing a rough finish on the roller-compacted sections. For these reasons and also because the bulldozer seemed to be doing an adequate job of compacting the material by making repeated passes over each freshly placed section, use of the roller was discontinued.

The densities achieved by compacting the waste with the bulldozer were determined by taking 4-inch-diameter core samples from the finished sections of the slope protection layer and measuring their dry densities.

Figure 2 shows a view of the toe trench dug for the slope protection layer; Figure 3 shows the water truck adding moisture to the spray dryer waste; and Figure 4 shows the bulldozer spreading and compacting the material on the slope of the Sherco pond. After the slope protection layer was constructed, additional core samples were collected from 13 locations around the perimeter of the pond. These cores were transported to UND, cured at 70°F for about one month, and tested for unconfined compressive strength. Figure 5 shows a section of the completed slope protection layer.

Figure 2. A view of the toe trench for the slope protection layer.

Figure 3. A water truck adding moisture to the Sherco spray dryer waste at the top of the pond slope.

Figure 4. A bulldozer spreading and compacting the slope protection material.

Figure 5. A completed section of the slope protection layer.

4.0 RESULTS AND DISCUSSION

4.1 Moisture Addition and Consistency Test Results

The working properties of wet by-product mixtures are highly dependent on the amount of water added to the mix. Typically, as the water content is increased, the mix consistency changes from a relatively dry and compactible material, to a slurry, and then to a thin grout. For fly ashes in particular, the consistency of the mix can change dramatically with relatively small increases in moisture content.

Past experience working with self-cementing ashes has shown that the highest strength is developed in cured ash-water mixtures at a moisture content close to that which produces the maximum compacted dry density (i.e., the optimum moisture). Also, as the moisture content is increased beyond the optimum, the strength of the cured mixtures tends to decrease (7). Thus for a specific ash, a well-compacted mix usually yields the highest strength.

Even though compactible ash mixtures generally produce higher strengths than slurry or grout mixes (for a specific ash), it was thought that it might be significantly less expensive to place the slope protection material as a slurry or a grout if it would flow down the slope by gravity and not require in-place compaction. This is the reason that materials with such a wide range of flow characteristics were studied for the slope protection application. The results of the moisture addition tests performed on the Riverside fly ash and Sherco spray dryer waste are summarized in Tables 2 and 3. For the Riverside fly ash, the maximum compacted standard Proctor density was 80.6 lb/ft^3 , obtained at an optimum moisture content of 26.3% of dry weight. The highest moisture content which still allowed the Riverside fly ash to be effectively compacted was about 31%. Above that level, the ash mix would not support the compaction hammer used for the Proctor test. At a moisture content of about 36%, the Riverside ash began to flow by gravity when placed on an inclined board with a 3:1 slope (run:rise), and the rate of flow increased rapidly as the moisture was raised to 46%. Above a moisture content of about 50%, the Riverside fly ash displayed a sufficiently high flow to be considered a grout.

For the Sherco spray dryer waste, the maximum measured dry density was 91.4 lb/ft^3 obtained at an optimum moisture content of 26% of dry weight. The highest moisture content which still allowed the Sherco mix to be effectively compacted was about 30%. At a moisture content of about 46%, the Sherco mix began to flow by gravity on an inclined board with a 3:1 slope (run:rise), and the rate of flow increased as the moisture content was raised to about 60%. Above a moisture content of about 65%, the Sherco mix had a sufficiently high flow to be considered a grout.

4.2 Strength and Time-of-Set Test Results

Using the results of the moisture addition tests, three moisture addition levels were selected to bracket each of four different mix consistencies (i.e., compactible, low-flow slurry, high-flow slurry, and grout) for each by-product. A fifth type of mix, a grout containing bottom ash, was also tested. The bottom ash was added as an aggregate filler to reduce the amount of by-product required in the mix.

TABLE 2
Riverside Fly Ash - Consistency and Density Data

Moisture Content (% dry wt)	Consistency	Dry Density (lb/ft ³)	Slump (in)	Flow (sec)
8.2	Compactible	74.4		
17.4	Compactible	76.3		
21.4	Compactible	78.4		
26.3	Compactible	80.6		
30.6	Compactible	79.1		
35.7	Marginally Compactible	75.3		
41.5	Slurry	67.7	0.75	
43.2	Slurry	67.7	9.0	
45.9	Slurry	64.1	10.4	
51.4	Grout	61.8		15
55.9	Grout	59.8		12
60.6	Grout	55.9		10

TABLE 3
Sherco Spray Dryer Waste - Consistency and Density Data

Moisture Content (% dry wt)	Consistency	Dry Density (lb/ft ³)	Slump (in)	Flow (sec)
11.0	Compactible	75.5		
16.5	Compactible	78.8		
21.0	Compactible	83.8		
24.3	Compactible	90.5		
26.0	Compactible	91.4		
28.1	Compactible	88.6		
31.0	Compactible	86.3		
36.4	Slurry	77.7	0.4	
43.2	Slurry	73.5	2.75	
47.0	Slurry	71.5	5.5	
52.3	Slurry	67.7	9.5	
62.1	Slurry-Grout	61.0		53
64.9	Grout	58.6		19
72.1	Grout	56.1		12

At each moisture addition level, duplicate test cylinders were prepared, cured for 28 days at 70°F, and tested for unconfined compressive strength. The strengths measured for the various Riverside and Sherco mixtures are summarized in Tables 4 and 5. The highest strength recorded for a Sherco mix was 2950 psi, which was obtained with a moisture addition of 26% of dry weight. The highest strength recorded for a Riverside mix was 1998 psi, which was also obtained with a moisture addition level of 26% of dry weight. The strengths developed by both by-product mixtures markedly decreased as the moisture content was increased above the level that produced maximum strengths. However, the Sherco mixtures appeared to be more sensitive to moisture increase than the Riverside mixtures.

For this research, a criterion for judging whether a particular ash mix was sufficiently strong and durable to serve as a slope protection material was adopted from the test methods used for soil-cement mixtures. Typically, the specifications for evaluating soil-cement mixtures indicate that these materials should exhibit a 7-day unconfined compressive strength greater than about 450 psi. Although the strengths measured for the Sherco and Riverside mixes were cured for 28 days rather than 7 days, the 450-psi criterion was still used as an indicator for selecting which mixes warranted further study.

Based on this criterion, it appeared that, for the Sherco spray dryer waste, only the compactible and low-flow slurry mixes might produce acceptable slope protection materials. For the Riverside fly ash, it appeared that the compactible, low-flow slurry, and grout with bottom ash mixes might produce acceptable slope protection materials. The high-flow Riverside slurry appeared to be marginally acceptable for use as a slope protection material.

The results of a series of time-of-set tests performed on the Sherco and Riverside mixes are listed in Table 6. Generally, the Riverside mixes set up faster (1 to 4 hours) than the Sherco mixes (4 to 48 hours), and the time of set tended to increase as the moisture content of the mix increased. It should be noted that these tests were performed at room temperature (about 20°C) and that the actual set times in the field could be shorter if the temperature is higher than 20°C.

4.3 Durability Test Results

The required design life of the by-product slope protection material was determined to be 5 years. This determination was based on the expectation that the water level in the pond would rise up the slope at a rate of no less than 3 feet per year, which meant that if the slope protection layer was to be placed as needed in 15-foot sections, each section would be fully submerged within a period of 5 years or less.

Based on a 5-year design life and the results of the preceding moisture addition and strength tests, eight specific slope protection mixes were selected for a series of follow-on tests to assess their long-term durability. Four mixes contained Riverside fly ash, and four contained Sherco spray dryer waste. The Sherco mixes were designated Sherco mix Nos. 1, 2, 3, and 4. And the Riverside mixes were designated Riverside mix Nos. 1, 2, 3, and 4 (see Section 3.4 for a list of the mixes selected for the durability tests).

TABLE 4

Riverside Fly Ash - Unconfined Compressive Strength Data
(28-day cure at 70°F)

Moisture Content (% dry wt)	Consistency	Unconfined Compressive Strength (psi)
21	Compactible	1333
26	Compactible	1998
31	Compactible	1227
36	Low-Flow Slurry	436
38	Low-Flow Slurry	694
40	Low-Flow Slurry	633
42	High-Flow Slurry	478
44	High-Flow Slurry	426
46	High-Flow Slurry	451
51	Grout	329
56	Grout	244
61	Grout	218
51	Grout Mixed with Bottom Ash	697
56	Grout Mixed with Bottom Ash	596
61	Grout Mixed with Bottom Ash	458

TABLE 5

Sherco Spray Dryer Waste - Unconfined Compressive Strength Data
(28-day cure at 70°F)

Moisture Content (% dry wt)	Consistency	Unconfined Compressive Strength (psi)
21	Compactible	1337
26	Compactible	2950
31	Compactible	1446
36	Low-Flow Slurry	860
41	Low-Flow Slurry	514
46	Low-Flow Slurry	252
51	High-Flow Slurry	248
56	High-Flow Slurry	202
61	High-Flow Slurry	161
66	Grout	99
71	Grout	81
76	Grout	67
66	Grout Mixed with Bottom Ash	140
71	Grout Mixed with Bottom Ash	67
76	Grout Mixed with Bottom Ash	62

TABLE 6
Time-of-Set Test Results for the Riverside and Sherco
Slope Protection Mixtures

Mixture Description	Time of Set
Sherco Spray Dryer Waste - Compacted	4 to 8 hours
Riverside Fly Ash - Compacted	1 to 2 hours
Sherco Spray Dryer Waste - Low-Flow Slurry	8 to 24 hours
Riverside Fly Ash - Low-Flow Slurry	1 to 2 hours
Sherco Spray Dryer Waste - High-Flow Slurry	8 to 24 hours
Riverside Fly Ash - High-Flow Slurry	2 to 3 hours
Sherco Spray Dryer Waste - Grout	24 to 48 hours
Riverside Fly Ash - Grout	3 to 4 hours
Sherco Spray Dryer Waste - Grout with Bottom Ash	24 to 48 hours
Riverside Fly Ash - Grout with Bottom Ash	3 to 4 hours

The purpose of the durability tests was to determine how well the various materials would stand up to weather-related stresses in the field, such as freeze-thaw cycles, wet-dry cycles, and wave erosion. The durability tests included 7-day unconfined compressive strength, 28-day splitting tensile strength, permeability coefficient, sulfate resistance, 100-cycle freeze-thaw resistance, freeze-thaw cycle durability for soil cements, and wet-dry cycle durability for soil cements. The results of the durability tests performed on the Riverside and Sherco mixes are contained in Tables 7 and 8, respectively.

Based on the initial results of the durability tests, one additional slope protection mix was developed and tested. This material was a mixture of Riverside fly ash and bottom ash having a relatively low slump (2.25 inches). This added mix was designated Riverside mix No. 5. An abbreviated set of durability tests was performed on the Riverside mix No. 5, and the results are also included in Table 7.

A primary criterion which was used for judging the durability of the various slope protection materials was the common soil-cement evaluation criterion which states that weight loss resulting from freeze-thaw and wet-dry tests should not exceed about 10% of the dry weight of the test specimen. Using this criterion, an examination of the test results shown in Tables 7 and 8 indicates that the Riverside mixes No. 1, No. 2, No. 5, and Sherco mix No. 1 appeared to have sufficient freeze-thaw cycle durability and wet-dry cycle durability to serve as slope protection materials.

TABLE 7

Riverside Fly Ash - Durability Test Results

Riverside Mix No. 1 Composition

100% Riverside fly ash
30% dry weight moisture added
26% dry weight moisture content after 30 minutes

Flow Characteristics: Compactible after material stiffened slightly, about 30 minutes after mixing

Strength: 7-day, 70°F, unconfined compressive strength - 745 psi
28-day, 70°F, splitting tensile strength - 354 psi

Permeability Coefficient: 5.5×10^{-6} cm/sec

SO₄ Resistance: No significant deterioration after 90-day soak in sulfate solution

100-Cycle Freeze-Thaw Durability: Samples lost material from surface and broke along compaction lifts.

Soil Cement Freeze-Thaw Durability: Less than 1% weight loss

Soil Cement Wet-Dry Durability: 1.4% weight loss

Riverside Mix No. 2 Composition

100% Riverside fly ash
48% dry weight moisture added
43% dry weight moisture content after 30 minutes

Flow Characteristics: Flowable material with a slump of 10.75 inches immediately after mixing

Strength: 7-day, 70°F, unconfined compressive strength - 489 psi
28-day, 70°F, splitting tensile strength - 96 psi

Permeability Coefficient: 2.5×10^{-6} cm/sec

SO₄ Resistance: No significant deterioration after 90-day soak in sulfate solution

100-Cycle Freeze-Thaw Durability: Samples lost material from surface.

Soil Cement Freeze-Thaw Durability: Less than 1% weight loss

Soil Cement Wet-Dry Durability: 40% weight loss

continued...

TABLE 7 (cont.)

Riverside Fly Ash - Durability Test Results

Riverside Mix No. 3 Composition

25% Riverside fly ash/75% bottom ash
29% dry weight moisture added
28% dry weight moisture content after 30 minutes

Flow Characteristics: Flowable material with a slump of 9.5 inches immediately after mixing

Strength: 7-day, 70°F, unconfined compressive strength - 180 psi
28-day, 70°F, splitting tensile strength - 40 psi

Permeability Coefficient: 3.4×10^{-6} cm/sec

SO₄ Resistance: No significant deterioration after 90-day soak in sulfate solution

100-Cycle Freeze-Thaw Durability: Approximately 20% weight loss

Soil Cement Freeze-Thaw Durability: 3.8% weight loss

Soil Cement Wet-Dry Durability: Samples failed after 8 cycles.

Riverside Mix No. 4 Composition

20% Riverside fly ash/80% bottom ash
33% dry weight moisture added
35% dry weight moisture content after 30 minutes

Flow Characteristics: Flowable grout

Strength: 7-day, 70°F, unconfined compressive strength - 21 psi
28-day, 70°F, splitting tensile strength - 5.3 psi

Permeability Coefficient: 5.7×10^{-5} cm/sec

SO₄ Resistance: Samples broke before test.

100-Cycle Freeze-Thaw Durability: Samples failed after 25 cycles.

Soil Cement Freeze-Thaw Durability: 17% weight loss

Soil Cement Wet-Dry Durability: 52% weight loss

continued...

TABLE 7 (cont.)

Riverside Fly Ash - Durability Test Results

Riverside Mix No. 5 Composition

25% Riverside fly ash/75% bottom ash
 18% dry weight moisture added
 17% dry weight moisture content after 30 minutes

Flow Characteristics: Low-flow material with a slump of 2.5 inches immediately after mixing

Strength: 7-day, 70°F, unconfined compressive strength - 537 psi

Soil Cement Freeze-Thaw Durability: 3.5% weight loss

Soil Cement Wet-Dry Durability: 6.7% weight loss

TABLE 8

Sherco Spray Dryer Waste - Durability Test Results

Sherco Mix No. 1 Composition

100% Sherco spray dryer waste
 25% dry weight moisture added
 26% dry weight moisture content after 30 minutes

Flow Characteristics: Compactible after material stiffened slightly, about 30 minutes after mixing

Strength: 7-day, 70°F, unconfined compressive strength - 700 psi
 28-day, 70°F, splitting tensile strength - 290 psi

Permeability Coefficient: 2.5×10^{-8} cm/sec

SO₄ Resistance: No significant deterioration after 90-day soak in sulfate solution

100-Cycle Freeze-Thaw Durability: Samples lost material from surface.

Soil Cement Freeze-Thaw Durability: 5.9% weight loss

Soil Cement Wet-Dry Durability: 2.0% weight loss

continued...

TABLE 8 (cont.)

Sherco Spray Dryer Waste - Durability Test Results

Sherco Mix No. 2 Composition

100% Sherco spray dryer waste
43% dry weight moisture added
42% dry weight moisture content after 30 minutes

Flow Characteristics: Low-flow material with a slump of 3.0 inches immediately after mixing.

Strength: 7-day, 70°F, unconfined compressive strength - 280 psi
28-day, 70°F, splitting tensile strength - 101 psi

Permeability Coefficient: 4.3×10^{-7} cm/sec

SO₄ Resistance: No significant deterioration after 90-day soak in sulfate solution

100-Cycle Freeze-Thaw Durability: Samples failed after 25 cycles.

Soil Cement Freeze-Thaw Durability: Samples failed after 4 cycles.

Soil Cement Wet-Dry Durability: Samples failed after 9 cycles.

Sherco Mix No. 3 Composition

25% Sherco spray dryer waste/75% bottom ash
17% dry weight moisture added
18% dry weight moisture content after 30 minutes

Flow Characteristics: Low-flow material with a slump of 2.3 inches immediately after mixing

Strength: 7-day, 70°F, unconfined compressive strength - 231 psi
28-day, 70°F, splitting tensile strength - 75 psi

Permeability Coefficient: 6.5×10^{-7} cm/sec

SO₄ Resistance: No significant deterioration after 90 days of soak in sulfate solution

100-Cycle Freeze-Thaw Durability: Samples failed after 25 cycles.

Soil Cement Freeze-Thaw Durability: Samples failed after 5 cycles.

Soil Cement Wet-Dry Durability: 14% weight loss

continued...

TABLE 8 (cont.)

Sherco Spray Dryer Waste - Durability Test Results

Sherco Mix No. 4 Composition

25% Sherco spray dryer waste/75% bottom ash
19% dry weight moisture added
21% dry weight moisture content after 30 minutes

Flow Characteristics: Low-flow material with a slump of 6 inches immediately after mixing

Strength: 7-day, 70°F, unconfined compressive strength - 156 psi
28-day, 70°F, splitting tensile strength - 58 psi

Permeability Coefficient: 4.3×10^{-4} cm/sec

SO₄ Resistance: Samples broke before test.

100-Cycle Freeze-Thaw Durability: Samples failed after 25 cycles.

Soil Cement Freeze-Thaw Durability: Samples broke after 5 cycles.

Soil Cement Wet-Dry Durability: 29% weight loss

In examining the durability test data, several interesting observations can be made. First of all, comparing the unconfined compressive strength data to the freeze-thaw and wet-dry data, it appears that, in general, the minimum strength criterion of 450 psi, which was used to evaluate some of the earlier strength data, does correlate fairly well with the results of the freeze-thaw and wet-dry tests (i.e., the general inference for a soil cement is that if the strength is greater than about 450 psi, then the materials will pass the freeze-thaw and wet-dry tests). The exception to this was Riverside mix No. 2, which had an unconfined compressive strength of about 490 psi, but did not pass the wet-dry test.

Other significant observations were that the measured splitting tensile strengths of the slope protection mixes generally ranged between 20% and 40% of their measured unconfined compressive strengths and that all of the materials tested appeared to have excellent resistance to attack from sulfate. The latter was important because the water in the pond had a high sulfate concentration.

The general conclusions drawn from the durability tests were:

1. The mixes containing Sherco waste had sufficient durability to serve as slope protection materials only when prepared in a relatively dry and compactible form because the durability of the material decreased significantly as the moisture content was increased.

2. The materials containing the Riverside fly ash had sufficient durability to serve as slope protection materials only when prepared in either compactible or low-slump forms.

4.4 Small-Scale Field Test Results

Based on the results of the durability tests, five slope protection mixes were selected for small-scale field tests.

Field mix No. 1 was a compactible mixture of 25% Riverside fly ash and 75% bottom ash. The first batch of this material mixed in the field was a zero-slump material that had just enough moisture to be effectively compacted. However, it was found that by the time the material was transported to the slope and placed (about 20 minutes after it was mixed), it was no longer cohesive and did not compact properly. The amount of water being added to the ash was then increased so that the material had a slump of 2.5 inches immediately after it was mixed. When this was done, it was found that by the time the material was transported to the slope, it had a moisture content of 18% of dry weight and a slump of zero inches, but still had enough moisture to be effectively compacted with a steel drum roller.

Field mix No. 2 had the same fly ash/bottom ash content as field mix No. 1, but with a higher moisture content. This mix had a 10-inch slump immediately after it was mixed, but stiffened to about a 3-inch slump by the time it was placed on the pond slope. This mix was spread on the slope with a bulldozer, but was not compacted with a steel drum roller.

Field mix No. 3 contained 100% Riverside fly ash with a moisture content of about 30% of dry weight. This mix was supposed to be dry enough to be compacted on the slope. However, the material set up while being transported to the pond slope (in a time period of about 20 minutes) and could not be placed. Therefore, no test slab was prepared for field mix No. 3.

Field mix No. 4 was a wet slurry containing 100% Riverside fly ash with a moisture content of about 45% of dry weight. The material was mixed with a venturi-type jet mixer, pumped through a hose to the pond slope, and allowed to run down the slope by gravity. The flow from the jet mixer was erratic at times, but a test slab was eventually produced. Field mix No. 4 had not performed well in the wet-dry durability tests, but it was still selected for a field test since it was decided that at least one slurry-placed material should be included in the field tests.

Field mix No. 5 contained 100% Sherco spray dryer waste with a moisture content of about 20% of dry weight. The material was obtained from the batch mixers used at the Sherco plant for waste conditioning, and it had an "as-received" moisture content of about 17%. Additional water was added to the material at the pond before it was placed. The target moisture content was 26%, but it was difficult to control the water addition, and the final moisture content was only 20%.

About 60 days after the slabs had been placed, several 4-inch-diameter core samples were cut from each slab. The cores were trimmed and tested for unconfined compressive strength in the laboratory. The strengths of the core samples are listed in Table 9.

TABLE 9

Unconfined Compressive Strengths of Core Samples Obtained
from the Small-Scale Field Tests

Field Mix	Unconfined Compressive Strength PSI After Approx. 80-Day Cure
Riverside Field Mix No. 1	991
Riverside Field Mix No. 2	435
Riverside Field Mix No. 3	Mix dropped due to quick setting problems in the field.
Riverside Field Mix No. 4	655
Sherco Field Mix No. 5	1512

After the slabs were installed, they were visually examined twice to determine how well the different slope protection mixes had withstood weather-related stresses encountered in the field. The slabs were first examined after they had been in the field for about 12 months and then examined again after about 20 months. The information gathered from these examinations correlated fairly well with behavior predicted by the laboratory durability tests.

Field mix No. 5 (Sherco spray dryer waste placed with a 30% moisture content) had exhibited the highest strength and lowest weight losses in the freeze-thaw and wet-dry tests. This mix showed almost no deterioration after 20 months in the field. Field mix No. 1 (25:75 Riverside fly ash and bottom ash with a moisture content of 18%) also passed the laboratory durability tests. This mix showed a slight loss of material from the surface of the slab, but no substantial deterioration after 20 months in the field. Field mix No. 2 and No. 4, which had both been placed with relatively high moisture contents and had both failed the wet-dry durability test in the laboratory, surprisingly only exhibited slight deterioration after 20 months in the field.

The major difference between the laboratory and field test results was that the higher moisture content mixes achieved higher strengths in the field than they did in the laboratory. The reason for this difference was probably the fact that some of the moisture in the wet mixes tended to drain out of the materials when they were placed in the field.

NSP personnel developed cost estimates for the various by-product-based slope protection materials used for the small-scale field tests. The estimates indicated that the various materials would cost between \$0.35/ft² and \$0.66/ft² to install in a 1-foot-thick lift. For the sake of comparison, it was estimated that conventional crushed rock riprap would cost about

\$1.21/ft² to install. The cost estimates are summarized in Table 10. The cost estimates generally indicated that the use of by-product-based slope protection materials in place of conventional riprap would result in a significant cost savings.

4.5 Demonstration-Scale Field Test Results

A single slope protection material was selected for a demonstration-scale field test. The mix contained 100% Sherco spray dryer waste with a target moisture content of 26% of dry weight, similar to field mix No. 5 used for the small-scale field tests. This particular mix was selected for the demonstration-scale field test because it developed a relatively high strength (1000 to 2000 psi unconfined compressive strength was expected) when it was properly compacted and because the spray dryer waste was produced at the Sherco plant in sufficiently large quantities so that construction activities would be able to proceed without having to wait for more material to be produced.

For the demonstration-scale field test, it took about 2 weeks to construct a 15-foot-wide, 1-foot-thick layer of slope protection material which extended approximately 6000 feet around three sides of the pond. Material was not placed on the fourth side of the pond because it was not usually exposed to wave action. The construction activities for the demonstration-scale field test are described in Section 3.7.

The quality of the slope protection layer constructed for the demonstration-scale field test was controlled by taking moisture measurements about every 30 minutes as the material was being placed. As was discussed in Section 3.7, a microwave drying procedure was used for the moisture tests to obtain quick results. The results of the moisture tests indicated that although the target moisture content was 26% of dry weight, the measured

TABLE 10
Estimated Costs for the Slope Protection Materials
Used for the Small-Scale Field Tests

Field Mix	Total Cost (per ft ²)	% of Riprap Cost
Riverside Field Mix No. 1	\$.74	61
Riverside Field Mix No. 2	\$.67	55
Riverside Field Mix No. 3	\$.73	60
Riverside Field Mix No. 4	\$.39	32
Sherco Field Mix No. 5	\$.39	32
Crushed Rock Riprap	\$1.21	100

moisture contents varied between 19% and 29.7% and that the moisture content of the slope protection material averaged over the entire construction period was 24.6%.

The relatively wide range of moisture contents measured for the material was due to the method used to add the water. When the Sherco spray dryer waste arrived at the pond, it already had a moisture content of about 19%, and additional moisture was added by spraying water on the stockpiled material. When the water was sprayed on the waste, it was usually possible to place the material with a moisture content within a few percent of the target moisture. However, occasionally the water was sprayed on unevenly and the moisture content ended up higher or lower than desired.

The density of the compacted slope protection layer was determined by taking core samples from the completed sections of the layer and measuring their dry densities in the laboratory. No attempt was made to check densities as the material was being placed. The average dry density of seven cores taken from the slope protection layer was 90 lb/ft³, which was very close to the maximum standard Proctor density obtained in the laboratory for the compacted Sherco spray dryer waste.

When the slope protection layer was completed, 15 additional core samples were collected for strength tests from 13 different locations around the perimeter of the pond. The cores were transported to the EERC, cured for about one month, trimmed, and then tested for unconfined compressive strength. The results of the strength tests are listed in Table 11, and a map of the

TABLE 11
Unconfined Compressive Strengths of Core Samples Obtained
from the Demonstration-Scale Field Tests

Core Number*	Curing Time (days)	Compressive Strength (psi)
1	41	1198
2	40	458
3A	39	805
3B	39	643
4A	39	583
4B-1	39	343
5	39	574
6	35	726
7	34	1066
8	33	286
9	33	896
10	32	1118
11	31	1141
12	29	2746
13	28	1176

* See pond sketch (Figure 6) for location of cores.

Figure 6. Diagram of the Sherco pond showing locations where core samples were taken for strength tests.

pond indicating where each core was taken is shown in Figure 6. The compressive strengths measured for the various cores ranged from 286 to 2745 psi. The average strength was 917 psi.

The minimum desired unconfined compressive strength for the cured slope protection material was about 450 psi, which was loosely based on a strength criterion commonly used to assess the durability of soil-cements. Although 450 psi was the minimum desired strength, strengths greater than 1000 psi were considered a more reliable indication that the slope protection material would last for the 5-year design life.

Looking at the strengths listed in Table 11 for the slope protection core samples, it can be seen that, of the 15 samples, two had strengths less than 450 psi and nine had strengths less than 1000 psi. Some of these strengths were significantly lower than had been predicted by the preliminary laboratory tests performed on the Sherco slope protection material. A partial explanation for the lower strengths achieved in the field may be that the moisture content of the material placed in the field was, on the average, several percentage points lower than the target moisture content. However, this was probably not the main reason.

The main reason for the low strengths measured for several of the field cores is believed to be that some of the Sherco spray dryer waste was not placed within the 1-hour period specified in the construction plan. Although the original intent was to prevent the material from sitting in stockpiles for more than 1 hour, it turned out to be very difficult to control the movement of all of the material that closely. This was important because the waste was a self-cementing material, and it was necessary to keep it from expending too much of its cementitious activity before it was placed.

The demonstration-scale slope protection layer was visually examined by NSP personnel about 10 months after it was placed. Their observations indicated that most of the layer appeared to be intact and performing well, but that a few areas were showing significant material losses. These observations are not surprising, considering the variability of the strength data obtained for the core samples and the fact that several of the cores had produced lower-than-desired strengths.

In future full-scale construction activities using the Sherco spray dryer waste, it is suggested that the material be moved directly from the conditioning operation to the construction site without intermediate stockpiling and that it be placed as soon as possible after it arrives at the construction site.

5.0 SUMMARY AND CONCLUSIONS

A research project was conducted to develop a cost-effective slope protection material for a 100-acre scrubber sludge disposal pond located at the Sherco power plant.

The technical objective of the project was to formulate and evaluate the performance of a slope protection material produced using self-cementing coal combustion by-products. The material was to have sufficient durability and erosion resistance to protect the underlying bottom ash fill and clay liner from wave erosion for at least 5 years when it was placed on the interior side slopes of the pond.

The research was conducted in three phases. The first phase was a laboratory study performed in 1989 and 1990, the second phase involved small-scale field tests performed in the summer of 1990, and the third phase was a demonstration-scale field test performed in the summer of 1991.

The two coal combustion by-products that were considered for use in the slope protection material were 1) a spray dryer waste and 2) a subbituminous coal fly ash. The spray dryer waste was approximately a 50:50 mixture of subbituminous coal fly ash and reacted, lime-based scrubber sorbent. The subbituminous coal fly ash was produced from a cyclone-fired boiler. Both by-products displayed self-cementing behavior when mixed with water.

After the materials had been characterized, a series of tests were done to evaluate the effect of various moisture addition levels on the consistency, time of set, and unconfined compressive strength of the by-product mixtures.

From the numerous by-product mixtures that were tested for time of set and unconfined compressive strength, nine were selected for follow-on durability tests. The purpose of the durability tests was to determine how well the materials would withstand weather-related stresses in the field, such as freeze-thaw cycles and wet-dry cycles.

Two general conclusions were drawn from the durability tests. The first was that the durability of materials containing the Sherco spray dryer waste decreased so rapidly as the moisture content of the mix was increased that only the relatively low moisture content, compactible mixes had enough durability to serve as slope protection materials. The second was that the materials containing Riverside fly ash were not as sensitive to moisture content as the Sherco materials and that the Riverside materials were sufficiently durable to serve as slope protection materials when they were prepared in either compactible or low-slump forms.

The results of the laboratory durability tests were used to select several slope protection materials for small-scale field tests. Of the nine materials tested in the laboratory, five were judged to have sufficient strength, freeze-thaw durability, and wet-dry durability to warrant follow-on field testing.

A test slab measuring approximately 10 feet by 15 feet and 1 foot thick was constructed for four of the slope protection mixes described above. These slabs were placed on the slope of the scrubber-waste disposal pond at the Sherco plant in July of 1990. The initial moisture addition levels used for the various mixes were determined from the results of the consistency tests conducted in the laboratory. However, these moisture levels had to be adjusted slightly in the field to achieve the desired consistencies for field placement.

The results of the field tests indicated that a slope protection slab prepared from Sherco spray dryer waste placed with a 20% moisture content showed almost no deterioration after 20 months in the field. A slab prepared from a mixture of 25% Riverside fly ash and 75% bottom ash with a moisture content of 18% showed a slight loss of material from the surface of the slab, but no substantial deterioration after 20 months in the field. Two other materials containing Riverside fly ash that were prepared with higher moisture contents showed somewhat more deterioration after 20 months, although none of the field test slabs appeared to have failed in that time period.

The final phase of this research was a demonstration-scale field test of the by-product-based slope protection material. From the four mixes studied in the small-scale field tests, the Sherco spray dryer waste with a moisture content of 26% of dry weight was selected for the demonstration-scale test. This selection was primarily based on estimated construction costs and the projected availability of the by-product.

The slope protection layer constructed for the demonstration-scale test was placed in a 15-foot-wide strip starting at the water line of the Sherco sludge disposal pond. The pond had 3:1 (run:rise) side slopes. The slope protection layer was about 1 foot thick and extended approximately 6000 feet around three sides of the 100-acre pond. The layer was keyed into the slope with a toe trench that was dug just above the water line. The slope section

below the water line was already protected with crushed granite riprap placed over a geotextile membrane.

After the demonstration-scale slope protection layer was constructed, 15 core samples were taken to evaluate the strength of the layer. A few of these cores had strengths that were significantly lower than expected, based on the preliminary laboratory tests performed on the Sherco slope protection material.

The demonstration-scale slope protection layer was visually examined by NSP personnel about 10 months after it was placed. Their observations indicated that most of the layer appeared to be intact and performing well, but that a few areas were showing significant material losses. These observations are not surprising, considering the low strengths obtained for some of the core samples.

The main reason for the low strengths measured for several of the field cores is believed to be that some of the Sherco spray dryer waste was not placed within the 1-hour period specified in the construction plan. Although the original intent was to prevent the material from sitting in stockpiles for more than 1 hour, it turned out to be very difficult to control the movement of all of the material that closely. Since the ash was a self-cementing material, it was important to keep it from expending too much of its cementitious activity before it was placed.

In future full-scale construction activities using the Sherco spray dryer waste, it is suggested that the material be moved directly from the conditioning operation to the construction site without intermediate stockpiling and that it be placed as soon as possible after it arrives at the construction site.

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