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TESTS FOR SOIL-FLY ASH MIXTURES FOR SOIL STABILIZATION AND CANAL LINING

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16. ABSTRACT
Laboratory tests were performed on various mixtures of fly ashes with sandy soils to determine possible usage as canal lining to reduce canal seepage and to increase the erosion resistance of the soil. For sands containing a relatively small amount of fines, fly ash was found to reduce soil permeability to an acceptable level. The addition of 2 percent of either portland cement, calcium sulfate, or hydrated lime to soil-fly ash mixtures significantly increased compressive strength and durability in freeze-thaw and wet-dry tests. Sodium citrate and borax were added, and different temperatures were used to reduce the setting time of mixtures with cementitious fly ashes. For one noncementitious fly ash, lime was added to dune sand and fly ash to provide cementation. For specimens formed pneumatically using laboratory shotcrete equipment, unit weights and compressive strengths of soil, fly ash, and portland cement mixtures were higher than those for specimens formed by impact compaction. The difference was particularly significant when concrete sand was substituted for dune sand. Small field test sections of canal lining placed with manually-operated mixing and compaction equipment were made with soil and fly ash with and without the addition of a small amount of portland cement. The laboratory and field tests indicated that with proper (1) mixtures, (2) field installation equipment, and (3) construction control, fly ash, particularly with additives, could provide a suitable canal lining.

17. KEY WORDS AND DOCUMENT ANALYSIS

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TESTS OF SOIL-FLY ASH MIXTURES FOR SOIL STABILIZATION AND CANAL LINING

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Geotechnical Branch
Division of Research and Laboratory Services
Engineering and Research Center
Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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Fly ash for the field test section on Lateral 1Z was donated by managers of the Laramie River Station Powerplant in Wheatland, Wyoming. William Grosz of Basin Electric Power Cooperative, who was present during the installation, provided helpful suggestions. The test section was installed by Royce Decker of the North Platte Project and by personnel of the Pathfinder Irrigation District.

This study was conducted under the supervision of W. G. Austin; Head, Soil and Rock Testing Section, who reviewed the report.

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INTRODUCTION

Where suitable soil is readily available, a compacted soil lining is one of the least expensive types of canal linings for seepage control. When soil from the canal excavation or within economical haul distance, is too pervious for compacted canal lining, it is sometimes feasible and economical to form an effective lining by adding fine soil or other additives to fill voids and reduce permeability to an acceptable limit. Therefore, it is logical to consider fly ash as an additive for this purpose in Bureau (Bureau of Reclamation) canal work. In addition to reducing permeability, some fly ashes (mostly in class C) have cementitious properties that increase the resistance of the material to erosion from canal water activity. Mixtures using noncementitious fly ashes (mostly in class F) can be made cementitious by adding lime. If a fly ash is found suitable for canal work, its economical use would depend primarily upon the amount required, the cost at its source, the cost of transportation to the canal site, and the extent of construction operations required to mix it with soil and to place the mixture. Fly ash with or without other additives has been used for highway soil stabilization [1][1].

This report presents the results of tests on soil-fly ash mixtures (soil with fly ash added) to determine possible use for canal linings. Soils for the tests were predominantly fine (dune) sands from Wyoming and Nebraska. The fly ashes were cementitious and noncementitious types from powerplants in Colorado, Wyoming, and Nebraska.

Properties determined for the mixtures investigated (some included small amounts of portland cement, lime, or calcium sulfate) were primarily compacted unit weight-moisture content relationships, compressive strength, durability in freeze-thaw and wet-dry tests, and permeability. These properties have not been directly correlated to field performance in canals. Because cementitious fly ashes harden rapidly when water is added, several methods to delay the set were investigated. Appendix A outlines the special test procedures used. Appendix B is a memorandum from the Chemistry, Petrography, and Chemical Engineering Section reporting results of chemical analyses on three fly ashes to determine "the possible toxic metal contribution to water supplies from use of fly ash materials as canal embankment stabilizers."

CONCLUSIONS

Based on the results of laboratory tests performed on specimens composed of soil (mostly dune sand) and fly ash with and without the addition of small amounts of portland cement, hydrated lime, or calcium sulfate, and on a small field test, the following conclusions were drawn:

- For fine sands with a relatively small percentage of particles passing a No. 200 (0.074 mm) sieve, fly ash fills voids, causing an increases in unit weight and a decrease in permeability.
- For a dune sand with about 5 percent passing a No. 200 sieve, about 30 percent fly ash (by dry mass of soil) is required to reduce the coefficient of permeability to a satisfactory level (10×10^{-6} cm/s) for canal lining. For a dune sand with over 30 percent passing a No. 200 sieve, the addition of fly ash reduces compacted unit weight and does not significantly change permeability.
- The addition of up to 30 percent cementitious fly ash to a dune sand when moistened and compacted, results in a weakly cemented material with a 7-day compressive strength of up to 350 lbf/in^2 (2400 kPa). Specimens of such material deteriorate significantly during freeze-thaw or wet-dry testing.
- The addition of 2 percent of either portland cement, hydrated lime, or calcium sulfate (by dry mass of soil) to a soil-fly ash mixture significantly increases compressive strength and durability in freeze-thaw and wet-dry tests.
- Borax in the amount of 1 percent (by mass) fly ash is somewhat more effective in delaying the set of soil-cementitious fly ash mixtures, causing less decrease in unit weight and durability than sodium citrate used in the amount of 0.1 percent (by mass) of fly ash. Delay of set is important during construction to allow sufficient time for placement and compaction.
- The set was delayed and compressive strength and durability of soil-fly ash mixtures were improved when placement was made during relatively low temperatures.
- Pneumatic placement (shotcrete) of soil specimens of dune sand, 20 percent cementitious fly ash, and 6 percent portland cement (both by dry mass of soil) with the laboratory equipment available, resulted in a higher unit weight than placement by impact compaction in molds. Pneumatic placement of a similar mixture with concrete sand instead of dune sand resulted in much higher unit weight and compressive strength.
- For a noncementitious fly ash mixed with dune sand, use of 20 percent fly ash and 4 percent lime (both by dry mass of soil) produced specimens of

[1]Numbers in brackets refer to entries in the bibliography.

higher compressive strength and greater durability in freeze-thaw tests than did 10 percent fly ash or 30 percent fly ash with either 2 or 4 percent lime.

- All field installations of soil-fly ash mixtures must be carefully controlled, and conventional heavy construction equipment designed for soil stabilization should be used.

- If proper materials and construction methods are used, fly ash with small amounts of cementitious additives (when required) is a promising material for soil stabilization and canal lining.

- With proper selection of tamper spring, number of layers, and number of tamps per layer, the maximum unit weight and optimum moisture obtained by the Harvard Miniature compaction method can be comparable with that of the standard Bureau compaction method. However, unit weights determined by the Harvard method on the wet side of optimum tend to be higher than those determined by the standard Bureau method.

- For three typical fly ashes investigated, toxic metals were present, but chemical analyses showed that "the levels of water-leached metals are much lower than EPA (Environmental Protection Agency) (hazardous waste) guidelines" (app. B).

FLY ASH

Fly ash is a particulate material collected from flue gases of coal-burning powerplants. Although some fly ashes are used for various purposes, they are largely waste products. Fly ash is a very fine dust with particles mostly in the silt size range. Physical and chemical properties vary among plants, depending on the source of coal, burning and handling methods, and the addition of materials to aid in the fly ash collection process. The principal constituents of fly ash are silica (silicon dioxide (SiO_2)), alumina (aluminum oxide (Al_2O_3)), and iron oxide (Fe_2O_3). There are smaller amounts of calcium oxide (CaO), magnesium oxide (MgO), sulfur trioxide (SO_3), sodium oxide (Na_2O), and unburned carbon. The specific gravity of fly ashes ranges from 2.1 to 2.6. Most of the particles are glassy spheres. The carbon particles are larger and more angular than the inorganic particles. Gradation analysis curves for three fly ashes, as determined by the hydrometer test method used for soils (designation E-6 of [2]) are shown on figure 1. Table 1 lists the composition of fly ashes from six powerplants located in Colorado, Wyoming, Nebraska, and New Mexico.

The constituent in fly ash most likely to affect stabilization properties of soil-fly ash mixtures is CaO. Fly ashes with relatively high amounts of CaO (generally considered as class C type) from plants shown in table 1 were used with soils from Mirdan Canal and laterals on the North Platte Project. Fly ash from the Four Corners Plant with a low amount of CaO (generally considered as class F type) was used with soil from the proposed Burnham Lateral. ASTM C 618-84 divides fly ashes into class C and class F, based on chemical properties, but there is not a clear distinction between the two.

When water is added to a sandy soil-fly ash mixture that has a fly ash with more than about 10 to 15 percent CaO, it reacts with the CaO to form calcium hydroxide (CaOH). This, in turn, causes a pozzolanic reaction with silica and alumina constituents to form a hardened mass. Such a material would provide a stabilized material for canals or other construction purposes. For a mixture of sandy soil, fly ash containing a low amount of CaO, and water, the addition of lime is required to supply the necessary CaO for pozzolanic action to result in hardening.

SOILS

With the exception of concrete sand for some of the tests with pneumatically-applied mixtures, the soils tested represented fine, sandy soils (fig. 1) typical of dune sand areas where a canal existed or was planned. The canals, sample locations, and laboratory index numbers are listed in table 2.

SPECIMEN DESIGNATIONS

Test specimens for each canal soil were designated as M for Mirdan, HC for Horse Creek (X10 or X11), and BL for Burnham Lateral. The canal symbol is followed by the percentage of fly ash used, and by the last two digits of the soils laboratory number for the fly ash (table 1). If an additive was used, this was indicated at the end of the designation by PC for portland cement, HL for hydrated lime, and CS for calcium sulfate. For example, HC(X10)-20-26-HL2 represents soil from the bank of Horse Creek Lateral with 20 percent fly ash from Glen Rock, Wyoming (42T-26), and containing 2 percent hydrated lime.

COMPACTION TEST SPECIMENS

Because soils in this testing program had maximum particle sizes smaller than the No. 4 (4.74 mm) size, the Harvard compaction apparatus (fig. 2), unless otherwise noted, was used for determining moisture-unit weight relationships and for molding test specimens [3]. The compaction mold was $1\frac{5}{16}$ inches

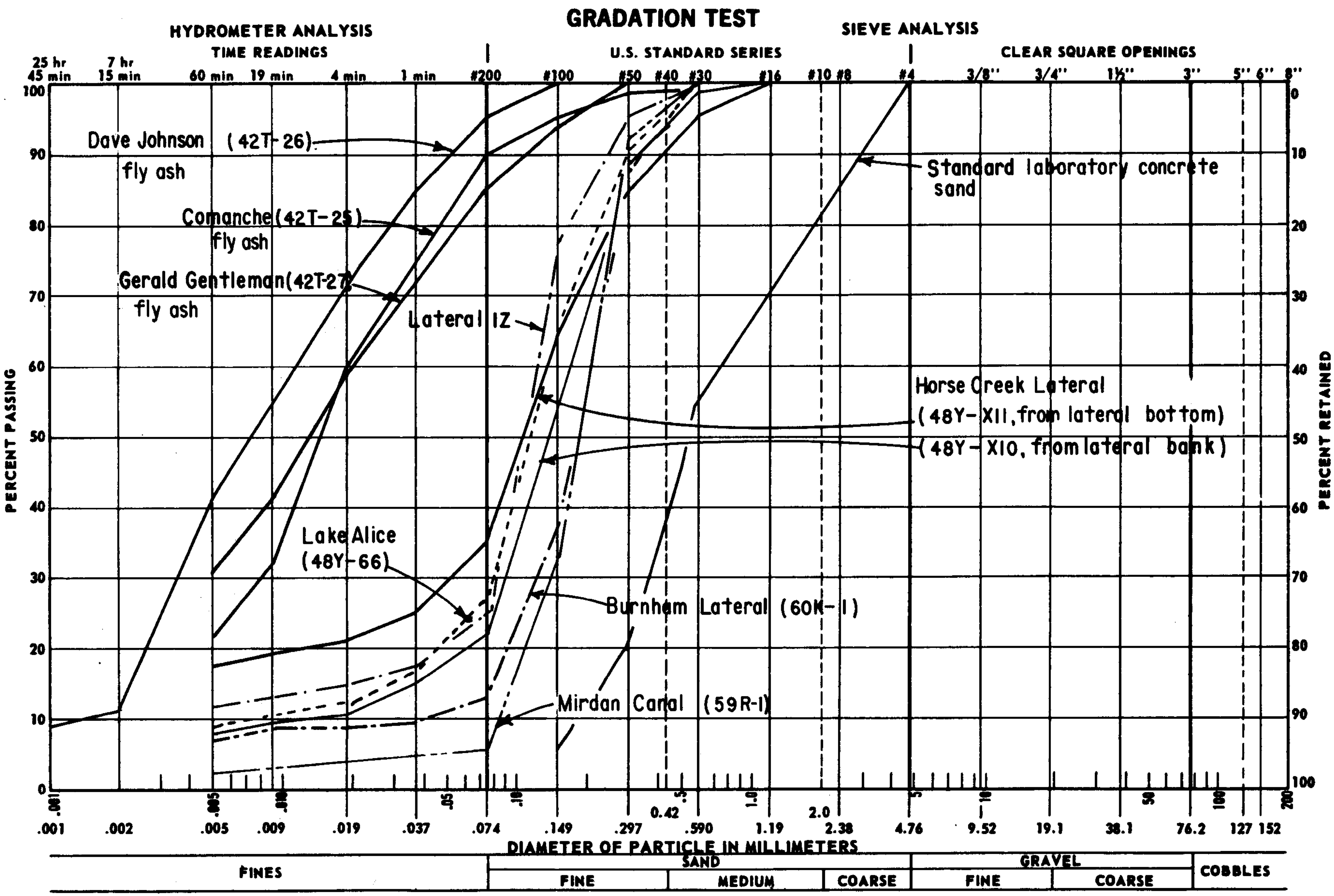


Figure 1. – Gradation analyses of canal soils and fly ashes.

Table 1. – Analyses of fly ashes used in soil-fly ash mixtures for canal linings. (In percent).

Plant	Comanche,	Dave Johnson,	Gerald Gentleman,	Wyodak,	Laramie River Station,	Four Corners[1],
Location	Pueblo, CO	Glenrock, WY	Sutherland, NE	Gillette WY	Wheatland, WY	Four Corners, NM
Soils Lab No.	42T-25	42T-26	42T-27	42T-29	42T-30	42T-21
Chem Lab. No.	E0075	E0076	E0077	E0094	E1823	E2046
Calcium oxide (CaO)	25.9	17.0	26.5	20.3	22.6	3.50
Magnesium oxide (MgO)	4.35	3.14	5.00	4.96	3.60	1.07
Iron oxide (Fe_2O_3)	4.03	3.20	4.85	5.17	4.50	4.69
Aluminum oxide (Al_2O_3)	20.4	22.4	19.1	22.5	24.1	30.9
Silicon dioxide (SiO_2)	34.0	49.0	35.0	39.0	43.0	55.0
Sodium oxide (Na_2O)	2.3	0.23	0.72	0.52	} 1.14	} 0.23
Potassium oxide (K_2O)	0.20	.14	.13	.19		
Sulfur trioxide (SO_3)	2.34	.38	1.73	.97	1.03	.26
Moisture	0.0	.3	0.0	.1	0.03	.0
Carbon (loss on ignition)	.7	.9	.4	.1	.40	1.07

[1]Noncementitious fly ash. The others listed are cementitious.

Table 2. – Laboratory index numbers of samples representative of soils at various canals.

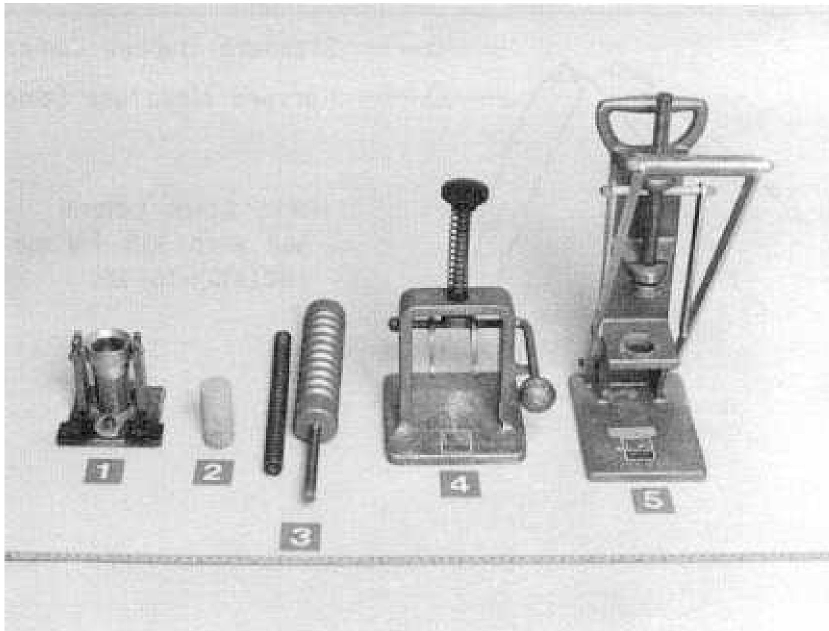
Canal	Sample location	Lab. index No.
Mirdan Canal, Pick-Sloan Missouri Basin Program, Nebraska	County road cut, 1200 ft N of the SE corner of sec. 6, T. 16 N., R. 21 W.	59R-1
Horse Creek Lateral, North Platte Project, Wyoming	Mile 13.1	[1]48Y-X10 and [2]48Y-X11
High-Line Canal, North Platte Project, Wyoming	Ridge near Lake Alice	48Y-66
Burnham Lateral, Navajo Indian Irrigation Project, New Mexico	Representative canal soils	60K-1

[1]Sample from canal bank above the waterline.
[2]Sample dredged from canal bottom during canal operation.

(33.3 mm) inside diameter by 2.816 inches (71.5 mm) high. A tamper with a 0.5-inch (12.7 mm) diameter rod was used for compacting the soil in the mold. The tamper had a handle with a spring arrangement so that a relatively constant force was applied to the soil as the surface of each layer was tamped. After some experimenting with 20- and 40-lbf (89- and 178-N) springs and with different numbers of soil layers in the mold, it was found that a 20-lbf (89-N) spring with 5 tamps on each of 5 layers produced maximum unit weight and optimum moisture values comparable with those produced in the Bureau compaction test (designation E-11, pp. 466-478 of [2]) (fig. 3). The Harvard compaction apparatus kneads the soil during compaction to form a more uniform specimen than does the impact from the tamper in the Bureau compaction test. It was noted that on the wet side of optimum moisture, the Harvard method generally resulted in higher unit weights than the Bureau method. A possible explanation is that the kneading action by the Harvard tamper allows more dissipation of pore pressures than does the sudden impact from the Bureau tamper and allows soil particles to move closer together. Figure 4 shows compaction test curves for Horse Creek Lateral and Burnham Lateral soils used in the testing program.

The Harvard apparatus includes a hand-operated extractor (fig. 2, item 5) for removing soil from the mold. For soil-fly ash mixtures, the extracted soil specimens were sufficiently cohesive that they could be used for testing. Immediately after extraction, the specimens were sealed in small metal cans with tight fitting lids and placed in a 120 °F (50 °C) oven for 7-day curing. Retention of moisture in the specimen was required for a sufficient period of time for hydration of the mixture and formation of a durable product. Selected full-size compaction test specimens were used for unconfined compressive strength testing.

Other full-size compaction specimens were cut into thirds for permeability, freeze-thaw, and wet-dry specimens; the middle third of each specimen was used for the permeability tests. Most of the compressive strength tests were performed on full-size



1. Compaction mold and collar in holder. 2. Soil specimen.
3. Compaction spring and tamper. 4. Collar remover.
5. Specimen extractor.

Figure 2. – Harvard compaction apparatus. P801–D–81067.

compaction specimens; a few were made on one-third portions previously subjected to either freeze-thaw or wet-dry tests.

TESTS ON MIRDAN CANAL SOIL

The addition of fly ash to a dune sand having relatively few particles passing the No. 200 (0.074 mm) sieve fills voids and significantly increases unit weight. This is shown by the compaction curves on figure 5 where 30 percent of two different fly ashes was added to Mirdan dune sand that had 5 percent of its particles passing the No. 200 sieve. Initial permeability tests performed in a triaxial cell where back pressure could be applied to increase the degree of saturation showed that Mirdan sand with 25 percent fly ash had a coefficient of permeability, k, of about 30×10^{-6} cm/s. To reduce the permeability to a more acceptable rate for a canal lining, 30 percent fly ash (by dry mass of soil) was used for tests with the Mirdan sand. Freeze-thaw and wet-dry tests were made on one-third portions of the compaction specimens (fig. 6a and 6b). The wet-dry specimens were relatively intact after 12 cycles (except for compaction specimen No. 5 on the wet side of optimum moisture), but surface material could be removed by rubbing with a finger. Freeze-thaw specimens were in poor condition.

Additional compaction tests were performed on Mirdan sand with 30 percent fly ash (M30-27) and 2 percent (by dry mass of soil) portland cement, or lime, or calcium sulfate. Unit weight and moisture content for specimens with the additives were similar to those for soil alone and 30 percent fly ash. As shown on figure 5, the permeability ranged from 0.02 to 0.06×10^{-6} cm/s.

All of the freeze-thaw and wet-dry test specimens with portland cement, lime, or calcium sulfate were in good condition after 12 cycles (fig. 6c). Table 3 lists compressive strengths of various full-size and one-third-size specimens after various conditions were imposed on the specimens.

Delay of Mixture Hardening

When water is added to a soil-cementitious fly ash mixture, the calcium hydroxide formed reacts chemically with silica and alumina, producing heat, and the mixture starts to set (harden) immediately. If compaction of the mixture is delayed significantly, as would occur during field installation, there is a decrease in compacted unit weight with a corresponding decrease in strength and a possible increase in permeability. To show the effects of time delay on these properties, compaction tests specimens were

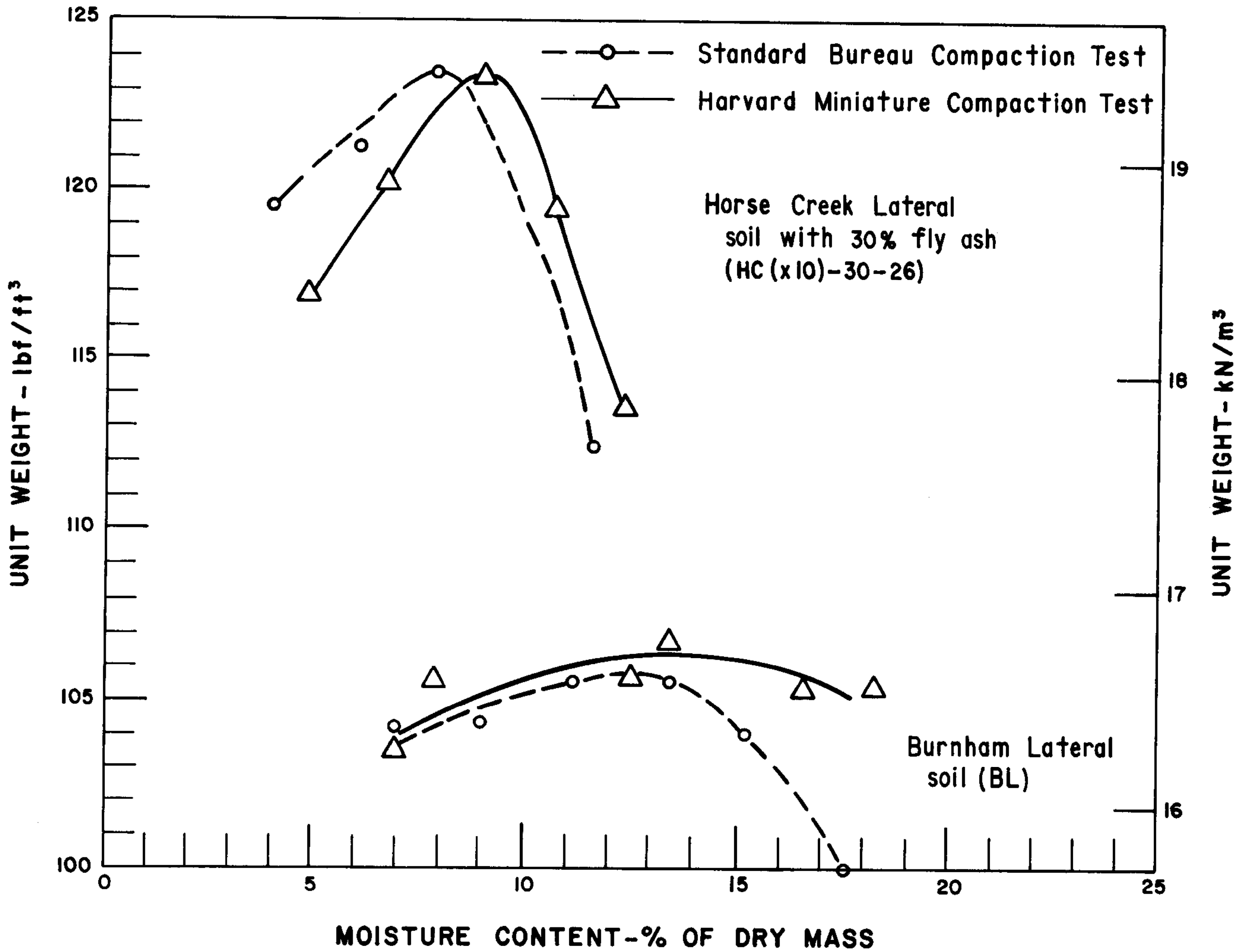


Figure 3. – Comparison of Bureau standard and Harvard Miniature compaction test curves.

made immediately after mixing (0 time) and at different time intervals up to 90 minutes after the prepared mixture had been placed in a covered container.

Mirdan dune sand (M) and 30 percent fly ash (42T-27) from Sutherland, Nebraska were used for the time-delay tests. Different series of tests were made on compaction specimens (1) with sodium citrate, (2) with borax, and (3) with compaction of soil specimens at different room temperatures. Compressive strength, permeability, freeze-thaw, and wet-dry tests were performed for the series with sodium citrate. For the other test series with retardant measures, only the effects on unit weight are shown on compaction curves. Results of maximum unit weight from compaction tests and compressive strength on specimens near maximum unit weight for the three test series are shown in table 4.

Sodium Citrate. – For the time-delay tests with sodium citrate, 2 percent calcium sulfate (by weight of soil) was added for increased strength and durability, and the tests were performed in a 75 °F (24 °C) room. Sodium citrate (0.10 percent by weight of fly ash) was added by solution in the mixing water for the compaction test specimens. Figure 7 shows compaction curves with mixtures without sodium citrate compacted after time delays of 0, 15, and 30 minutes, and mixtures with sodium citrate compacted after 30 and 60 minutes. Although the unit weights for all tests decreased a maximum of 5 percent, the compressive strength after 15 minutes decreased 50 percent for specimens with no citrate. After a 30-minute delay, the compressive strength of specimens with the citrate was 35% higher than without citrate for the same time delay. After a 60-minute delay, the compressive strength for specimens with citrate had decreased to a low value of 384 lbf/in² (565 kPa).

For permeability tests on specimens with or without sodium citrate, permeability rates were significantly

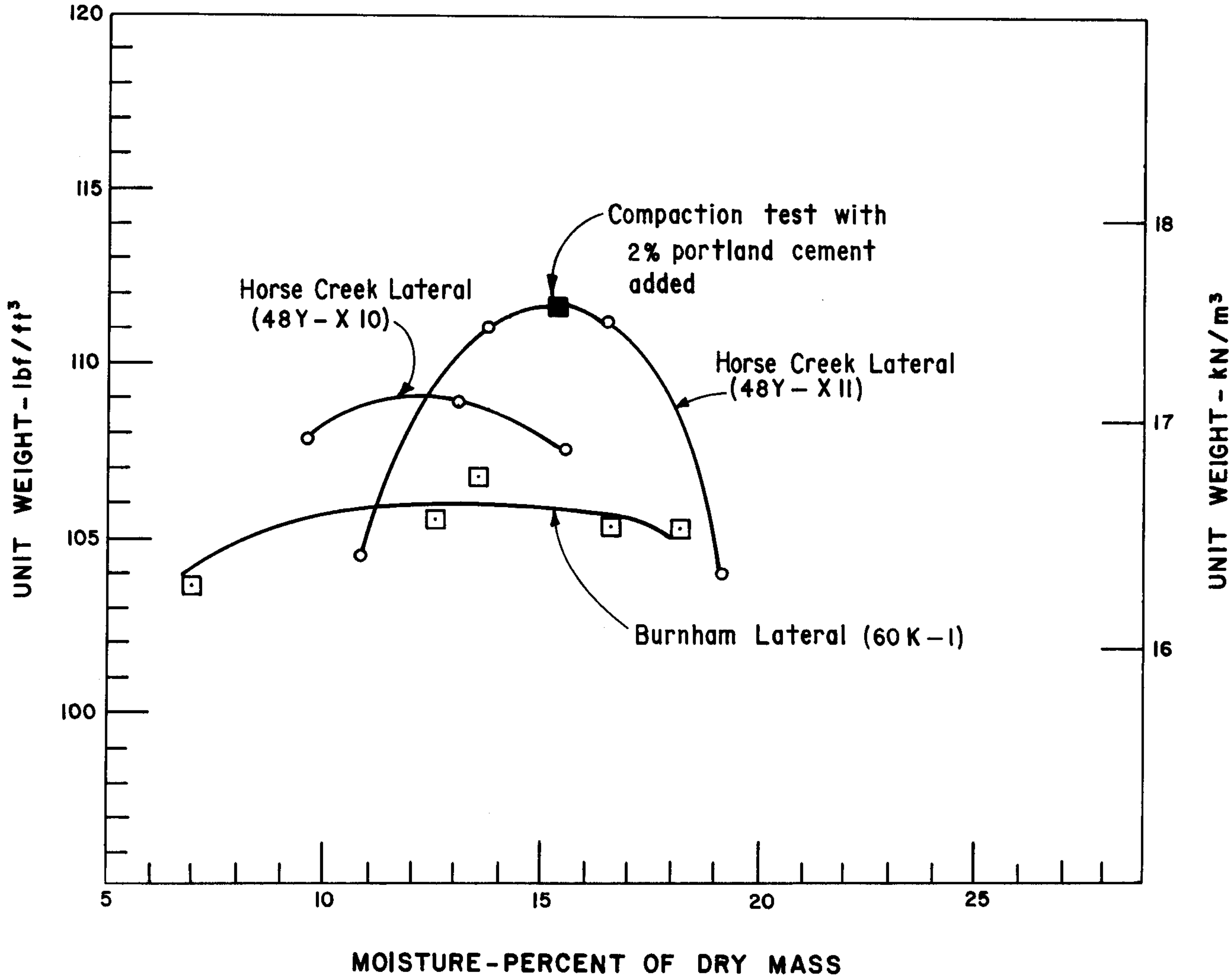


Figure 4. – Moisture-unit weight relationships of soils in soil-fly ash mixtures.

lower on the wet side of optimum than on the dry side.

For the time-delay tests with sodium citrate, all of the freeze-thaw and wet-dry tests were continued for 12 cycles and the specimens remained in fair to good condition. The specimens formed immediately after the mixtures were prepared performed the best. A knife blade was required to scrape material from the sides of the freeze-thaw specimens; whereas, a fingernail could remove material from the wet-dry specimens. As the delay increased to 30 and 60 minutes, conditions of the specimens worsened, but even after a 1-hour delay they were in fair condition with no cracks. However, abrasive action with light fingernail action would penetrate the sides of all specimens.

Borax. – A series of compressive strength tests were made on soil-fly ash compaction specimens to which borax had been added to delay the set. The compaction tests were performed in a 60 °F (16 °C) room. At this temperature the maximum amount of borax that could be dissolved in water was slightly less than 4 percent. This solution was added to the mixing water for the soil-fly ash mixture to provide the desired 1 percent borax by weight of fly ash. The compaction specimens were prepared 30, 60, and 90 minutes after completion of mixing. After specimens had cured, compressive strength tests were made to determine the effect of the time delay. A companion series of tests were made on soil-fly ash specimens without borax. Results of these test series are shown on figure 8.

Although there was no significant difference between the maximum unit weights of the 30- and 60-minute-delay tests with borax and the 0-minute-delay tests without borax, the average compressive

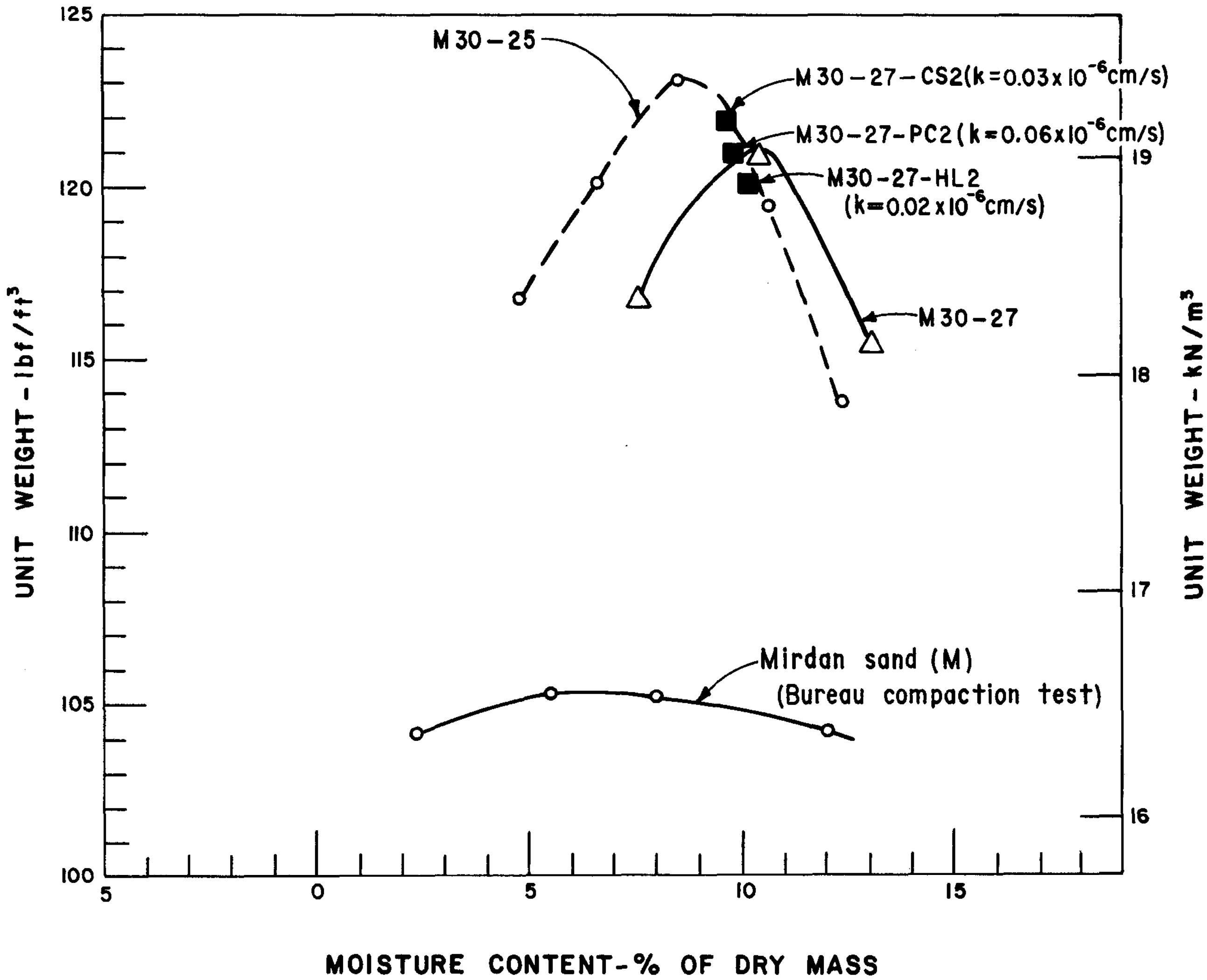


Figure 5. – Compaction test results on the Mirdan dune sand alone and on the sand with 30 percent fly ash from the Comanche and Gerald Gentleman powerplants. Permeability coefficients, *k*, are shown for specimens with 2 percent portland cement, lime, or calcium sulfate.

strengths were about 28-percent less for the borax-treated specimens near maximum unit weight. At 90 minutes, the maximum unit weight of the borax-treated material was approximately the same as for the material without borax at 30 minutes; however, the compressive strength was 19 percent less. According to these tests, borax was significantly more effective than sodium citrate in preventing decrease in unit weight and compressive strength with time.

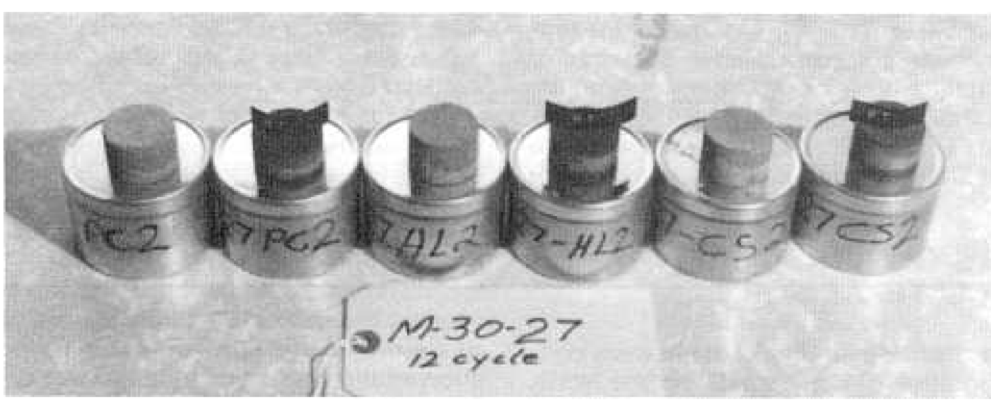
Temperature. – Because hardening of cementitious fly ash is caused by a chemical reaction, and temperature affects the rate of such reactions, hardening of soil-fly ash mixtures can be delayed by lowering temperature. Therefore, compaction test specimens of dune sand (M) with fly ash were prepared both at a normal laboratory temperature of approximately 75 °F (24 °C) and in rooms where the temperature was controlled at 60 °F (16 °C) and at 45 °F (7 °C), and the compressive strength, after the curing period, was determined to assess the effect of temperature on strength (fig. 9).

For the tests at 75 °F (24 °C), the decrease in maximum unit weight for mixtures compacted at 30 or 60 minutes was about 8 percent, and the corresponding decrease in compressive strength averaged 73 percent.

For the test at 45 °F (7 °C), the maximum unit weights were not significantly different between 0 and 30 minutes, and both were comparable with the maximum unit weight of specimens formed at 75 °F (24 °C) immediately after mixing. However, at 60 minutes the unit weight decreased about 7 percent, and the corresponding average decrease in compressive strength was about 63 percent.

a. Specimens before testing. P-801-D-81068

b. Specimens after 12 cycles of wet-dry (top row) and freeze-thaw (bottom row) testing. P-801-D-81069



c. Specimens with portland cement (2 on left), lime (2 in middle), and calcium sulfate (2 on right) after 12 cycles of freeze-thaw (with black tape on top) and wet-dry testing. P-801-D-81070

Figure 6. – Freeze-thaw and wet-dry specimens of Mirdan soil and 30 percent fly ash (M30-27) without and with 2 percent portland cement, lime, or calcium sulfate.

Table 3. – Compressive strengths of various full-size and one-third-size specimens.

	Portland cement, lbf/in² (kPa)	Hydrated lime, lbf/in² (kPa)	Calcium sulfate, lbf/in² (kPa)
Full size[2]	250 (1700)	600 (4100)	–
After permeability test (one-third size)[2]	540 (3700)	520 (3600)	[1]1,100 (7600)
After wet-dry test (one-third size)	610 (4200)	510 (3500)	[1]1,100 (7600)
After freeze-thaw test (one-third size)	510 (3500)	920 (6300)	[1]1,100 (7600)

[1]Compressive strength exceeded the capacity of the testing machine being used.
[2]Specimens not subjected to freeze-thaw or wet-dry conditions.

Table 4. – Effects of retardant measures on maximum unit weight and compressive strengths of specimens with 30 percent fly ash in dune sand.

Time, minutes	Tests	Sodium citrate series[1]		Borax series		Temperature series		
		No citrate	0.1% citrate	No borax	1% borax	75 °F	60 °F	45 °F
0	Max. unit wt.	[2]123	–	121	–	121	–	122
	Comp. strength	[3]918	–	353	–	353	–	476
15	Max. unit wt.	122 (1)[4]	–	–	–	–	–	–
	Comp. strength	460 (50)	–	–	–	–	–	–
30	Max. unit wt.	118 (4)	119 (3)	118 (2)	121 (0)	111 (8)	118	121 (1)
	Comp. strength	404 (56)	544 (41)	245 (31)	223 (37)	108 (69)	245	297 (38)
60	Max. unit wt.	–	117 (5)	115 (5)	121 (0)	111 (8)	115	113 (7)
	Comp. strength	–	384 (58)	175 (50)	283 (20)	83 (76)	175	176 (63)
90	Max. unit wt.	–	–	112 (7)	118 (2)	–	112	–
	Comp. strength	–	–	132 (63)	199 (44)	–	132	–

[1]For the sodium citrate test series, 2 percent calcium sulfate was added. This accounts for the compressive strengths being higher than for the other series of tests.
[2]Unit weight values are in lbf/ft³ (1 lbf/ft³ = 0.1571 kN/m³).
[3]Compressive strength values are in lbf/in² (1 lbf/in² = 6.895 kPa).
[4]Numbers in parentheses show the percent decrease in unit weight or compressive strength after delay in compaction compared with no delay (0 time). For the sodium citrate- and borax-treated specimens, the percent decrease is based on untreated specimens with no delay.

For the tests at 60 °F (16 °C), the maximum unit weight of specimens compacted after 90 minutes was approximately the same as specimens compacted at 30 and 60 minutes at 75 °F (24 °C) and 60 minutes at 45 °F (7 °C), with the compressive strength having an intermediate value.

TESTS ON HORSE CREEK LATERAL SOIL

The soil samples from Horse Creek Lateral were considered representative of dune sands on the North Platte Project (fig. 1).

Sample from Lateral Bottom

Soil sample 48Y-X11, taken (under water) from the lateral bottom, contained fine sediment mixed with dune sand, and about 35 percent passed the No. 200 sieve. Soil similar to this would be used if material excavated from a canal were to be used in a soil-fly ash lining. A field test was later made on Lateral 1Z of the North Platte Project where material from the canal was used for the soil-fly ash lining. Figure 10 shows compaction curves of this soil with 20, 25, 30, and 35 percent fly ash (42T-26). As the percentage of fly ash was increased, the maximum unit weight decreased a small amount, indicating that the voids in the sand were overfilled with fines. Results of permeability tests on compaction specimens showed that variation in the amount of fly ash made little difference in permeability because the permeability of this soil without fly ash would probably be low. Freeze-thaw and wet-dry tests were performed on specimens of these mixtures, but durability was poor and the specimens disintegrated after a few cycles.

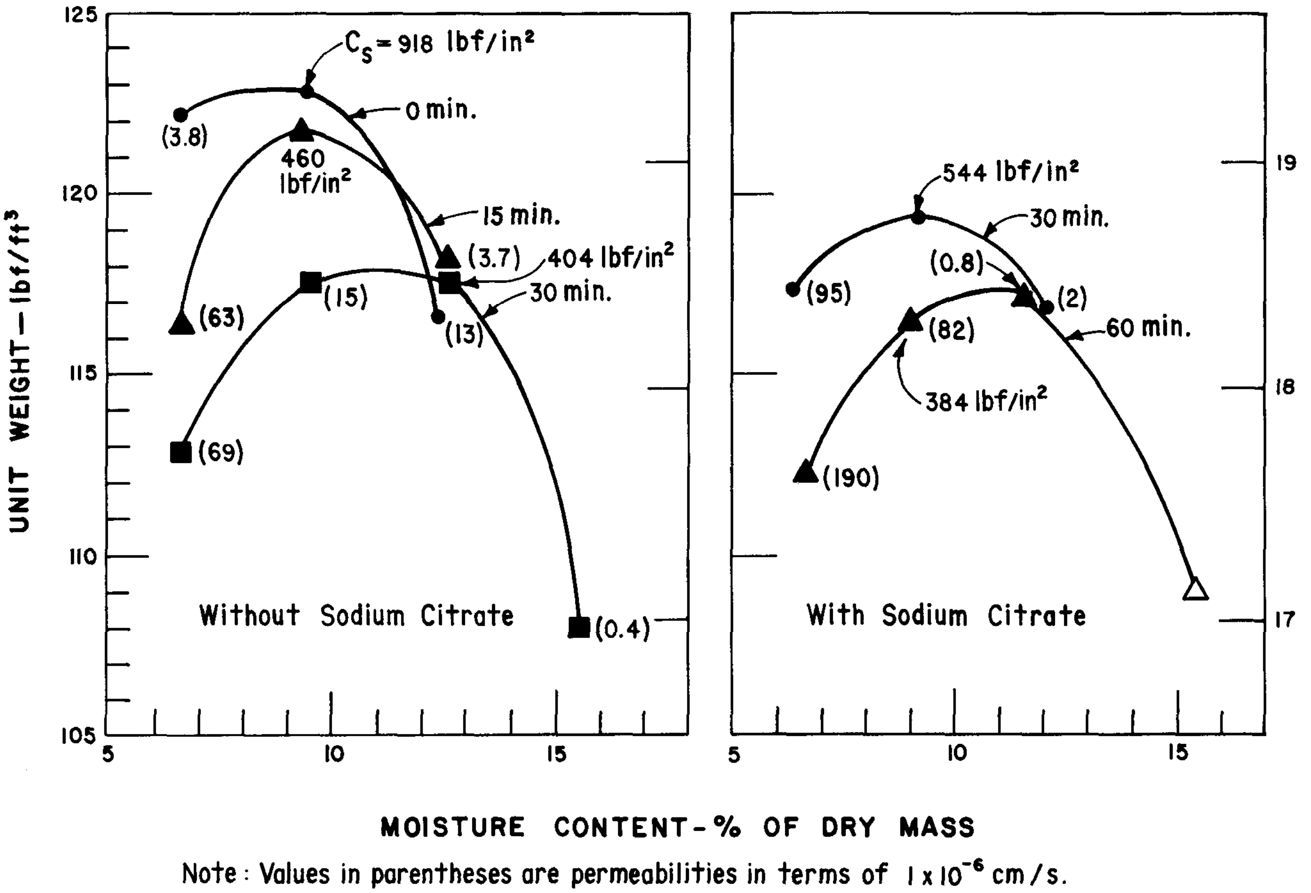


Figure 7. – Compressive strengths and permeability test values from compaction specimens without and with 2 percent sodium citrate added as a retardant. Permeabilities, *k*, (in parentheses) are in 10^{-6} cm/s, and compressive strengths, C_s, is in lbf/in².

Figure 11 shows results of compaction, compressive strength, and permeability tests on sample 48Y-X11 soil and various combinations of 0, 10, and 30 percent fly ash with either 2 percent portland cement, hydrated lime, or calcium sulfate. The compressive strength (238 lbf/in²) (1,641 kPa) of the test with 2-percent portland cement and no fly ash (HC(X11)-0-PC2) was significantly lower than that for the other tests containing either 10 or 30 percent fly ash. This indicates the cementitious value of the fly ash. The strength test result for 30 percent fly ash without additives was approximately the same as that for the test with 2 percent portland cement and no fly ash.

Compressive strength tests on specimens with 30 percent fly ash and 2 percent portland cement or 2 percent hydrated lime (shown on fig. 11) were performed on specimens 0.94 inch (24 mm) high, that were previously subjected to freeze-thaw, wet-dry, and permeability tests only. It was noted that specimens increased in strength after the durability tests, as shown in table 5. Apparently durability testing, particularly the wet-dry procedure, accelerated curing to cause the increase in strength.

The freeze-thaw and wet-dry test specimens of 48Y-X11 soil with 30 percent fly ash and either 2-percent portland cement or lime were in good condition after 12 cycles. The specimens with 30 percent fly ash and 2 percent calcium sulfate were in poor condition; large vertical and numerous hairline cracks appeared at the end of the seventh cycle. However, these specimens had been cured at 230 °F (110 °C). It was discovered that specimens with calcium sulfate cured subsequently at 120 °F (50 °C) fared much better in the durability tests. It is believed that curing at the higher temperatures produced ettringite, which caused expansion and cracking.

Sample from Lateral Bank

The Horse Creek sample from the lateral bank (48Y-X10) had 22 percent fines. Figure 12 shows compaction curves for soil alone and for soil with 20 and 30 percent fly ash. The maximum unit weights of soil with 20 and 30 percent fly ash from Sutherland, Nebraska (42T-27), were comparable and about 6 percent higher than those for the soil without fly ash and 3 percent higher than those for soil with 30 percent fly ash from Glen Rock, Wyoming (427-26). The

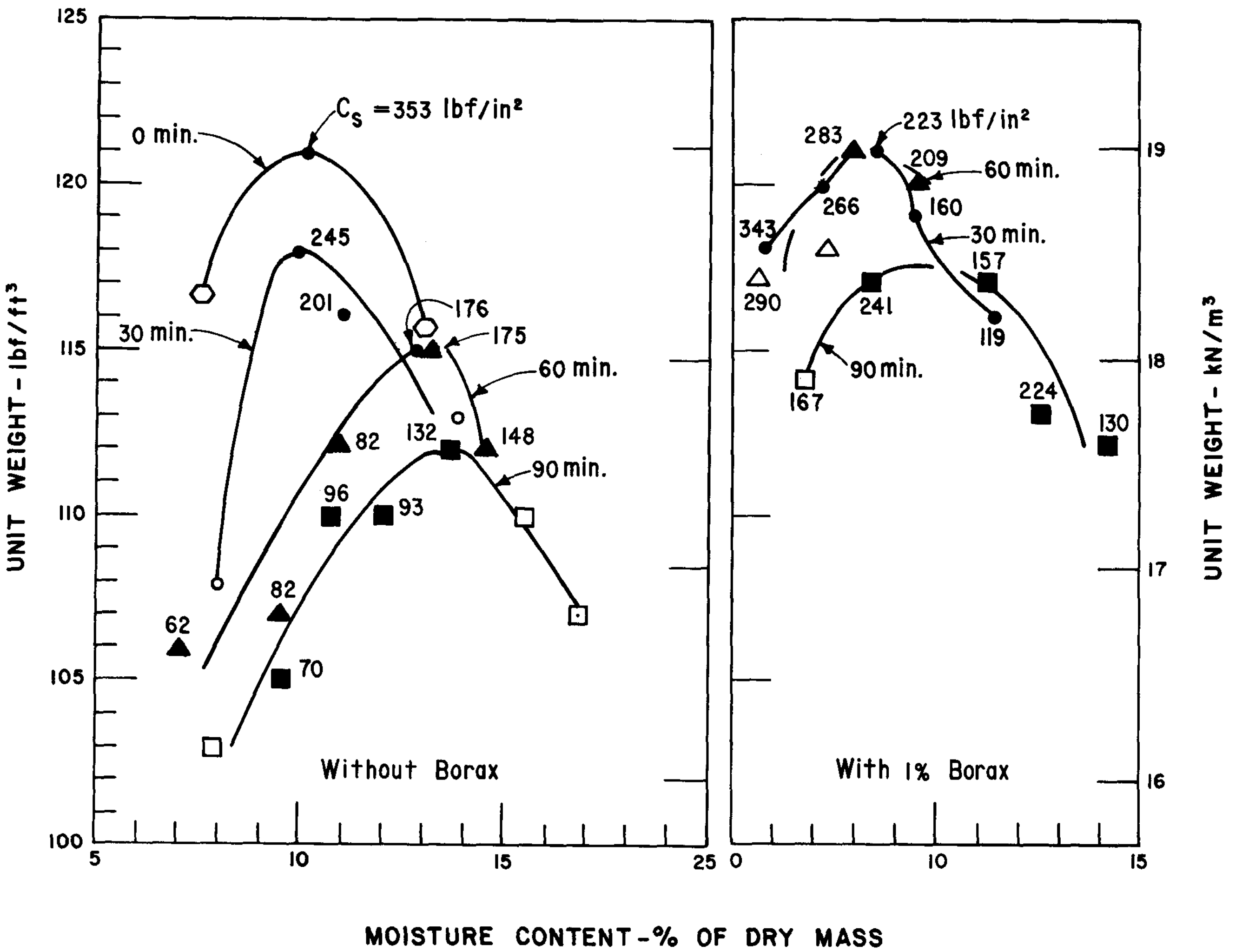


Figure 8. – Compressive strengths of soil-fly ash compaction test specimens without and with 1 percent borax, at 30, 60, and 90 minutes after mixing. C_s in lbf/in².

higher compressive strengths for specimens with portland cement, calcium sulfate, and lime compared with compaction specimens without these additives are evident. Furthermore, the compressive strengths of specimens with either 10 or 20 percent fly ash and lime were relatively low. The highest unit weight and compressive strength was obtained on HC(X10) soil with 30 percent fly ash and 2 percent calcium sulfate. The corresponding coefficient of permeability was 0.08 × 10^{6} cm/s. A similar soil-fly ash mix with 2 percent portland cement had nearly the same unit weight with a coefficient of permeability of 2.3 × 10^{-6} cm/s.

All freeze-thaw tests performed on specimens of HC(X10) soil with 30 percent fly ash and 2 percent portland cement, lime, or calcium sulfate, were in good condition after 12 cycles. For the wet-dry tests, all specimens with portland cement were in good condition after 12 cycles. For the specimens with lime only, the one at maximum unit weight was in good condition after 12 cycles. The specimen dry of optimum had developed a crack after 12 cycles. For the specimens with calcium sulfate, some cracking appeared early in the test cycles, but the specimens remained intact and the test was continued for the 12 cycles.

FIELD TEST WITH SOIL FLY ASH ON LATERAL 1Z

During October 14 and 15, 1980, a small test section of soil-fly ash lining was placed in Lateral 1Z of the Pathfinder Irrigation District on the North Platte Project near Torrington, Wyoming. The test site was about 1 mile (1.6 km) from the Lateral 1Z turnout on the main canal. Although there was no seepage evident at this particular location, it provided a convenient place for a field test in the sandy soils typical of the general area.

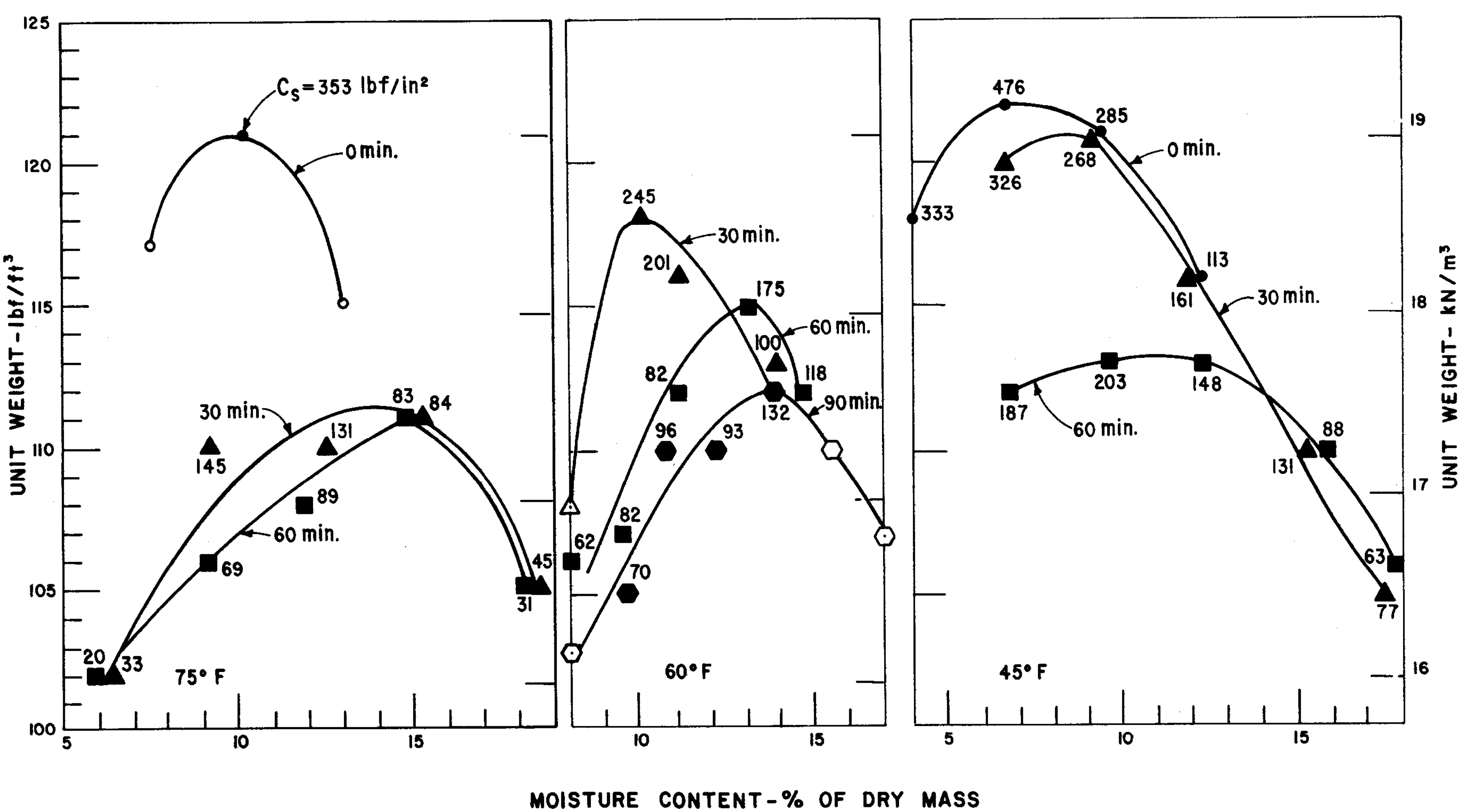


Figure 9. – Moisture-unit weight relationships with compressive strengths of soil-fly ash mixtures compacted at 75, 60, and 45 °F with 0- to 90-minute time delays. C_s is in lbf/in².

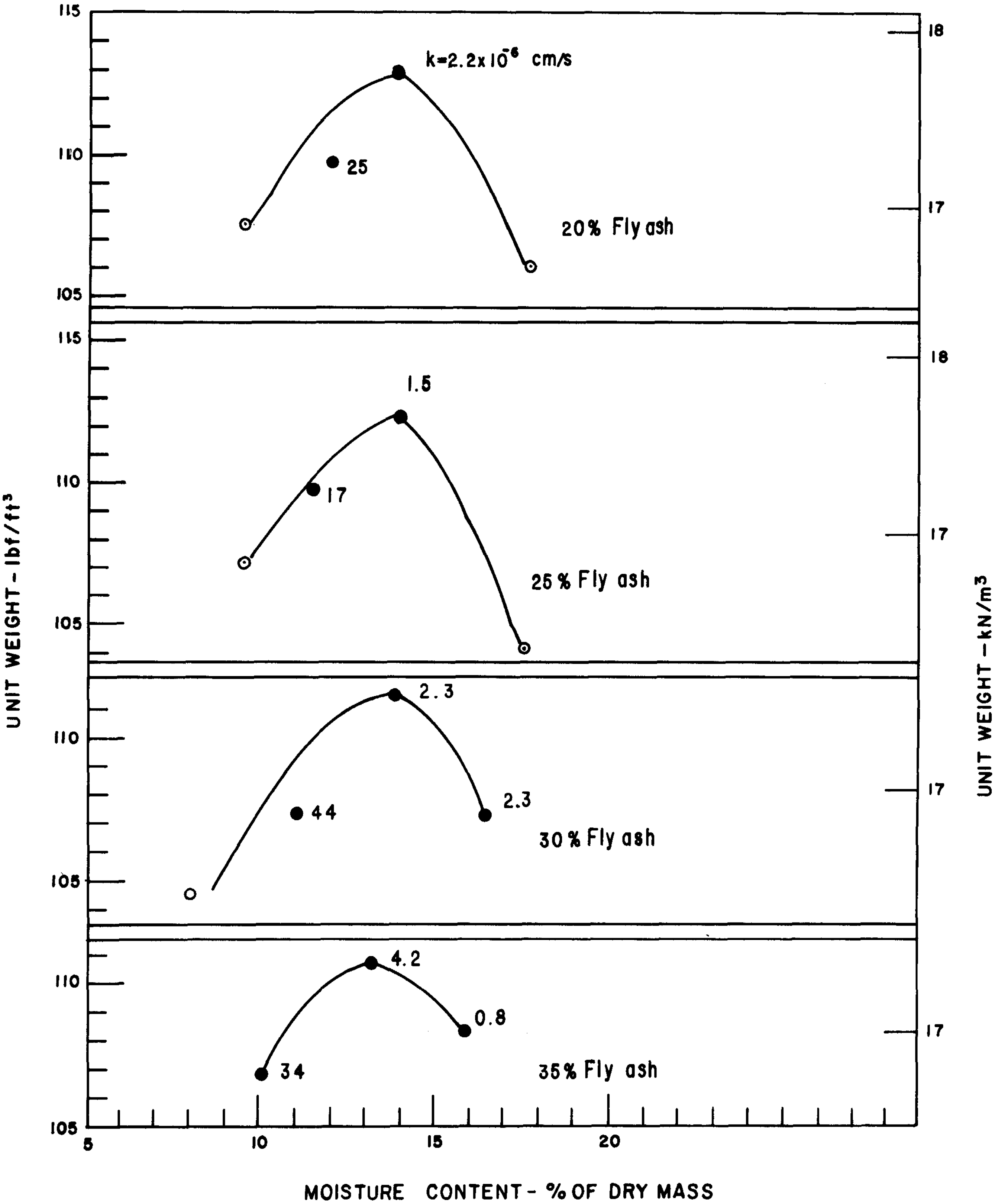


Figure 10. – Moisture-unit weight relationships and permeabilities of soil (48Y-X11) with different amounts of fly ash (42T-26). Permeabilities, *k*, are in 10^{-6} cm/s.

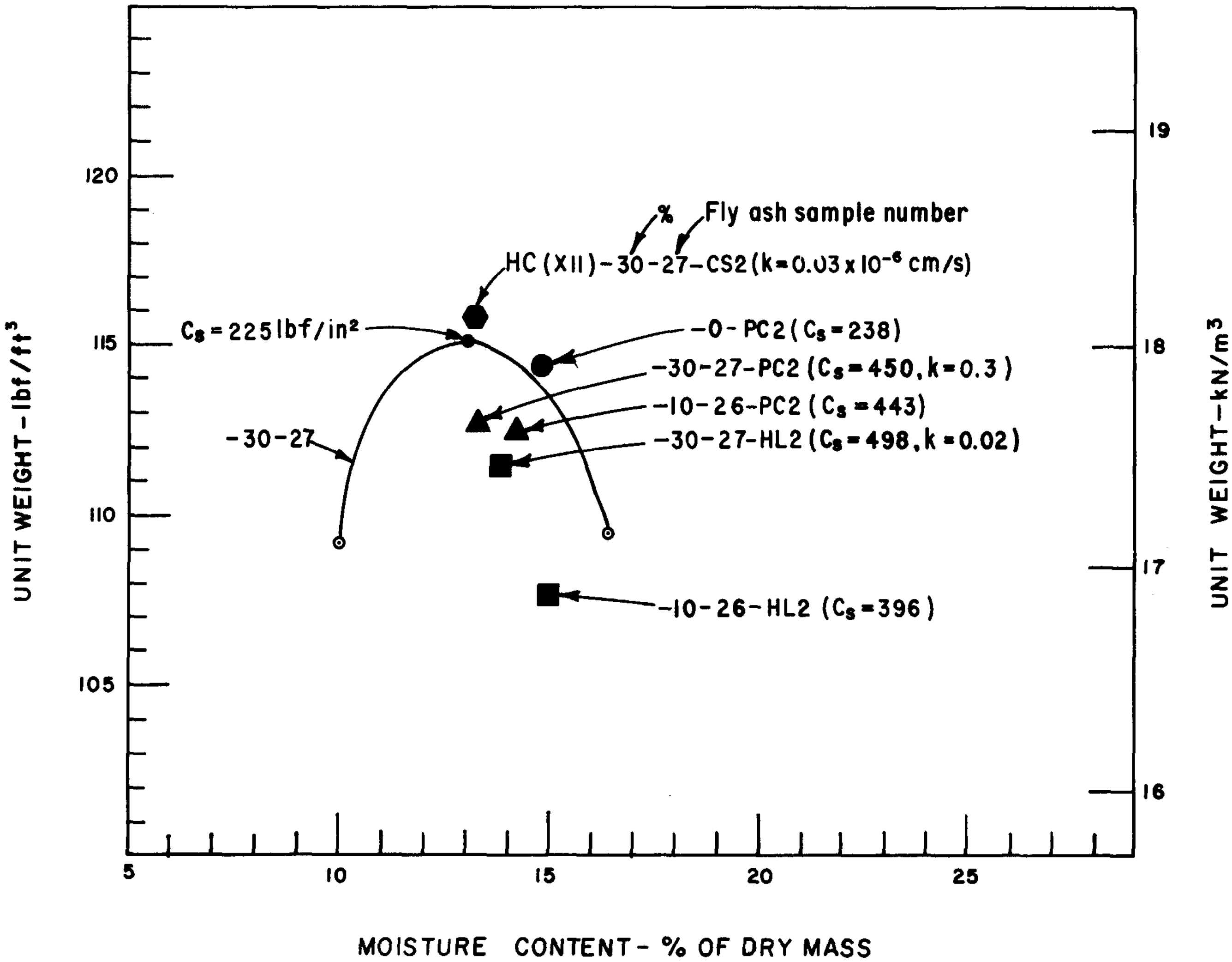


Figure 11. – Compaction test curve for Horse Creek Lateral soil (HC-X11) with 30 percent fly ash. Results of compressive strength and permeability tests with either 2 percent portland cement, calcium sulfate, or lime added to soil fly ash mixtures. C_s is in lbf/in².

Before the test installation, a short section of the lateral was cleaned with a Gradall to remove sediment and place the bottom in undisturbed subgrade sand. The excavated lateral section had a bottom width of 4 feet (1.2 m) and a side slope length of 5.8 feet (1.8 m) on a 2:1. The operating water depth was 2 feet (0.6 m) and the lateral discharge rate was 10 ft³/s (0.3 m³/s). The test reach was about 70 feet (21 m) long and was divided on the lateral bottom and side slopes into different sections for treatment with fly ash with and without the addition of portland cement.

Soil

The subgrade soil was a typical dune sand with an inplace dry unit weight of about 90 lbf/ft³ (14kN/m³). The soil excavated from the lateral, which contained a mixture of the subgrade sand and sediment, was used for the lining; this had 25 percent passing a No. 200 sieve (fig. 1). The soil for lining had a maximum laboratory unit weight of 112 lb/ft³ (17.6 kN/m³), and an undisturbed permeability of about 400 × 10^{-6} cm/s.

Fly Ash

Two truckloads of fly ash were obtained by Pathfinder District personnel from the Laramie River Station Powerplant located in Wheatland, Wyoming. A typical analysis of the fly ash from this plant is given in table 1.

Installation Procedure

Excavated soil stockpiled on the lateral bank was distributed in the lateral bottom as evenly as possible by a Gradall on the top of the canal bank. The fly ash was then dumped on the loose soil by a front-end loader. These materials were spread by hand and proportioned by estimation to provide a mixture for a 5- to 6-inch (125- to 150-mm) thick compacted layer in the lateral bottom with about 20 percent fly ash by dry weight of soil. During two passes of a small hand-operated garden rototiller that was 16 inches (406 mm) wide with tines on a 12-inch (305 mm) diameter rotor, water from a small firetruck was added by hose to bring the moisture to estimated optimum moisture content. After three or four passes of the rototiller, the mixture was compacted by three passes of a small hand-operated, plate-type vibrator. Without a better distribution of soil, fly ash, and water, it was inevitable that there would be considerable variation in (1) the percentage of fly ash, which was later established, (2) compacted layer thickness, and (3) the degree of compaction.

Table 5. – Compressive strengths after permeability and durability tests.

Test specimens	Previous test	Comp. strength lbf/in²	Comp. strength kPa
HC(X11)-30-27-PC2	permeability	450	(3100)
	freeze-thaw	516	(3600)
	wet-dry	1,113	(7700)
HC(X11)-30-27-HL	permeability	498	(3400)
	freeze-thaw	560	(3900)
	wet-dry	702	(4800)

Material for the side slope lining was deposited and mixed in the lateral bottom on lining placed the day before, and dragged up on the slopes by the Gradall. A small plate-type vibrator tied to the Gradall bucket was first tried for compacting the lining on the slopes, but this proved to be a slow and ineffective process and was soon abandoned. Instead, the slope lining was lightly compacted by dragging the Gradall bucket up the slope with downward pressure applied to the bucket. This was a much faster method, but it was obvious that very little compaction was being

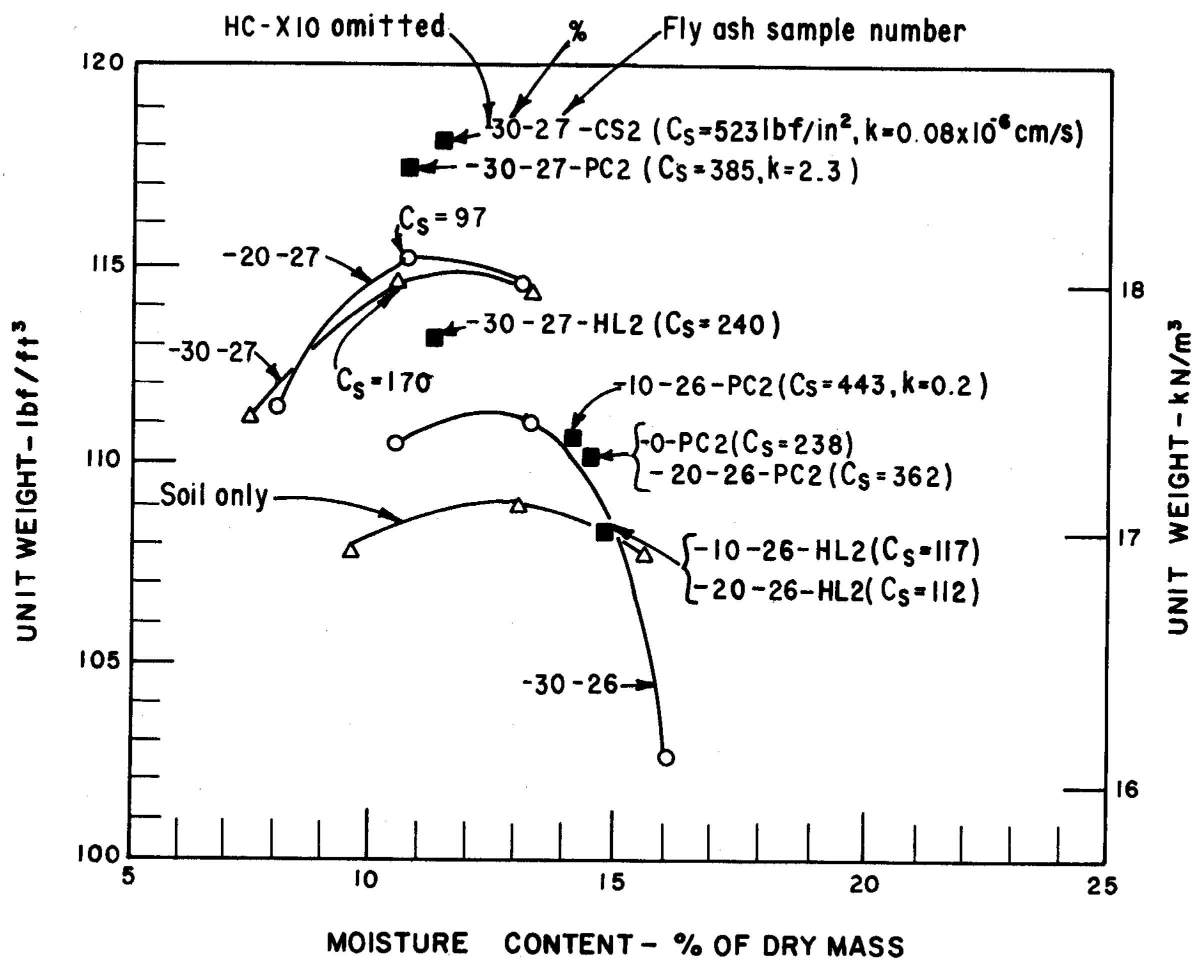


Figure 12. – Compaction test curves of Horse Creek Lateral soil (HC-X10) with 20 and 30 percent fly ash. Compressive strength and permeability test results without and with portland cement, calcium sulfate, or lime. C_s is in lbf/in².

accomplished. In some of the sections, 2 percent portland cement (by mass of soil) was added to the mixture to increase the strength.

After lining was placed, a 9-inch (229-mm) thick loose layer of wet, excavated lateral soil was placed on it to retain moisture in the lining for curing.

The bottom lining was placed on October 14, when the soil temperature was about 54 °F (12 °C). During that night about 0.5 inch (13 mm) of rainfall was recorded at the Pathfinder Irrigation District headquarters, which is about 15 miles (24 km) from the test site. On October 15, the temperature of the mixture was about 50 °F (10 °C). Next morning, the day after the installation was completed, the air temperature fell below freezing and it snowed.

Tests and Results

During the field test installation, unit weight tests were performed on the stabilized soil with a thin-walled, metal ring, about 2 inches (50 mm) in diameter and 1.25 inches (32 mm) high. The ring, which had a sharpened edge, was pushed into the fresh mixture after compaction. The ring, filled with the stabilized material, was excavated and removed from the lining, and after excess material was trimmed off even with the ends of the ring, the remaining material was extruded into a small metal can and sealed for laboratory determination of mass and moisture content. The dry unit weight of the material was calculated from the known volume of the ring, the mass of the mixture, and the moisture content. In addition, at the time of field installation, undisturbed samples of material were cut from bottom lining sections stabilized with fly ash and with fly ash and portland cement.

In April 1986, undisturbed block samples for laboratory testing were cut with a chain saw from sections in the bottom lining stabilized with fly ash and with fly ash and portland cement. At that time, the bottom lining was covered with from 6 to 12 inches (152 to 305 mm), and the side slopes with 2 feet (610 mm) or more of sediment.

Results of tests performed on samples of lining taken in 1980 at the time of installation and in 1986 are shown in table 6. Permeability test results for 1986 samples were much lower values than for the 1980 samples. The compressive strength for soil with fly ash only was not significantly different, but that for material with portland cement was much higher for the 1986 tests (140 lbf/in^2) than for the 1980 tests (25 lbf/in^2) when the specimens were oven-cured for 7 days at 120 °F (50 °C).

The approximate percentages of fly ash in lining samples were determined from chemical analyses for calcium content. For five samples taken from sections where no portland cement was added, the percentage of fly ash ranged from 20 to 50 percent. For three samples from a section where portland cement was added, the percentage of fly ash was 14, 16, and 39 percent; however, some of the calcium content was from portland cement. The chemical tests showed the high degree of nonuniformity of the mixtures.

It was obvious from the construction method used that the lining would not be homogeneous. The mixing and compacting equipment was too small to do a good job. During installation, examination of chunks in the compacted mixture showed divisions between raw soil and an excessive amount of cementing material. The construction was much too slow for economical application. For better and faster

Table 6. – Results of tests on fly ash-stabilized soil lining without and with 2 percent portland cement.

Unit weight, lbf/ft^3	Moisture content, %	Compressive strength, lbf/in^2	Permeability, cm/s × 10^{-6}	Remarks
		1980 tests (after lining installation)		
105 (4)[1]	12.1 (4)	–	6 (3)	soil + fly ash[2]
104 (4)	11.3 (4)	38 (3)	40 (4)	soil + fly ash
97 (4)	12.0 (4)	25 (5)	30 (5)	soil + fly ash + portland cement
		1986 tests		
92 (2)	20.5 (2)	30 (2)	0.2 (1)	soil + fly ash
95 (4)	21.1 (4)	140 (11)	0.2 (4)	soil + fly ash + portland cement

[1]Numbers of tests performed are indicated in parentheses.
[2]Tests on samples extracted from unit weight test rings. The other tests were on specimens cut from undisturbed block samples.

construction, larger equipment like the type used on highway construction would be needed.

PNEUMATICALLY-APPLIED SOIL-FLY ASH

Pneumatically-applied mortar (shotcrete) canal linings of sand and portland cement have been used to a limited extent [4]. For the dry-mix process used in tests described in this report, soil, fly ash, and portland cement were mixed with enough water to prevent dusting, and the mixture was forced by compressed air through a delivery hose with water added at the nozzle (p. 467 of [5]). Tests were made to compare unit weight and compressive strength test results from pneumatically-placed specimens with specimens tamped in molds by the Harvard Miniature compaction method. If successful, field application of a soil-fly ash-cement mixture using shotcrete equipment could be accomplished by irrigation O&M (operation and maintenance) personnel to repair canal seepage areas.

Equipment and Procedure

A 4-ft^3 laboratory concrete mixer was used for mixing soil, fly ash, cement, and a small amount of water. The mixture was then transferred to the laboratory shotcrete test equipment. This equipment consisted essentially of a hopper into which the mixture was shoveled, rotating cylinders through which the mixture dropped, and a compressed-air system that forced the mixture from the cylinders through a delivery hose (fig. 13). A water line separate from the house main line was attached to the nozzle where the operator could control the water flow rate to judge the amount needed for proper consistency of the mixture.

To prevent scattering of materials in the laboratory, specimens were prepared in a small area, enclosed except for an open door (fig. 14). Specimens were formed by blowing the mixtures into bottomless wooden molds 10 inches by 10 inches by 3 inches (254 mm by 254 mm by 76 mm) deep. Three molds, one above the other, were clamped on a ¾-inch (19-mm) thick steel plate with a sheet of plastic film between the plate and specimen bottom to prevent sticking (fig. 15). The three-mold arrangement allowed the operator to vary the water content between specimens without stopping until all of the molds were filled.

After the molds were filled, the top of each specimen was trimmed even with the top of the mold (fig. 16); the trimmings were used for moisture content tests. Wet unit weight was determined from the mass of material in the mold and the inside dimensions of the mold.

Figure 13. – Laboratory shotcrete equipment used to form soil-fly ash-cement specimens. P-801-D-81077

Specimens in the molds were enclosed by plastic sheeting and transferred to a 140 °F (60 °C) temperature-controlled room where they were allowed to cure for 7 days.

Six 2-inch (50-mm) cubic specimens were sawed from the central portion of each molded block for unit weight and compressive strength tests.

Materials

Soils used in the pneumatic tests consisted of dune sand and concrete sand (fig. 1). The dune sand was taken from a ridge below Lake Alice on the North Platte Project in Wyoming. The soil was representative of material at a seepage area on High-Line Canal. The concrete sand was the standard sand used by the Concrete and Structural Branch for research; it was from a local source and was separated into fractions and reconstituted to a specified average concrete sand grading.

The fly ash (42T-34) was a cementitious type from Laramie River Station Powerplant at Wheatland, Wyoming (similar to 42T-30 in table 1).

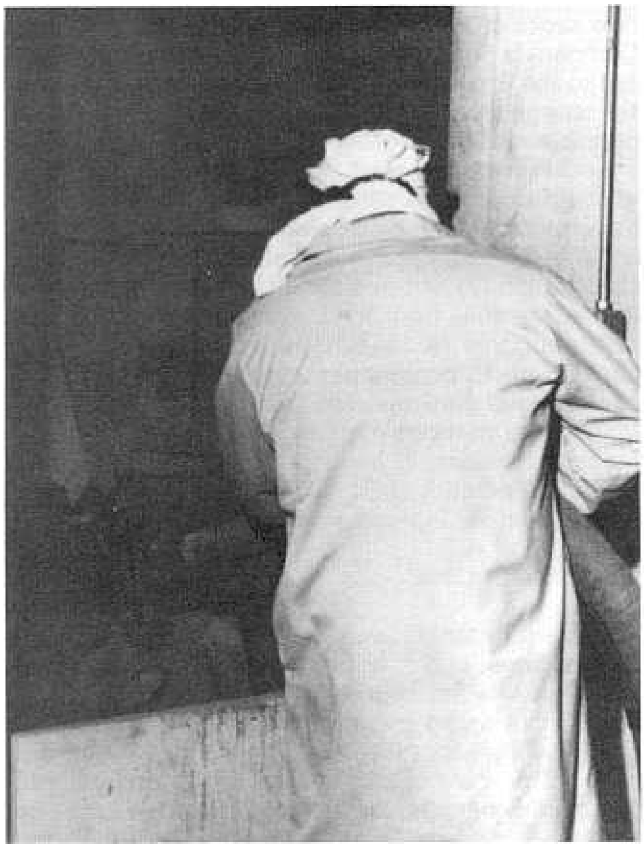


Figure 14. – Specimen being formed in a partially confined area by shotcrete equipment. P-801-D-81078

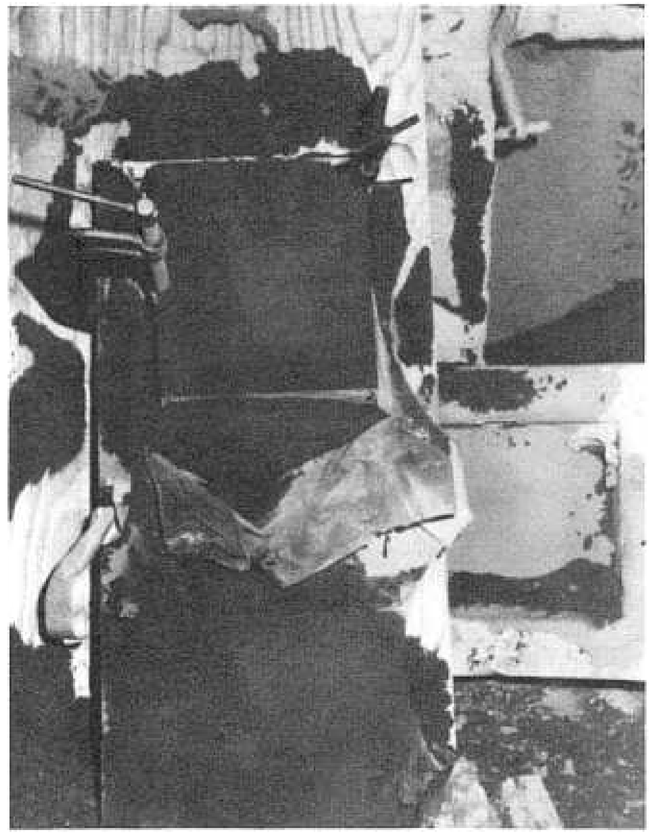


Figure 15. – Fresh soil-fly ash-cement specimens formed pneumatically. P-801-D-81078

The portland cement was a standard cement used by the Concrete and Structural Branch for research; it conformed to requirements of the ASTM (American Society for Testing and Materials) for type 2 portland cement.

For mixtures with either dune or concrete sand, 20 percent fly ash with and without 6 percent portland cement were used. The percentages for both materials were based on the dry weight of sand.

Problems

The laboratory shotcrete equipment was not designed for soils containing a large proportion of fines. The dune sand contained 27 percent of particles passing the No. 200 sieve; therefore, the additional 20 percent fly ash was too much for the equipment to function properly.

It was difficult to premix the right amount of water to prevent an excessive amount of dust caused by the compressed-air system and still keep the soil from balling and sticking in the equipment.

To obtain a high unit weight mixture in the molds, air pressure was applied as high as possible. An attempt was made to maintain a 50-lbf/in^2 (345-kPa) air pressure, but for many of the tests a constant pressure could not be maintained and the pressure varied mostly on the low side. During several of the tests, the air pressure caused a rubber gasket to rupture and interrupted the tests.

When cubic specimens were sawed, some layering of material was noticed. For a field application of shotcrete, skill of the nozzle operator is very important and a good operator can apply material with a minimum of layering. However, it is particularly difficult to prevent layering of specimens in small molds.

The concrete sand contained an insignificant percentage of fines passing the No. 200 sieve, and with 20 percent fly ash and 6 percent cement, the material worked somewhat better than dune sand in the shotcrete equipment.

Test Results

The results of unit weight tests and 8½-month compressive strength tests on cubes sawed from the pneumatically-placed block specimens, along with those of cylindrical compaction specimens for comparison, are shown on figure 17. Because of the problems encountered, which undoubtedly caused many

Figure 16. – Trimming surface of soil-fly ash cement specimen. P-801-D-81080

poor specimens, only the best compressive strength and unit weight test results are shown. The most impressive results were the high unit weights and compressive strengths obtained with the pneumatically-applied specimens of concrete sand with 20 percent fly ash and 6 percent portland cement; the unit weights averaged about 9 percent higher and the compressive strengths about 46 percent higher than for the maximum unit weight compacted specimen with similar amounts of materials. For the dune sand specimens with 20 percent fly ash and 6 percent cement, the unit weight of the pneumatically placed specimens was about 3 percent higher, and the compressive strength 10 percent higher than for the compacted specimen. The compressive strength of the dune sand specimen with 6 percent cement had a compressive strength over 7 times that for a specimen without any cement (not shown on fig. 17). The maximum compacted unit weight of concrete sand with 20 percent fly ash and 6 percent cement sand was about 8 lbf/ft^3 (1.3kN/m^3) higher than the mixture without cement (not shown).

TESTS ON BURNHAM LATERAL SOIL

Accompanied by a letter dated July 10, 1979 [6], five sacks of soil from the Burnham Lateral area and two sacks of fly ash from the Arizona Public Service Company's Four Corners Powerplant were transmitted to the Engineering and Research Center. The letter suggested testing soil-fly ash mixtures for possible stabilization of embankments for the proposed Burnham Lateral. There was concern about wind erosion of the sand, particularly erosion of embankments and subgrade slopes, until concrete lining could be placed. For this reason, laboratory chemical stabilization [7] and petrographic tests [8] were performed on soils from the Burnham Lateral area. The soil (laboratory No. 60K-1) was a typical dune sand (fig. 1) with 13 percent passing a No. 200 sieve. The coarser sand particles were mostly subrounded. The No. 30 size particles contained 83 percent quartz, 8 percent feldspar, 2 percent sandstone, 1 percent phyllite, 5 percent chert, 0.5 percent pyroxene, and 0.5 percent ferruginous material.

Fly Ash and Lime

The Four Corners Powerplant fly ash (42T-21) is not cementitious, and it will not, by itself, form a hardened mass when mixed with soil and water. However, a cemented mass will result if lime is added. Table 1 shows that the Four Corners fly ash contains only 3.5 percent calcium oxide, much less than the 17 to 26.5 percent for the other five cementitious-type fly ashes listed.

The lime used was ASTM type N (normal hydrated).

The following mixtures were tested (the percents listed are by mass of dry soil):

Percent fly ash	*Percent lime*
10	4
20	2
30	4
30	2

Test Procedures

Procedures for these tests were the same as for the mixtures with Mirdan Canal and Horse Creek Lateral soils. For each mixture, compaction tests were made using the Harvard Miniature compaction test equipment. After oven curing, the compaction test specimens were tested for compressive strength, permeability, and resistance to wetting and drying and to freezing and thawing.

Test Results

Results of compaction, compressive strength, and permeability tests on the Burnham Lateral soil without and with different percentages of fly ash and lime are shown on figure 18. The addition of 10 percent fly ash and 4 percent lime to the soil caused about

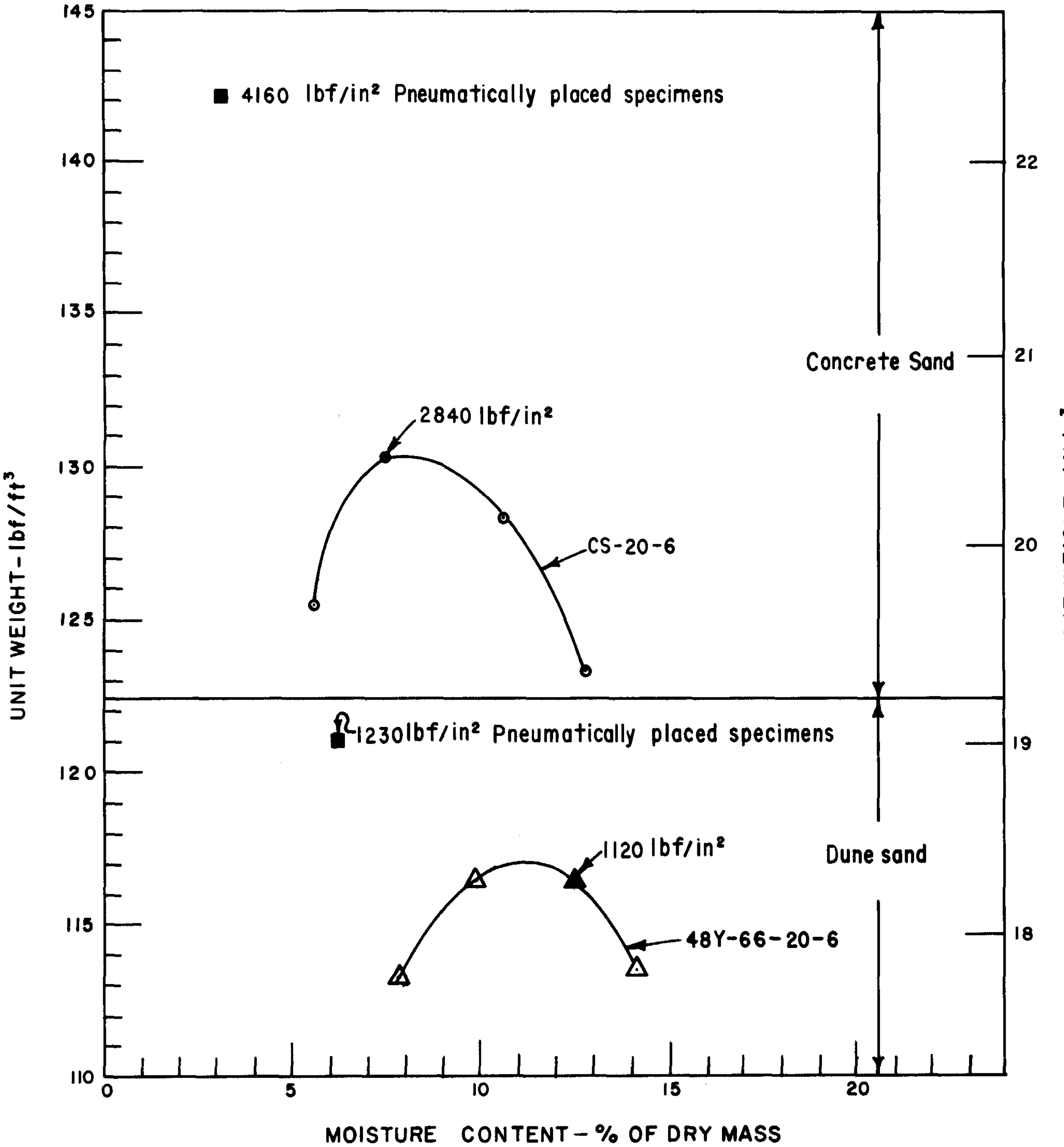


Figure 17. – Results of 8½-month compressive strength tests on compaction specimens (on curves) and on specimens placed pneumatically for dune sand (48Y-66) and concrete sand (CS) with 20 percent fly ash and 6 percent portland cement.

1 percent increase in maximum unit weight; however, as the fly ash was increased to 30 percent, the unit weight decreased significantly. The highest compressive strengths, 183 and 139 lbf/in^2 (1260 and 960 kPa) on specimens selected near maximum unit weight, occurred with the use of 20 percent fly ash and 4 and 2 percent lime, respectively. The lowest strengths were with 30 percent fly ash for either 4 or 2 percent lime. The much lower permeability on the wet side of optimum than on the dry side is significant.

Durability tests were performed on specimens wet and dry of optimum moisture (fig. 19). The specimens with 30 percent fly ash were all in poor condition after freeze-thaw and wet-dry tests. There

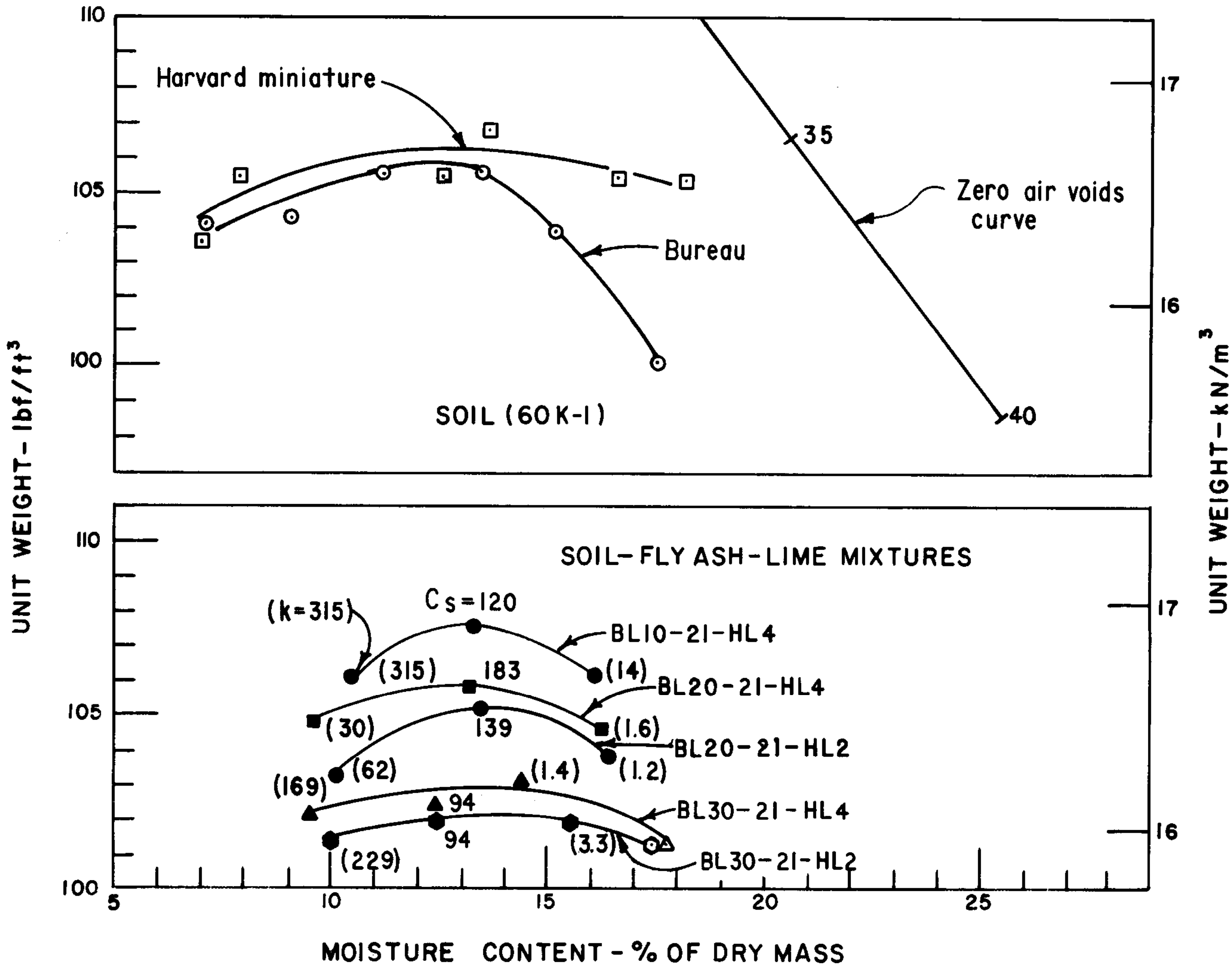


Figure 18. – Compaction curves on Burnham Lateral soil and soil-fly ash-lime mixutres. C_s is in lbf/in², *k* (in parentheses) is in 10^{-6} cm/s.

were no cracks, but material could be scraped off with a fingernail, and the specimens could be broken by finger pressure. Specimens with 20 percent fly ash and 4 percent lime were in good condition after the freeze-thaw and wet-dry tests, and most of their corners were still sharp. The specimens with 20 percent fly ash and 2 percent lime were intact after 12 cycles, but their corners were rounded, and light brushing caused striations in surfaces. Specimens with 10 percent fly ash and 4 percent lime were in relatively poor condition after 12 cycles of freeze-thaw and wet-dry testing. Optimum amounts of fly ash and lime, for the mixtures tested, were 20 percent fly ash and 4 percent lime.

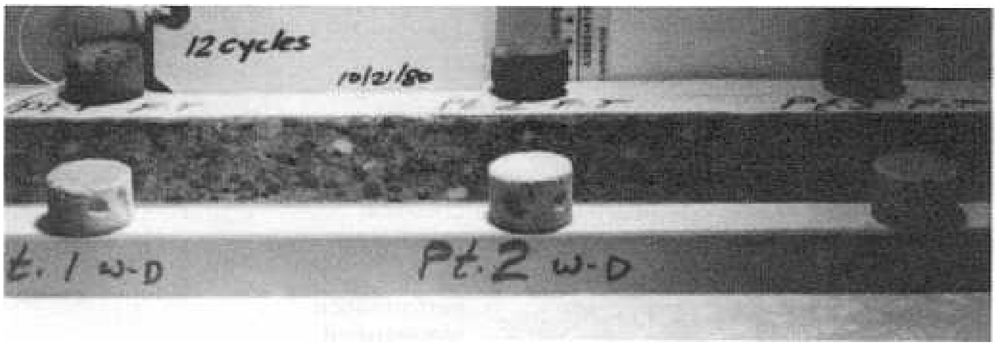
Additional Tests by the Materials Science Section

With portions of the same materials tested by the Geotechnical Branch, the Materials Science Section of the Applied Sciences Branch tested mixtures of Burnham Lateral soil, Four Corners fly ash, and lime [9]. These tests provided a comparison with tests previously made with several spray-applied chemical soil stabilizers for surface stabilization to prevent wind erosion [7]. The mixtures used were:

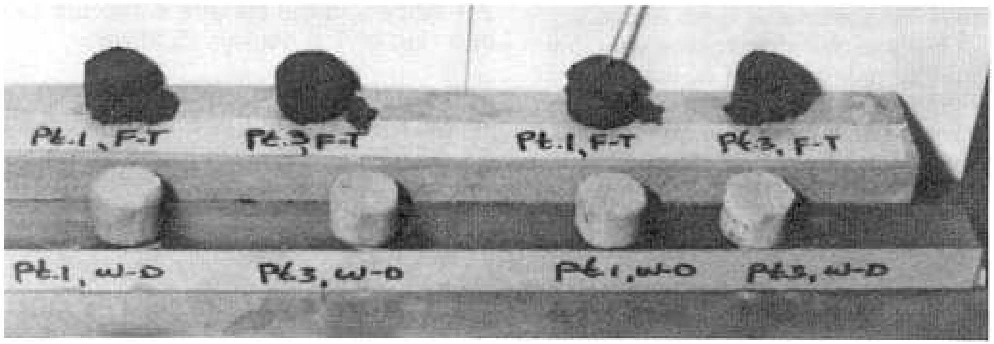
1. Ten percent fly ash and 4 percent lime, both by weight of dry soil.

2. Twenty percent fly ash and 2 percent lime.

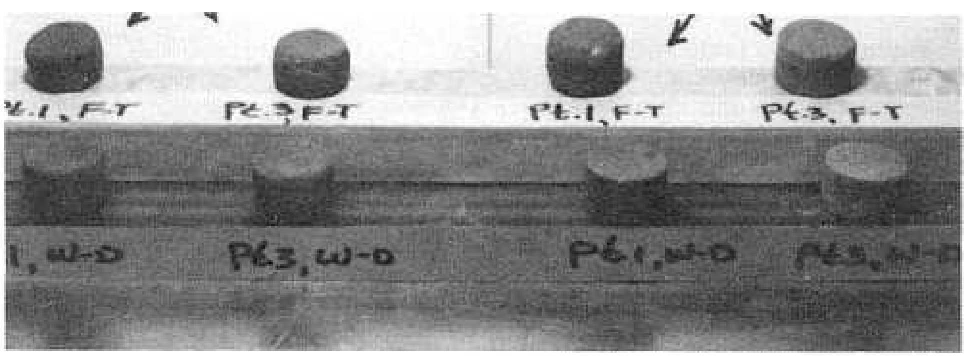
Compressive strength, water erosion, and weatherability tests were made by the same test procedures used for the chemical stabilizers. The test procedures are described in [7] and [10]. Performance requirements for the chemical stabilizers listed below comparing test results are tentative for control of surface erosion. They are based on an application of 0.1 gal/yd² (0.45 L/m²) on Cherry Creek sand graded as specified on p. 9 of [10].



a. Ten percent fly ash and 4 percent lime. P–801–D–81071



b. Twenty percent fly ash with 2 percent lime (two on the left) and with 4 percent lime (two on the right). P–801–D–81072



c. Thirty percent fly ash with 2 percent lime (two on the left) and with 4 percent lime (two on the right). P–801–D–81073.

Figure 19. – Freeze-thaw (FT) and wet-dry (WD) specimens of Burnham Lateral soil and Four Corners Powerplant fly ash and hydrated lime.

Compressive Strength. – The compressive strength specimens were cylinders 2 inches (50 mm) in diameter by 2 inches high in which the lime and fly ash or chemical stabilizer were mixed before compaction. One group of specimens was cured for 7 days in air at 73 °F (23 °C) with 50 percent humidity, and the other in an oven at 140 °F (60 °C). The results of compressive strength tests on specimens of soil-fly ash-lime were:

	Air cured, lbf/in² (kPa)	*Oven-cured, lbf/in² (kPa)*
Untreated control	246 (1696)	218 (1503)
Mixture 1 (10% fly ash, 4% lime)	42 (290)	20 (138)
Mixture 2 (20% fly ash, 2% lime)	22 (152)	44 (303)

As shown, the compressive strengths of the soil-fly ash-lime mixtures were much lower than those of the untreated specimens. All specimens were tested dry without soaking. A likely explanation for the very low strength of the lime-fly ash mixtures is that during curing the specimens were unconfined, and there was no provision made to retain the moisture necessary for hydration.

Results of compressive strength tests on chemically-stabilized soil were:

	Air-cured lbf/in² (kPa)	*Oven-cured lbf/in² (kPa)*
Untreated control	122 (841)	170 (1172)
Recommended chemical stabilizer	319 (2200)	322 (2220)
Minimum performance requirements	100 (690)	100 (690)

Water Erosion. – Water erosion tests with a submerged jet were made on cylindrical specimens prepared in the same manner as for the compressive strength specimens. One group of specimens was tested immediately (0 time) after curing for 7 days at 140 °F (60 °C), and another after 7 days immersion in water. The results of 2-hour jet tests on soil-lime-fly ash specimens were:

	Time of test after curing, days	*Percent erosion by weight*
Untreated control	0	78 (after 30 seconds)
Mixture 1 (10% fly ash, 4% lime)	0 7	0.26 0.25
Mixture 2 (20% fly ash, 2% lime)	0 7	0.86 0.29

The results of 2-hour jet tests on the chemically-stabilized soil specimens were:

	Time of test after curing, days	*Percent erosion by weight*
Untreated control	0	78 (after 30 seconds)
Recommended chemical stabilizer	0 7	3.8 0.7
Maximum performance requirement	7	1.0

Surface-runoff tests with water were performed on 12- by 12- by 2-inch (305- by 305-by 51-mm) compacted block specimens of soil-fly ash-lime without curing. During testing, a specimen was placed on a 2:1 slope and the surface subjected to water runoff at a rate of 1.5 gal/min (5.8L/min).

The results of the surface-runoff tests on soil-lime-fly ash mixtures on the soil surface were:

	Duration of test	*Weight loss, %*
Untreated control	1 min	22
Mixture 1 (10% fly ash, 4% lime)	6 h	0.1
Mixture 2 (20% fly ash, 2% lime)	6 h	0.1

The results of surface-runoff tests on soil-fly ash with the recommended chemical stabilizer sprayed on the soil surface were:

	Duration of test	*Weight loss, %*
Untreated control	1 min	22
Recommended chemical	6 h	1.5

Weatherability. – For the weatherability tests, compacted, uncured, block specimens of soil measuring 12 by 12 by 2 inches were placed on a 2:1 slope in an outdoor exposure test area and left there for 1 year. At the end of that time, weight loss for mixture 1 was 30 percent and that for mixture 2 was 56 percent. These losses are greater than the 21-percent weight loss for an untreated specimen of similar soil tested previously. The tentative performance requirement for weatherability is no loss after 1 year.

The results of the compressive strength and weatherability tests, which were not water-cured, are good examples of the necessity of curing of soil-fly ash-lime mixtures. The submerged jet erosion tests on the specimens cured without water, and on uncured surface-erosion specimens performed better than expected.

Normally during field construction, a completed installation of soil-fly ash-lime would be immediately followed by the application of moist curing, which would be continued for a minimum of 7 days. Sometimes instead of a continual application of water or a covering of soil kept continuously wet, an asphalt coating is applied to retain moisture during placement.

APPLICATIONS

The use of fly ash, much of which is a waste product, is encouraged and may eventually be mandated by the EPA (Environmental Protection Agency) for the type of construction toward which this research is directed. The small-scale field test pointed out the need for improvement in construction equipment and construction control to obtain a satisfactory canal lining on an economical production basis. Performing laboratory tests such as those described in this report is an economical first step in research, which may lead to the eventual application of fly ash in field work. Performance of the materials used in various proportions was unpredictable, and laboratory results indicate how the various combinations of materials may or may not perform in long-term field usage. The results provide the investigator with a basis for selecting the most promising combinations for further research, which generally proceeds from small to larger field applications.

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APPENDIX A

BRIEF DESCRIPTION OF LABORATORY TEST PROCEDURES

UNCONFINED COMPRESSIVE STRENGTH

The unconfined compressive strength test was performed in accordance with the triaxial shear method (designation E-17 of [2]), except that the lateral pressure was equal to atmospheric or zero gauge pressure. Specimens were submerged in water for a 4-hour period just before the compressive strength test. The specimens were tested at a strain rate of 0.02 inch/min (0.5 mm/min). Compressive strength was calculated by dividing the maximum axial load by the specimen area.

FALLING HEAD PERMEABILITY

Specimen

The permeability test specimen was the middle third cut from the center of a Harvard Miniature compaction test specimen after it had been cured for 7 days in a 120 °F (50 °C) oven.

Permeameter

The permeability cylinder for a specimen was a section of clear acrylic tubing about 2 inches (50 mm) in diameter by 1.8 inches (46 mm) long. A section of No. 8 screen was cemented to one end and formed the bottom of the cylinder, and a No. 100 screen was cut to fit inside the cylinder on the bottom beneath the specimen. A rubber stopper was placed in the top of the cylinder with a piece of ¼-inch (6-mm) diameter plastic tubing connected by plastic or rubber tubing to a head tank. The head tank was glass tubing about 3 feet (1 m) long and 0.6 inch (15 mm) inside diameter. The complete permeameter with the head tank supported on a rack is shown on figure A-1c.

Materials

De-aired water (maximum of 1.0 p/m of dissolved oxygen) was used for the test. Modeling clay was used to seal between the cylinder wall and specimen.

Procedure

After measuring the height and diameter of specimen it was placed in the permeability cylinder and modeling clay was tamped firmly in the space between the specimen and the cylinder wall (fig. A-1a). This was done carefully with a glass stirring rod to ensure that water would not flow between the cylinder wall and the specimen.

The permeability cylinder with the specimen was placed in a beaker, and the beaker was filled with water to a level above the soil specimen surface. This was done to saturate the specimen from the bottom upward, and the apparatus was left until water appeared on the specimen surface. The permeability cylinder with the specimen was then removed from the beaker of water. The space over the specimen in the cylinder was filled with fresh de-aired water, and the stopper with tubing was inserted in the top of the cylinder. The permeameter was assembled with the head tank supported with clamps on a support stand. The permeameter cylinder with specimen was submerged in a beaker full of water.

The head tank was filled with water. The distance from the water overflow surface in the beaker to the water level in the head tank was measured.

A test run was accomplished by measuring the time it took for the water level in the head tank to drop a minimum of one-third the head tank length. The coefficient of permeability was calculated by the following formula:

$$k_{20} = \frac{2.3\,aL}{A(t_1 - t_0)} \log_{10}\left(\frac{h_o}{h_1}\right)$$

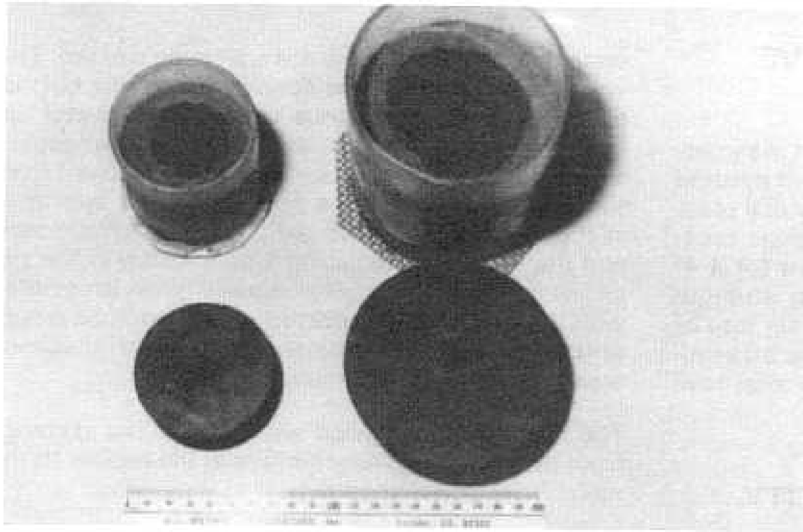
where:

k_{20} = coefficient of permeability corrected to a viscosity at 20 °C (designation E-36, fig. 36-4 of [2]),
a = cross-sectional area of head tank,
L = length of specimen,
A = cross-sectional area of specimen,
t_0 = time when water in the standpipe was at level h_0 at beginning of test,
t_1 = later time when the water in the standpipe was at level h_1,
h_0 = water level at start of test run, and
h_1 = water level at end of test run.

The head tank was refilled and the test continued until the calculated permeability test results were relatively uniform.

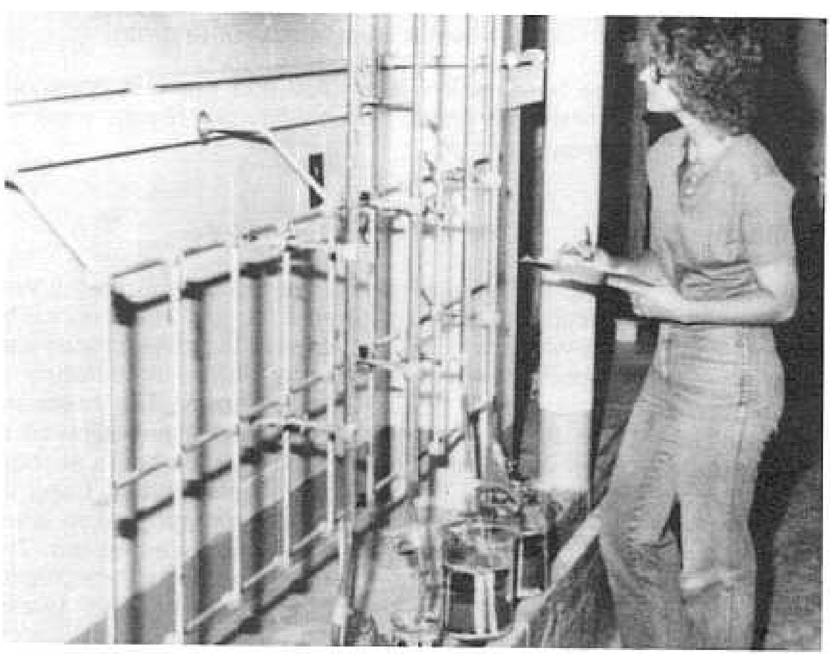
FREEZE-THAW

After the mass of a specimen was recorded, it was placed on a water-saturated felt pad in a 4-ounce tin can with a lid. The specimen in the covered can was placed in a freezing cabinet with a temperature of about −10 °F (−23 °C) for 24 hours. The specimen was then removed from the freezer and allowed to thaw in the can without cover for 24 hours at room temperature. The specimen was examined and its condition was recorded by photographs taken when significant changes in its condition were noted. The procedure described above constituted one freeze-thaw cycle. The test was continued until twelve



a. Two sizes of acrylic permeability cylinders with specimens prepared for testing. Space between specimen and cylinder wall was filled with modeling clay. P–801–D–81074

b. Specimens soaked in plastic cylinders set in beaker filled with de-aired water. Water rose through the bottom to the top where it appeared on the surface of the specimen. P–801–D–81075



c. Reading the water level in the glass head tank to measure the volume of water passing through the specimen. P–801–D–81076

Figure A-1. Falling-head permeability test.

cycles were completed, unless the specimen was observed to have deteriorated excessively. From this test it was possible to compare the performance of the different mixtures in a qualitative manner.

WET-DRY

A specimen for the wet-dry test was placed in a can without a felt pad. The specimen was covered with tap water and let to stand at room temperature for 24 hours. Then the water was poured from the can and the specimen surface was dried.

The specimen was then placed uncovered in an oven at 160 °F (71 °C) for 24 hours. The specimen was removed from the oven, carefully examined, and its condition noted. When there were significant changes in its appearance, photographs were taken. This constituted one wet-dry cycle. This procedure was repeated for twelve cycles, unless there was a significant deterioration in condition before the end of the twelve cycles. In a manner similar to the freeze-thaw test, this test allowed a qualitative comparison between the performance of specimens with different mixtures under wet-dry conditions.

APPENDIX B

CHEMICAL TESTS TO DETERMINE TOXIC LEVELS IN FLY ASH

OPTIONAL FORM NO. 10
JULY 1973 EDITION
GSA FPMR (41 CFR) 101-11.6

UNITED STATES GOVERNMENT

Memorandum

Memorandum — Denver, Colorado

TO : Head, Soil Testing Section — DATE: June 29, 1981

FROM : Head, Chemistry, Petrography, and Chemical Engineering Section

SUBJECT: Discussion of Testing Procedures Used in the Investigation of Metals Contained in Fly Ash

The following tests were performed to determine the possible toxic metal contribution to water supplies from the use of fly ash materials as canal embankment stabilizers.

Test 1

Three fly ash samples were treated with 1 percent nitric acid (HNO_3) at 90 °C. The metals in the fly ash sample are soluble under these conditions and dissolve from the fly ash into the acidic solution. The concentrations of acid-extractable metals, silver (Ag), cadmium (Cd), chromium (Cr), iron (Fe), mercury (Hg), lead (Pb), selenium (Se), zinc (Zn), and arsenic (As), were determined by spectroscopic analysis of the nitric acid solution. Concentrations of acid-extractable metals from fly ash samples are shown in table 1.

Table 1. - Acid-extractable metals (mg/g)

Fly ash	Ag	Cd	Cr	Fe	Hg	Pb	Se	Zn	As
42T-25	0.0006	0.0008	0.007	0.007	ND	0.010	0.130	0.010	2.76
42T-26	0.0004	0.0013	0.024	3.25	ND	0.011	0.075	0.024	11.4
42T-27	0.0004	ND 1/	0.003	0.010	ND	0.010	0.129	0.002	1.68
Detection limit	0.0004	0.0004	0.0004	0.0004	0.00001	0.004	0.004	0.0004	NA 2/

1/ ND = Not detectable at listed detection limit.
2/ NA = Not available.

Acid extraction of the fly ash material does not simulate the leaching effect of the canal water on the embankment material. Rather, it provides concentration values which are the total amounts of each metal contained in a given weight of fly ash. The acid extraction then expresses the worst case condition of the metal's availability to the water supply.

Test 2

Two fly ash samples and three soil/fly ash mixtures were mixed with distilled water for 1 week at room temperature. The water was then separated from the solid material, acidified, and analyzed for metals by spectroscopy. The concentrations of water-leached metals (Pb, Cr, As, Se) per gram of sample are listed in table 2.

Table 2. - Water-extractable metals (mg/g)

Sample No.	Pb	Cr	As	Se
42T-26 (30%) + 59R-1	ND	0.010	ND	ND
42T-21 (30%) + 60K-1	ND	ND	ND	ND
42T-30 (30%) + 48Y-X31	ND	0.010	ND	ND
42T-29	ND	0.030	ND	0.01
42T-27	ND	0.020	ND	ND
Detection limit	0.002	0.002	0.02	0.02

The water leaching of the fly ash and soil/fly ash mixtures was done to more realistically estimate the availability of metal through solutioning of the embankment lining by the canal water.

EPA (Environmental Protection Agency) Hazardous Waste Guidelines

The EPA has established guidelines for the maximum concentrations of certain metals which may be leached from solid materials placed in the environment. Although fly ash is specifically exempted from regulation as a hazardous waste (Part 261.46 of the EPA Hazardous Waste Management System), a comparison of the test data was made with EPA toxicity guidelines.

The available metal concentrations as described by the EPA are determined by analysis of an acetic acid solution (pH5) which has been in contact with the solid material for 24 hours in a ratio of 16 parts leaching solution to 1 part of sample by weight. If the concentration of any of the metals listed exceeds specified amounts, the solid material is considered a hazardous waste, and special handling is required for placement in the environment. The maximum concentrations of metals allowable in the leachate under EPA guidelines are contained in table 3.

Table 3. - Maximum allowable leachate concentrations (mg/L) (EPA)

Contaminant	Ag	As	Ba	Cd	Cr	Pb	Hg	Se
Concentration	5.0	5.0	100	1.0	5.0	5.0	0.2	1.0

From Federal Register, vol. 45, No. 98, May 19, 1980, p. 33,122.

To compare the acid- and water-extracted metal's values to EPA guidelines, the leach ratio of 1:16 was used to convert the EPA allowable levels in milligrams per liter to milligrams per gram of sample. The following concentration levels were calculated:

EPA hazardous waste guidelines (mg/g)

Contaminant	Ag	As	Ba	Cd	Cr	Pb	Hg	Se
Concentration per weight of sample (mg/g)	0.08	0.08	1.6	0.02	0.08	0.08	0.003	0.02

A review of the nitric acid-leached fly ash data (table 1) shows that concentrations of arsenic and selenium clearly exceed EPA guidelines. Table 2 results show that levels of water-leached metals are much lower than EPA guidelines.

If further testing is desired, it is recommended that the EPA extraction procedures be followed. This test, according to EPA, provides a close approximation to environmental conditions, and the data can be evaluated against EPA established toxicity guidelines.

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The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

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