Use of Ash in Embankment Construction

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This paper summarizes the annual quantities of fly ash, bottom ash, and boiler slag recently produced by major electric utilities in the United States and makes projections for future production. Similar data for England are also presented. Available data on the chemical, index, and engineering properties of these materials and on the use of fly ash, bottom ash, and boiler slag by the construction industry in the United States and England are presented. Since the use of fly ash as a highway embankment fill material in the United States appears to be extremely promising, the paper describes several projects in the United States, England, and Scotland in which large quantities of fly ash have been used successfully and economically.

The magnitude of global energy problems combined with dwindling natural resources has made it clear to a substantial and growing segment of the engineering community that the use of power industry by-product resources, such as fly ash, bottom ash, and boiler slag, must be substantially increased over the next several decades if we are to effectively resolve these serious problems. In fact, the need for developing new technologies of conservation and use becomes more apparent and urgent with each passing month, as we are confronted by the challenge of rapidly diminishing natural construction materials.

Fortunately, through the combined efforts of the National Ash Association, the Bureau of Mines, universities, private practitioners, and others, the technology for using fly ash, bottom ash, and boiler slag in highway construction is, by and large, available. Fly ash is currently being used as a fill material in the construction of highway embankments, and fly ash, bottom ash, and boiler slag are being used as fillers in asphalt pavements. In addition, fly ash is being used as a pozzolan in cement-aggregate or lime-aggregate base course construction, and bottom ash is used as the aggregate in many cases. The technology for the design and construction of cement-bound fly ash base courses was developed in Europe and is being further developed in the United States through a project funded by the National Ash Association. Bottom ash and boiler slag are also being used as antiskid materials for roadways during winter.

A logical and potentially promising area for the large-volume use of fly ash is the construction of highway embankments. This paper describes several projects in which fly ash has been used as a fill material in highway embankment construction. In addition, quantities of ash collected and used both in the United States and England are summarized, and the chemical, index, and engineering properties of fly ash, bottom ash, and boiler slag are discussed.

COLLECTION AND USE

Figure 1 shows by state the approximate quantities of coal burned by major electric utilities during 1973. More than 85 percent of the coal is burned by utilities located east of the Mississippi River. Figure 2 shows the approximate quantities by region of coal burned and the amount of ash produced and used in the United States during 1973, and Figure 3 shows a compilation by year of coal consumption and ash production by electric utilities in the United States based on data from the National Ash Association (1) from actual data up to 1975 and projected for subsequent years.

Table 1 gives data compiled by the National Ash Association on the use of ash in the United States during 1974. Table 2 gives a comparison of ash collected and used in the United States from 1966 through 1974. These data indicate that ash production during this period increased by about 135 percent and that use increased by more than 180 percent. They also indicate that a substantial volume of ash must currently be placed in storage areas each year. For example, approximately 46 Tg (51 million tons) of ash went unused in 1974. Therefore, the stockpiles of these valuable by-product resources are growing throughout the United States and will continue to do so, especially with the recent order by the Federal Energy Administration to many utilities to convert from oil to coal. It seems logical, therefore, to direct our efforts toward increasing ash use in highway construction.

As given in Table 1, the U.S. highway construction industry in 1974 used about 2 Tg (2.2 million tons) of

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Figure 1. Approximate quantities of coal burned by electric utilities by state.

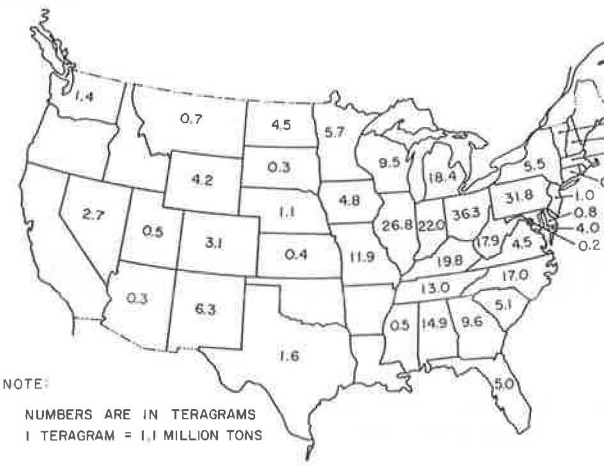


Figure 2. Approximate quantities of coal burned and ash produced and used by electric utilities by region.

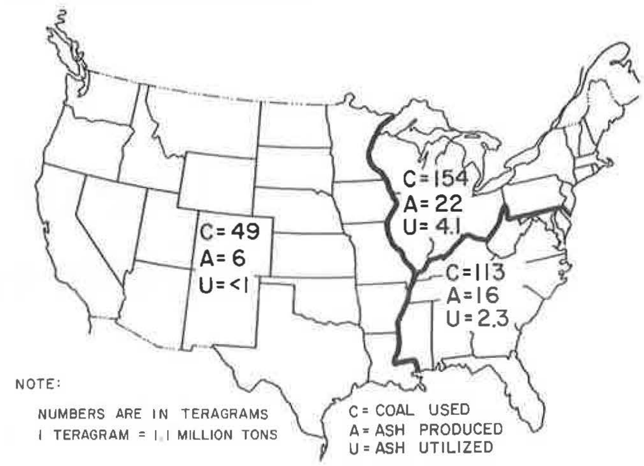


Figure 3. Coal consumption and ash production by U.S. electric utilities.

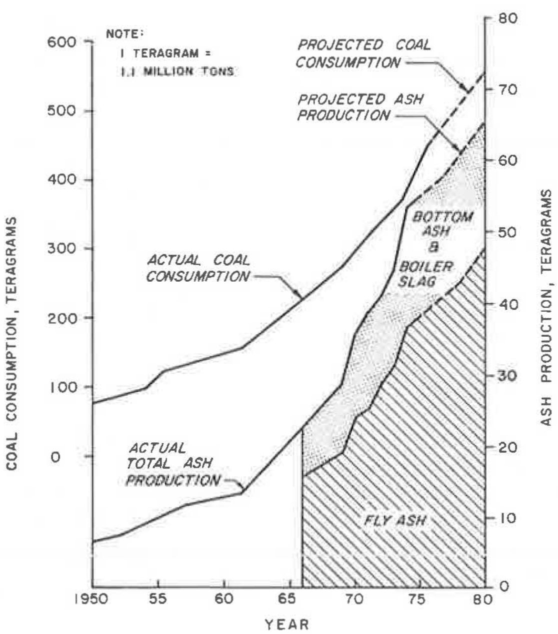


Table 1. Ash uses, ash removed from the plant site, and ash used from storage in the United States in 1974.

Item	Fly Ash (Tg)	Bottom Ash (Tg)	Boiler Slag[a] (Tg)	Total Ash (Tg)
Ash use				
In type 1-P cement ASTM 595-71 or mixed with raw materials before forming cement clinker	0.4	<0.1	–	0.4+
Partial replacement of cement in concrete or concrete products	0.5	–	–	0.5
Lightweight aggregate	0.1	0.1	–	0.2
Stabilization and roads	0.3	0.5	1.1	1.9
Filler in asphalt mix	0.1	<0.1	<0.1	0.1+
Miscellaneous	0.4	0.8	0.9	2.2
Total	1.8	1.5+	2.0+	5.3+
Ash removed from plant site at no cost to utility	0.4	0.5	0.1	1.0
Ash used from storage	0.9	0.6	0.1	1.6
Total use by weight				
Amount	3.1	2.6	2.2	7.9
Percent	8.5	20.0	50.0	14.6

Note: 1 Tg = 1.1 million tons.

[a]If separated from bottom ash.

Table 2. Ash collected and used in the United States from 1966 through 1974.

	Ash Collected (Tg)				Ash Used: Fly Ash		Bottom Ash		Boiler Slag		Total	
Year	Fly Ash	Bottom Ash	Boiler Slag	Total	Amount (Tg)	Percent	Amount (Tg)	Percent	Amount (Tg)	Percent	Amount (Tg)	Percent
1966[a]	15.5	7.4	–	22.9	1.3	8.4	1.5	20.3	–	–	2.8	12.3
1967	16.7	8.2	–	24.9	1.3	7.8	2.1	25.6	–	–	3.4	13.7
1968	18.0	6.6	2.4	27.0	1.7	9.4	1.6	24.2	1.4	58.3	4.7	17.4
1969	19.1	6.9	2.6	28.6	1.7	8.9	1.8	26.1	0.9	34.6	3.7	12.9
1970	24.0	9.0	2.5	35.5	2.0	8.3	1.6	17.8	1.0	39.4	4.6	13.0
1971	25.2	9.2	4.5	38.9	3.0	11.9	1.5	16.3	3.4	75.6	7.9	20.3
1972	28.8	9.7	3.5	42.0	3.3	11.5	2.4	24.7	1.2	34.3	6.9	16.4
1973	31.4	9.7	3.6	44.7	3.5	11.1	2.1	21.6	1.6	44.4	7.2	16.1
1974[b]	36.6	13.0	4.4	54.0	3.1	8.5	2.6	20.0	2.2	50.0	7.9	14.6

Note: 1 Tg = 1.1 million tons.

[a]First year for data.

[b]More comprehensive data collection program was developed, thus resulting in substantial increase over previous year.

ash, or approximately 25 percent of the total ash used. By contrast, as given in Table 3, the highway construction industry in England used about 1.6 Tg (1.8 million tons) in 1973-74 in roads and embankments alone, or 35 percent of the total ash used. In the past, this figure has been as high as 67 percent. Without a doubt, the highway construction industry is the number one potential bulk user of ash in the United States. To this end, the Federal Highway Administration is currently sponsoring two projects related to the use of ash in highway construction. Ohio State University was awarded a research contract to study power plant bottom ash in black base and bituminous surfacing. The objectives of the study are to investigate the feasibility of using bottom ash in bituminous mixtures and to develop technical data on the physical and engineering properties of the material.

GAI Consultants, Inc., was awarded the second research contract to study the use of fly ash as a construction material for highways. As with the Ohio State University study, the main objective of the GAI study is to develop a user's manual encouraging design and construction engineers to provide for the use of fly ash on highway projects. The manual is intended to supply data and information on the use of fly ash in the following applications: as a material for subbase and base course construction with cement or lime stabilization, as a soil stabilizing material, as embankment fill material, as a lightweight fill in slope stabilization projects, in grouting operations, and for structural backfill.

CHEMICAL PROPERTIES OF ASH

Fly Ash

Figure 4 shows the variations in chemical composition of fly ash produced in the United States (8). As shown, the principal constituents of fly ash are silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), and there are smaller amounts of calcium oxide (CaO), magnesium oxide (MgO), sulfur trioxide (SO_3), sodium oxide (Na_2O), and unburned carbon. The constituents most likely to affect the index and engineering properties of fly ash are free lime and unburned carbon. Free lime influences the pozzolanic activity of fly ash, and unburned carbon affects compaction and strength characteristics. The water soluble constituents are calcium and sulfur.

Bottom Ash and Boiler Slag

Figure 5 shows the variation in chemical composition of bottom ash and boiler slag (9). As with fly ash, the major constituents of bottom ash and boiler slag are silica, alumina, and iron oxide, and there are smaller quantities of calcium oxide, magnesium oxide, sodium oxide, potassium oxide (K_2O), sulfur trioxide, and other compounds.

INDEX PROPERTIES OF ASH

Fly Ash

Fly ash is characterized by low specific gravity, uniform gradation, and lack of plasticity. The specific gravity of fly ash particles varies with chemical composition. The results of 46 tests conducted on fly ash produced in western Pennsylvania indicate that the specific gravity can vary from about 2.3 to 2.6 and averages about 2.4. In contrast, the specific gravity of most soils ranges from about 2.6 to 2.8.

The range of grain-size distribution for fly ash is shown in Figure 6, which also indicates the relatively uniform grain-size distribution of fly ash compared with that of several types of soil. Because of its spherical shape, small surface area, and the uniform silt size of individual particles, fly ash has no plasticity.

Bottom Ash and Boiler Slag

Table 4 (2) gives the specific gravity of several samples of bottom ash and boiler slag. In general, boiler slag tends to have a higher specific gravity than bottom ash. Since the specific gravities of these ashes are a function of their chemical constituents, it is apparent that ashes with high iron contents (Fe_2O_3) have correspondingly high specific gravities.

Figure 7 (2) shows the range of grain-size distribution for bottom ash and boiler slag. These materials range in size from fine sand to fine gravel. The boiler slags, however, tend to be more uniform.

ENGINEERING PROPERTIES OF ASH

Fly Ash

Figure 8 shows the dry unit weight-water content relationships for seven compaction tests conducted in accordance with AASHTO T-180 (3). The shape of the compaction curves is generally similar to that obtained for cohesive soils. In other words, fly ash displays an optimum water content at which the greatest density is achieved for a given compaction energy in much the same manner as cohesive soils. The maximum density varied from a high of about 1426 kg/m^3 (89 lb/ft^3) at an optimum water content of 19 percent to a low of 1233 kg/m^3 (77 lb/ft^3) at 29 percent water content.

The results of six relative density tests (ASTM D 2049-69) on dry samples of fly ash are also plotted along the zero water content axis in Figure 8. The maximum relative densities vary from about 1250 to 1410 kg/m^3 (78 to 88 lb/ft^3). The corresponding minimum relative densities vary from approximately 961 to 1073 kg/m^3 (60 to 67 lb/ft^3).

The shear strength of fly ash depends on the degree of compaction. The results of direct shear tests and triaxial shear tests conducted on freshly compacted samples of fly ash are shown in Figure 9 (3) and indicate the general range of the relationship between the angle of internal friction and dry unit weight for fly ash produced in western Pennsylvania. These strength data indicate that a loosely placed, completely drained fly ash embankment can be safely constructed by using a fill slope of about 4 horizontal to 1 vertical; a well-compacted and drained fly ash embankment can be constructed at a 2 horizontal to 1 vertical slope. In addition, it has been shown that fly ash possesses significant cohesive strength because of capillary stresses in the pore water (3) and that the shear strength of fly ash can change significantly with time because of age hardening or pozzolanic behavior (4). Age hardening has been best correlated to the amount of free lime present in fly ash.

Fly ash behaves much like a cohesive soil in terms of consolidation; that is, on application of vertical pressure, the stress is initially shared by the soil structure and pore water. The excess pore water pressure gradually decreases as the water is squeezed out of the pores, and, as the pore water pressure decreases, the load is transferred to the fly ash structure; this produces a volume change. Laboratory consolidation tests have indicated that compaction can significantly reduce the compressibility of fly ash (3).

The coefficient of permeability for fly ash depends

Table 3. Ash collected and used in England from 1973 through 1974.

Item	Ash[a] (Tg)
Total ash collected	8.8
Ash use	
Cement manufacture, prekiln and postkiln	<0.1
Concrete	0.1
Concrete block	1.3
Lightweight aggregate	0.2
Grouting	0.1
Fill	
Roads and embankments	1.6
Building sites	0.9
Other	0.1
Total use	
Weight	4.3+
Percent	48.9

Note: 1 Tg = 1.1 million tons.
[a]From stations fired with pulverized fuel.

Figure 4. Variation in chemical constituents of fly ash in United States.

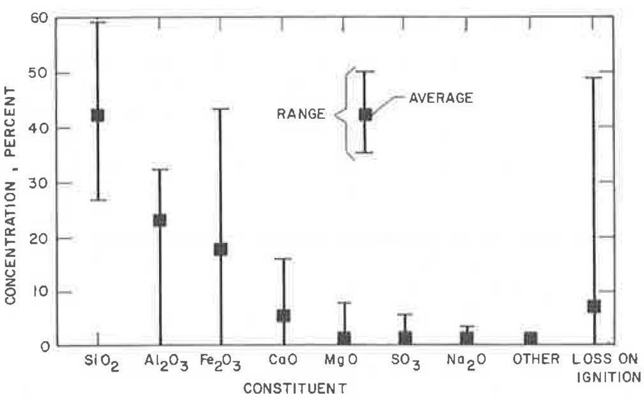


Figure 5. Variation in chemical constituents of bottom ash and boiler slag in United States.

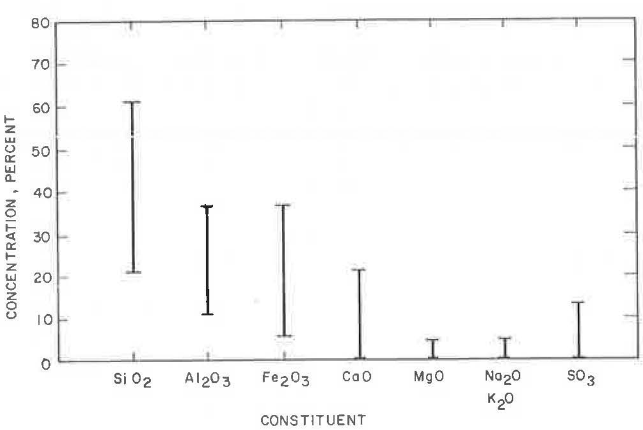
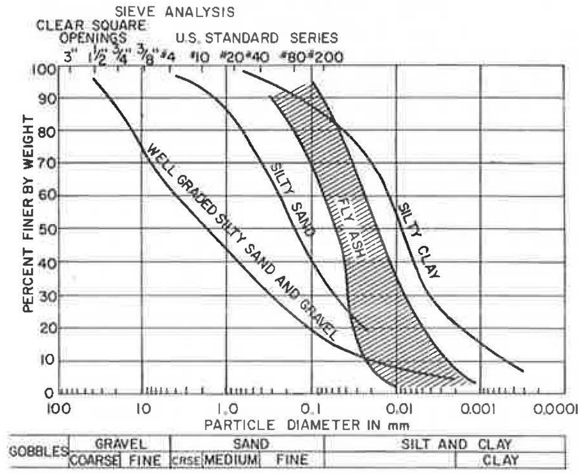


Table 4. Specific gravity of bottom ash and boiler slag.

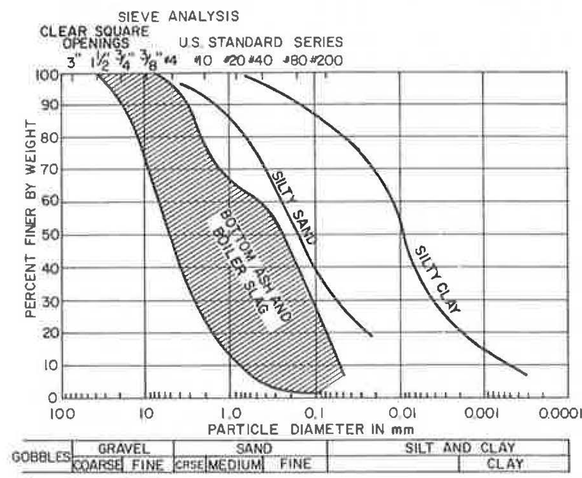
Source	Bottom Ash	Boiler Slag	Specific Gravity
Fort Martin			
Unit 1	Dry bottom		2.35
Unit 2	Dry bottom		2.48
Kammer		Wet bottom	2.72
Kanawha River	Dry bottom		2.28
Mitchell	Dry bottom		2.78
Muskingham		Wet bottom	2.47
Willow Island		Wet bottom	2.61

Figure 6. Grain-size distributions for fly ash.



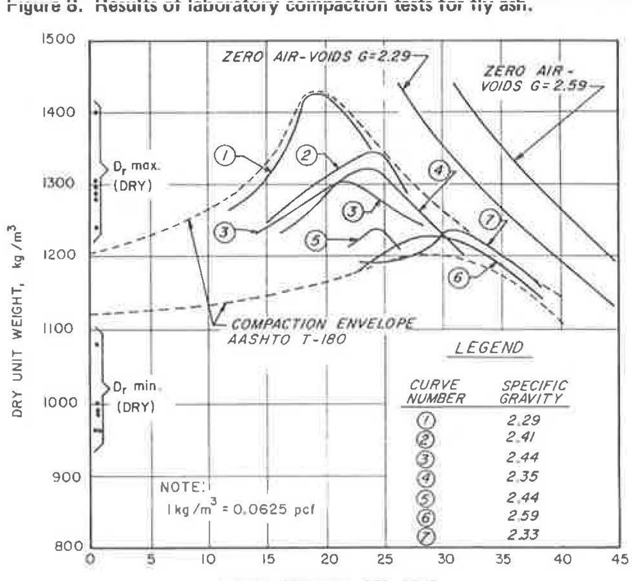
Note: 1 mm = 0.04 in.

Figure 7. Grain-size distributions for bottom ash and boiler slag.



Note: 1 mm = 0.04 in.

Figure 8. Results of laboratory compaction tests for fly ash.



on its degree of compaction and the pozzolanic acitivity. The coefficient of permeability for fresh fly ash in the United States has been found to range from 1 to 5 μm/s (0.04 to 0.2 μin/s). The addition of 10 percent lime or cement to fly ash can reduce the coefficient of permeability by a factor as high as 10 (5).

Bottom Ash and Boiler Slag

Published data on the range of compaction, strength, and permeability properties to be expected for bottom ash and boiler slag are somewhat limited. The maximum and minimum relative densities for bottom ash were found to range from 1105 to 1860 kg/m^3 (69 to 116 lb/ft^3) and from 800 to 1458 kg/m^3 (50 to 91 lb/ft^3) respectively (2). The maximum and minimum relative densities for boiler slag were found to range from 1458 to 1762 kg/m^3 (91 to 110 lb/ft^3) and from 1137 to 1410 kg/m^3 (71 to 88 lb/ft^3) respectively (2).

As with fly ash, the shear strength of bottom ash and boiler slag varies with the degree of compaction. The angle of internal friction for bottom ash and boiler slag

Figure 9. Angle of internal friction versus dry unit weight for fly ash.

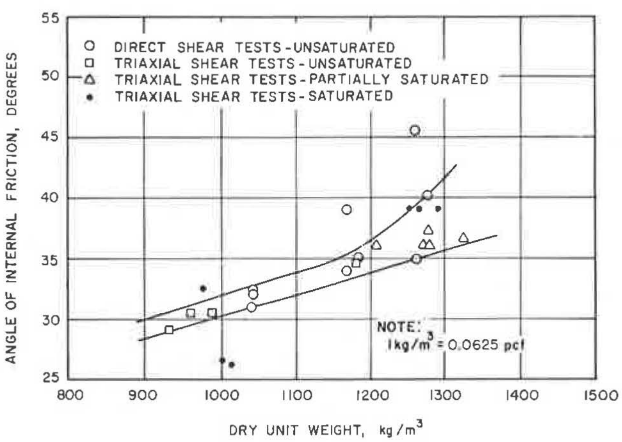
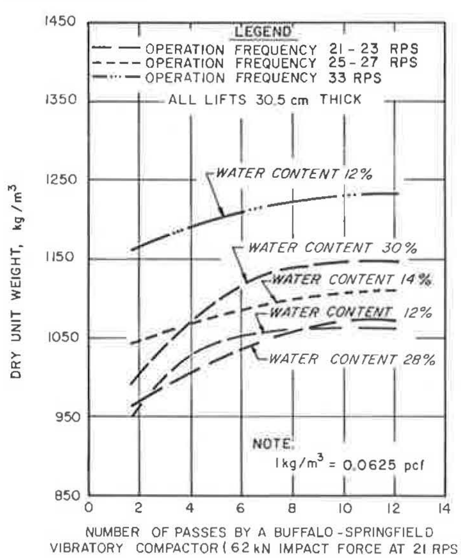


Figure 10. Results of field vibratory compaction tests for fly ash.



in a loose condition can vary from 38 to 42.5 deg and can average 41 deg. The coefficient of permeability has been shown to vary from 0.3 to 0.9 mm/s (0.012 to 0.035 in/s) (2).

ROADWAY EMBANKMENT PROJECTS IN UNITED STATES

Melvin E. Amstutz Expressway

The Melvin E. Amstutz Expressway project (6) involved the construction of a fill embankment for a four-lane highway divided by a 12.8-m-wide (42-ft) median between Grand and Greenwood avenues in Waukegan, Illinois. The contractor submitted a bid of \$2.42/m^3 (\$1.85/yd^3) for alternate D, the construction of a fly ash embankment. The alternate bids indicated that a fly ash embankment would realize a savings of approximately \$62 000 over an earth fill embankment. The contract called for the placement and compaction of 188 845 m^3 (247 000 yd^3) of fly ash. The average height of the fly ash embankment was 1.1 m (3.5 ft), although 5.5 to 6.1-m-high (18 to 20-ft) embankments were constructed in ramp areas. The fly ash embankment was covered by 0.6 m (2 ft) of earth fill in the median area and by 2.4 m (8 ft) of earth fill on the outside of the fly ash slopes.

The fly ash was trucked to the site, either from closed dry storage silos or from stockpiles located outside the power plant, and placed in 15.2-cm (6-in) lifts. Each lift was compacted with a vibrostatic roller to a minimum density of 85 percent of the maximum laboratory density (AASHTO T-99). The maximum dry density for the fly ash used on the project was 1426 kg/m^3 (89 lb/ft^3) at an optimum water content of 25 percent. The contractor added water when necessary to obtain the required density.

Before the fly ash embankment was constructed, unsuitable in-place soils were removed and replaced with a granular fill to a level 0.6 m (2 ft) above the groundwater table.

Based on the experience gained through this project, the Illinois Department of Transportation (6) concluded:

All indications are that the fly ash embankment being placed on the project will provide a lightweight stable fill which will be stronger than most natural soils, due to the age hardening characteristics of the material. When the moisture content is controlled within a range of 20-25 percent, the material is workable and stable provided the proper construction methods are utilized. Excellent compaction and penetrometric results were obtained when the fly ash was compacted at a moisture content of 2-5 percent below optimum.

The contractor was able to work and place embankment on the job, on many days when other jobs with earth embankment could not be worked due to wet conditions. The lightweight material may find use in many areas where it is desirable to bridge weak soils. In order to utilize fly ash economically, an available source of sufficient quantity must be located close to the proposed job site.

US-250

A slide caused by poor drainage had occurred along US-250 (7). Engineers of the West Virginia Department of Highways decided to remove the slide mass, install subsurface drainage, and replace the slide material with compacted fly ash. The fly ash was hauled to the site in open trucks; no dusting problems were encountered in the the operation. The fly ash was tailgated by the trucks and spread into 23-cm-thick (9-in) lifts by a road grader. Each lift was compacted by a rubber-tired vibratory roller to a density equal to or greater than 98 percent of the maximum laboratory density (AASHTO T-99).

Fly Ash Storage Area Access Road

An eastern utility decided to construct an access road into its fly ash storage site by using compacted fly ash and bottom ash. Before any fill was placed, the access road embankment site was cleared and stripped of all unsuitable material. A 0.9-m-thick (3-ft) coarse bottom ash drainage blanket about 30.5 m (100 ft) wide was placed beneath the toe of the downstream slope, and a 1.8-m (72-in) corrugated metal drainage conduit with concrete head walls was placed in the valley to carry the small stream under the embankment. The access road embankment had a maximum height of 23 m (75 ft) and upstream and downstream slopes of 3 horizontal to 1 vertical and was covered with about 0.3 m (1 ft) of topsoil.

To determine the behavior of fly ash under vibratory field compaction, several series of tests were conducted on 30.5-cm-thick (12-in) lifts compacted with a vibratory compactor. The static weight of the compactor was about 5900 kg (6.5 tons), and the dynamic force was about about 62.3 kN (7 tons) per impact at 21 revolutions/s. Typical results of the test program are shown in Figure 10 (3), which is a plot of the compacted dry unit weight versus the number of passes by the roller. Each curve in Figure 10 indicates the results of successive density tests on the same lift after various numbers of roller passes. Each series of tests (each curve in Figure 10) was conducted at the same water content and vibratory frequency as indicated in the figure. The results show that the density of fly ash increases rapidly for the first five or six passes of the compactor but increases little after eight passes. Neither the maximum density achieved nor the rate of density increase with number of passes correlates well with the water content of the fly ash. Although this lack of dependence on water content is an important and beneficial feature of vibratory compaction, since it can be difficult and costly to control the water content of fly ash, the maximum densities achieved in the field were generally less than those achieved in the laboratory. The laboratory compaction characteristics of the fly ash used on the project are similar to those shown by curves 3 and 4 in Figure 8.

The higher vibrating frequencies were more effective in compacting fly ash. It was not determined whether frequencies higher than the maximum value of 33 revolutions/s used in this series would be more or less effective.

ROADWAY EMBANKMENT PROJECTS IN ENGLAND AND SCOTLAND

Production of fly ash in England for 1973-74 was about 8.8 Tg (9.7 million tons) (Figure 3). The Central Electricity Generating Board (CEGB), which designs, builds, and operates power stations in England, faced a tremendous disposal problem because of limited land area. Consequently, the CEGB embarked on a program of developing commercial outlets for large volumes of fly ash to appreciably reduce the disposal costs and help preserve the environment.

As indicated in Table 3, the main use of fly ash in England has been as fill on road construction projects and building sites. A short summary of some roadway embankment projects undertaken in England and Scotland follows.

Motorway M9

In February 1966, construction began on a fly ash embankment for a portion of Motorway M9 between Edinburgh and Sterling, Scotland, at the Earlsgate Interchange. The alluvium beneath the proposed route was as much as 39.6 m (130 ft) thick and very compressible, and this made construction of an earth fill embankment difficult because of stability and settlement problems. The maximum height of the embankment was 7.9 m (26 ft).

Construction began with the removal of unsuitable materials and the placement of a 1.07-m-thick (3.5-ft) gravel drainage blanket. The fly ash was placed in thin lifts and compacted to 95 percent of the maximum laboratory density determined by British Standard Test Methods, with a total of 0.54 Tg (0.6 million tons) of fly ash being used on the project. The embankment was constructed with side slopes of 2 horizontal to 1 vertical and covered with 15 cm (6 in) of top soil.

Alexandria Bypass

This truck road diversion was built in two stages and bypasses Alexandria and three other towns situated in the valley of the River Leven in Dumbartonshire, Scotland. The 9.2-km-long (5-mile) diversion provides access from the heavily industrialized area of the River Clyde into the rural highlands and the shores of Loch Lomond.

The first stage of the project consisted of crossing the floodplain of the River Leven, the outlet from Loch Lomond. A high approach embankment was required on both sides of the river so that navigational clearance on the river could be maintained. Poor subsoil conditions consisting of saturated silt dictated that a lightweight fill for the embankment and more than 0.41 Tg (0.45 million tons) of fly ash be used for this stage. Even with the use of the fly ash, a settlement of more than 0.9 m (3 ft) has been recorded near the river, most of it having occurred during construction.

Construction of the second stage began in 1973, and started near the edge of the floodplain and extended along the hillside above Alexandria. The high embankment begun in the first stage had to be continued onto the rising ground, this time to a bridge over an electric railway and a local road. An additional 54 Gg (60 000 tons) of fly ash were used for this purpose since the subsoils consisted of the same weak silts encountered in the first stage. Two years after construction, the 11-m-high (36-ft) embankment had settled only 25 cm (10 in). Working in a rather confined area, the contractor used a D6 bulldozer for spreading the fly ash and a D4 bulldozer towing a 3600-kg (4-ton) vibrating roller for compaction and successfully placed 1.1 Gg (1 200 tons) of fly ash per day at an average dry density of 1121 kg/m^3 (70 lb/ft^3).

Motorway M5

The 7.2-km-long (4.5-mile) Avonmouth section of Motorway M5 starts at the southern end of Filton Bypass and ends at the Portway between Bristol and Avonmouth, England. The western 3.2 km (2 miles) of roadway are built on the plain of compressible alluvium with some peat layers. This portion of the roadway is built on an embankment about 2.1 m (7 ft) above the original ground. High 6.1-m (20-ft) embankments above the motorway carry Lawrence Weston Road, Kings Weston Lane, and the link road over it. High embankments also carry the motorway at its western end on the approach to Avonmouth Bridge. The motorway has dual 11.0-m-wide (36-ft) pavements and 3.05-m-wide (10-ft) shoulders; the overall width at the top of the embankment is 39.4 m (129 ft).

A trial fly ash fill embankment was constructed in August 1965. The embankment was planned to be 9.1 m (30 ft) high and 30.5 m (100 ft) square at the top and had side slopes of 2 horizontal to 1 vertical. The base of the

embankment was a 46-cm-thick (18-in) layer of sand to allow for the relief of pore water pressures in the subsoils. The building of the trial embankment proved that a high quality of motoring could be achieved after the subsoils were temporarily surcharged to accelerate the dissipation of pore water pressure and strengthen the subsoils.

SUMMARY

The use of power industry by-product resources such as fly ash, bottom ash, and boiler slag in highway construction can solve two significant problems: (a) in the highway construction industry, rapidly diminishing natural construction materials, and (b) in the power industry, ever-increasing quantities of fly ash, bottom ash, and boiler slag requiring disposal. As indicated by the highway embankment projects described in this paper, the technology for using fly ash as a fill material is well developed. In addition, the technologies for using all of these materials in many other aspects of highway construction are also available. It is clear that the time has come for engineers in both industries to direct their efforts toward solving each others' problem.

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