UTILIZATION OF ASH FROM COAL-BURNING POWER PLANTS IN HIGHWAY CONSTRUCTION

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Studies conducted at West Virginia University have shown that the engineering properties of bottom ash are comparable to those of conventional construction materials. Nevertheless, bottom ash and fly ash have not been widely used in highway construction in the United States. During the past 3 years, considerable experience has been gained in West Virginia and the surrounding states in the utilization of coal ash in highway construction. The applications have included use of bottom ash or fly ash or both in nonstabilized base courses, portland cement and bituminous stabilized base courses, bituminous surface courses, lightweight structural fill, and underdrain filters. It was found that ash materials can be used satisfactorily in these applications providing their unique properties are recognized and appropriate construction techniques are employed. It is shown that these materials do not always fit within the framework of existing materials and construction specifications and that adherence to these specifications does not always ensure satisfactory performance. In fact, in some instances better performance and greater economy were achieved with ash mixtures that did not meet existing specifications. If ash is to be used effectively in highway construction, new specifications must be developed that take into consideration the unusual properties of ash and the specialized construction techniques required.

•IN recent years, many areas of the United States have been faced with a growing and potentially serious shortage (11) of suitable natural aggregates for use in highway construction. In addition, the necessary handling and processing operations have resulted in a dramatic increase in the cost of natural aggregates. At the same time, the production of coal ash (bottom ash and fly ash) by coal-burning electric utilities in the United States has continued to increase, while concern over protection of the environment has made satisfactory disposal of the ash increasingly more burdensome. For example, in the 5-year period from 1966 to 1971, the annual production (1, 4) of fly ash and bottom ash has increased from 25.2 to 42.2 million tons, while utilization (1, 4) increased from 3.1 to 8.6 million tons. Although, on a percentage basis, the increase in ash utilization (177 percent) greatly exceeded the increase in production (67.5 percent), utilization still lagged production substantially, e.g., by 33.6 million tons in 1971. Thus, there are ever-growing stockpiles of ash in many parts of the United States where the need for materials for highway construction is currently acute or will become so in the foreseeable future. It, therefore, seems logical to direct our attention toward increased utilization of fly ash and bottom ash in highway construction.

There is considerable information available on the properties of fly ash and its applications (2, 3), and there is a substantial body of information that indicates that fly ash can be used successfully in highway construction, notably in embankments (6, 8), portland cement concrete (2, 3), and various pavement elements (9). In contrast, relatively little appears in the literature about the properties of bottom ash. However, the results of a recent study (7) conducted at West Virginia University have indicated that the engineering properties of many bottom ashes compare very favorably with those of conventional highway construction materials. Nevertheless, fly ash and bottom ash are not widely used in highway construction in the United States. In the case of bottom ash (boiler slag), this is primarily because of the lack of laboratory and field data on the properties, construction handling, and performance of this material. A similar reason cannot be cited for lack of utilization of fly ash because more than 10 years of laboratory and field experiences have been reported by the British in various publications (2, 6, 8, 9, 10). In the authors' view, reasons other than those mentioned are largely responsible for the current state of practice in the United States. Among the more important reasons are (a) reliance on somewhat rigid material and construction specifications to exclude utilization of coal ash materials rather than consider their acceptance upon proof of equal or better performance; (b) lack of consideration of the unique properties of coal ash materials, i. e., applying criteria developed for conventional highway aggregates to materials inherently different; (c) lack of foresight in developing the necessary techniques to effectively utilize these materials prior to an acute shortage of conventional aggregates; and (d) hesitancy of organizations to support research that may profit a single industry.

During the past 3 years, fly ash and bottom ash have been used, either singly, in combination with each other, or with other materials, in a variety of highway and highway-related applications in West Virginia and the surrounding states. These applications have included the use of ash in nonstabilized and stabilized base courses, paving mixtures, lightweight structural fills, the grouting of landfills, and filters for underdrain systems. A considerable amount of experience on the utilization of ash in highway construction has been accumulated as a result of these applications. It is the purpose of this paper to share some of that experience.

BASE COURSE APPLICATIONS

Nonstabilized Bases

In the authors' experience, one of the first attempts to utilize nonstabilized bottom ash in base courses, while satisfying standard highway specifications, was in the 1971 construction of the access road to the Law School-Computer Center complex on West Virginia University's Evansdale campus. Bottom ash produced by the Fort Martin Station of the Allegheny Power System was used as it came from the ash hopper without screening or additional treatment. It was found that the material in this condition would pass the specified gradation, abrasion, and sulfate soundness requirements of the West Virginia Department of Highways for class 2 base courses as given in Table 1.

The bottom ash was placed with a conventional spreader box and was compacted using a 10-ton tandem steel-wheeled roller. It was found that the bottom ash could be spread and compacted very well when placed at the optimum moisture content, or slightly above, as determined by the standard Proctor compaction procedure. In fact, the densities achieved generally equaled or exceeded the required 95 percent of the laboratory maximum dry density, which was 85.0 lb/ft^3. However, it was found that the bottom ash lost stability when it dried out, and it was necessary to keep the material wet in order that paving and other construction equipment could be operated satisfactorily on its surface. The relatively low compacted density is attributable in part to the low specific gravity of the ash (2.32), but it is felt that the angularity of the ash particles and their porous surface texture (7) may be contributing factors. The behavior of this ash upon drying is characteristic of a uniformly graded material, even though it would classify before compaction as a well-graded material by the Unified Classification System. It is suspected that degradation during compaction may have played an important role in this phenomenon. This cannot be confirmed, however, because the material was not sampled after compaction. In any event, the confinement provided by the placement of the overlying bituminous concrete base and surface courses resolved the problem, and no further difficulty was experienced.

Similar behavior was observed in the utilization of untreated bottom ash in base courses for shoulders and lightly traveled access roads constructed as a part of the relocation of West Virginia Route 2 in the Ohio Valley south of Wheeling. In this application, bottom ash from Ohio Power's Cardinal Plant at Brilliant, Ohio, was placed at an average moisture content of 14 percent and compacted with two passes of a 10-ton tandem steel-wheeled roller followed by four passes of a 30-ton pneumatic roller. This material also became unstable upon drying, even though it met gradation and quality requirements and had been compacted to densities in excess of 95 percent of the standard Proctor value.

In contrast to these two experiences, higher densities and excellent dry stability were achieved on another West Virginia Route 2 base course application where a mixture of bottom ash and blast furnace slag was used. Bottom ash from American Electric Power Company's Mitchell Plant was blended with blast furnace slag, meeting ASTM No. 467 grading, in order to satisfy the gradation requirements of the West Virginia Department of Highways for class 1 crushed-aggregate base course. Because of variations in gradation of the ash, the percentage of slag required to satisfy the Department's gradation requirements varied from 15 percent to 40 percent by weight of aggregate. A comparison between the requirements for class 1 crushed-aggregate base course and the properties of a typical ash-slag mixture is given in Table 2.

The mixture was placed and compacted in two lifts to a total thickness of 9 in. Although compaction water content varied, it was generally within the specified limits of 6 to 8 percent. Final compaction was obtained by means of 4 to 6 passes of a 30-ton pneumatic roller. Field measurements indicated that the compacted dry density generally exceeded the specified value of 95 percent of the laboratory maximum dry density, which was 105 lb/ft^3. This experience was encouraging because it proved that untreated ash could be used to construct a satisfactory base course when the proper gradation and combination of materials were employed. It also called attention to the need for further research into the basic properties of bottom ash by itself and in combination with other materials.

In an effort to find a solution to the problem of loss of stability upon drying, a laboratory study was conducted at West Virginia University using bottom ash and fly ash from the Fort Martin Station. It was found that the addition of fines in the form of fly ash provided the required binder and that good initial density and dry stability could be obtained. Although various combinations of the materials were studied, it was found that best results were obtained in the laboratory with a mixture of 70 percent bottom ash and 30 percent fly ash. However, the unique properties of coal ash again manifested themselves when it was found that the greatest initial stability was produced at a moisture content several percent below optimum.

Fortunately the authors had an opportunity to follow this study into the field when the engineers for the Allegheny Power System elected to use a mixture of bottom ash and fly ash as the base course for the reconstruction of the access roads to its Fort Martin Station. Although the roads do not carry a large volume of traffic, many of the vehicles are trucks carrying ash and weighing in excess of 30 tons. Because the engineers were not constrained by material and construction specifications, they chose to experimentally determine the relative proportions of bottom ash and fly ash to blend to obtain a well-graded mix with good compactness. Based on laboratory studies, independent of the West Virginia University tests, they also selected a mixture of 70 percent bottom ash and 30 percent fly ash.

The materials were placed in trench-like excavations approximately 6 to 8 ft in width and varying from 2 to 5 ft in depth depending on the topography of the particular location. Sections at essentially natural grade were excavated approximately 28 in. through an existing roadway and the natural subgrade. Deeper sections were used to replace existing side-hill fills. Initially, a drainage layer consisting of 7 in. of compacted bottom ash was placed. This was followed by successive lifts of a bottom ash-fly ash mixture. Loose lift thicknesses of approximately 12 in. were utilized for the bottom ash-fly ash mixture. The mixed materials were dumped from trucks and spread to the desired loose lift thickness by a small bulldozer.

Initially, the 70-30 bottom ash-fly ash combination was tried, but difficulty was encountered because of excessive moisture and an accompanying loss in stability during compaction. A 60-40 combination was then tried and proved to be a satisfactory blend for the working conditions encountered. Combination of the materials was accomplished with a front-end loader simply by alternately dumping and mixing bottom ash and fly ash in volumetric proportions estimated to achieve the desired combination. Laboratory grain size distribution tests, performed on field samples of the 60-40 and 70-30 ash mixtures, showed that the gradation curves for both mixtures fell within their expected tolerance bands. At the time of the mixing the fly ash was essentially dry, but the bottom ash had water draining from it. Generally, the stockpiled mixture was then left for varying periods of time during which some additional drainage of water took place. During the early stages of the work, bottom ash was taken directly from the decantation tank and as a result contained excessive moisture to the extent that water drained from it as it was carried by trucks to the construction site. Later, the bottom ash was stockpiled prior to use. This permitted drainage of the excessive water and resulted in better compaction. Compaction was first attempted with a three-wheeled, steel-wheeled roller that proved to be unsatisfactory. Loss of stability beneath the roller on slight grades made the use of this roller impractical, and it was replaced with a vibratory roller having rubber-tired rear driving wheels and a steel-wheeled front roller (Rayco Model 400RT-1). This roller gave good performance both on the bottom ash alone and on the bottom ash-fly ash mixture. Visual observation and the specification of minimum roller coverages were used for compaction control. Generally, 6 to 10 passes of the vibratory roller were sufficient to produce a stable, well-compacted bottom ash layer.

As many as 20 passes of the vibratory roller were made to produce a visually stable and compact layer of the bottom ash-fly ash mixture. However, field density measurements indicated that only modest densification was achieved for the last 10 passes; e.g., dry densities of approximately 100 and 103 lb/ft^3 were achieved for 10 and 20 roller passes respectively. Furthermore, it was observed that lower dry densities were obtained, for 20 roller passes, for each succeeding lift. For example, at one location compacted dry densities of 103.1, 100.9, and 99.9 lb/ft^3 were achieved for the first, second, and third compacted layers respectively. The increasing relative compressibility of the ash mixture probably accounts for this observation. Some slight evidence of instability was noted in the field during compaction, becoming more noticeable with increasing thickness of the ash mixture.

Field moisture contents varied from 16.2 to 19.3 percent, having an average of 18.1 percent for eight measurements. This moisture content was considerably in excess of the standard Proctor optimum moisture content of approximately 10 percent. However, the dry densities achieved in the field (93.6 to 103.1 lb/ft^3) ranged from 96.0 to 105.7 percent of standard Proctor maximum density (97.5 lb/ft^3). All of these measurements were made on the 60-40 bottom ash-fly ash mixture. A field moisture-density test conducted on a 70-30 ash mixture in place for 2 months indicated a dry density of 101.6 lb/ft^3 at a moisture content of 12.4 percent. This layer had no cover and had been exposed to traffic and the weather during the 2-month period.

The exceptionally high densities achieved for the "wet-of-optimum" moisture conditions are somewhat surprising. However, the type and magnitude of field compaction effort as compared to that used in the standard laboratory compaction test may suggest a partial explanation. In addition, although most fly ashes alone tend to exhibit a marked decrease in strength when compacted wet of optimum (5), the loss in strength of the fly ash-bottom ash mixture compacted wet of optimum is gradual. This behavior was observed while conducting laboratory cone penetrometer tests on compacted samples of a 60-40 bottom ash-fly ash mixture. Although the results are inconclusive, the strength of the mixture was a maximum when compacted slightly dry of optimum and decreased gradually with increasing compaction moisture content. Although the percentage of decrease in strength was as large as 100 percent, samples at high moisture contents (6 percent above optimum) still exhibited good strength. It is apparent that the presence of the granular bottom ash tends to limit the strength loss.

Current standard highway specifications for base course materials attempt to control the quality and hence the performance of the materials by specifying acceptable limits for gradation, soundness, abrasion, percentage of fines, and Atterberg limits of fines. Although many bottom ashes can satisfy soundness, abrasion, and percentage of fines requirements, they may not meet gradation requirements. The experience cited indicates that other materials can be blended with bottom ash to overcome the gradation deficiency. However, within the framework of existing specifications, mixtures of ash containing percentages of fly ash (fines) greater than those specified for base course materials would be unacceptable. It should be pointed out that the fines, in this case, are not only nonplastic but are actually cementitious. Thus, it appears that, for untreated base courses, strict adherence to standard highway specifications in all instances is neither satisfactory nor reasonable.

Stabilized Bases

Portland Cement Stabilization—The first known large-scale application of a portland cement stabilized bottom ash base course in the United States was in the 1971-72 relocation and reconstruction of West Virginia Route 2 south of Wheeling. The aggregate for this project consisted of a blend of bottom ashes from American Electric Power Company's Kammer Plant and its nearby Mitchell Plant. This blend was necessary in order to meet the West Virginia gradation specification for class 5 cement-treated aggregate base course. Variations in the gradation of the two ashes, as produced, necessitated some adjustments in the relative proportion of each used in the mixture. A typical mix consisted of 46 percent (dry-weight basis) of Kammer ash and 54 percent of Mitchell ash. It was specified that the mix be stabilized by the addition of 5 percent portland cement by weight of dry aggregate. The optimum moisture content and the maximum dry density were determined by the standard Proctor procedure to be 8 percent and 114 lb/ft^3 respectively. The material was placed in one lift and compacted with a 30-ton pneumatic roller to a thickness of 6 in. In general, the field densities achieved equaled or exceeded the specified 97 percent of the standard Proctor value. In this application, it is believed that excellent results were achieved at a substantial reduction in cost as compared to the use of conventional aggregates.

In order to study further the potential use of portland cement stabilized ash base courses, a study of cement-treated mixtures of bottom ash and fly ash was undertaken at West Virginia University during the summer of 1972. This study was conducted in cooperation with the West Virginia Department of Highways, which provided laboratory personnel to perform the sampling and testing. The laboratory facilities, technical guidance, and supervision of the work were provided by the authors.

Bottom ash and fly ash from Allegheny Power System's Fort Martin Station were also used in this study. Because consideration was being given to the use of the material in the reconstruction of secondary roads, one objective of the work was to produce a mixture that would have a high initial stability in order to permit traffic to use the roadway prior to the placement of the surface course. As indicated earlier, it was found that high initial stability could be obtained with a mixture of 70 percent bottom ash and 30 percent fly ash compacted on the dry side of optimum. Therefore, this blend of ashes and a compaction moisture content of 12 percent were adopted.

In order to explore the variations that might be expected from materials produced at a single power station, five different samples of bottom ash at Fort Martin were obtained for use in the study. Sample C was obtained directly from the bottom ash decantation tank, whereas samples A, B, D, and E were obtained from different locations within the stockpile area. In addition, two types of fly ash were used. One of these was dry fly ash (H) taken directly from the ash hopper, and the other was stockpiled fly ash (S) that had been exposed to the weather for some time. The grain size characteristics of these materials are shown in Figure 1. The average specific gravity of the bottom ashes was 2.33, whereas those of the hopper and stockpiled fly ashes were 2.36 and 2.41 respectively.

The compaction procedure used to produce specimens for strength testing in this study was one that produced a higher energy input (20,666 ft-lb/ft^3) than the standard Proctor procedure. The applicability of this procedure was discovered when a number of specimens were accidentally prepared using this compactive effort. It was found that the moisture-density relations obtained by this procedure more nearly duplicated those being obtained by compaction equipment in the field than did the standard Proctor procedure.

Compacted specimens of the cement stabilized ash were stored in the moist room and tested in unconfined compression at 8, 30, and 60 days. For comparison purposes,

Table 1. Comparison of base course (class 2) and bottom ash.

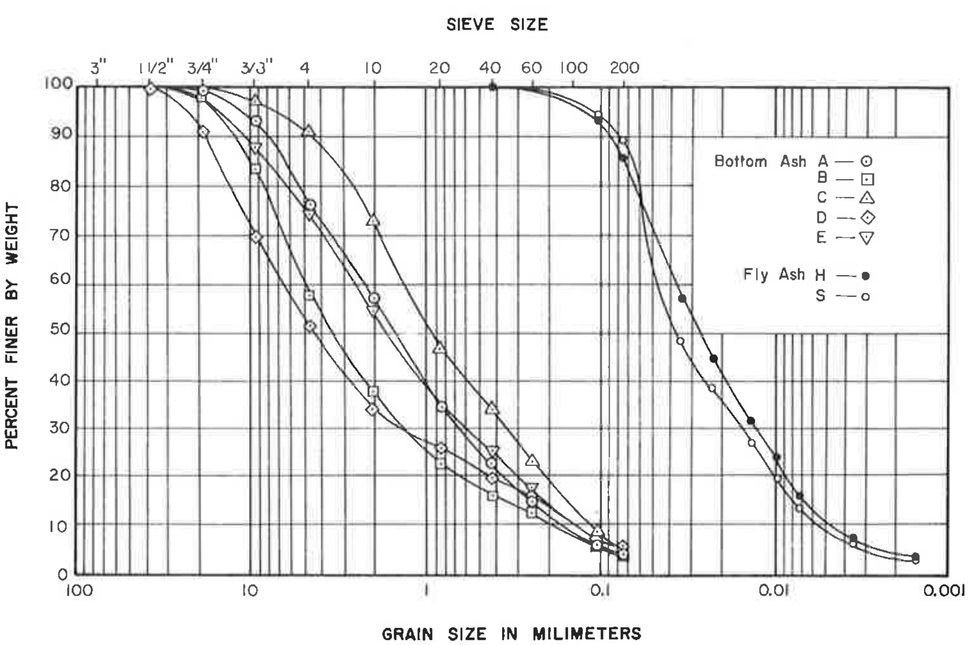
Material	Los Angeles Abrasion	Sodium Sulfate Soundness	Sieve (percent finer) 1½ In.	¾ In.	No. 4	No. 40	No. 200
Base course (class 2)	<50	<12	100	80 to 100	35 to 75	10 to 30	0 to 10
Bottom ash	27 to 40	4 to 8	100	97	70.3	23	4.5

Table 2. Comparison of base course (class 1) and bottom ash-slag mixture.

Material	Los Angeles Abrasion	Sodium Sulfate Soundness	Sieve (percent finer) 1½ In.	¾ In.	No. 4	No. 40	No. 200
Base course (class 1)	<50	<12	100	50 to 90	20 to 50	5 to 20	0 to 7
Bottom ash-slag mixture	37[a]	10[a]	100	78.6	40.6	13.1	2.5

[a]Maximum for Mitchell bottom ash only.

Figure 1. Grain size distribution of bottom ash and fly ash.



parallel series of specimens were prepared using two sources of limestone aggregate (PH and MA) commonly employed to construct cement stabilized base courses in north central West Virginia. The results of these tests are given in Table 3.

Although it is evident from Table 3 that the average strength of the cement stabilized limestone mixtures is greater than that of the cement stabilized ash mixtures, the difference is not large. In fact, several of the ash mixtures had greater 30- and 60-day strengths than did the PH limestone mix. The notable exception to this was the mixture prepared with bottom ash D and fly ash H (hopper ash). This mix gave every indication of having been prepared with reactive aggregates, in that the specimens displayed very noticeable evidence of expansion and cracking after having been cured for 8 days. It is felt that this was caused by the presence of pyrites in the bottom ash. One of the combustion units at the Fort Martin Station separates pyrites from the coal before it is burned, but unfortunately the pyrites are disposed of by dumping them into the bottom ash hopper. Although an attempt is made to segregate the stockpiles of ash from this unit, so that it will not be used where its reactive nature could cause problems, occasionally this ash is encountered, particularly in the older stockpiles. In any event, the combustion unit involved is being altered so that, in the near future, all of the ash collected at Fort Martin will be free of pyrite.

These experiences show that satisfactory portland cement-treated ash base courses can be produced using either bottom ash alone or an appropriate mixture of bottom ash and fly ash. Moreover, British experience has shown (9) that satisfactory base courses can be produced with cement-treated fly ash alone. However, it should be noted again that the use of the mixture of bottom ash (70 percent) and fly ash (30 percent), and the use of fly ash alone, in the preparation of cement-treated bases would not be permitted within the framework of most existing highway department materials and construction specifications in the United States.

Bituminous Stabilized Base—Bottom ash was allowed as an alternate base course aggregate in the repaving of some 40 to 45 miles of light-duty, rural secondary roads in West Virginia in the summer of 1972. The base course material was placed directly on the existing roadway in a single lift 2 to 6 in. deep. Most of the existing roadway was gravel or, at best, badly deteriorated chip and seal surface treatment. Existing ditches were cleared and regraded, and obvious soft spots in the roadway were replaced with granular material, but there were no other preparations prior to laying the base course. Ultimately, this material will receive a surface treatment; however, this will most likely be deferred until the 1973 construction season.

Both dry and wet bottom ash were used in various sections of the project. The wet bottom ash was furnished from the Kammer power plant, and the dry bottom ash was furnished from the Fort Martin power plant. As produced, the gradation and physical and engineering properties of dry and wet bottom ash are quite different (7). Gradation data for typical Kammer and Fort Martin ashes are given in Table 4. The wet bottom ash is of one size, predominately No. 4 to No. 16 mesh, and must be blended with other aggregates in order to meet the class 2 gradation requirements for base course material. The dry bottom ash more closely approximates the class 2 specification as given in Table 1.

The physical appearance of the two types of ash is quite different. The wet bottom ash is glassy and angular, resembling an angular crushed glass (7), and a very small percentage of the particles are spherical or string-like. Most of the particles evidence fractured faces, the result of the rapid quenching as the molten slag is dropped from the boiler into cooling water. Because of its glass-like surface texture and uniformity, wet bottom ash by itself possesses little internal stability and must generally be blended with other aggregates in order to produce acceptable bituminous mixtures.

In contrast, many dry bottom ashes produced in West Virginia give the appearance of a fine sand (7). Although generally lower in specific gravity than the wet bottom ashes, they are only slightly absorptive in nature. Saturated surface dry moisture contents are seldom more than a few percent, and it would appear that these materials are internally rather than externally porous. Many of the particles resemble wet bottom ash, i. e., black and glassy in appearance, but the predominant material is light in color with a sandpaper-like surface texture. In spite of the fact that the dry bottom ash is rather fine-graded (compared to class 2 base course, Table 1), it is, by itself, exceedingly stable, often giving Marshall stabilities in excess of 1,000 lb. This is attributed to the fact that it is well-graded and that the individual particles have a rough microtexture.

On those projects where wet bottom ash was used, it was necessary to blend the ash with other aggregate in order both to develop adequate stability and to meet the class 2 gradation specification (Table 4). Whenever possible a locally available aggregate, generally bank run gravel, was used. With 25 percent bank run gravel and 5 percent residual asphalt, Hveem stabilities for these mixtures ranged from 18 to 25. The mixes were "pugmilled" while cold at a central mixing plant and stockpiled for 10 days or more. The material was cold-laid with a paver or spreader box and, in some cases, end-dumped and leveled with a grader. Although several different compaction procedures were used, generally adequate compaction was achieved from several passes with a pneumatic roller followed by a steel-wheeled roller.

The dry bottom ash was used as produced by the power plant without any blending with other aggregate. The design asphalt content was approximately 7 percent, about 2 percent higher than that for the wet bottom mixes. At 7 percent asphalt content, the Hveem stability of these mixes was in excess of 40.

The lay-down characteristics of the dry bottom mixes were excellent either with a spreader box or with a conventional paving machine. Optimum densities were achieved with 3 to 4 passes from a pneumatic roller followed by one or two leveling passes with a steel-wheeled roller. Lifts up to 8 in. thick (uncompacted) were attempted with a spreader box with good results. With these thicker lifts it was necessary to work or track the mix with one or two passes of a grader before attempting initial compaction. Although not attempted, it is expected that lifts much thicker than 8 in. would be difficult to compact, the difficulty coming from instability during initial compaction. However, density checks with depth showed that good compaction was achieved throughout lifts up to 8 in. thick.

The Fort Martin dry bottom mixture was used as the top course in the shoulder construction on several miles of access road to the Fort Martin Station. The material was placed cold with a conventional shoulder or widening machine with very satisfactory results. The most satisfactory compaction was again achieved after three to five passes with a pneumatic roller.

The previously mentioned mixtures have been in service for less than a year, and it is too early to draw any meaningful conclusions as to their ultimate performance. In several instances these roads receive heavy loads from considerable coal truck traffic. Even under these heavy loads, with the exception of several base failures, there has been no appreciable rutting or shoving, and the performance to date is certainly encouraging.

BITUMINOUS PAVING MIXTURES

Not much engineering information has been published on the use of boiler slag as a major component in paving mixtures (2). As indicated previously, because of an inherent lack of stability, the wet bottom ash must generally be blended with other aggregates in order to produce a stable paving mixture. Typically these mixtures are sand asphalts and may be dense or open-graded. The use of boiler slag in wearing mixtures is permitted in the specifications of several states including West Virginia (in both standard and supplemental specifications), Indiana, and Ohio, and it has been used in cities such as Tampa, Columbus, and Cincinnati (7).

Wet bottom boiler slag has often been promoted as a premium aggregate for surface or deslicking mixtures. Any additional cost for this material is then justified on the basis of its hardness and angularity, desirable properties for a skid-resistant aggregate. Unfortunately, most wet bottom boiler slag is entirely lacking in aggregate microtexture, an undesirable property both in terms of skid resistance and in terms of the ability of the aggregate to retain its asphalt coating.

Wet bottom boiler slag has been used with some success in West Virginia in deslicking applications. A short section of US-119 near Morgantown was resurfaced with a thin deslicking overlay in 1969, as reported in an earlier paper (7). The dramatic reduction shown in the reported accident data before and after deslicking is evidence of the antiskid characteristic of this mixture. This mixture was a blend of river and limestone sand, fly ash, and Kammer wet bottom boiler slag meeting West Virginia wearing course 3 specifications as given in Table 5.

Considerable resurfacing has been done in the northern panhandle of West Virginia using a wearing course 3 mixture composed of approximately 50 percent wet bottom ash, 39 percent river sand, 3 percent fly ash, and 8 percent asphalt cement. The gradation of this mixture is also given in Table 5. The mixture is hot-mixed and hot-laid as a conventional sand mix in depths of ½ to 2 in. The mix is first broken down with a steel-wheeled roller, followed by several passes with a pneumatic roller. Various pavement sections have been in service for up to 6 years, and, although there has been some loss of surface aggregate, the rate of wear is not considered excessive. Performance under heavy truck traffic has been good with little or no tendency to rut or shove, and the surface texture of the pavement has changed little with service. It should be emphasized that, in this application, the boiler slag is considered to be an economical replacement for locally scarce natural aggregates and is not promoted as a premium skid-resistant aggregate.

The authors know of no reported use of dry bottom boiler ash in surface or wearing courses. The inherent stability of this material, along with an acceptable soundness and abrasion loss (Table 1), suggests that this material might be used as an acceptable surface mix for light or medium traffic. There is, however, a tendency for some of the more loosely agglomerated bottom ash particles to degrade under the action of heavy traffic. This has been observed with some of the Fort Martin base mixtures that have not received a surface treatment. In all fairness, these base mixtures were not designed as surface mixtures; as surface mixtures they would be considered deficient in asphalt and contain excessive voids (10 to 12 percent).

In summary, although wet bottom boiler slag is generally promoted as a premium skid-resistant aggregate, it should be emphasized that this is not the only application for this material. Experience in West Virginia has shown that it can successfully compete as an economic replacement for natural aggregates. Although little or no use has been made of dry bottom ash in wearing courses, its inherent stability suggests that it may be acceptable as a sand mix at a substantial savings in cost.

LIGHTWEIGHT STRUCTURAL FILL

As pointed out in the paper by Gray and Lin (5), much of the experience with the use of compacted fly ash in fills has been gained in Great Britain. Beginning with field trials in 1958, fly ash, or pulverized fuel ash (PFA) as designated by the British, has been used extensively and successfully in highway embankments and bridge abutment backfills (2, 6, 8). British experience has demonstrated that fly ash is a pozzolanic material because it self-hardens when compacted in a moist condition. It has been found that the pozzolanic activity is the greatest when moisture is added to fresh fly ash at its source. For effective compaction, loose lift thicknesses not exceeding 9 in. should be used and should be well "tracked" with a bulldozer prior to rolling. Compaction equipment giving the best performance includes tandem vibrating rollers with a dead weight of at least 1,700 lb, towed vibrating rollers with a dead weight of at least 3,000 lb, and self-propelled pneumatic rollers, 7 to 10 tons in weight, having a tire pressure of 30 to 36 psi. Generally, six to eight passes are required to meet the density specification. Experience has indicated that a minimum dry density of 90 percent of maximum British Standard (B. S. 1377:1967-Test No. 11) dry density should be specified. Smooth-wheeled (small, medium, or large) rollers, sheepsfoot rollers, grid rollers, and vibrating plates have not been successful in compacting fly ash.

The wet weight of compacted fly ash per cubic yard varies between 0.9 and 1.1 tons compared to approximately 1.4 for clay and 1.7 for sand. It is easily trenched; i. e., neat trenches can be excavated using a minimum of bracing. The inertness and alkalinity of fly ash make it generally harmless to essentially all types of embedded pipes.

Table 3. Results of unconfined compression tests on base course mixes.

Material	Unconfined Compression Strength (psi)[a]		
	8 Days	30 Days	60 Days
Bottom ash A and fly ash H	406	665	726
Bottom ash B and fly ash H	224	505	644
Bottom ash C and fly ash H	478	635	479
Bottom ash D and fly ash H	23[b]	112[b]	163[b]
Bottom ash E and fly ash H	487	512	653
Average	399	579	651
Bottom ash A and fly ash S	520	772	912
Bottom ash B and fly ash S	454	805	681
Bottom ash C and fly ash S	—	—	—
Bottom ash D and fly ash S	313	449	759
Bottom ash E and fly ash S	376	426	560
Average	416	613	728
Limestone PH	525	569	638
Limestone MA	616	961	906
Average	571	765	773

[a]Average of 3 tests. [b]Excluded from average.

Table 4. Comparison of base course (class 2) with wet bottom boiler slag and boiler slag-gravel mixtures.

Material	Los Angeles Abrasion	Sodium Sulfate Soundness	Sieve (percent passing)						
			$1\frac{1}{2}$ In.	$\frac{3}{4}$ In.	$\frac{3}{8}$ In.	No. 4	No. 16	No. 40	No. 200
Base course (class 2)	<50	<12	100	80 to 100	—	35 to 75	—	10 to 30	0 to 10
Kammer (wet bottom)	26	2.5	100	100	99	96	16	3	0
75 percent Kammer and 25 percent gravel	—	—	100	99	92	85	40	11	1

Table 5. Comparison of wet bottom ash surface mixtures and wearing mixture 3.

Material Designation	Asphalt Content (percent)	Sieve (percent passing)					
		$\frac{3}{8}$ In.	No. 4	No. 8	No. 16	No. 50	No. 200
Specification	5 to 11	100	90 to 100	60 to 90	40 to 65	10 to 30	3 to 15
U. S. 119	7	100	95	85	48	16	6
Northern panhandle	8	100	95	80	52	14	6

However, certain precautions should be taken when utilizing fly ash as road and structural fill. Among these are the following:

1. Fly ash is a borderline frost-susceptible material. However, the use of adequate drainage and/or stabilization of the fly ash with lime or cement (5) is effective in eliminating or reducing frost effects.

2. Although, generally speaking, the sulfate content of most fly ashes is too low to be troublesome, it is possible that an exceptional fly ash may be encountered in which the sulfate content is sufficiently high to warrant some precautionary measures if it is to be used adjacent to concrete. In such rare cases, simply coating the contacting concrete with bituminous paint or rubberized componds should result in satisfactory protection.

In Great Britain, compacted fly ash is being used extensively as backfill for bridge retaining walls (8). Two favorable characteristics of the compacted fly ash are largely responsible for this practice, namely, the very low compressibility and the shear strength characteristics of the compacted fly ash. In both these instances the age-hardening characteristics of the fly ash are especially important. Not only will the settlement of the fly ash backfill be small, but the settlement of the foundation soil will be reduced because of the low unit weight of the fly ash as compared to conventional materials. Based on an active pressure analysis, the theoretical lateral pressure at the base of a typical wall may be negative or only slightly positive. In practice, however, significant positive lateral pressures can develop as a result of construction and design practices. Wilson and Pimley (10) reported positive lateral pressures in excess of those calculated on the basis of an equivalent fluid having a density of 14.8 lb/ft^3. They attributed their findings to the combined effects of a rigid wall and lateral pressures induced by the compaction process.

Fly ash was recently used as a lightweight structural fill in a landslide correction project on Route 250 near Fairmont, West Virginia. The project, implemented by a district maintenance force of the West Virginia Department of Highways, consisted of removal of the landslide debris, installation of an underdrainage system, placement of the fly ash fill, and sealing of the fill.

Initially, 6-in. perforated concrete pipes were placed in trenches at the base of the excavation to form an underdrainage system. The main collection pipe was placed immediately adjacent to the excavated slope and parallel to the roadway centerline. Three additional pipes were placed perpendicular to the roadway centerline and connected to the main collection pipe. All pipes were surrounded with approximately 3 in. of ½-in. graded stone. An 18-in. thick blanket of 2-in. graded stone was then placed over the entire base area. Additionally, in the process of filling, an 18-in. thick layer of the same stone was placed between the fly ash fill and excavated slope to the bottom of the road subbase.

Approximately 5,000 tons of fly ash were utilized in the fill having 1½:1 side slopes and an average height of 25 ft. The ash was hauled to the job in open trucks from its source, which was the Fort Martin Station of the Allegheny Power System. Water was added to the ash by spray nozzles as it left the storage hopper. For ease in dumping at the construction site, a layer of dry ash was placed in the truck before the wet ash. After the ash was tailgated from the trucks and additional water added, when required, it was spread by a road grader to an 8-in. lift thickness. Before effective compaction could be accomplished, the fly ash was "tracked" by using several coverages of the road grader or a bulldozer. Following the tracking operation, the fly ash was compacted to the specified density with a 10- to 12-ton pneumatic roller.

Based on standard Proctor compaction, the ash utilized in this fill had a maximum dry density of 92 lb/ft^3 and an optimum moisture content of 19 percent. For field control, a density of 95 percent of standard Proctor maximum dry density and a moisture content of 18 percent were specified. Field density test results indicated that densities ranging from 91 to 99 (average of 97) percent of standard Proctor maximum dry density and moisture contents ranging from 15 to 19 (average 16) percent were obtained. Approximately six to eight passes of the roller were required to obtain the specified density. On completion, the top of the fill and a portion of the slope were sealed by hand spraying with a coat of road tar (RT-12).

It is apparent from the preceding discussion that the acceptance of fly ash as an embankment material for highway construction would require changes in existing material and construction specifications. However, the advantages associated with its use, in terms of cost and performance, would suggest that such modifications of existing specifications might very well be warranted.

UNDERDRAIN APPLICATIONS

The authors are personally acquainted with three engineering projects utilizing bottom ash as an underdrain filter material. Although these projects were not strictly highway-related, the similarity to typical highway-related installations is apparent. Boiler slag (bottom ash) from American Electric Power Company's Kammer Plant was utilized to construct an underdrain system for a landslide correction project at the site of the McElroy Mine coal preparation plant near Moundsville, West Virginia. The underdrain system consisted of a trench in which 8-in. perforated asphalt-coated metal pipe was surrounded by river gravel for approximately 6 in. and then filled with boiler slag compacted into place. A concrete paved ditch was placed over the drain to collect surface water. The bottom ash was selected in lieu of river sand because it satisfied applicable filter criteria, was low in cost, and was readily available. This drain was installed in 1968 and has functioned satisfactorily ever since.

A multiple-purpose dam is being constructed on Charles Fork near Spencer, West Virginia, in which 1,800 yd^3 of boiler slag from the Willow Island Plant of the Monongahela Power Company is being utilized in the blanket and toe drain. The boiler slag met the filter criteria specified by the Soil Conservation Service and was selected on the basis of its lower cost as compared to available natural aggregates. Tests verified that the boiler slag did not contain sufficient quantities of soluble solids (204 to 240 mg/l) to be detrimental to the performance of the filter or affect the durability of concrete. A distilled water-boiler slag mixture gave pH readings ranging from 6.7 to 7.0 after 4 days. The boiler slag had a coefficient of permeability of 2.5×10^{-2}cm/sec at a void ratio of 0.77 (7). The boiler slag was placed by tracking with a small bulldozer while the slag was continually sprayed with water. After some field experimentation, the bulldozer, equipped with a front-end loader, was able to place the boiler slag in the filter zone on the relatively steel abutment slopes while operating over the compacted slag. Abutment slopes varied from 5:1 to 2:1.

Bottom ash from the Fort Martin Plant was recently utilized as fill behind a retaining wall and beneath floor slabs for a Holiday Inn addition near Morgantown, West Virginia. Because the bottom ash is free draining, it also serves as a filter drain behind the retaining wall. Perforated plastic pipe surrounded by gravel carries the water collected by the bottom ash backfill. Small tamping compactors were used to compact the bottom ash in 6- to 9-in. compacted lifts.

Experience with bottom ash thus far suggests that it is quite acceptable as an underdrain material, providing it meets the gradation requirements for a filter. In addition, the variability in gradation of the ashes studied (7) is generally equivalent to that specified for aggregates by ASTM. Therefore, the uniformity of the ash from load to load poses no problem. The permeability of the ash is good, being equivalent to that of a clean sand. The environmental effects of utilizing bottom ash in underdrains are negligible, with both respect to the drain itself and the surrounding appurtenances. Placement of the ash can be accomplished by conventional methods as currently used for clean granular materials.

APPLICABILITY OF EXISTING MATERIAL AND CONSTRUCTION SPECIFICATIONS

The experience that has been accumulated to date on the utilization of bottom ash (boiler slag) and fly ash in highway construction has raised serious doubts as to the applicability of existing materials and construction specifications. Most specifications have been developed after many years of laboratory and field experience with available natural soils or aggregates. Accordingly, when the same natural soils or aggregates are used in accordance with these specifications, adequate performance is usually ensured. However, the unique properties of bottom ash and fly ash lead to the possibility that an unsatisfactory result can be obtained even though existing specifications are met. On the other hand, it is possible that excellent results can be achieved with ash at a substantial savings in cost when gradation or other existing specification requirements are not met. Illustrations of both of these occurrences are included in the applications discussed in the preceding sections of this paper. Furthermore, it is possible that much of the savings that can be effected by the use of ash can be absorbed by the increased cost of screening and blending to satisfy existing gradation requirements, which may have little or no effect on the performance of the ash being used.

There is a very definite need to recognize that bottom ash and fly ash have unique chemical and physical properties and to consider these materials apart from conventional highway construction materials. If ash is to be used effectively in highway construction, new specifications must be developed that take into consideration the unusual properties of the ash and the specialized construction techniques required to ensure adequate performance. Assuredly, this will require additional study, both in the laboratory and in the field. However, interim specifications based on performance would open the way to expanded utilization of ash in highway construction and provide a fund of data on which more detailed material and construction specifications could be based.

SUMMARY

Although more laboratory and field research will be required in order to provide a sufficient store of knowledge to justify generalized acceptance of bottom ash and fly ash as highway construction materials, the experience described herein shows that much of the ash produced by coal-burning power plants can be utilized in one form or another in highway construction. As ash production increases and supplies of natural aggregates diminish in the years to come, it will become increasingly more desirable to utilize bottom ash and fly ash in a more productive manner. This will require the modification of existing materials and construction specifications to permit the use of ash in a variety of highway applications, with the provision that the resulting performance be equal to, or better than, that obtained with conventional construction materials. If this can be done, it will constitute a significant contribution to the conversion of a burdensome "solid waste" into a valuable national resource.

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