Use of Coal-Associated Wastes in Low-Volume Roads

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Coal-associated wastes are by-products of the power-plant industry or of coal preparation plants. The materials include fly ash, bottom ash, boiler slag, and coarse, fine, and combined coal refuse. They may be used in the construction of low-volume roads, primarily in surface, base, and subbase courses, or in embankments and underdrains. They may be incorporated in road construction singly, in various combinations with each other, in combination with other natural or waste materials, or with stabilizing agents such as asphalt, cement, lime, and sulfur. An overview of coal-associated waste materials and their physical, chemical, and engineering properties is presented. The principles related to the stabilization of and with these materials are described, along with a mix design philosophy. Brief descriptions of a number of construction applications are given with emphasis on their use in low-volume roads. Finally, the potential of coal-associated wastes for widespread use in low-volume roads is assessed with regard to the technical, practical, and economic feasibility of such use.

In recent years, use of various waste products in highway construction has gained considerable attention in view of the shortages and high costs of suitable conventional aggregates, increasing costs of waste disposal, and environmental constraints. Use of waste materials in the construction of low-volume roads is particularly attractive because this would generally lend itself to a low-cost application (depending on location), help alleviate disposal costs and environmental damage, and conserve high-type highway materials for higher-priority uses.

Coal-associated wastes are by-products of coal-burning power plants (fly ash, bottom ash, and boiler slag--collectively named power-plant ash) or of coal preparation operations after mining (coal refuse). The total annual production of power-plant ash in the United States has increased from 25 million tons in 1966 to more than 75 million tons in 1980 and is expected to exceed 100 million tons in 1985. Ash utilization for various construction purposes such as cement, concrete, lightweight aggregate, fills, road bases, etc., has increased steadily; however, more than half of the production still remains for disposal (1,2). The figures on coal refuse production are not very precise. It is estimated that 3 billion tons are now stockpiled in the United States; 110 million tons are produced annually. It is suggested that the annual production may double by 1985 (3). Although significant use of coal refuse has been achieved in the United Kingdom, particularly in highway embankments, not much has been used in the United States outside of coal recovery from refuse piles.

Research and limited practice have shown that coal-associated wastes are potentially feasible materials that may be used in highway construction, primarily in surface, base, and subbase courses and embankments. Secondary application may be in backfills and underdrains. The materials may be used singly, in various combinations with each other, in combination with other natural or waste materials, or with stabilizing agents such as asphalt, cement, lime, and sulfur.

In this paper, first an overview of coal-associated waste materials and their physical, chemical, and engineering properties is presented. Then the principles related to the stabilization of and with these materials are described, along with a mix design philosophy. Following that, brief descriptions of a number of construction applications are given with emphasis on their use in low-volume roads. Finally, an assessment of the potential of coal-associated wastes for widespread use in low-volume roads is offered with regard to the technical, practical, and economic feasibility of such use.

MATERIALS

Substantial research has been conducted in the past few decades to characterize the physical, chemical, and engineering properties of coal-associated wastes, and thus a large body of information exists in the literature (3-13). The coal-associated waste materials exhibit significant variability from source to source and from time to time within a single source, depending on the source and type of coal, plant operations, disposal, handling, and storage practices. Complete coverage of specific research findings is outside the scope of this paper. Instead, an overview of these materials and their properties related to utilization in highway construction will be presented.

Power-Plant Ash

Power-plant ash is produced as a result of the combustion of coal at high temperatures in steam-generating boilers or furnaces. Fly ash is the finer portion of the pulverized coal ash residue that is carried out by the boiler unit with flue gases and collected by mechanical or electrostatic precipitators at the stack. Typically, it amounts to 75-85 percent of the total boiler ash. The coarser portion of the ash rejected by the stack and collected at the bottom of the furnace is called bottom ash if it is produced by dry-bottom boilers that have open grates and boiler slag if it is produced by wet-bottom or slag-tap type boilers. Power-plant ash may be disposed by dry or wet methods. Dry methods of fly-ash disposal entail short-term storage in hoppers or extended storage in silos. Wet methods involve the addition of sizable quantities of water to transport the ash in a slurry form to settling lagoons or conditioning it with relatively small amounts of water to facilitate hauling by trucks and compacting at a disposal fill. The bottom-ash materials may be mixed with fly ash for disposal purposes but it has been common practice to dispose of them separately by hydraulic means or by end dumping from trucks (7).

Fly Ash

Fly ash is generally grayish in color and consists of predominantly silt-sized, nonplastic smooth-textured spherical particles with a uniform gradation (5,7,10). Its chemical composition, for the most part, includes SiO_2, Al_2O_3, and Fe_2O_3. Carbon and calcium compounds may also be present. Fly ash exhibits varying degrees of self-hardening and pozzolanic reactivity, which results in cementitious properties. Pozzolanic activity occurs as a result of the reaction of fine glassy constituents with calcium and aluminum compounds in the presence of moisture. The specific gravity of fly ash may vary between 1.2 and 2.9; however, it has been indicated (14) that most of the U.S. fly ash has specific gravities that fall within a range of 2.2 and 2.5 and is thus considered lightweight material. The specific gravity of fly ash will depend on the carbon and iron oxide contents. High carbon content will result in a low specific gravity, whereas high iron oxide content will produce a high specific gravity. The hollow nature of the spherical particles also contributes to lower specific gravities. The leachates from fly ash contain predominantly calcium and sulfate ions and are often alkaline in character; pH ranges from 6 to 11 (7).

Standard Proctor maximum dry densities for fly ash generally range from 70 to 95 pcf; values as high as 110 pcf have also been reported (7,14). These values are obtained at optimum moisture contents that vary between 15 and 30 percent; the lower moisture content is associated with higher densities. Naturally, dry density varies with specific gravity. Permeability, compressibility, and shear strength of fly ash largely depend on the degree of compaction and cementation. Coefficients of permeability measured on fly ash are of the order of 10^{-4} to 10^{-7} cm/s but are typically 10^{-5} cm/s (15). The compressibility characteristics are similar to those of medium stiff clays (10). The effective angle of internal friction is typically in a range of 28-38, and aging may result in considerable cohesion due to cementation in some ashes (10,14).

Bottom Ash and Boiler Slag

It is important to distinguish between bottom ash and boiler slag, since these materials have distinct properties. Bottom ash solidifies before it drops to the bottom of the furnace, whereas boiler slag is in a molten state and is tapped off as a liquid that quenches and fractures into glassy particles when it drops into water underneath the surface. Both materials can be further crushed to form a sandlike product. Bottom ash is generally dark gray in color and well-graded from coarse to fine; most varieties are vesicular with an irregular shape and a rough, gritty texture. It may contain varying quantities of absorptive, friable popcornlike particles, which are loosely sintered agglomerates of coarse fly ash (9,16). Boiler slag, in contrast, is shiny black in color, uniformly graded, angular, and smooth textured. Some varieties may be vesicular, especially in coarser sizes. Depending on the degree of vesicularity, specific gravity values for bottom ash vary from 2.1 to 2.7, whereas the range of specific gravities for boiler slag is typically from 2.4 to 2.85. Bottom ash generally exhibits water absorption values (1-25 percent) much higher than those for boiler slag (0.1-4 percent); coarser fractions show higher absorptivity for both materials (8,9, 16). The materials are generally nonplastic. The chemical compositions of bottom ash and boiler slag are somewhat similar to that of fly ash. Some ashes may contain soluble salts (6) and may be contaminated with pyrite.

The nature of the individual ash particles controls many of the engineering properties of these materials. Because of the complex pore structure of the particles, bottom ash may produce irregularly shaped compaction curves (17,18). Maximum standard Proctor dry densities range from 70 to 115 pcf; optimum moisture content ranges from 15 to 30 percent. For boiler slags, the maximum dry densities are typically between 90 and 100 pcf, and the optimum moisture contents vary from 14 to 22 percent (4). Substantial degradation can occur under compaction, because bottom ash and boiler slag are brittle materials that yield somewhat high Los Angeles (LA) abrasion losses (higher than 40). However, LA values below 30 have also been reported (4,9). Sulfate soundness losses may vary between 1 and 40 percent; a typical range is between 5 and 20 (18). The permeability coefficients are typically of the order of 10^{-2} cm/s, such as those encountered in sands. It has been found that the compressibility characteristics of bottom ash and boiler slag are also very similar to those of sands (4). Direct shear tests (4,9) performed on bottom-ash samples have yielded angles of internal friction that range between 32 and 46. Similar tests on boiler slags produced friction angles of 37-46. These values appear to be high; most likely they result from the angular particle shape and rough surface texture (for bottom ash). It must be noted that shear strength in these granular materials is controlled by relative density.

Coal Refuse

Coal refuse materials are generated as discards from coal preparation and processing, which removes impurities (nitrogen, sulfur, ash, claystone, sandstone, shale, etc.) from coal. The processes vary widely and range from simple crushing and loading to the more sophisticated dense media separation, hydraulic concentration, and froth-flotation techniques. Basically, two types of refuse are produced at the preparation plant: coarse coal refuse and fine coal refuse. The dividing size between the two is the No. 28 sieve. Coarse coal refuse generally amounts to 75-80 percent by weight of the total refuse production; the remainder is fine refuse (2).

The disposal methods for coal refuse can generally be grouped into two categories: impounding and nonimpounding. Impounding methods usually include building dikes with coarse refuse and pumping the fine refuse in the form of a slurry behind these dikes. With the nonimpounding disposal methods, the refuse is transported by trucks, scrapers, conveyors, or continuous bucket trains and placed in a pile. This method does not trap water and is used for coarse refuse alone or a mixture of coarse refuse and a thickened slurry of fines (such mixtures are called combined coal refuse). The resulting embankment can attain various configurations depending on the method of transport to the disposal facility.

Coarse Coal Refuse

Coarse coal refuse is composed of roof and floor rock, rock materials incorporated in the coal seam, the coal itself, and the rock originating from shaft and slope cuts. The roof and floor rocks, which are most abundant in coarse refuse piles, are commonly shale or claystone with minor amounts of silty material (3). The coarse coal refuse particles are generally dark gray in color and flat and elongated and exhibit poor resistance to weathering. The material is mostly well graded with a maximum size of 3 or 4 in, which classifies it as gravel to gravelly sand (11). Clay sizes are frequently present in increasing quantities in the weathered materials. The fine fraction of coarse coal refuse is moderately plastic; the liquid limit ranges from 16 to 42 and the plasticity index from 5 to 16. Some coarse refuse, however, may be nonplastic (3). The specific gravity varies between 1.7 and 2.6 and correlates well with coal or carbon content (3,11,12). The major constituents in coarse coal refuse are Al_2O_3, SiO_2, and Fe_2O_3; minor quantities of P_2O_5, TiO_2, CaO, MgO, Na_2, K_2O, S, and SO_3 are also present. Percentages of carbon vary (11). Because of the presence of iron pyrite (FeS_2), the leachate may be quite acidic. It has been noted (3) that when iron pyrite is exposed to air and water, it becomes oxidized to ferrous sulfate and sulfuric acid through an exothermic reaction, which may cause spontaneous combustion in the refuse piles containing carbon. However, alkaline minerals present in coal refuse tend to neutralize the acidic products and proper compaction prevents spontaneous combustion.

Coarse coal refuse generally shows good compaction characteristics (19). The moisture-density relationships exhibit well-defined peaks and yield standard Proctor maximum dry densities from around 85 to 120 pcf within a moisture content range of 8-22 percent (3,12,18). The variation of dry densities is attributed to the specific gravity of the material, the initial gradation, and the amount of breakdown that takes place during compaction. It has been shown that considerable degradation of coarse refuse may occur under compaction, but this may actually enhance the densification process (18). Besides the mechanical degradation, slaking in the presence of moisture also causes appreciable particle breakdown. Although the LA abrasion losses on dry coarse refuse are around 35-40, wet abrasion tests produce much higher losses. In a recent study, we performed Franklin slaking-durability tests (18) on coarse coal refuse samples and obtained slaking indices varying between 64 and 89. The sodium sulfate soundness losses are also very high, generally in excess of 70 percent (16). These are indicative of the poor weathering characteristics of the material.

The engineering properties of coarse coal refuse such as permeability, compressibility, and shear strength vary over a wide range due to large variations in gradation, density, and degree of weathering. It is suggested that the full range of permeability from fresh uncompacted materials to very dense, compacted materials can be as great as 10^{-1} to 10^{-8} cm/s (13). The laboratory permeabilities of samples compacted by standard Proctor effort at optimum moisture are of the order of 10^{-5} to 10^{-7} cm/s (11). The compressibility characteristics of coarse coal refuse have not been reported. The shear-strength characteristics, on the other hand, have been extensively studied and reported (13). The effective shear-strength parameters on undisturbed or remolded samples show very low or no cohesion, and friction angles typically range between 30 and 40. It has been cautioned that the in situ shear strength of coarse coal refuse may be much lower than that determined by normal testing procedures.

Fine and Combined Coal Refuse

Fine coal refuse is a black, sandy, silty material that generally has a high coal content. It is produced and disposed in a slurry form and will thus have excessive amounts of moisture. It can be moderately plastic or nonplastic and is lightweight; specific gravities usually range between 1.4 and 2.2 (13). Few data are available on the chemical composition of fine refuse; however, it is believed that the noncoal portion is basically the same as that of coarse refuse. Because sulfur-bearing minerals are present in fine coal refuse, the leachate shows a low pH value.

The lightweight nature of fine coal refuse is reflected in the compacted dry densities, which typically vary between 40 and 70 pcf in the Appalachian region. Permeability ranges from 10^{-4} to 10^{-7} cm/s, depending on the degree of compaction. One-dimensional consolidation tests have indicated that fine coal refuse is more compressible than commonly found sands and silts that have similar gradations (13). The material usually has little or no cohesion; effective friction angles vary between 20 and 43 degrees.

Combined coal refuse is a mixture of coarse and fine refuse; thus, it will have properties somewhat intermediate between these two materials. Relatively few data are available on the properties of combined coal refuse. It is known that its high natural moisture and fines contents generally pose problems in placement and compaction; however, if moisture can be controlled, standard Proctor dry densities of 90-100 pcf can be easily achieved within a moisture content range of 8-14 percent. The permeability is generally low, of the order of 10^{-6} or 10^{-7} cm/s. Effective shear-strength parameters indicate small values of cohesion and moderately low friction angles, e.g., 30-35 (13). Research is now underway at West Virginia University to characterize combined coal refuse materials and to study their feasibility for use in road construction.

STABILIZATION OF AND BY COAL-ASSOCIATED WASTES

Definitions and Purposes of Stabilization

A definition of the verb "to stabilize" is "to make stable or firm; to hold steady; to prevent fluctuations" (20). For highway construction applications, stabilization is understood to be any process that makes materials of construction firm and unchanging. For this presentation, "firm" is linked with material strength, whereas "unchanging" is related to material durability. Consequently, purposes of stabilization are to render a candidate construction material both sufficiently strong to withstand relevant loads and sufficiently durable to withstand detrimental effects of the relevant environment. Well-compacted, unstabilized, coal-associated wastes are sufficiently strong for many highway construction applications; however, the durability of such materials is not well established. Fortunately, stabilization can both increase strength and markedly enhance the durability of coal-associated wastes.

Sufficiencies of stabilized materials are assessed on the basis of comparisons of objective measures of material strength and durability with performance-based criteria. Thus, the objective of this section is to present and briefly discuss stabilization processes and performance criteria. Included are comments on stabilizing agents and mix design procedures. The comments apply to stabilization of coal-associated wastes, stabilization with coal-associated wastes, and costabilization, i.e., stabilization of a coal waste by substances that contain other coal wastes. Successive examples are stabilization of fly ash with lime or sulfur, stabilization of aggregate with lime--fly-ash mixtures, and stabilization of coal refuse with cement--fly-ash mixtures.

Stabilization Processes and Agents

In Table 1 an overview is presented of several stabilization processes and agents that have been successfully employed with coal-associated wastes in the field and/or in the laboratory. No attempt was made to include all stabilization techniques. Agents 1 through 4 are commonly encountered stabilizers. Asphaltic substances (agent 5) are all potentially useful, although little field experience has been reported where asphalt cement was the stabilizing agent. Significant experience with liquid asphalts, particularly emulsified asphalts, has been reported (21). Modified sulfur (agent 6) is another potential stabilizing agent for coal-associated wastes (22). To date, we are unaware of any field experience where sulfur was employed in this fashion.

Review of Table 1 indicates that the following items are important in establishing the quality of stabilized coal-associated wastes employed in highway construction:

1. Amount of stabilizing agent: For a given set

Table 1. Stabilization processes and agents.

Agent	Mode of Stabilization	Comments
Portland cement	Formation of cementitious products from reactions of cement with water; mixture particles bound together in concretelike mass	Requires adequate compaction and favorable curing conditions; time required for compacted mixture to attain desired characteristics
Lime[a]	Formation of cementitious products from reactions of calcium products with water and silica/aluminum compounds; mixture particles bound together in concretelike mass	Requires adequate compaction and favorable curing conditions; time required for compacted mixtures to attain desired characteristics is usually greater than with cement-stabilized mixtures; requisite silica/aluminum compounds commonly supplied by pozzolanic substance in mixture such as fly ash
Portland cement and lime	See first two entries above	See first two entries above
Lime–fly-ash	See second entry above	See second entry above
Asphaltic substances	Coating of mixture particles with cohesive film and frictional resistance developed from particle-to-particle contact	Requires adequate compaction; compacted mixture may be placed into service quickly; stabilization with asphalt cement requires heating of all ingredients
Modified sulfur[b]	Binding of particles into hard mass as modified sulfur cools from melt	Probably requires compaction; mixture may be placed into service quickly; process requires heating of all ingredients

[a]Includes all types of hydrated lime; high-calcium, magnesium, and dolomitic-hydrated lime; by-product limes; and slaked limes in dry, wet, or slurried form.
[b]Sulfur mixed and reacted with various substances to inhibit a phase transformation that occurs when sulfur cools from melt. A modifying agent is dicyclopentadiene.

of materials, an optimum amount of stabilizing agent can usually be determined on the basis of cost and attainment of minimum levels of desired characteristics such as strength and/or durability.

2. Compactive effort: The field compaction process must be well controlled to ensure proper densification of the blended materials. The result of improper compaction is an inferior or unusable product. Stabilized coal-associated wastes have been successfully compacted in the field with both steel wheel vibratory compaction devices and rubber-tired compactors (24).

3. Curing procedure: Favorable curing conditions are required for coal wastes stabilized with lime, cement, or mixtures containing lime and cement. Favorable conditions involve access to moisture or provisions for moisture retention after the material has been compacted in place. In addition, moderate, nonfreezing temperatures should be maintained. Detailed recommendations for curing are well documented elsewhere (7,23).

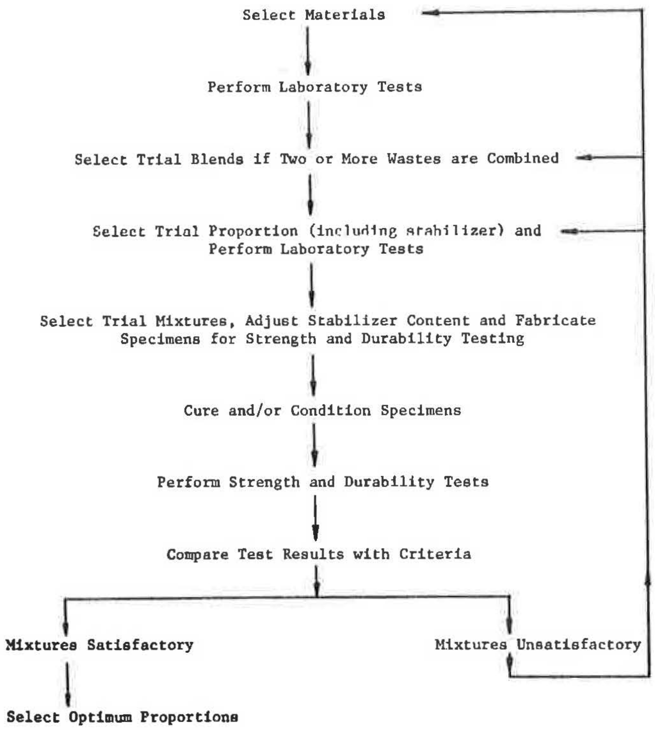
Mix Design

Mix design is an empirical process for determining both proportions of ingredients of a stabilized mixture and relevant construction operation so that the resultant product will adequately and economically serve its intended purposes. Frequently, the prospective stabilizing agent will be the most costly ingredient on a unit basis. Consequently, a common goal of the mix design process is to achieve a strong and durable mixture in which the stabilizer content is a minimum consistent with anticipated construction conditions. Mix design is empirical in that the process involves arbitrary selection of a set of trial proportions, fabrication of specimens, testing specimens for strength and durability, and assessment of results relative to selected criteria. Subsequently, reiteration of at least some of the steps is necessary to facilitate optimization of proportions in light of test results, economic considerations, and construction realities. It should also be noted that a universal stabilizing agent awaits discovery. Thus, of fundamental concern is the ability of a candidate agent to accomplish stabilization. In our experience, portland cement was a proper stabilizer for certain mixtures of coal-associated wastes. Hydrated high-calcium lime was the choice for other mixes, whereas certain coal wastes could be stabilized only with asphaltic substances (25).

Numerous factors are involved in mix design. Essentially, these are the same factors as those noted previously that affect the quality of stabilized coal-associated wastes, namely, amounts of ingredients (stabilizer, materials to be stabilized, water), type and level of compactive effort, and curing conditions (generally including age of stabilized material). Interactive effects are also present, such as the interdependency of unit weight, water content, and compactive effort. Because the number of variables is large, it is not surprising to find several mix design schemes in the literature accompanied by various rules of thumb, which serve as guides in the initial phases of choosing relative amounts of ingredients (2,23,26,27). In view of their wide availability, no attempt will be made here to list specific mix design methods; however, as an indicator of the procedures, a generalized mix design schema is presented in Figure 1. Accompanying and amplifying Figure 1 is Table 2, in which mix design operations, typical laboratory tests, and guidelines are listed, and Table 3, in which representative strength and durability criteria appear.

The representative criteria appearing in Table 3 for lime, cement, and mixtures of lime, cement, and fly ash are actually based on durability considerations. Experience in Great Britain with cement-stabilized fly ash indicated that such mixtures with minimum unconfined compressive strengths of 400 psi after curing exhibited satisfactory durability in highway base-course applications (23). The criterion of a minimum strength of 400 psi after vacuum saturation stipulated in ASTM C593 is also based on experience. Either or both of the 400-psi strength or durability criteria may be much too stringent for other applications or for materials in base courses constructed in favorable climates. It is unlikely that a stabilized coal-associated waste base course for a lightly loaded, low-volume road in a warm, dry climate requires either high strength or significant freeze-thaw resistance. Indeed, the magnitude and type of strength and the extent and type of durability required of stabilized coal-associated waste mixtures are all functions of the application; i.e., they are all use and location specific. Consequently, realization of the full economic advantages of such mixtures presupposes establishment of relevant and appropriate strength and durability criteria. To be sure, a few agencies have published guidelines that differ from those appearing in Table 3 (2). Nonetheless, much work remains to be accomplished in criteria development. Until more relevant results are available, the criteria in Table 3 can be employed with confidence for low-volume road construction purposes.

Figure 1. Generalized mix design schema.



APPLICATIONS

During the past 12 years, various coal-associated wastes have been used in a variety of highway and highway-related applications in West Virginia and the surrounding states. For the most part, these applications have involved lightly traveled secondary or low-volume roads. Included in these applications were the use of coal-associated wastes in pavement systems, encompassing unstabilized and stabilized bases and subbases and bituminous paving mixtures; structural fills; and drainage blankets or filters for underdrain systems. A considerable amount of experience on the utilization of these materials in road construction has been accumulated as a result of these applications. This experience is in an abbreviated form in the following paragraphs. However, further details presented can be found in the references cited.

Pavement Systems

Unstabilized Bases and Subbases

In our experience, one of the first attempts to use unstabilized coal-associated wastes in a base course while satisfying standard highway specifications was in the 1971 construction of the access road to the Law School on West Virginia University's Evansdale Campus (28). Bottom ash produced by the Fort Martin station of the Allegheny Power Sytem was used as it came from the ash hopper without screening or additional treatment. It was found that the material as

Table 2. Mix design operations.

Operation[a]	Typical Laboratory Tests, Mixture Proportions, and Guidelines	Purpose of Test or Trial	Representative Test Method[b]
Select materials	-	-	-
Perform tests	Specific gravity and absorption	Facilitate weight-volume determinations, voids analyses, and water-content calculations	C127, D854
	Gradation	Determine particle-size distribution	D422
	Moisture-density relationships	Determine relationships between water content, unit weight, and compactive effort	D698, D1557
		Estimate particle surface area	C110, C204, C430
	Loss on ignition	Estimate carbon content	C114, C311
	Composition tests	Determine elements and chemical compounds in sample	
Select trial blends	Proportion trial blends to achieve reasonably well-graded mixture and near maximum dry unit weight	Eliminate unsuitable blends	D698, D1557
Select trial proportions and perform tests	Select stabilizer contents and perform compaction tests; based on total dry weight of mixture, representative stabilizer contents are lime, 2-20 percent; cement, 8-15 percent; asphalt, 5-20 percent; sulfur, 10-30 percent	Determine mix proportion that yields maximum or near-maximum compacted dry unit weights or acceptable strength/stability/flow characteristics	C593, D1557, D1559, AASHTO T134, Asphalt Institute MS-2 and MS-19
Select trial mixtures, adjust stabilizer content, and fabricate specimens	Select mixtures based on results of previous operation; if stabilizer contains lime or cement, increase lime/cement content 0.5-3 percent to accommodate construction variability; fabricate specimens for strength and durability testing	Produce specimens for strength and durability testing	C593, D1557, D1559, D1560, AASHTO T134, Asphalt Institute MS-2 and MS-19
Cure and/or condition specimens	Curing processes	Facilitate strength/durability of development of specimens	C593, D1559, D1560, D1632
Perform strength and durability tests	Unconfined compression test[c]; vacuum saturation test; stability and flow tests; freeze-thaw and wet-dry tests	Determine strength/durability characteristics	C39, C593, D1559, D1560, Asphalt Institute MS-19, D559, D560
Compare test results with criteria	Comparisons of test results with use/performance criteria	Identify adequate mixtures	See criteria in Table 3
Select optimum proportions	-	Select optimum mix proportions based on preceding operation and economic considerations	-

[a]See Figure 1.
[b]ASTM standard test methods unless otherwise noted.
[c]Representative ranges of results are as follows: lime/cement-stabilized mixtures: 7-day cure, unconfined compressive strength, 500-1500 psi; asphalt-stabilized mixtures: Marshall stability, 500-3000 lb; modified sulfur mixtures: unconfined compressive strength, 1000-3000 psi.

Table 3. Representative strength and durability criteria for stabilized coal-associated wastes.

Stabilizer	Strength Criterion	Durability Criterion
Lime; lime-fly ash; lime-cement-fly ash	Minimum 400 psi unconfined compressive strength at 7 days after accelerated cure[a] or 28 days after standard cure[b]	Minimum 400 psi unconfined compressive strength after vacuum saturation
Cement	Minimum 400 psi unconfined compressive strength at 7 days after standard cure and strength increasing after 28 days' standard cure	Minimum 400 psi unconfined compressive strength after vacuum saturation
Asphalt cement	Minimum 500 lb Marshall stability; flow between 0.08 and 0.20 in	-
Emulsified asphalt	Minimum 500 lb soaked Marshall stability	Following 4-day soak at 72°F: maximum stability loss, 50 percent; maximum absorbed moisture, 4 percent; minimum aggregate coating, 50 percent
Modified sulfur	Not established	Not established

[a]Specimens stored in sealed containers at 100°F.
[b]Specimens moist cured at 70°F.

supplied would satisfy the gradation, abrasion, and sulfate soundness specifications of the West Virginia Department of Highways (WVDOH) for class-2 base courses. Placement of the ash with a conventional spreader box and compaction with a 10-ton tandem steel-wheel roller at standard Proctor optimum water content, or slightly above, produced densities that equaled or exceeded the required 95 percent of the laboratory maximum dry density. However, it was observed 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 effectively on its surface. Once the contractor became familiar with this phenomenon and its treatment, the construction progressed satisfactorily. Furthermore, the confinement provided by the placement of a bituminous surface course completely resolved the problem and satisfactory performance has been achieved. 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 WV-2 in the Ohio Valley south of Wheeling (28). In this application, bottom ash from Ohio Power's Cardinal plant at Brillant, Ohio, was placed at an average moisture content of 14 percent and compacted with two passes of a 10-ton tandem steel-wheel roller followed by four passes of a 30-ton pneumatic roller. This material also became unstable on 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.

Subsequent laboratory studies and field applications (28), however, proved that untreated ash could be used to construct a satisfactory base course without this dry stability problem when the proper gradation and combination of materials were used. In one such application, high densities and excellent dry stability were achieved in a base course on another WV-2 project, where bottom ash from American Electric Power Company's Mitchell power plant was blended with blast furnace slag, meeting ASTM 467 grading, in order to satisfy WVDOH gradation requirements for class-1 crushed-aggregate base course. This mixture, which consisted of 70 percent bottom ash and 30 percent blast furnace slag, was placed at a water content of from 6 to 8 percent and was compacted in two lifts to a total thickness of 9 in with four to six passes of a 30-ton pneumatic roller. Field measurements indicated that the compacted dry density generally exceeded 95 percent of the laboratory maximum dry density of 105 pcf.

In another such application (28), engineers for the Allegheny Power System elected to use a mixture of bottom ash and fly ash from the Fort Martin power station as the base course for the reconstruction of the access roads to the same station. Although these roads do not carry a large volume of traffic, many of the vehicles are trucks that carry ash and weigh 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 in the blend to obtain a well-graded mix with good compactability. Based on laboratory studies, they concluded that best results were obtained with a mixture of 70 percent bottom ash and 30 percent fly ash. These same proportions were arrived at during an independent laboratory study conducted at West Virginia University (29). Thus, this 70-30 bottom-ash--fly-ash combination was selected for use. However, problems with excessive moisture in the bottom ash dictated a change to a 60-40 blend, which proved to be satisfactory for the working conditions encountered in the field. This mixture was placed in trenchlike excavations approximately 6-8 ft in width and varying from 2 to 5 ft in depth. Sections at natural grade were excavated approximately 28 in through the existing roadway and the natural subgrade. Deeper sections were used to replace sidehill fills. Initially, a drainage blanket of 7 in of bottom ash was placed, followed by successive lifts of the bottom-ash--fly-ash mixture. A loose lift thickness of approximately 12 in was used. Compaction was achieved with a vibratory roller that had rubber-tired rear driving wheels and a steel-wheel front roller (Rayco Model 400 RT-1). Although the field moisture contents were generally substantially above the standard Proctor optimum of approximately 10 percent, the dry densities achieved ranged from 96.0 to 105.7 percent of the laboratory maximum dry density.

These four roadway sections, in which unstabilized bottom ash was used either by itself or blended with blast furnace slag or fly ash, have now been in service for 10 years or more with satisfactory performance. More-recent applications (1981), reported to us by A.W. Babcock of WVDOH, used a 6-in untreated bottom-ash subbase on the construction of a new access road to the Marion County Industrial Park. This was overlaid by 11 in of class-1 limestone base, 3 in of asphalt base mix, and 2 in of asphalt wearing course. A similar application was used on the I-470 off ramps in Wheeling, West Virginia. To date, these pavement sections have also performed satisfactorily.

Stabilized Bases and Subbases

The first large-scale application of a portland cement stabilized bottom-ash base course in the United States known to us was also in the 1971-1972 relocation and reconstruction of WV-2 south of Wheeling previously mentioned (28). The aggregate for this project was a blend of 46 percent boiler slag from American Electric Power Company's Kammer plant and 54 percent bottom ash from its nearby Mitchell plant. This blend was necessary in order to meet the WVDOH gradation specification for class-5 cement-treated aggregate base course. This mix was stabilized with 5 percent portland cement by weight of dry aggregate. The material was placed in one lift at water content very close to the standard Proctor optimum of 8 percent and was compacted with a 30-ton pneumatic roller to a thickness of 6 in. In general, the field densities equalled or exceeded the specified 95 percent of the standard Proctor value, which was 114 pcf. In this application, it is believed that excellent results were achieved at a substantial reduction in cost.

In later applications involving cement-treated bottom-ash base and subbase courses (21,30), substantial savings in cost were realized in the reconstruction and/or widening of many miles of low-volume secondary roads in WVDOH District I in southern West Virginia. Although it was found that bottom ash from five of American Electric Power Company's power plants in southern West Virginia and Ohio were suitable for use in cement-treated bases, most of the ash used for these applications came from the John Amos and Kanawha River plants. The bottom ash was mixed in pug mills with 10-11 percent by weight (5-6 percent by volume) of portland cement and sufficient water to achieve optimum water content at the job site. The mixture was spread with a jersey box or asphalt paver in a single uniform lift to produce a 6-in compacted thickness. Excellent compaction was achieved with several different types of compaction equipment; both pneumatic and steel-wheel vibratory rollers proved to be most satisfactory. Normally six to eight passes of the compaction equipment were required to obtain the desired compaction. Compacted dry densities ranging from 96 to 105 percent of the standard Proctor were achieved at moisture contents that ranged from 11.5 to 20.0 percent. In general, the surfacing placed over these base courses consisted of from 1 to 3 in of hot-laid bituminous concrete. The performance of these base courses, some of which are now as much as 7 years old, has generally been quite satisfactory.

Although laboratory studies have shown that portland cement-stabilized mixtures of bottom ash and fly ash can have substantial potential for use as highway base courses (29,31), and one such mixture has been used experimentally in a parking lot test section at American Electric Power's Mountaineer power plant on the Ohio River north of Huntington, West Virginia (24), we do not know of a full-scale field application of this combination of materials. However, cement-stabilized fly ash has been used successfully in the construction of base courses for haul roads and parking lots (7,24). In one of these applications, a parking lot pavement that consisted of a cement-stabilized fly-ash base course 203 mm thick and a 76-mm bituminous-concrete wearing surface was constructed at the Allegheny Power Service Corporation's Harrison power station in Haywood, West Virginia, in September 1975 (7). The fly ash used on the project was taken directly from the hoppers of the Harrison station and was mixed in a pug mill with the portland cement and water by using a job mix consisting of 83 lb of fly ash, 10 lb of cement, and 18 lb of water per cubic foot of mix. This mixture was tailgated directly from dump trucks, spread with a tracked bulldozer, compacted by an 8-ton vibratory roller, fine-graded with a grader, and then rerolled with the vibratory roller. By this method, the 8-in compacted design thickness of the base was achieved from a loose lift thickness of 12 in with six passes. An average in-place density of 98.5 percent of the maximum standard Proctor of 92.5 pcf was obtained at an optimum water content of 14 percent. Average unconfined compressive strengths of cores taken from the completed base course at 7 and 90 days were 566 and 869 psi, respectively.

Cement-stabilized fly ash was also used in the construction of a base course for a haul road near American Electric Power's Clinch River power plant in southwestern Virginia (24). Basically, this construction involved the relocation of a portion of Virginia County Road 665. The cement-stabilized fly-ash base course was designed by the procedures presented by GAI Consultants (7). The resulting pavement consisted of a cement-treated fly-ash base course 5.5 in thick and an emulsified asphalt-stabilized bottom-ash ("ashphalt") surface course 1.5 in thick (6,21). A cement content of 14 percent of the dry weight of the fly ash and a water content of 17 percent were selected for the base-course mix. These materials were mixed in place and compacted with a steel-wheel vibratory roller. Although this haul road is subjected to a low traffic volume, many of the vehicles are heavily loaded trucks. This road has now been in service for four years and it has been reported to continue to perform satisfactorily.

Lime and fly ash have been used for some time to stabilize aggregates and soils to produce roadway bases and subbases, and experience with the design, construction, and performance of these mixtures has been well documented (32). However, the use of lime and/or fly ash to stabilize coal-associated or industrial wastes has received less attention, although relatively recent studies have shown that these materials have considerable potential for use in roadway base courses (25,33,34). One such study (25,33), which was conducted jointly by GAI Consultants and West Virginia University, investigated the use of coal refuse-fly ash compositions as highway base-course materials. Both unstabilized mixtures of coal refuse and fly ash and similar mixtures stabilized with lime, portland cement, and asphalt were evaluated in the laboratory. The results of these laboratory studies showed that both unstabilized and stabilized mixtures of coal refuse and fly ash can meet current criteria (strength, durability, gradation, etc.) for conventional base-course materials. In fact, a comparative analysis conducted as part of this study suggested that thinner surface and base-course layers with equal or more favorable serviceability indices and damage parameters are possible for blends of stabilized coal refuse and fly ash than for some crushed-stone aggregates. However, to our knowledge no comprehensive in-service testing of these materials has yet been undertaken, although a field evaluation of the use of unstabilized and lime-stabilized mixtures of fly ash and coal mine refuse as a base course in a parking lot at the U.S. Environmental Protection Agency's drainage control field site in Crown, West Virginia, was reported earlier (11,31,35). Although limited in extent, the results of this study did suggest that mixtures of coal refuse and fly ash had significant potential for use as a replacement for more costly conventional aggregates as base courses on low-volume roads.

In our experience, one of the best examples of the use of asphalt to stabilize coal-associated wastes for use in base courses of low-volume roads is the WVDOH practice of using asphalt-stabilized bottom ash (ashphalt) as a base course in upgrading many miles of secondary and rural roads in northern West Virginia (6,21,28). Most of this ash is cold mixed with 6 to 7 percent residual asphalt by using a cationic asphalt emulsion (although some anionic emulsion has also been used). This material has the advantage that it can be pugged and stockpiled in advance and has proved to be quite economical. Field laydown experience with this material has been excellent. Although a bit "fluffy" in the spreader, little or no difficulty has been encountered whether the material was placed with a paver or spreader box or merely end dumped and leveled with a grader. The mix is very stable under a pneumatic roller in depths up to 6-8 in, although in the greater depths it has had to be "tracked" with a grader before it could be successfully rolled. Compaction is usually achieved after four to five passes with a pneumatic-tired roller. In general, this material has held up well in service. Although designed as a base course to be covered by a wearing surface, much of the material has never been surfaced and has performed well under traffic.

Bituminous Paving Mixtures

Generally speaking, relatively little appears in the technical literature with respect to the use of power-plant ash in bituminous paving mixtures even though boiler slag has been used successfully at various locations in the United States. The material has been used in Texas and has been evaluated by the State of Florida as an aggregate in surface mixtures. It has also been used locally by the City of Tampa and in paving the parking lot at Disney World (6).

Considerable use has been made of boiler slag in bituminous mixtures in West Virginia (6,28). Boiler slag has been regularly used in the northern panhandle as an aggregate in a WVDOH Type III wearing-course mixture. This mixture is typically 50 percent boiler slag, 39 percent river sand, 3 percent fly ash, and 8 percent asphalt. A great deal of this material has been placed over the years in areas where it has been exposed to heavy truck traffic and it has exhibited a good record of service. A similar mixture was used for deslicking purposes on an accident-prone stretch of road on Easton Hill in Morgantown, West Virginia (6,28). This mixture was composed of 52 percent boiler slag, 25 percent limestone sand, 25 percent river sand, and 4 percent fly ash. Field skid data are not available, but the overlay did significantly reduce the accident frequency at the site (28).

Structural Fill

Although the highway applications of coal-associated wastes discussed above indicate that the most experience with the use of these materials has been in pavement systems, perhaps the greatest potential for the utilization of large tonnages of coal-associated wastes in low-volume roads lies in their use as structural fills (embankments). Substantial experience has been accumulated with the use of both fly ash and coal refuse as highway embankment materials in the United Kingdom (3,7). However, experience with the use of these materials in embankments in the United States has been rather limited.

One excellent example of the use of fly ash as a highway embankment involved the relocation of WV-60/12 to eliminate an S-curve in Kanawha County near Malden, West Virginia (36). The project was conducted through an agreement between the WVDOH and the American Electric Power Service Corporation. The fly ash for the embankment was obtained from AEP's Kanawha River plant. The 40-ft-wide, 1100-ft-long embankment, with an average depth of 15 ft, was constructed in 12-in lifts compacted with six passes of a 20-ton vibratory roller. The compaction requirements specified by the WVDOH (i.e., 95 percent of the standard Proctor maximum dry density) were satisfied throughout the placement of the fill, and the final lift immediately beneath the subbase was compacted to 100 percent of the standard Proctor. Bottom ash from the Kanawha River plant was used as a granular drainage layer beneath the fill and to backfill the 2-ft undercut that was made across the entire fill area. Thus, a total of 4 ft of this material was used beneath the fill. All of the topsoil stripped from the area was used as cover material for the fly-ash fill slopes. This embankment has now been in service for more than 5 years and its performance is judged to be excellent.

WVDOH has also used fly ash successfully as lightweight embankment material in several landslide correction projects (21,28). For example, fly ash was used in a landslide correction project on WV-250 near Fairmont. The project, implemented by a district maintenance force of WVDOH, consisted of the removal of the landslide debris, installation of an underdrainage system, placement of the fly-ash fill, and sealing of the fill surface to prevent erosion. A similar slide correction that involved a substantial amount of fly ash and bottom ash was carried out by WVDOH on WV-33 west of Clarksburg.

Additional applications of fly ash as an embankment material in the United States that we are aware of have included the construction of a highway embankment in Illinois (37) and the use by WVDOH of fly ash as backfill behind a bridge abutment near Powhatton Point, Ohio.

The only application of coal refuse as an embankment material in the United States that we are aware of is its use by the Pennsylvania Department of Transportation in the construction of a section of US-219 in Cambria County and in the Cross Valley Expressway in Luzerne County (3,38). The US-219 project used approximately 190 600 yd^3 of coarse refuse material (3), whereas the Cross Valley Expressway used about 1.5 million yd^3 of both coarse refuse and "red dog" or burned coal refuse (3,38). The refuse was covered with earth as a precaution against possible detrimental environmental effects. The indications are that both applications have proved to be satisfactory in terms of economics and performance.

Subsurface Drainage Systems

Although applications of coal-associated wastes in drainage blankets and underdrain systems connected with roadway construction have not been reported, we are acquainted with several projects in which bottom ash and boiler slag have been used for this purpose (28). Both the permeability and the gradation of many boiler slags and bottom ashes are such that they could very well be considered as a replacement for conventional aggregates in drainage blankets and as filter media in underdrain installations.

POTENTIAL FOR USE IN LOW-VOLUME ROADS

Coal-associated wastes are readily available wherever coal is mined and/or burned; this covers many parts of the United States and the world. The characteristics of and successful applications with these materials described in the foregoing sections indicate that they show very good promise for use in low-volume roads from a technical and practical standpoint. It is often possible to attain adequate performance characteristics with coal-associated wastes for various highway construction applications; however, it must be borne in mind that proper engineering is essential for achieving effective utilization. The stabilization and mix design principles cited previously should be helpful in assessing the technical feasibility of use, along with proper procedures for material evaluation. It is important to recognize that many of the coal-associated wastes exhibit special characteristics (16,18), which require due consideration in accepting or rejecting these materials for a given application. Construction with coal-associated wastes generally requires little additional attention over what is done with conventional materials; minor adjustments in construction procedures may be required depending on the characteristics of the material used.

The economic feasibility of using coal-associated wastes is probably the most important consideration that will govern their widespread use in low-volume roads. These materials are in many cases available at minimal cost at the source, unless extensive beneficiation is done to improve uniformity and quality. The transportation costs, however, will often restrict their use to local applications, unless the particular material in consideration has premium qualities that could make it compete with other available construction materials and the continuity of supply does not present a problem. Economic analysis schemes, such as those reported by Collins and Miller (12), McQuade and others (33), and DiGioia and Niece (39), should prove helpful in making a final decision with regard to the feasibility of use.

In summary, there is substantial evidence of the successful use of coal-associated wastes in highway construction, particularly in low-volume roads. The necessary technology has mostly been developed, and continuing research is filling the existing gaps. In a time of diminishing supplies of conventional construction materials and tight budgets, coal-associated wastes appear to be a valuable resource that should be considered for exploitation in building low-volume roads.

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Use and Properties of Emulsified Asphalt Mixtures in Low-Volume Roads

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The use of cold-mixed, emulsified asphalt mixtures in low-volume roads has been widely accepted by highway engineers in the past few decades. A comprehensive experimental investigation has been performed in order to characterize a marginal-quality mixture prepared by mixing sand and gravel with emulsified asphalt. A mix preparation procedure has been developed that simulates the cold-mixing operation usually used in the pavement of low-volume roads either in base courses or in surface treatment. The emulsion mixture properties were evaluated by using Marshall and Hveem procedures at ambient temperature. The tensile and resilient characteristics of the mix were obtained at three different temperatures. The effects of emulsion content, curing, and vacuum saturation were investigated. The influence of adding a small amount of portland cement was also evaluated. Finally, the properties of the emulsion mixture and asphalt concrete were compared. Significant results were obtained, which provide the highway engineer with a better understanding of the integral behavior of the emulsified asphalt mixture. This may help in increasing the use of emulsified asphalt as a binding agent in the pavement of low-volume roads in a more optimal way.

Low-volume roads represent a major portion of the highway system in the United States as well as in other parts of the world. In spite of their widespread distribution, low-volume roads have not received much attention and have been kept in a mostly unsurfaced condition. A major problem currently facing highway agencies is the continuous deterioration of these roads because of the increasing traffic loads and volume. Compounding the problem is the continuous increase in maintenance costs due to the increasing cost of materials, labor, and equipment. On the other hand, the use of hot-mixed asphalt concrete in maintaining or surfacing these roads may not be cost effective because of the large amount of energy associated with this operation. New low-cost, environmentally sound pavement materials should be used in order to reduce the cost of construction and maintenance of such low-volume roads.

The use of emulsified asphalt mixtures in the construction of low-volume roads has received wide acceptance by highway engineers because of the ecological performance and economic advantages of these mixtures. Unlike asphalt cement, emulsified asphalt reduces or eliminates heating requirements when it is mixed with aggregate. This has a significant effect on reducing energy demands and air pollution. Either road mix or plant mix can be used for the preparation of emulsified asphalt mixtures. The most critical shortcoming of emulsified asphalt mixtures, however, is the relatively low strength at early ages and the slow development of strength, which is controlled by the rate of water loss in the mixture. In addition, the possibility of erosion and a drop in strength due to the presence of water in the system before the final curing can be important. A thorough understanding of the integral behavior of the mixture would be useful in implement-