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Processing, Transporting, and Utilizing Coal Combustion By-Products

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KEYWORDS: coal, by-products, processing, transportation, utilization, separation, construction

ABSTRACT

Processing, transportation, and utilization of coal combustion by-products are presented in three distinct phases. Processing of residues from coal combustion by-products with commercial applications are discussed. The comparison of three transportation systems; trucks, rail cars, and containers; are also presented. The final phase addresses the most recent laboratory and field studies on the utilization of Illinois fluidized bed and pulverized coal combustion by-products for highway materials.

INTRODUCTION

The United States is a major producer of agricultural, industrial, mining, and municipal by-products. Traditional methods of by-product disposal most often have resorted to landfill and stockpiling on land. The accumulation of these by-products presents considerable environmental, aesthetic, economical and social problems. With various public and private agencies actively promoting alternative methods of solid by-product disposal, recycling and conversion into viable construction materials seems to be a logical solution that allows for the conservation of natural resources, abates further pollution, and preserves the environment.

Currently, the coal and utility industries are the major source of mining and industrial wastes in the state of Illinois. The readily available supply of coal and its use in coal burning electric generating plants and co-generation pulverized coal combustion facilities has resulted in production and accumulation of large quantities of by-product residues (over five million tons per annum). Additionally, the use of scrubber sludge to facilitate sulfur reduction of Illinois high-sulfur coal also generates large quantities of scrubber sludge annually. With only 20% utilization, where the remaining by-products are disposed in landfills and ponds, and the expected growth in power generation; the industry is faced with a lack of available disposal space, storage cost, and environmental consequences for surrounding communities.

This paper addresses three sequential components involved with coal combustion by-products, namely, processing, transportation and utilization. In the first phase, processing of ash from coal combustion and its ability to yield products with commercial applications are introduced. Four processed products, including cenospheres, magnetic material, high-carbon content material, and base material for cement/concrete applications, are discussed. The paper then discusses transportation and hauling of coal combustion by-products using three major groups of transportation systems: trucks, rail cars, and containers. The selection of one technology over the other based on system cost, and as affected by transportation distance and material volume, is examined thoroughly. Finally, the paper addresses the most recent laboratory and field studies dealing with utilization of fluidized bed and pulverized coal combustion by-products for highway applications. The results of a number of laboratory and field investigations are used to ascertain the suitability of coal combustion residues as paving materials in road applications.

RESULTS AND DISCUSSION

Processing

The fly ash generated from coal combustion is a composite of several different minerals that may be used in bulk form for large, low-value applications, such as in roadway construction materials, or separated into the basic mineral components and applied in specialty, high-value applications. For example, the separation and recovery of cenospheres using a gravity-based technique is being commercially employed in the U.S. and the product used as a filler material in plastics and other applications. Recovering the magnetic fraction from fly ash for use as heavy-media in coal cleaning plants received considerable attention in the 1980s as the source of raw magnetite was thought to be dwindling. This application resulted in a commercial plant installation. An untapped resource from fly ash is the unburned carbon, which may have potential beyond reburning as a fuel. Applications include filter media, substitute for activated carbon, and a replacement for industrial carbon. The recovery of cenospheres for filler material in plastics and other applications yields a high-valued product that has resulted in several commercial installations.

In the recovery of different minerals from fly ash, the unit processes exploiting large differences in particle size and density can be used. The data indicate that a relatively easy separation of carbon from most of the other minerals is achievable at a particle size of 75 • m (200 mesh) and screening should be utilized as the primary separation mechanism for fly ash. This finding has also been observed from several different fly ash sources.

Similarly, gravity-based separations can be evaluated in the same manner as shown in Figure 1. It is evident that significant reductions in carbon content could be realized using a separation density of about 2.1 gm/ml. At this density, the carbon content can be reduced for the sample in Figure 1 from 12% to less than 0.5% at a recovery of over 50% of the material. Glass is the only component that has the same tendency as the carbon material with the majority having a particle size greater than 75 • m and a density less than 2.1 gm/ml. The glass material generally exists as broken hollow spheres fused with other components such as char or base material and is a desirable component for pozzalonic purposes. A comparison of the two methods indicates that a separation based on particle density differences may be more efficient than a particle size separation. As a result, a density separation of a 75 • m screen overflow should yield a material acceptable for concrete application and an enriched carbon product.

The density distributions of the carbon material in a high carbon fly ash are shown in Figure 2 as a function of particle size. An interesting finding from this data is that the average particle density of the carbon material increases with a decrease in particle size. The trend is a result of the nature of the combustion process and the feed particle size. The typical coal being fed to a boiler has a particle density range between 1.1 and 1.6 gm/ml. Incomplete combustion of coal particle, such as that commonly realized in low NO_x boilers, results in a relatively low particle density distribution with the majority of the carbon particles having a density less than 1.7 gm/ml. However, in high temperature boilers, the unburned carbon particles are more likely to form a char, which can be classified as isotropic or anisotropic. The isotropic chars have thin wall structures, a particle density between 1.7 and 1.9 gm/ml, and have the potential to be used in activated carbon applications. The anisotropic chars have a particle density between about 1.9 to 2.2 gm/ml, thick wall structure and, thus, have little potential for activation. Thus, the application of an enriched carbon material obtained from a given fly ash source may be determined from the density profile of the LOI material. In addition, the analysis results provided in Figure 2 indicate that gravity-based separation can be used to achieve a desirable carbon enrichment for some fly ash sources, especially those from low NO_x systems.

The particle size-by-size analysis of several fly ash samples have indicated that the majority of the low-density cenospheres are concentrated in the +75 • m size fractions. Thus, a primary particle size separation in a fly ash treatment circuit may provide three purposes: 1) production of a fly ash usable in cement-concrete applications, 2) concentration of carbon material, and 3) recovery of cenospheres while minimizing water consumption. The screen overflow could be treated in a dry gravity-based separator to further concentrate the carbon and cenospheres prior to the use of a water-based separation process such as froth and/or skin flotation. A test was conducted using the screening/dry gravity separation concept. The fly ash was initially dry screened at 53 • m and the overflow stream treated in a dry fluidized bed unit developed by researchers at Lehigh University to achieve a gravity based separation. The fluidized bed system reduced the loss-on-ignition (LOI) material from 11.9% to 6.4%, which, after combing the screen underflow and the heavy underflow stream from the density separator, resulted in a low LOI of 3.70%.

Finally, the recovery of the magnetic material from fly ash has been commercially practiced. To further evaluate the feasibility of magnetite recovery, a separation test program using continuous drum-type separators was conducted on a fly ash sample by Eriez Magnetics. The sample was subjected to a two stage dry separation in order to concentrate the magnetite. The magnetic concentrate was in turn subjected to an additional two stage wet separation in order to produce a high grade ferromagnetic product. The dry separations were conducted using the Model DFE-25 magnetic drum for which a rougher/cleaner arrangement was employed. The rougher stage was conducted at a unit capacity of 3 tph/foot of drum width at a drum speed of 300 ft/min. The cleaner stage was conducted at a unit capacity of 2 tph/foot of drum width at a drum speed of 500 ft/min. The dry magnetite concentrate was subjected to another two stage separation using a wet drum to further upgrade the ferromagnetics. The first stage wet drum separation was conducted at a magnetic field strength of 1000 gauss while a magnetic field strength of 750 gauss was used for the second stage. The amount of magnetics was concentrated from 11.5% in the feed to 98.9% in the final product with a mass yield of 13.2%

Transportation

Long distance transportation of coal combustion by-products can be accomplished basically with three major groups of transportation systems: trucks, rail cars, and containers.

1. Trucks: These could be pneumatic trucks, rear-dump trucks, tarped rear-dump trucks, and bottom-dump container trucks. The major environmental concern in CCB transportation is the fugitive dust due to extremely small size of the particles. Pneumatic trucks (PT) were found to be most environmentally acceptable system in transporting dry products. Rear dump trucks on the other hand are suitable and economically advantageous in transporting products with 15-25% moisture content such as scrubber sludge. Pneumatic trucks are loaded by gravity at the plant and unloaded by a blower mounted on the truck or by a stationary blower at the delivery site. These trucks are approximately 20-25 tons in capacity and can offload in about 20-25 minutes.

2. Rail Cars: These could be pressure differential rail cars and coal hopper cars. The Pressure Differential Rail Car (PD-car) is a special type of rail car used to handle powdered materials. They are operated under the principle of pressure differences between the car and the container (or the silo) to which the product is discharged. PD-cars are best suited to transportation of dry byproducts. The coal hopper cars on the other hand can be used in the transportation of wet product such as scrubber sludge containing 10 to 15% moisture. When these cars are used for dry byproduct transportation, they can either be tarped or the exposed surface on top can be chemically sprayed to prevent fugitive dust while traveling. The major drawback in chemical spraying is that even if the crust formation is successful, baghouses are needed both at the loading and offloading points to prevent fugitive dust. Also, penetration of water or moisture through the crust, leading to heating or settling may cause severe handling problems. Coal hopper cars become very beneficial when there is coal fronthauling from the mine to the plant and coal combustion by-products backhauling from the plant to the mine where the residues are disposed.

3. Containers: These could be rectangular and cylindrical steel containers, cylindrical aluminum containers, and collapsible containers. Containers are intermodal, that is, they can be carried on flat-bed rail cars, trailers, and in barges. They have approximately 20-25 ton capacity assuming an average density of 60 pcf for byproducts. These containers have been recently developed and demonstrated for coal combustion ash transportation. In general, a container can be filled by gravity through a flexible spout hanging out from the combustion residues silo of the plant. At the disposal, or utilization site special offloading equipment might be needed to empty these containers.

The Collapsible Intermodal Containers (CIC™) are made of rubber coated aramid and nylon fabric with polyester webbing. The CICs are collapsible storage bins that are portable and suitable to ride inside coal cars, barges and trucks. Depending on the number of bays in a coal hopper car, three or four of the CICs can ride in one car.

The selection of one technology over the other is based on the system cost, which is a function of the transportation distance and volume of coal combustion by-products to be transported. In a recently conducted study, the above mentioned systems were compared for cases that could be considered typical for central and southern Illinois. In southern and central Illinois, annual coal combustion residues production ranges between 50,000 and 200,000 tons, and typically plants are 50 to 320 km (30 to 200 miles) away from underground mines. Therefore, all evaluations were conducted for distance-tonnage combinations within these ranges. Specifically, three annual product tonnages, 50,000, 100,000, and 200,000 tons were considered, and each tonnage was evaluated for transportation distance of 50, 160, and 320 km (30, 100, and 200 miles). One system is selected from each group of transportation systems, namely, pneumatic trucks (PT), cylindrical containers (CC), and PD-cars. All three systems were evaluated based on a project life of 10 years; a minimum required rate of return of 12% and an effective tax rate of 40%. The results, in terms of $/ton/km, for 50,000 tons and 200,000 tons are shown in Figures 3 and 4 respectively. The reported costs are for delivery to the point of placement.

At 50,000 tons per year (Figure 3), the PT system gave lower unit costs than the PD-car and CC technologies up to approximately 180 km (112 miles). The costs in PD-car and CC technologies were almost the same for all distances. The unit costs in PD-car and CC technologies decreased significantly between 50 to 160 km (30 to 100 miles), and kept decreasing, though moderately, between 160 to 320 km (100 to 200 miles). In contrast, the unit costs in PT technology remained almost unchanged for all distances. This is an indication that the unit cost in PT transportation is insensitive to distance, whereas the opposite is true for the other technologies. It is noted that although the unit cost ($/ton/km) in PT transportation is insensitive to distance the total cost, expressed in $/ton, will be very sensitive to distance. Of course, the opposite will be true for the other two systems.

At 100,000 tons per year, the PT system gave lower unit costs than the PD-car and CC systems up to a distance of approximately 150 km (94 miles). At 200,000 tons per year (Figure 4), the advantage of the PT system over the others moved down to 130 km. Moreover, with increases from 50,000 to 200,000 tons per year, significant decreases in unit costs in the PD-car and CIT systems were found. The decrease in unit costs in the PT technology, however, is very slight for all production rates. This is an indication that the economies of scale are favoring the PD-car and CC systems over the PT system.

Utilization

In September 1991, the Department of Civil Engineering at Southern Illinois University Carbondale (SIUC) and Illinois Clean Coal Institute (ICCI) co-sponsored a two-year research program dealing with the utilization of FBC residues in cement and non-cement concrete mixtures. An effective preconditioning method was developed to alleviate the excess expansion when using FBC residues. Both FBC spent bed and fly ash were used in combination with portland cement to produce a variety of vibratory-placed concretes. It was found that the inclusion of FBC spent bed increases the demand for mixing water in obtaining the required workability. As a result, fresh properties, expansion, and early strength properties are adversely affected. When a low dosage of portland cement was used or the fine aggregate component of the matrix consisted of 20 to 40% (solid mass) natural fine aggregate, the engineering properties of concretes made with FBC spent bed, for the most part, were comparable to those of conventional mixes. The use of FBC fly ash in portland cement-based mixtures of low C_3A content, up to 15%, was tolerable without any adverse effect on short- and long-term properties of concrete products. The results of the roller compacted FBC concretes have been spectacular. Superior engineering properties attained, under the adopted consolidation method, for the mixes containing no portland cement. Strength development followed the well known pattern of conventional concrete and improved as the cementitious materials content of the matrix increased. Expansion under soaked conditions increased as the fly ash content of the mix increased. However, it was drastically reduced and was virtually nonexistent under sealed testing conditions. The use of low water-cementitious materials ratio in compacted matrices also resulted in less shrinkage cracking.

In September 1994, under the sponsorship of ICCI, a field demonstration project, aimed at evaluating the constructability and engineering performance of the experimental slabs utilizing FBC spent bed and PCC fly ash was constructed. A nearly 300 ft. road, comprised of 23 different base and surface course slab sections, was constructed at a site located in Carterville, Illinois by two construction contractors who were part of the industrial participants of the FBC-based research project at SIUC. Both conventional (vibratory) and roller compacted concrete placement techniques were utilized. Once the pavement sections were placed and finished a coat of chemical sealant was spread on the slab surface to maintain sufficient moisture for hydration of cementitious binders. The road was seal-cured for nearly ten days before it was opened to traffic. The results of PCC/FBC non-cement roller compacted concrete slabs are shown in Table 1. In general, test results were extremely encouraging. Strength and elastic modulus followed the well-known patterns of conventional concrete, and improved as cementitious binder content of the matrix increased. Expansion strains, based on internal sulfate attack, were minimal and virtually nonexistent. The slabs containing a low dosage of portland cement (5% by weight of total dry solids) exhibited an improved tensile strength, linear expansion, abrasion wear, and freezing and thawing properties. Bi-weekly inspection of the paved surfaces indicated that, after nearly three years from the date of initial casting, the sections were crack-free and have remained in excellent surface condition. Moreover, after three years of exposure to freezing and thawing cycles of the winter climate, no deterioration or surface scaling has been experienced by any of the PCC/FBC surface course roller compacted concrete slabs. Only one surface slab of vibratory-placed PCC/FBC concrete displayed surface scaling. The examination of the cores taken 3 years after construction of PCC/FBC base course slabs revealed no damage due to freezing and thawing of the winter climate. The engineering properties of the field slabs clearly indicate that this source of cementing and secondary materials can be used as a surface course for secondary roads, as well as high-performance base course for high-volume primary roads.

In September 1994, field roller compacted slabs were also prepared using composites made with PCC fly ash, FBC spent bed, and natural fine aggregate. The slabs served as bases for secondary/country roads. The surface course was built with two inches of asphalt concrete. The results are summarized in Table 1. Test results showed that compressive strength and linear expansion of PCC/FBC composites improved with increases in PCC fly ash content of the matrix. In addition, compressive strength increased and expansion decreased when testing conditions changed from soaked to sealed to air-dried. When a low dosage of portland cement (0.75 - 1.2 % by mass of total dry solids) was added, an average increase of 50% in compressive strength and a decrease of 35% in one year linear expansion were found. Test results also concluded that the engineering properties of the PCC/FBC composites exceeded those of the conventional mixes used in low-volume roads. The field results reaffirmed that the engineering characteristics of the laboratory mixtures could be easily attained in the field.

Under a separate program and over the past five years, the Department of Civil Engineering at SIUC has also directed a comprehensive laboratory program in order to ascertain the basic engineering characteristics of PCC dry bottom ash and their potential applications for the construction industry. Such a versatile approach in better understanding of the material mechanics has provided a number of potentially viable applications for PCC bottom ash by-products. Both lignite and bituminous dry boiler bottom ash were used, as a fine aggregate, in structural grade vibratory-placed and roller compacted concretes. The study addressed: (1) physical and chemical properties of the matrix constituents; (2) fresh characteristics including workability, setting time, early volume change (stability), air content and unit weight; (3) strength and stiffness properties, drying shrinkage and swelling; and (4) long-term durability in terms of abrasion wear, and resistance to freezing and thawing. Laboratory test results of vibratory-placed PCC bottom ash conclude that, due to the high absorption rate, angular shape, and porous surface, the bottom ash mixes necessitated the use of a higher water content to achieve the degree of lubrication needed for a workable mix. The increased water demand, in achieving a similar consistency, had a minor to moderate effect on plastic properties, early-age strength, and physical and chemical durability of the bottom ash mixtures. As a general rule, the lignite-based bottom ash mixes displayed early-age properties that were superior to those of bituminous bottom ash concretes and comparable to the properties offered by the conventional concrete mixes. With the exception of chloride permeability, the lignite bottom ash concrete ash mixes exhibited a resistance to external sulfate attack, freezing and thawing, and rapid chloride permeability similar to those, and in most cases superior to the equivalent conventional concrete samples. For roller compacted concrete containing PCC dry bottom ash, concrete samples of different mixture proportions (cement content ranging from 9 to 15%, and coarse aggregate contents of 50, 55, and 60% by mass of total dry solids) were prepared at their optimum moisture content and consolidated in accordance with the requirements of ASTM C 1170. Test results conclude that RCC samples containing dry high-calcium bottom ash offer excellent strength, deformation, stiffness, and long-term characteristics, considering the range of cement factor utilized. Mixing water requirements varied from 6.75% to 8.25% by mass of total dry solids. Times of vibration were 60 ± 20 seconds and 80 ± 20 seconds for cylindrical and beam-shaped specimens, respectively, offering one-day unit weights of 140.7 to 149.6 pcf. As shown in Table 1, the compressive strength, splitting tensile resistance, and flexural strengths, and modulus of elasticity varied from 2439 to 7222 psi, 374 to 726 psi, 567 to 1103 psi, and 3033 to 5539 ksi, respectively. The year-old drying shrinkage strains ranged between 203×10^{-6} to 298×10^{-6}, nearly half of that of vibratory-placed conventional concretes. Resistance to freezing and thawing, sulfate attack, and wear improved with increases in cement and/or coarse aggregate contents. Abrasion under wet conditions was consistently worse than that under dry conditions. Length change due to external sulfate attack varied from 0.27% to 0.413%, while no mass loss or reduction in strength were found for any of the mixture proportions used in this investigation. After 300 rapid freezing and thawing cycles, the RCC containing dry bottom ash displayed a maximum mass loss of 2.1% and a minimum durability factor of 91.21%.

In 1996, a field demonstration project was conducted at a site located in Illinois Coal Development Park, Carterville, Illinois. Three cement factors, namely, 550, 650, and 750 lb/ft^3, were used. Cores from small paving slabs were extracted at different ages and tested for fresh and hardened properties. Test results are displayed in Table 2. The final time of setting for bottom ash concrete ranged from 3.77 to 4.72 hours as compared to 4.93 to 5.87 hours exhibited by the control samples (a decrease of 20 to 24%). The bleeding of freshly mined bottom ash concrete was significantly lower than that of control concrete (0.01 - 0.04% vs. 0.18 - 0.22%). The unit weight of bottom ash slabs ranged from 135 to 140 pcf as compared to 146 to 148 pcf for control paving slabs. The strength properties of bottom ash concrete slabs were higher, than those of control paving sections, by nearly 10% after 28 days and 15% after 90 days from the date of initial casting. The bottom ash concrete also displayed chloride impermeability (a measure of corrosion potential for steel reinforcements) far superior to that found for the equivalent conventional concrete slabs. Due to the porous nature of bottom ash aggregate, the resistance to abrasion and rapid freezing and thawing of the control slabs slightly out performed those exhibited by the bottom ash paving sections.

CONCLUSIONS

1. The physical characteristics of the mineral components in the fly ash are strongly dependent upon the boiler type. The fly ash characterization data for high carbon content materials indicates that significant differences in particle size and density exists between the carbon particles and the remaining components which should allow for effective process separations.

2. The dry fluidized bed density separator developed by Lehigh University was found to provide a significant reduction in LOI content, especially for the +150 • m particle size fractions.

3. Using a series of dry and wet magnetic separation devices, the amount of magnetics in a fly ash sample was concentrated from about 10% to nearly 99% with overall mass yields to the magnetic product of 13%.

4. A combination of screening at about 75 • m and gravity-based processing of the screen overflow using preferably a dry-based system should provide an effective production of sufficiently low LOI material for cement/concrete applications and an enriched carbon product from relatively high LOI-type fly ash.

5. At shorter transportation distances and lower volume of coal combustion by-products, trucking system is preferred to rail and container systems. The latter systems are equally favorable especially when the distance is long and the volume is large.

6. The selection of a transportation system is also dependent on factors such as existing materials handling facilities, possibility of backhauling the material, and availability of contractors.

7. Various PCC/FBC roller compacted concretes tested in the laboratory and field have shown promising results for high-performance base pavements of high-volume and secondary/county roads.

8. PCC dry bottom ash has exhibited remarkable performance in replacing the fine aggregate component of structural-grade concrete pavements.

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Table 1. Test results for Various Composites Containing Coal Combustion Residues

Composite Types	Mechanical Properties and Long-term Durability[1]						
	Compressive Strength (psi)	Split-Tensile Strength (psi)	Modulus of Rupture (psi)	Elastic Modulus (x 10^6, psi)	One-year Expansion/ Shrinkage (%)	Resistance to Wear (x 10^4, in.)[2]	Resistance to Freezing & Thawing[d]
PCC/FBC Non-Cement Roller Compacted Concrete Pavements[a]	2728-5435	301-500	487-702	2.51-3.70	+0.005% to + 0.025%[3]	170-451	High, but comparable to equivalent non-air-entrained Portland cement Concrete[4]
PCC/FBC Roller Compacted Composites for Secondary/County Roads[b]	3589-3773	391-434	[5]	2.1-2.9[6]	+0.015% to + 0.038%[3]	[5]	Mass loss of 0.16-0.55%[7]
Laboratory-made Roller Compacted Concrete Containing PCC Dry Low Calcium Bottom Ash[c]	2439-7222	374-726	567-1103	3.03-5.54	-203×10^{-6} to -298×10^{-6} [8]	116-178	Mass loss of 0.25-2.10% and Durability factor 91.2-97.5%[4]

[a] PCC = pulverized coal combustion fly ash as a cementitious binder and FBC = fluidized bed combustion spent bed as a fine aggregate and an agent to activate pozzolanic properties of PCC fly ash; [b] mixes contained 0.75-1.2% Portland cement by mass of total dry solids; [c] mixes contained 9-15% Portland cement by mass of total dry solids; and [d] all specimens were non air-entrained.

[1] 90-day cured specimens; [2] 20 minutes test duration, air-dry at testing, and using ASTM C 779, Procedure C, Ball Bearings;
[3] represents expansion in terms of length change given in percentage; [4] 300 F-T cycles and using ASTM C 666, Procedure A; [5] not required since composites are used for base and/or sub-base course materials, [6] Poisson's ratio varied from 0.125-0.151; [7] 12 F-T cycles, using fully saturated samples, and ASTM D 560; and [8] represents drying shrinkage strains.

Table 2 - Tests Results for Vibratory-Placed PCC Dry Bottom Ash Concrete Pavements

Engineering Characteristics[1]	Composite Types: PCC Dry Bottom Ash Concrete	Composite Types: Equivalent Conventional Concrete
Initial Time of Setting (hours)	3.03-4.02	3.77-5.27
Final Time of Setting (hours)	3.77-4.72	4.93-5.87
Bleeding (%)	0.01-0.04	0.18-0.22
Weight (pcf)	135-140	146-148
Compressive Strength (psi)	3087-7158	2949-6070
Splitting-Tensile Strength (psi)	379-717	375-628
Flexural Strength (psi)	589-816	542-678
One-Year Drying Shrinkage (%)	0.034-0.048	0.026-0.041
Rapid Chloride Permeability (Coulombs)	145-691 (very low)	2361-3677 (moderate)
Resistance to Abrasion[2] (x 10^{-4} in.)	253-330	205-269
Resistance to Rapid Freezing and Thawing[3]	durability factor of 96.51- 97.71 and mass loss of 0.23 to 0.41%	durability factor of 95.43- 97.92 and mass loss of 0.18 to 0.31%
Resistance to Freezing and Thawing with Deicing Salt[4]	mass loss of 0.96-2.59%	mass loss of 0.71-1.18%
Absorption (%)	1.28-1.70	1.93-2.50

[1] Unless otherwise stated, all samples were 90 days field cured
[2] 20 minutes test duration and using ASTM C 779, Procedure C, Ball Bearings
[3] 300 F-T cycles and using ASTM C 666, Procedure A
[4] 50 F-T cycles and using fully salt-saturated specimens

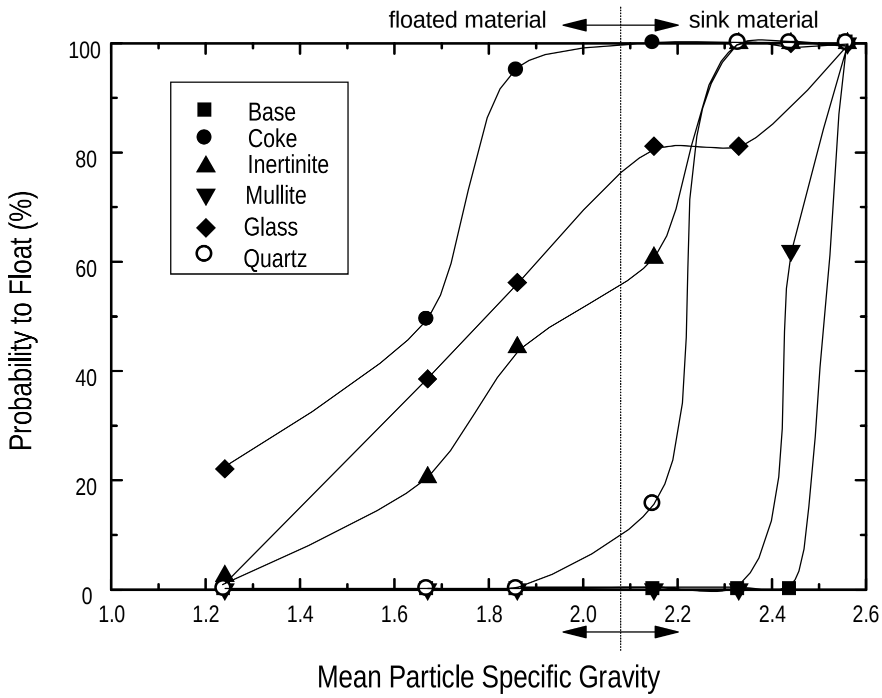

Figure 1. Partition curves on the basis of the mean particle density for each of the petrographic components found in a PCC fly ash. The line represents a hypothetical separation for reducing the carbon content of a high carbon fly ash.

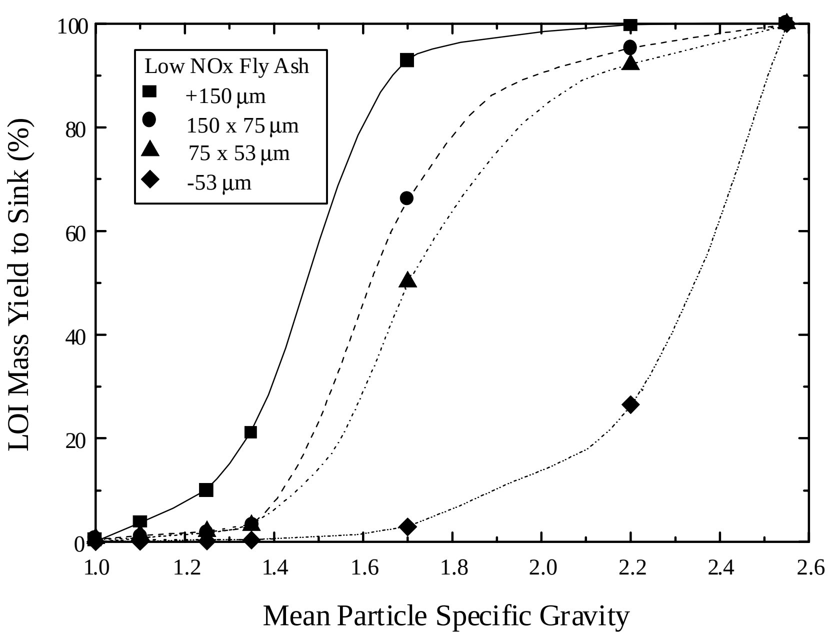

Figure 2. Particle size-by-size particle density distributions of the LOI (i.e., combustible) material in the low NO_x fly ash sample which show an increase in particle density with decreasing particle size

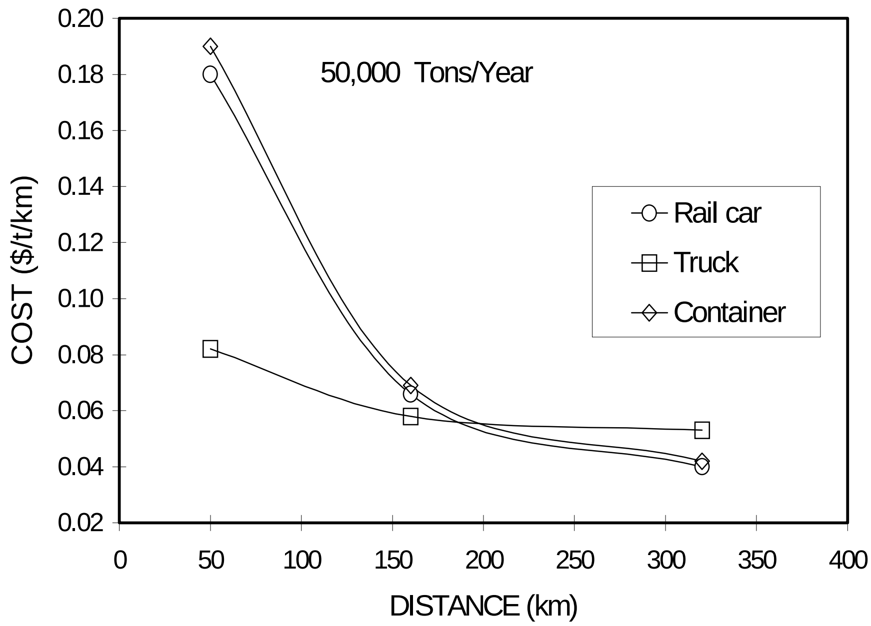

Figure 3. Unit costs in the transportation of 50,000 tons of product by three different systems

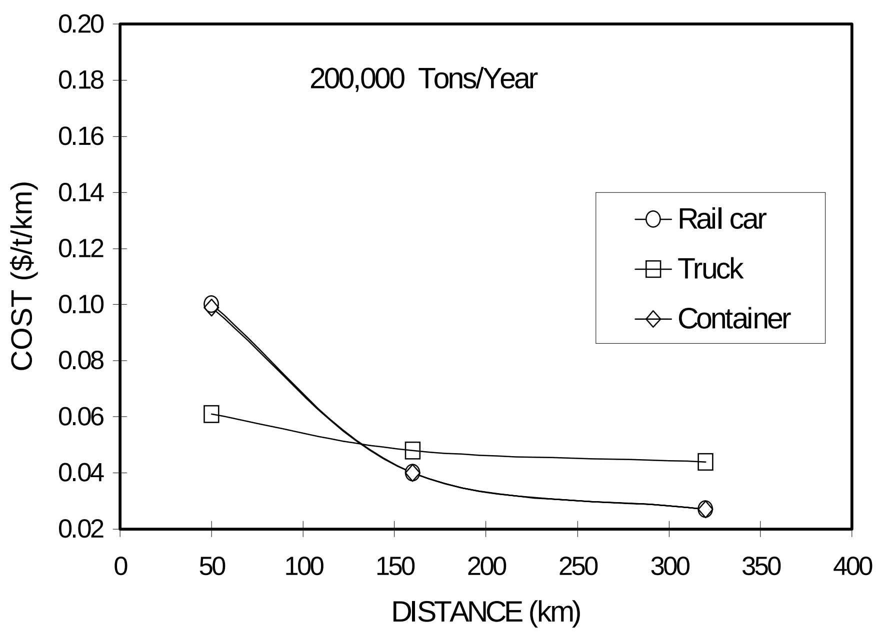

Figure 4. Unit costs in the transportation of 200,000 tons of product by three different systems