Bottom Ash as a Highway Material

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The physical, chemical, and engineering properties that are likely to affect the use of bottom ash as a highway material were assessed. Laboratory studies conducted on Indiana bottom ashes included three phases: ash characterization tests, engineering property tests, and environmental evaluation. Ash characterization tests consisted of physical appearance observation, chemical composition analysis, specific gravity determination, and gradation analysis. Engineering property tests included the testing of durability, abrasion resistance, maximum and minimum void ratio, permeability, compaction, degradation, shear strength, compressibility, and California bearing ratio. The test results are compared with representative values obtained for typical granular soils. The environmental evaluation shows that bottom ashes have a nonhazardous nature, minimal effects on ground water quality, low radioactivity, and low erosion potential, but they may be potentially corrosive. In conclusion, with favorable engineering properties and minimal adverse environmental effects (except for corrosiveness), untreated bottom ashes can be extensively used in highway construction, such as embankments, subgrades, subbases, and even bases. However, those bottom ashes having high corrosiveness should not be placed in the vicinity of any metal structure.

The diminishing supply of natural high-quality materials has directed attention toward the search for innovative materials. On the other hand, a huge quantity of coal ash is produced from the utility power plants at a steadily increasing rate. Waste disposal of ash is costly and may cause an environmental hazard, especially in urban areas. If a productive use of ash becomes more common, it may not only solve a potential solid waste disposal problem, but also provide an economic alternative construction material. The use of coal ash provide an economic saving, on a local or regional basis, to both electrical utilities and highway agencies. However, before this goal is fully realized, the physical and chemical properties as well as mechanical behavior of coal ashes should be more thoroughly examined to ensure that they meet current requirements for conventional and natural materials.

Coal ash is produced in two forms: bottom ash and fly ash. Bottom ash is the slag that builds up on the heat-absorbing surfaces of the furnace and subsequently falls through the furnace bottom to the ash hopper below. Because it is collected by gravity, bottom ash is a relatively coarse material. Fly ash is the fine-grained dusty material that is recovered and collected from furnace flue gases by ash precipitators.

Although considerable information on the properties of fly ash has been accumulated because of its higher production and its widespread use in soil stabilization and as a cement replacement in concrete, few experimental data are available for bottom ash. Laboratory tests conducted on Indiana bottom ashes provide additional information on the properties that will affect the use of bottom ash as a highway material. The experimental program was performed in three phases: ash characterization tests, engineering property tests, and environmental evaluation. Both the engineering suitability and environmental acceptability of bottom ash utilization were assessed.

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FORMATION AND NATURE OF BOTTOM ASH

Coal ash, incombustible mineral matter, accounts for 10 to 20 percent, by weight, of the coal consumed in power plants. Ash characteristics are affected by the type of boiler and the operation procedure, as well as by the type of coal burned. Depending on the boiler type, the ash under the furnace bottom is categorized as dry bottom ash or wet bottom ash.

If the ash is in a solid state at the furnace bottom, it is called dry bottom ash. The ash particles are usually gray, irregularly shaped, and highly porous. Wet bottom ash is more often called boiler slag. The term "wet" refers to the molten state of the ash, which leaves the furnace as a liquid. The molten ash is quenched in a water-filled hopper to form boiler slag. Boiler slag is a hard, black, and angular material with a smooth surface texture. Bottom ash is crushed to the size of gravel to facilitate subsequent handling.

There are three categories of coal-burning boilers, each producing different types and quantities of coal ash. These types are: (a) pulverized coal-fired furnaces; (b) stoker-fired furnaces; and (c) cyclone furnaces. The first two types of furnaces contain several subtypes of boilers. Table 1 shows the relative quantities of coal ash collected for various boilers. Modern large utility boilers burn pulverized coal and have dry bottom furnaces.

ASH DISPOSAL

Basically, ash handling and disposal is accomplished either by wet or dry methods. Dry disposal implies transport and deposition of dry or moistened ash. This process may involve temporary storage of ash in silos, subsequent hauling by trucks, and compacting at a landfill. Most power plants in urban areas handle ash by the dry method because of difficulties in land acquisition and environmental restrictions.

The wet method for disposal uses water to flush ash through pipelines to settling ponds or lagoons. This method is more commonly used because of economy. The major advantage of wet disposal is that ash ponds minimize dust problems and are simple to operate.

TABLE 1 RELATIVE QUANTITIES OF COAL ASH PRODUCED FROM VARIOUS BOILERS

Boiler Type	Sub-Type	Production Percent (%)		
		Fly Ash	Dry Bottom Ash	Wet Bottom Ash
Pulverized Coal-fired	Dry	60-80	20-40	0
	Slag-tap	50	0	50
Cyclone		15-30	0	70-85
Stoker-fired	Underfeed	10-20	80-90	0
	Spreader	15-55	45-85	0

Nationally, ash disposal costs ranged from \$5 to \$10 per ton, and the total cost of ash disposal to the electric utility industry in 1980 was estimated between \$375 and \$740 million (*1*).

PRODUCTION AND UTILIZATION

The production of ash in the United States has steadily increased with the increase in coal-fired generating capacity. Based on data from the American Coal Ash Association (ACAA) (*2*), the annual ash production in the United States has increased from 39.2 million tons in 1970 to 66.8 million tons in 1986.

Of the 17.5 million tons of bottom ash produced in 1986, 13.4 million tons were dry bottom ash and 4.1 million tons were wet bottom ash. Only 26.7 percent of the dry bottom ash was used, whereas 51 percent of the wet bottom ash was used. The utilization trend of coal ash in the 1980s shows that the percentage of bottom ash uses has remained unchanged, while the use of fly ash has improved significantly (*2*). ACAA also reported the end uses of coal ash, including eight ash utilization categories (*2*). Wet bottom ash is used in blasting grit, roof granules, and snow and ice control; dry bottom ash is mainly used for antiskid and ice-control purposes, and for highway fills and pavement courses.

EXPERIMENTAL PROGRAM

Selection of Ash Sources

Eleven bottom ashes were collected for study from 10 power stations in Indiana, with consideration to boiler type, source of coal burned, geographic distribution, and ash disposal method. Of the samples selected for testing, one (Schahfer 14 ash) was wet bottom ash and 10 were dry bottom ashes. Of the 10 dry bottom ashes, one (Perry ash) was produced from stoker-fired boilers and the others were from pulverized coal-fired furnaces. Only two plants disposed of their ashes by the dry method; in these cases, samples were collected directly from the hoppers or silos. The other nine ashes were wet-disposed bottom ashes, collected as grab specimens from ash deposits at the end of sluice pipes.

In order to examine the variability of ash properties in detail, the list of 11 ashes was reduced to four. Huang (*3*) describes the logic used in the selection. Each source was sampled at least twice. All ashes were subjected to a series of chemical and physical characterization tests, and representative ashes were then chosen for detailed testing of their engineering properties and potential environmental effects.

Physical Appearance

In order to characterize the particle shape and surface texture of bottom ash, a microscopic examination was conducted. The majority of wet bottom ash particles were angular to subangular in shape, had a smooth surface texture, and looked much like crushed glass. On the other hand, dry bottom ashes had quite angular particles and a highly porous surface texture was observed even in the finer bottom ash particles. The ash produced from stoker-fired boilers (Perry ash) was extremely porous, had a popcorn-like texture, and low resistance to breaking with the fingers.

Chemical Composition

The chemical analysis of bottom ashes was performed primarily by means of atomic absorption spectrophotometric methods, and the results are shown in Table 2. The principal constituents are silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). There are smaller quantities of calcium oxide (CaO), magnesium oxide (MgO), potassium oxide (K_2O), sodium oxide (Na_2O), and sulfur oxide (SO_3), as well as minute traces of other elements. As can be seen from Table 2, the chemical composition of each ash shows a reasonable degree of uniformity, except those ashes from Perry, Stout, and Richmond. These stations were burning different sources of coal just prior to the dates of sampling, and this is reflected by greater variations in chemical composition of the bottom ash. The loss on ignition gives an approximate indication of the unburnt carbon content.

For purposes of comparison, the typical ranges of chemical composition for most ashes (*4*) are shown at the bottom of Table 2. Stout ash shows a rather high iron content, but the other ashes are reasonably typical in chemical composition.

Gradation

Grain size analysis was performed using sieve analysis in accordance with the AASHTO T27 procedures. Figure 1(a)

TABLE 2 CHEMICAL COMPOSITION OF INDIANA BOTTOM ASHES

		Percent by weight								
Ash source	Date sampled	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Loss on ignition
Schahfer Unit 14	6-19-87	60.1	5.2	10.4	16.6	5.7	0.9	0.4	0.9	0.3
	5-12-88	53.4	6.0	13.5	18.5	5.7	1.2	0.3	1.0	0.1
Schahfer Unit 17	6-19-87	58.1	15.2	12.7	7.0	0.8	1.9	0.3	2.2	0.1
	5-12-88	52.1	23.2	13.2	4.8	0.9	1.4	0.2	1.5	0.8
Gibson	5-18-87	58.7	14.6	14.1	3.1	0.8	2.0	0.4	1.3	0.4
	5-17-88	53.6	20.8	14.8	2.6	1.0	1.9	0.5	1.1	1.0
Gallagher	5-26-87	41.2	28.4	11.2	12.6	0.7	1.6	0.3	1.0	0.9
	5-14-88	49.3	24.2	16.4	3.9	0.9	1.7	0.2	2.6	1.4
Perry[a]	5-19-87	48.9	22.2	13.0	0.8	0.7	2.2	0.3	0.6	7.2
	5-14-88	52.5	6.0	24.3	0.9	0.1	2.3	0.4	0.6	6.2
Mitchell	6-19-87	58.8	6.8	7.8	7.9	2.2	1.4	0.1	3.3	8.1
	5-12-88	51.3	6.5	14.2	8.5	3.0	0.9	0.3	1.0	8.0
Wabash	6-23-87	55.7	21.5	14.3	1.7	0.7	1.9	0.3	0.8	0.2
	4-26-88	51.7	23.0	16.0	1.7	0.9	1.9	0.3	0.6	1.0
Richmond[a]	8-17-87	48.3	33.3	11.9	1.3	0.4	0.9	0.2	1.7	2.2
	5- 5-88	41.6	20.9	18.6	1.3	0.6	1.1	0.1	1.9	14.1
Stout[a]	5-27-87	24.2	42.0	6.9	2.2	0.4	0.6	0.2	0.8	18.4
	6-20-88	54.9	20.2	16.7	1.6	0.9	1.9	0.8	1.8	0.3
Culley	8-21-87	35.6	30.1	11.7	14.6	0.8	1.4	0.3	1.0	0.0
	5-14-88	31.0	31.1	11.8	13.9	1.1	0.5	0.2	0.9	0.3
Brown	8-21-87	48.1	27.6	13.4	3.1	0.8	2.1	0.3	1.7	1.9
	5-17-88	38.5	38.0	12.6	3.8	0.7	1.3	0.2	3.3	1.1
Average		48.6	21.2	13.6	6.0	1.4	1.5	0.3	1.4	3.4
Typical range for ash [4]		20-60	5-35	10-35	1-20	0.3-4		1-4[b]		0-12

[a] Plants were burning different sources of coal prior to the dates of sampling

[b] Range for the sum of K_2O and Na_2O

shows the range of gradations for the 11 bottom ashes, as well as for fly ashes from the same sources (*5*).

Dry bottom ash and wet bottom ash have quite different gradation characteristics. Dry bottom ashes exhibited well-graded size distribution ranging from fine gravel to fine sand sizes, whereas the gradation of the single wet bottom ash was quite uniform, with a majority of the sizes occurring in a narrow range between the No. 8 and No. 30 sieves. The fines passing the No. 200 sieve for dry bottom ashes range from 0 to 14 percent and are all nonplastic. The wet bottom ash is essentially free of fines. Of the 11 bottom ashes studied, 10 were classified by the Unified Soil Classification System as sand and the other one as gravel. Classification of bottom ashes by the AASHTO system showed that all bottom ashes fall in the A-1 group, with seven ashes classified as A-1-a and the remaining four as A-1-b.

The potential variability in gradation was indicated by the gradation curves for bottom ashes sampled at different times. Figure 1(b) gives typical variations in the gradation of bottom ash. The single wet bottom ash had less variation between samplings than did the dry bottom ashes.

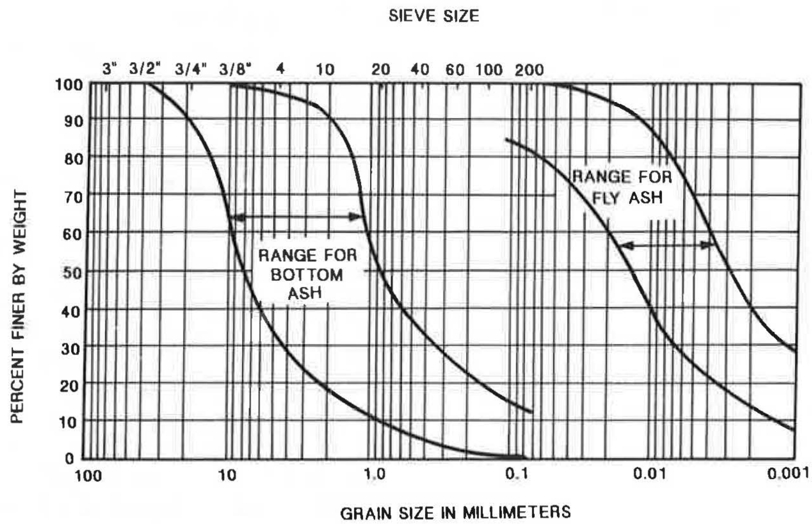
Specific Gravity

The specific gravity was determined by AASHTO T84 for fine aggregates and by AASHTO T100 for soils. The specific gravity of the 11 bottom ashes, as tabulated in Table 3, ranges between 1.9 and 3.4, which is much wider range than that of most soils (between 2.5 and 2.8 (*6*)). The specific gravity of the ash is a function of the chemical composition. Obviously, high carbon content will result in a low specific gravity, whereas high iron content will produce high specific gravity. It should be noted from Table 3 that, for most ashes, the specific gravity values determined by AASHTO T100 are greater than those determined by AASHTO T84.

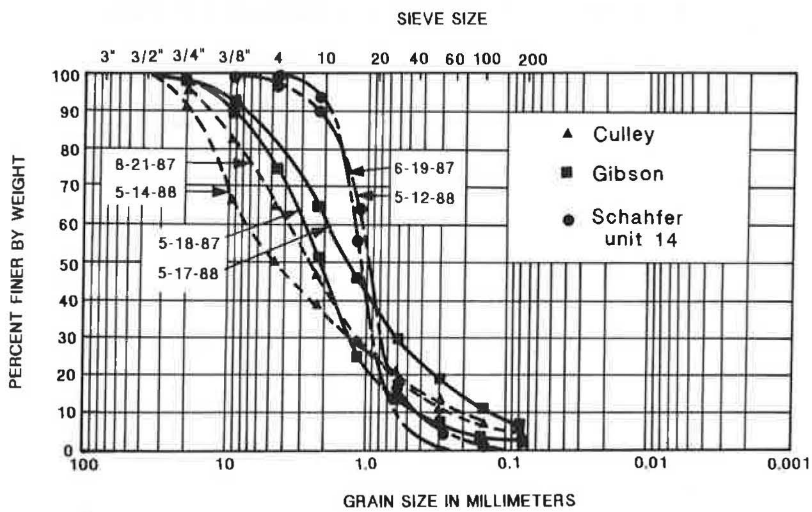
Comparison of the surface textures of bottom ashes with Table 3 indicates that the ash with a low specific gravity always has a very porous or vesicular texture, which is the characteristic of popcorn-like particles. Because popcorn-like particles are usually readily degradable under loading or compaction, porous texture is expected to be somewhat related to the degradation resistance of the material. Therefore, the specific gravity may be used as an indicator of this quality of a bottom ash.

Durability

To evaluate the durability to frost action, which is prevalent in the northern tier of states, 50-cycle freeze-thaw tests (AASHTO T103) and 5-cycle sulfate sodium soundness tests (AASHTO T104) were conducted. The weighted losses (in



(a) Ranges of gradation for bottom and fly ashes



(b) Typical variations in gradation of bottom ash

FIGURE 1 Range and variations in gradation of bottom ashes.

percentages) of these two durability tests for bottom ashes are tabulated in the left part of Table 4. In viewing the results for the first four ashes in Table 4, it can be found that the two durability tests yield comparable weighted losses, reflecting that both provide similar deterioration energy to the specimens. Accordingly, it may be possible to replace freeze-thaw tests with the simpler soundness tests.

The weighted losses of soundness tests on bottom ashes varied from 1.25 to 8.12 percent. The wet bottom ash had the lowest weighted loss, probably because of its glassy surface texture and low porosity. The weighted losses for dry bottom ashes ranged from 2 to 6 percent, except for Perry ash. This ash produced from stoker furnaces had the highest weighted loss because of its popcorn-like texture. All bottom ashes examined meet the most rigorous acceptable level (i.e., 10 percent) for fine aggregate for concrete (AASHTO M6).

Abrasion Resistance

The percent wear values determined by the Los Angeles abrasion tests (AASHTO T96) are summarized in the right part of Table 4. All ashes studies, except the stoker ash, have Los Angeles abrasion values less than or equal to 45 and therefore meet the ASTM D1241 and AASHTO M147 specifications (i.e., 50) for soil-aggregate base and subbase.

The ratio of the loss after 100 revolutions to that after 500 revolutions indicates the uniformity of the material hardness (AASHTO T96). A ratio of 0.2 represents an uniform hardness of the material tested. The ratios obtained from bottom ashes ranged from 0.28 to 0.39, which indicates that more particles broke down during the early stage of the test.

A comparison between the sulfate soundness weighted losses and the abrasion values reveals that bottom ashes with high

TABLE 3 APPARENT SPECIFIC GRAVITY OF BOTTOM ASHES

Ash source	AASHTO T 84[a]		AASHTO T 100[b]	
	1st[c]	2nd[d]	1st[c]	2nd[d]
Schahfer				
Unit 14	2.81	2.81	2.82	2.81
Unit 17	2.47	2.49	2.57	2.57
Mitchell	2.35	2.44	2.44	2.47
Gibson	2.50	2.50	2.55	2.54
Gallagher	3.05	2.57	3.07	2.64
Wabash	2.45	2.41	2.56	2.48
Brown	2.70	2.95	2.74	2.97
Culley	3.20	3.20	3.21	3.23
Richmond	2.79	2.25	2.90	2.40
Perry	1.84	1.60	2.12	1.94
Stout	3.43	2.40	3.46	2.45

[a] Standard test method for specific gravity and absorption of fine aggregate
[b] Standard test method for specific gravity of soils
[c] The first sample from the source
[d] The second sample from the source

sulfate soundness weighted losses also have high percentage wears. Of course, totally different deterioration mechanisms are developed in these two tests (simulated hydraulic pressure and abrasion, respectively).

Maximum and Minimum Void Ratio and Permeability

The maximum and minimum densities of the selected bottom ashes, along with the corresponding minimum and maximum void ratios, are summarized in the left part of Table 5. Among the five ashes, the wet bottom ash had the highest maximum and minimum densities, which are comparable to those for Ottawa sand (*6*). In contrast, Perry ash, because of its highly porous nature and low specific gravity, had the lowest maximum and minimum densities. All ashes except Perry ash meet the ASTM specification (ASTM D1139) requiring the unit weight of slag for bituminous mixtures be larger than 70 pcf.

TABLE 4 DURABILITY AND ABRASION RESISTANCE OF BOTTOM ASHES

Material	Durability: Weighted loss (%) Soundness	Durability: Weighted loss (%) Freeze/Thaw	Abrasion Test: Grading	Abrasion Test: % wear	Abrasion Test: ratio[a] 100/500
Perry	8.12	7.66	D	48	0.39
Gibson	2.84	3.38	D	34	0.39
Schahfer 14	1.25	2.26	-[b]	-	-
Schahfer 17	2.53	3.55	D	38	0.35
Gallagher	2.19	*[c]	D	37	0.31
Mitchell	5.49	*	C	36	0.30
Wabash	2.64	*	D	41	0.32
Richmond	2.19	*	-	-	-
Stout	6.34	*	C	43	0.30
Culley	3.93	*	C	40	0.38
Brown	6.70	*	D	45	0.38

[a] The ratio of the loss after 100 revolutions to the loss after 500 revolutions
[b] Denotes samples with less than 20 percent coarser than the No. 8 sieve
[c] not determined

TABLE 5 VOID RATIOS, DENSITIES, AND PERMEABILITIES OF SELECTED BOTTOM ASHES

Material	Void ratio Max.	Void ratio Min.	Unit weight (pcf) Max.	Unit weight (pcf) Min.	Coeff. of permeability k (cm/sec)	percent fines[d]	Hazen's C[e]
Schahfer							
Unit 14[a]	0.82	0.48	118.3	96.3	0.101	0.3	0.57
Unit 17	1.23	0.68	95.5	72.0	0.034	3.5	0.85
Gibson	0.87	0.51	105.5	85.5	0.009	6.5	0.45
Perry[b]	2.92	1.53	52.3	33.8	0.014	5.9	0.12
Gallagher	0.99	0.55	106.7	82.9	0.003	10.1	0.53
Standard							
Ottawa sand[c]	0.80	0.50	110.0	92.0			
Fine to coarse sand[c]	0.95	0.20	138.0	85.0			
Silty sand and gravel[c]	0.85	0.14	146.0	89.0			
Uniform coarse sand[c]					0.4		
Well-graded sand and gravel[c]					0.01		

[a] Wet bottom ash
[b] Stoker ash
[c] From Hough [6]
[d] Percent finer than the No. 200 sieve (0.075 mm)
[e] $C = k/D_{10}^2$

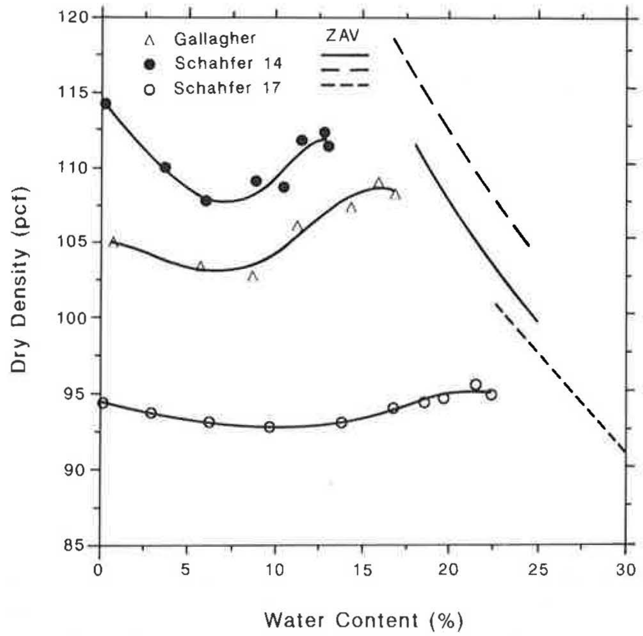


FIGURE 2 Compaction curves for bottom ashes.

Table 5 also gives the results of falling head permeability tests conducted on selected bottom ashes at a relative density of approximately 90 percent. The measured coefficients of permeability ranged from 0.002 to 0.10 cm/sec. The wet bottom ash displayed the greatest value of permeability because of its uniform size distribution and absence of fines. Table 5 indicates that the percentage of fines has a predominant effect on the permeability of bottom ash. Generally, the permeability of bottom ashes falls in a medium permeability range and is comparable to that of granular soils with similar gradings (*6*).

The calculated *C* constant in Hazen's equation, also shown in Table 5, varied from 0.1 to 0.9. Considering the wide range of coefficients of permeability for soils, Hazen's equation may be applicable for estimating the coefficients of permeability for bottom ashes whenever testing is not convenient.

Moisture-Density Relation

The relationship between dry density and moisture content was determined for bottom ashes by the standard Proctor compaction procedures (AASHTO T99). The resulting relations are shown in Figure 2. The shapes of these moisture-density curves are typical of those for cohesionless materials (*7,8*). These curves are characterized by a fairly high dry density for the air-dried condition, a low dry density at intermediate moisture, and a high dry density at near saturation. Generally, field compaction curves also exhibit maximum dry density at either an air-dried condition or a flushed condition. When the air-dried condition is not practicable for field construction, it is recommended that bottom ash be maintained in a flushed condition for attaining the greatest densification. When compared with conventional granular materials (*9*), bottom ashes are found to have lower maximum dry densities.

Degradation

The degradation of bottom ash samples occurring under standard Proctor compaction at optimum moisture content was determined. In order to quantify the degradation, the index of crushing and the increase in percent of fines were determined. The former was obtained by calculating the weighted mean size of the sample before and after compaction and expressing the percent reduction between the two mean sizes based on the initial mean size. Table 6 summarizes these values for bottom ashes and several conventional aggregates. The indices of crushing for bottom ashes (except wet bottom ash) are found to be higher than those of conventional aggregates, probably due to the breakdown of the weak and porous particles present in the ashes. However, it is interesting to note that the increases in percent of fines for bottom ashes (except Perry ash) were less.

Shear Strength

A series of direct shear tests was conducted on bottom ashes with normal stress varying from 5 to 34 psi. Table 7 summarizes the measured angles of shearing resistance along with

TABLE 6 DEGRADATION OF BOTTOM ASHES UNDER COMPACTION

Material	Percent fines: Before compaction	Percent fines: After compaction	Percent fines: Increase	Index of crushing %
Schahfer				
Unit 14[a]	0.3	0.4	0.1	4.8
Unit 17	2.5	3.5	1.0	11.5
Gibson	6.1	6.5	0.4	10.0
Gallagher	9.4	10.1	0.7	5.1
Perry[b]	2.4	5.9	3.5	32.6
Crushed limestone aggregate[c]	3.0	6.0	3.0	4.9
Natural river aggregate[c]	1.0	3.0	2.0	6.5

[a] Wet bottom ash
[b] Stoker ash
[c] From Usmen [9]

TABLE 7 RESULTS OF DIRECT SHEAR TESTS ON BOTTOM ASHES

Material	Loose (Average Dr=15)		Dense (Average Dr=76)	
	Strength intercept (psi)	Values of ϕ', deg	Strength intercept (psi)	Values of ϕ', deg
Schahfer				
Unit 14[a]	0.48	35.1	1.49	46.3
Unit 17	0.14	39.2	3.12	47.7
Gibson	0.20	44.8	1.66	55.0
Gallagher	0.49	41.3	2.00	51.6
Perry	0.49	41.5	3.00	50.6
Medium sand, angular[b]		32-34		44-46
Sand and gravel[b]		34		45

[a] Wet bottom ash
[b] From Leonards [10]

the strength intercepts. The angles of shearing resistance for bottom ashes in both loose (relative density, Dr = 15) and dense (relative density, Dr = 76) conditions were quite large, ranging from 35 to 45 degrees and from 46 to 55 degrees, respectively. (A straight line Mohr-Coulomb envelope is assumed.) It is found that the angle of shearing resistance for the wet bottom ash falls within the same range as that for natural granular soils (*10*). The values obtained from dry bottom ashes are higher than those for conventional soils. This difference can be attributed to the rough surface texture and angularity of the bottom ash particles, so that a higher degree of interlocking was developed in the shearing process. If bottom ash is used in embankments, subgrades, or subbases, the resulting stability or the bearing capacity for the corresponding use can be higher than that for natural granular soils.

One-Dimensional Compression

One-dimensional compression tests were performed on saturated bottom ashes in a dense condition. Because of the high permeability of bottom ash, the deformations took place in a very short time and no considerable consolidation was observed. No measurable creep was found. The one-dimensional stress-strain relationships for several bottom ashes and a uniform medium sand (*11*) are presented in Figure 3. For embankments built of bottom ashes, which are known to be cohesionless and granular, the secant constrained modulus can be used in estimating the settlement caused by vertical loading. Figure 4 shows the secant constrained modulus versus vertical stress curves derived from Figure 3. It is found that the moduli for Schahfer 14 ash are comparable to those of the sand, while the values for the other ashes are somewhat lower than those for the sand, especially at the high stress level. The crushing of angular particles at high stress may play an important role in this phenomenon (*12*). As can be concluded from Figures 3 and 4, bottom ashes are slightly more compressible than the sand.

California Bearing Ratio

The California bearing ratio (CBR) values of three bottom ashes, as determined by AASHTO T193, are summarized in Table 8. It is found that soaking does not affect the CBR of bottom ashes, as expected because of their granular nature. The CBR values for bottom ashes ranged from 40 to 70. Compared to the typical CBR values for a number of soils and base course materials (*13*), bottom ashes fall in the categories of "good subbases" and "good gravel bases." As can be seen from Table 8, the CBR values at high moisture contents are higher than those on the dry side. Again, this finding suggests that it is advantageous to compact bottom ash in a flushed condition.

Potentially Hazardous Nature

Bottom ash leachates generated from the extraction procedure (EP) toxicity tests (*14*) were analyzed for heavy metals to predict their potentially hazardous nature. The EP toxicity test was designed by the Environmental Protection Agency (EPA) to simulate the leaching of a solid waste occurring in

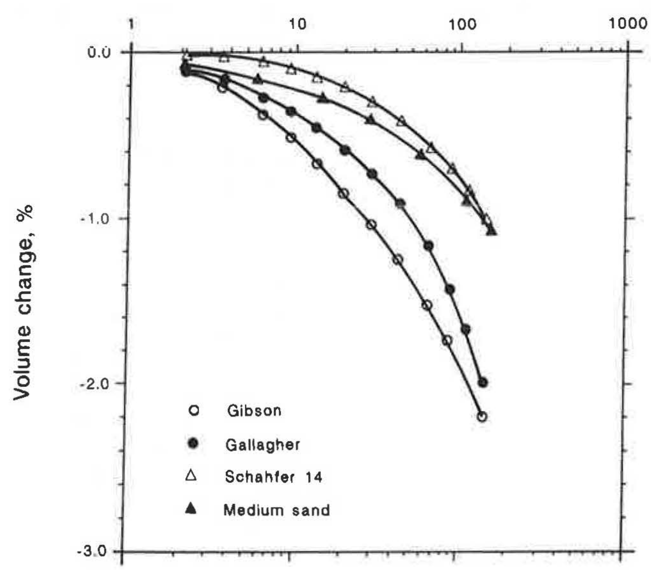


FIGURE 3 Stress-strain curves for bottom ashes.

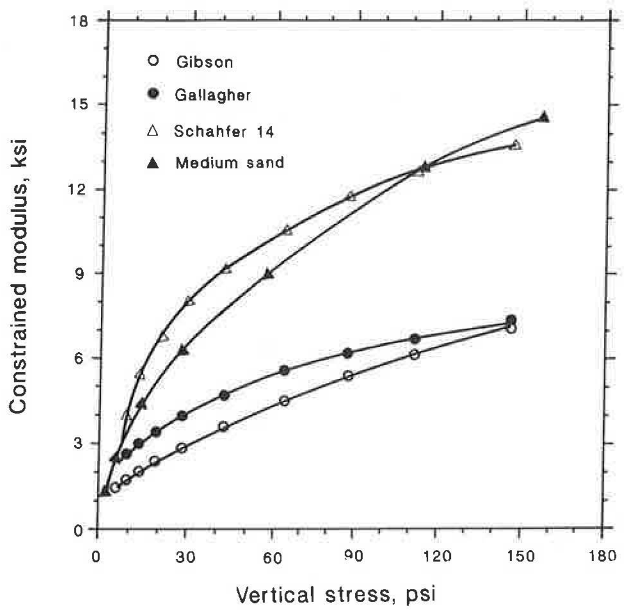


FIGURE 4 Relationship between constrained secant modulus and vertical strain for bottom ashes.

a sanitary landfill. In this test, a representative sample of a solid waste is extracted with deionized water maintained at a pH of 5 using acetic acid. The maximum contaminant levels (MCL) specified for characterizing hazardous solid wastes are 100 times the National Primary Drinking Water Standards (NPDWS). Table 9 summarizes the analyzed results of bottom ash leachates. The concentrations of heavy metals for bottom ash extracts are far below the MCL specified by the EPA. Therefore, bottom ashes are characterized by the EP toxicity test as nonhazardous. Moreover, it appears that bottom ash extracts would also satisfy the NPDWS.

Effects on Ground Water Quality

The effects of bottom ash use on the ground water quality were evaluated by the salt contents of bottom ash leachates, tested by the leaching method test specified in the Indiana Administrative Code 329, IAC 2-9-3 (*15*). The Indiana leaching method test is conducted as specified for the EP toxicity test, except with no addition of acetic acid. Table 10 summarizes the test results and the MCL specified for the most

TABLE 8 CBR TEST RESULTS ON SELECTED BOTTOM ASHES

		CBR			
Ash source	Initial Moisture content[a] (%)	Unsoaked at 0.1 in.	Unsoaked at 0.2 in.	Soaked at 0.1 in.	Soaked at 0.2 in.
Schahfer Unit 14[b]	0.2	36	40	46	53
	8.5	40	47	39	46
	10.6	44	51	38	47
	12.8	41	51	45	52
	14.1	45	52	41	47
Schahfer Unit 17	14.3	44	48	47	52
	18.1	46	52	46	48
	20.9	41	47	40	48
	22.3	50	59	47	50
	24.1	45	53	43	49
Gibson	0.4	59	70	58	70
	13.8	50	55	43	53
	17.4	54	67	51	63
	20.0	45	56	47	58
	22.4	50	60	45	54

[a] Water content prior to compaction
[b] Wet bottom ash

TABLE 9 RESULTS OF EP TOXICITY TEST ON SELECTED BOTTOM ASHES

	Concentrations (mg/L)					
Contaminant	Schahfer Unit 17	Gibson	Schahfer Unit 14	Perry	EPA allowable	Drinking water[a]
Mercury	0.0002	0.0001	<0.0001	0.0002	<0.2	<0.002
Silver	0.001	<0.001	<0.001	<0.001	<5.0	<0.05
Cadmium	0.0008	0.025	0.0007	0.0004	<1.0	<0.01
Chromium	0.0009	0.0005	0.0012	0.0009	<5.0	<0.05
Arsenic	0.020	0.010	0.005	0.008	<5.0	<0.05
Selenium	0.005	0.005	0.003	0.004	<1.0	<0.01
Barium	0.098	0.103	0.136	0.108	<100.0	<1.0
Lead	0.007	0.002	<0.001	0.005	<5.0	<0.05

Primary Drinking Water Standard

TABLE 10 RESULTS OF INDIANA LEACHING METHOD TEST ON SELECTED BOTTOM ASHES

Contaminant	Concentrations (mg/L) Schahfer unit 17	Gibson	Schahfer unit 14	Perry	Indiana Maximum Allowable	Secondary drinking water standard
Barium	0.098	0.103	0.136	0.108	1	1
Boron	0.21	0.19	0.02	0.47	2	-
Copper	<0.1	<0.1	<0.1	0.1	0.25	1
Chlorides	<1	<1	<1	1	250	250
Cyanide, total	<0.005	<0.005	<0.005	<0.005	0.2	-
Fluoride	<0.1	<0.1	<0.1	<0.1	1.4	1.4-2.4
Iron	0.1	0.4	0.1	0.1	1.5	0.3
Sodium	0.8	1.0	<0.5	1.5	250	-
Sulfate	31	55	19	26	250	250
Sulfide	<0.1	<0.1	<0.1	<0.1	1	-
Zinc	0.1	0.3	<0.1	<0.1	2.5	5
Total Dissolved Solids	90	140	10	145	500	500
Calcium	19	24	2	30	-[a]	-
Magnesium	0.7	2.0	0.2	0.1	-	-
Potasium	1.0	0.7	0.1	2.0	-	-
	Standard units					
pH	8.9	8.4	7.8	7.7	6-9	6.5-8.5

[a] not regulated

restricted waste site (Type IV) in the code, along with the Secondary Drinking Water Standards. The salt concentrations of the bottom ash extracts meet all the requirements, and hence bottom ashes have minimal effects on the ground water quality. As can be observed from Tables 8 and 9, the wet bottom ash had the lowest concentrations of heavy metals and salts because of its glassy and nonporous surface, which retards the diffusion of soluble substances contained in the ash particle into ground and surface water systems.

Corrosiveness

The corrosion of adjacent metal structures caused by the interactions between ash mass and the surroundings may lead to failure of these metal structures and metal ion pollution to the ground water. Four electrochemical characteristics (minimum resistivity, pH, soluble chloride, and soluble sulfate) (*16*) were used in predicting the corrosiveness of bottom ash. The materials with lower minimum resistivity and pH and with higher contents of soluble chloride and sulfate are more corrosive. Table 11 presents the values of these characteristics, which were mainly determined by the California test methods (*17–19*). Also, because of its glassy surface texture, the wet bottom ash was found to be less corrosive than dry bottom ash. The noncorrosive levels suggested by Ke (*16*) are a minimum "minimum resistivity" of 1,500 Ohm-cm, a minimum pH of 5.5, a maximum soluble chloride content of 200 ppm, and a maximum soluble sulfate of 1,000 ppm. Accordingly, of the 11 ashes examined, seven ashes (about 64 percent) are classified as corrosive. Bottom ashes with high corrosiveness should not be placed in the vicinity of any metal structure without adequate protection.

Radioactivity and Erodibility

The radioactivity of bottom ash was evaluated by the specific activity of Radium-226. The test results of bottom ashes are tabulated in Table 12, along with the typical values for soils

TABLE 11 CORROSIVENESS OF INDIANA BOTTOM ASHES

Ash Source	Minimum Resistivity (Ohm-cm)	pH	Soluble Cl^- (ppm)	Soluble SO_4^{2-} (ppm)
Perry	980	4.8	15.5	589
Gibson	2201	7.6	7.3	1127
Schahfer 14[a]	>6663	9.6	0.4	50
Schahfer 17	3082	8.6	6.1	383
Gallagher	335	9.1	-[b]	-
Mitchell	1771	8.0	-	-
Wabash	1051	5.7	-	-
Richmond	247	8.2	-	-
Stout	4249	6.6	-	-
Culley	486	8.5	-	-
Brown	213	3.2	-	-

[a] wet bottom ash
[b] not determined

TABLE 12 RADIUM-226 RADIOACTIVITIES OF SELECTED BOTTOM ASHES

Ash Source	Specific Activity (pCi/g)
Perry	4.74
Gibson	3.96
Schahfer 14	4.03
Schahfer 17	3.02
Average of soil [20]	0.8
Average of fly ash [21]	
from western coal	2.6
from eastern coal	3.7

(*20*) and fly ashes (*21*). As shown, bottom ashes have higher radium radioactivities than natural soils. However, all bottom ashes examined satisfy the 5.0 pCi/g criterion set before 1978. As of November 1990, no regulatory criteria existed for solid waste radioactivity.

The most widely used method to estimate the erosion rate is the Universal Soil Loss Equation (*22*), which involves soil erodibility (K) and other external factors such as slope length, rainfall, steepness, and surface covering. If those external factors are set to be constants, then the soil erodibility factor directly represents the erosion potential. Based on the soil erodibility nomograph proposed by Wischmeier et al. (*23*), Table 13 shows the obtained K values for bottom ashes, all less than 0.1 unit. Compared to the typical values of benchmark soils (*23*), it is concluded that bottom ashes have low erosion potential.

SUMMARY AND CONCLUSIONS

The results of laboratory tests are presented for evaluating the engineering suitability and environmental acceptability of bottom ash. The ash characterization examinations show that bottom ashes have unique physical and chemical properties when compared to conventional materials, and the variability of bottom ash parameters from a given power plant is small if the coal and other conditions of combustion do not change much. Based on the results of the engineering property tests, bottom ashes have favorable properties and are comparable to traditional natural granular soils. The evaluation of environmental effects associated with the use of bottom ash reveals that bottom ashes are nonhazardous, have minimal effects on the ground water quality, are of low radioactivity, and have low erodibility, but they may be potentially corrosive. Corrosive bottom ashes should not be placed near any metal structure; they are to be further avoided as aggregate for reinforced concrete.

TABLE 13 ERODIBILITY OF SELECTED BOTTOM ASHES

Ash Source	Perry	Gibson	Schahfer Unit 14	Schahfer Unit 17
% Silt+Fine Sand (0.002-0.05mm)	1	3	0	2
% Sand (0.05-0.1mm)	9	52	92	37
% Residual Carbon	6.7	0.7	0.2	0.5
% Organic Matter[a]	0	0	0	0
First Approximation of Erodibility	0.005	0.01	0.0	0.005
Ash Structure	4	3	2	3
Permeability	1	1	1	1
Erodibility Factor[b] (K)	0.075	0.10	0.02	0.045

[a] Set to be zero (on the conservative side)
[b] For benchmark soils [23], K ranges between 0.1 and 0.5, in units of ton*acre*hour / (hundreds of acre*foot-tonf *inch)

In conclusion, in accordance with their favorable engineering properties and minimal environmental effects (except for corrosiveness), bottom ashes can be successfully used as a highway material in construction of embankments, subgrades, subbases, and even bases. Before this use becomes routine, special selection criteria and effective construction techniques for bottom ash must be developed through trial uses in the field. As the need for compensating for the diminishing supply of natural high-quality construction materials becomes more urgent, extensive use of bottom ash will become more desirable.

ACKNOWLEDGMENTS

The authors would like to thank the Indiana Department of Transportation and FHWA for support of this work. The invaluable cooperation of the utility companies who provided information and samples is gratefully appreciated.

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Publication of this paper sponsored by Committee on Soil and Rock Properties.