Physical and Environmental Properties of Asphalt-Amended Bottom Ash

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A 2-year study is under way to evaluate the physical and chemical properties of the bottom ash process stream from the 500 tons/day waste-to-energy facility in Concord, New Hampshire. The use of bottom ash as an aggregate substitute product in asphaltic base course is envisioned. Research is under way to characterize the time-dependent properties of the bottom ash for product acceptance, to develop asphalt concrete mixes with varied percentages of bottom ash, and to evaluate the leachate release rate characteristics from various asphalt blends using a variety of batch and lysimeter leach tests. Results to date suggest that the bottom ash product stream is relatively constant, hot mix formulations meet New Hampshire Department of Transportation specifications, and bitumen is effective in encapsulating bottom ash and reducing salt leachability.

In the United States consideration is being given to the use of bottom ash from municipal solid waste combustion as an aggregate substitute in construction materials (*1*). The anticipated hierarchy for use in the United States reflects regulatory concerns that certain waste products be encapsulated or stabilized before use. Consequently, the use of bottom ash is likely to be in bituminous base course, bituminous wearing course, bituminous stabilized aggregate base, and concrete construction materials before it is used in granular subbase, structural fill, or embankment applications. This hierarchy differs somewhat from typical uses of bottom ash in Europe as a granular, soillike material (*2–4*).

Earlier work in the United States by Walter (*5,6*) presented hot mix formulations using 50 percent bottom ash with asphalt cement contents of 5.5 to 6.5 percent by weight. Other researchers developed similar formulations, which led to a number of demonstrations in the 1970s and early 1980s using bottom ash in base course and wearing courses (*7–11*). General observations from these studies (*1*) suggest that conventional asphalt mixing and paving equipment can be used, the ash loss-on-ignition should be less than 10 percent, fly ash should not be incorporated into the blends, vibrators on feed bins are necessary, and plant temperature control is important with regard to the high moisture content of the bottom ash. These studies suggest that optimum mixes for hot mix work can contain 50 to 75 percent bottom ash substituted for conventional aggregate.

Recent work by Chesner et al. (*12*) showed bottom ash from the Southwest Brooklyn, New York, combustor is a viable aggregate substitute. Performance was as good as the control at the 30 percent substitution level.

Chesner (*13*) examined economic, regulatory, and environmental concerns surrounding the use of bottom ash and has suggested that institutional issues may be the largest impediment to active utilization in the United States despite the fact that its use is technically and economically feasible.

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OBJECTIVES OF RESEARCH

The objectives of the project are threefold: to characterize the physical properties of the bottom ash over time, to obtain an optimum structural blend of bottom ash/asphalt for hot mix formulations, and to examine the environmental properties of bottom ash and bottom ash/asphalt blends under laboratory and field conditions.

Bottom ash collected during the first 7 months of a 2-year study has been evaluated for its physical and chemical properties. Hot mix designs were developed for a control mix and 25, 50, 75, and 100 percent bottom ash blends. Leaching properties of the bottom ash and bottom ash/asphalt blends were evaluated using batch and lysimeter leaching tests.

MATERIALS AND METHODS

The bottom ash evaluated is produced in a 500 tons/day mass burn combustor located in Concord, New Hampshire. The facility is owned by Wheelabrator Concord L.P. and operated for the Concord Regional Solid Waste/Resource Recovery Cooperative. The facility has two process trains consisting of von Roll reciprocating stoker grates, Babcock and Wilcox boilers, and Wheelabrator Technology dry lime scrubber/fabric filters. The bottom ash from each train is quenched in its own quench tank.

A daily composite was collected on each of the 10 sampling days during the 7-month period. Economizer and fly ash streams were diverted from the bottom ash drag chain conveyor during sampling. Bottom ash grab samples were obtained randomly every 10 min by sampling from the drag chain to create 250-lb hourly composites. Four hourly composites were collected each test day. Combustor performance was also monitored to relate bottom ash quality to combustor operation.

The tests indicated in Table 1 were conducted at varying frequencies for the evaluation of the time-dependent physical and chemical properties of the bottom ash.

TABLE 1 TESTS USED FOR BOTTOM ASH USE IN GRANULAR AND ASPHALTIC MATERIALS

Ash Tests	
Chemical	**Physical**
- Elemental Composition	- Moisture Content (ASTM D2216)
- Acid Neutralizing Capacity (ANC)	- Percent Rejected (>3/4")
- Total Availability Leach Test	- Organic Content/LOI (24)
- pH Dependent Leach Test	- Ferrous Content
- Monolith Leach Test	- Size Distribution (ASTM)
- Toxicity Characteristics Leaching Procedure	- Absorption and Specific Gravity (ASTM C127 and C128)
- Lysimeter Leach Test	- Unit Weight and Voids (ASTM C29)
	- Moisture Density Test (ASTM D1557)
	- CBR (ASTM D1863)
	- Sodium Sulfate Soundness of Aggregates (ASTM C-88)
	- Los Angeles Abrasion (ASTM C131)
	- Unconfined Compressive Strength (ASTM D2166)
	- Marshall Stability (ASTM D1559)

RESULTS AND DISCUSSION

Time Dependence

The physical and chemical properties of bottom ash are of great importance in evaluating its potential use as a substitute for conventional aggregate in bituminous mixtures. The sampling program was designed to examine the hourly, daily, weekly, and monthly variability in physical and chemical characteristics of the bottom ash. Table 2 presents the statistical data of the ash physical testing accomplished over the first 7 months of the project. All average and standard deviation values were calculated on the basis of 40 hourly composite samples obtained during the first 10 sampling events except where noted.

TABLE 2 ASH CHARACTERISTICS AND STATISTICAL VARIATION

	Average	Standard Deviation
Mass <3/4" (%)	67.1	6.6
Moisture Content (%)	36.7	6.4
Specific Gravities:		
Bulk fine	1.90	0.15
Bulk Coarse	2.25	0.11
Bulk SSD fine	2.15	0.11
Bulk SSD coarse	2.35	0.09
Apparent fine	2.51	0.16
Apparent coarse	2.51	0.08
Absorption fine (%)	12.6	2.9
Absorption coarse (%)	4.7	1.4
Loss on Ignition (%)	7.1	2.2
Ferrous Content (%)	26.7	5.6
Passing #4 sieve (%)	48.9	5.3
Passing #200 sieve (%)	4.1	1.1
LA Abrasion Grading B (%)[a]	47.3	1.3
LA Abrasion Grading C (%)[a]	43.4	1.1
Soundness <no. 4 (%)[a]	13.5	1.2
Soundness >no. 4 (%)[a]	2.6	0.2
Modified Proctor Density (pcf)		
Maximum	109.4	1.3
Density[b]	107.8	2.7

[a] average of two composites.
[b] average of seven composites compacted at 16% moisture.

The amount of material passing ¾ in. that could potentially be used as an aggregate is 67.1 percent on the average, with a standard deviation of 6.6 percent. Although it was not collected, a significant amount of aggregatelike material ranging from approximately 3 to ¾ in. in size is also potentially available for use as aggregate.

The ash in general consists of equal amounts of glass and ferrous and nonferrous metals. The glass and nonferrous metals commonly melt and create conglomerate particles. The particles are therefore variable in texture and shape and, in the case of the glass, tend to be brittle. A minor amount of degradation of the brittle particles is to be expected during compaction.

The moisture content of the bottom ash is 36.7 percent on the average, with a standard deviation of 6.4 percent. Moisture contents of bottom ash from other facilities have been reported to range from 20 to 57 percent (*14*).

Figure 1 shows the bulk specific gravity as a function of test day. The data for each test day is the average of four hourly samples.

LOI is 7.1 percent on the average, with a standard deviation of 2.2 percent. The test consists of heating ash passing the No. 4 sieve to 600°C. The LOI increases as ash particle size decreases as shown in Figure 2.

Ferrous content, as defined by passing a magnet across a dispersed sample of dried, < ¾-in. material, is 26.7 percent with a standard deviation of 5.6 percent.

The degradation of bottom ash, as measured by the Los Angeles abrasion test, meets the ASTM D692 maximum 50 percent requirement for use in bituminous paving mixtures. The degradation is high due to the severity of the test and the brittleness of the glass particles.

The sodium sulfate soundness test for coarse fraction of ash (≥ No. 4) meets the ASTM D692 specification (≤ 12 percent). The fine fraction of ash (< No. 4) is less dense and not as strong. However, since the fine fraction of the ash comprises less than 50 percent of the bottom ash, the natural combination of the coarse and fine fractions passes the ASTM requirement.

The maximum modified proctor dry density is 109.4 lb/ft^3 on the average with a standard deviation of 1.29. Figure 3 shows the density and zero air void relationship for a typical bottom ash.

The gradation of any aggregate to be used in asphaltic concrete is important because of its direct effect on performance. Figure 4 shows the average gradation of bottom ash along with the upper and lower limits as required for a Type B NHDOT binder mix. All data are calculated on the basis of the 40 hourly samples. The bottom ash is well graded from the coarse to the fine sizes and meets the New Hampshire state gradation specifications for Type B base course.

Aggregate Blends

The conventional aggregates used in this study were obtained from Pike Industries Inc., a materials supplier, asphaltic concrete producer, and contractor, as well as Concord Sand and

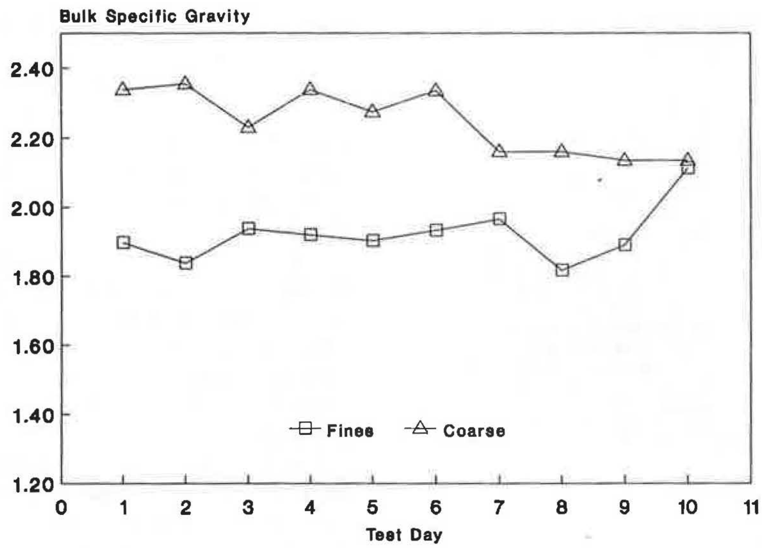

FIGURE 1 Bulk specific gravity versus test day.

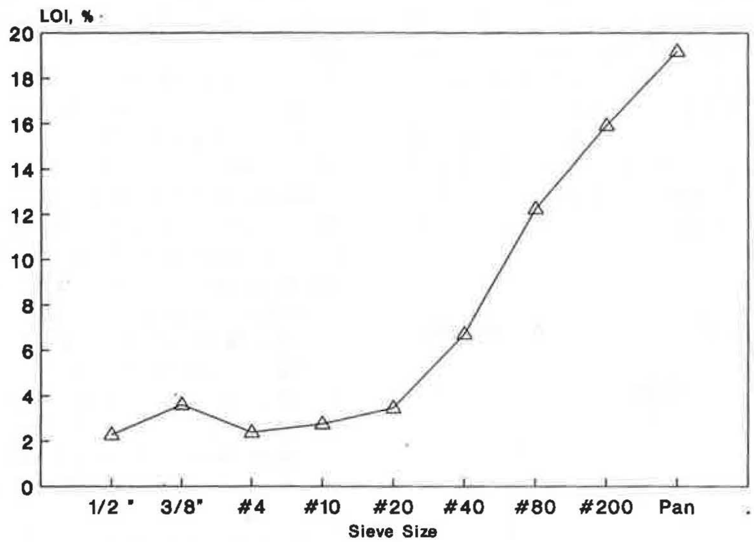

FIGURE 2 Loss on ignition versus sieve size.

Gravel, a materials supplier. The Pike aggregates used in this study (¾ in., ½ in., ⅜ in., manufactured dust, and manufactured washed dust) are manufactured crushed stone. The sand supplied by Concord Sand and Gravel is glacial in origin.

Five blends of the Pike aggregates and bottom ash were selected for asphaltic concrete testing. The control consisted of a unique combination of Pike aggregates that met the midpoint gradation requirements of a NH Type B mix. Bottom ash was substituted on a weight basis for the Pike aggregates. The blends evaluated were 0, 25, 50, 75, and 100 percent bottom ash.

Figure 5 shows the unit weight and void relationships of the blends as a function of ash content. The unit weight of the aggregate blends decreases from 119.8 lb/ft^3 for the control to 76.6 lb/ft^3 for 100 percent bottom ash, and the voids, by absolute volume, increase from 26 to 39 percent as the bottom ash increases 0 to 100 percent.

Figure 6 shows the specific gravity of the aggregate blends and the effective porosity as a function of ash content. The specific gravities decrease with increased ash as would be expected. The fact that the apparent specific gravity changes very little with increasing ash content relative to the bulk specific gravity gives an indication that most of the voids in the ash are interconnected and continuous. The effective porosity indicates that the quantity of continuous pores is relatively high compared with conventional aggregate. The most significant effect of the unique pore system is to create an absorptive aggregate.

In that the ash has a much smaller specific gravity, and the blends were created by substituting the ash on a weight basis,

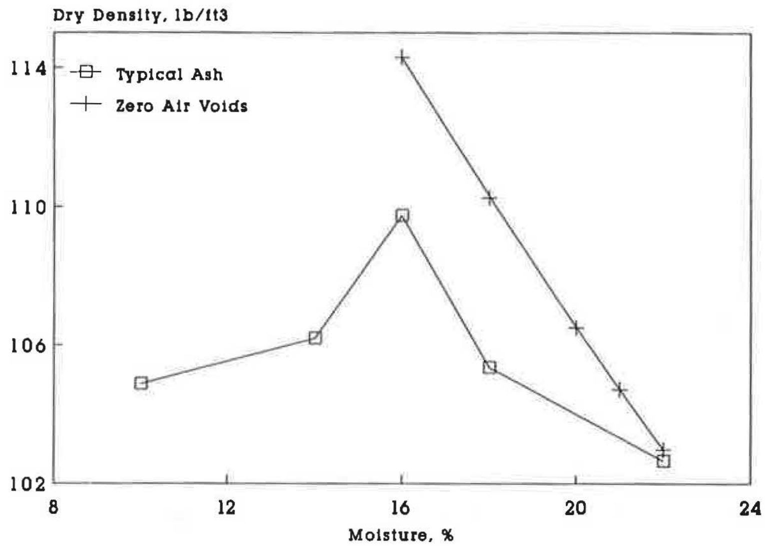

FIGURE 3 Density versus moisture content.

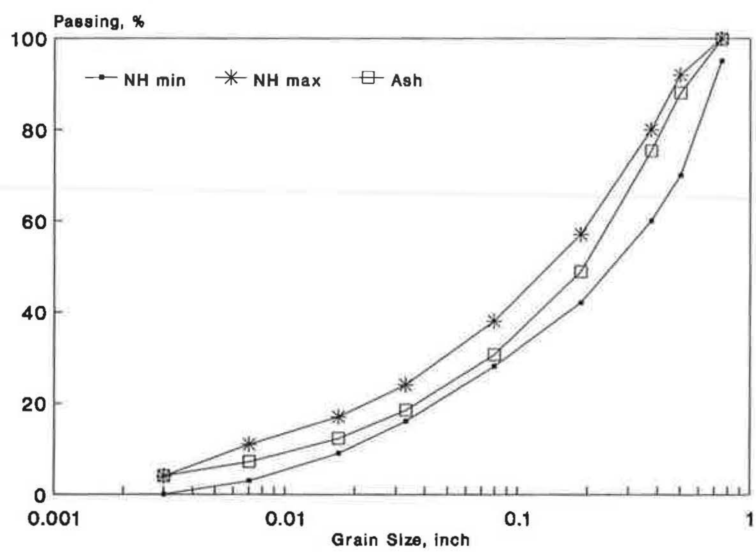

FIGURE 4 Average grain size distribution.

the mix volumes increase on a relative basis with increasing ash. All blends meet the requirements of NHDOT specifications, as shown in Figure 7.

Asphalt Concrete Mixes

The Marshall mix design method using a 50-blow compactive effort was used to develop the asphalt concrete mixes. AC-20 asphalt cement was employed. The Marshall mix design results are presented in Figures 8 through 13.

The effect of the low specific gravity of the ash is indicated by the lower unit weights, which range from 124.6 to 147.9 lb/ft^3, as shown in Figure 8. This reduced weight to volume relationship for the ash mixes has also been noted by Collins et al. (*9*).

An average of three test specimens was used in the Marshall mix design analysis. Stability as shown in Figure 9 ranges from 1,840 to 2,903 lb and exceeds the New Hampshire specification. Depending on the asphalt content, the presence of the ash is capable of increasing the stability compared with the control. This could be due to the particle shape of the ash, which is a combination of angular and rounded particles.

Figure 10 shows flow as a function of asphalt content. The Asphalt Institute requires the flow to be in the 8 to 18 range for medium traffic. The ash mixes exhibit higher flow values than the control mix due to the increased asphalt contents. Flow varies in an inconsistent manner as asphalt content is varied for 75 and 100 percent ash mixes. Collins et al. (*15*) have reported that Marshall flow values for mixtures using ash residue are sometimes erratic due to variation of the ash properties.

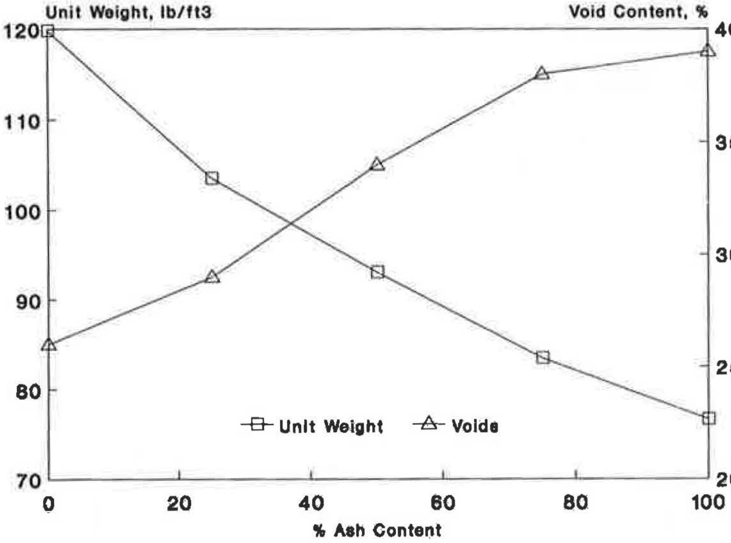

FIGURE 5 Unit weight and void content versus ash content.

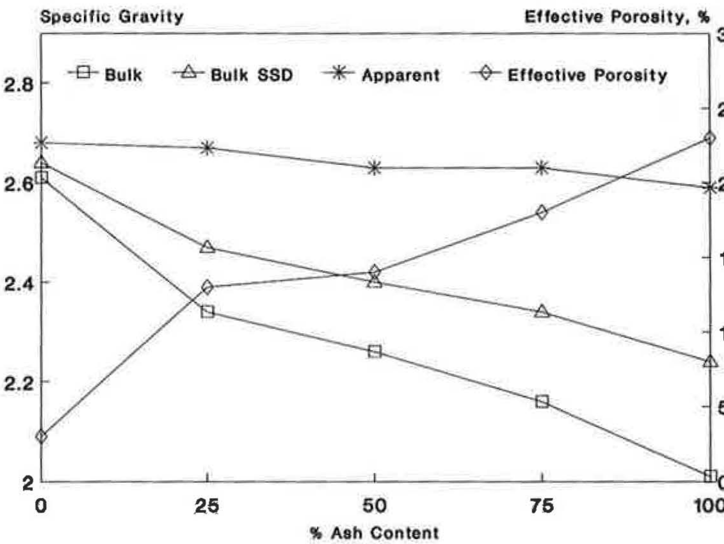

FIGURE 6 Specific gravity and effective porosity versus ash content.

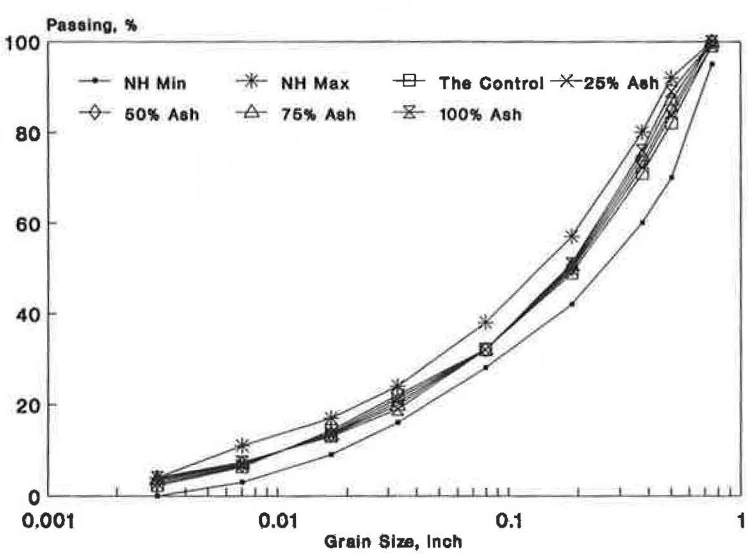

FIGURE 7 Master gradation curves of test blends.

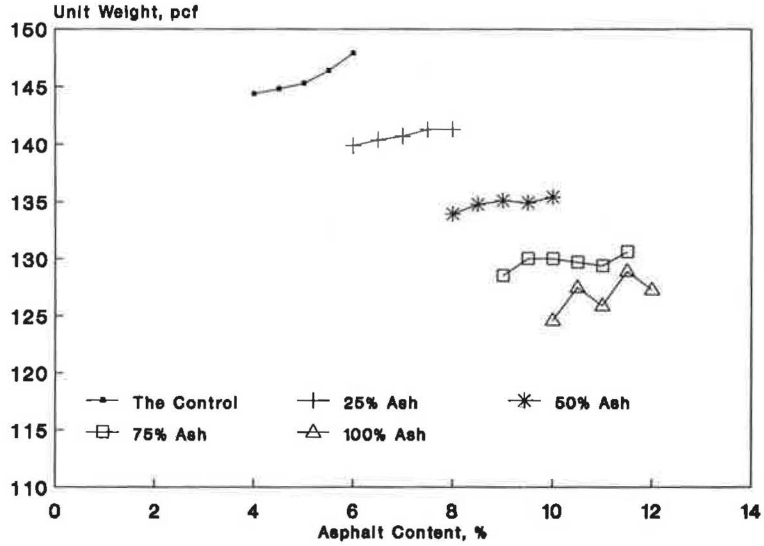

FIGURE 8 Unit weight versus asphalt content.

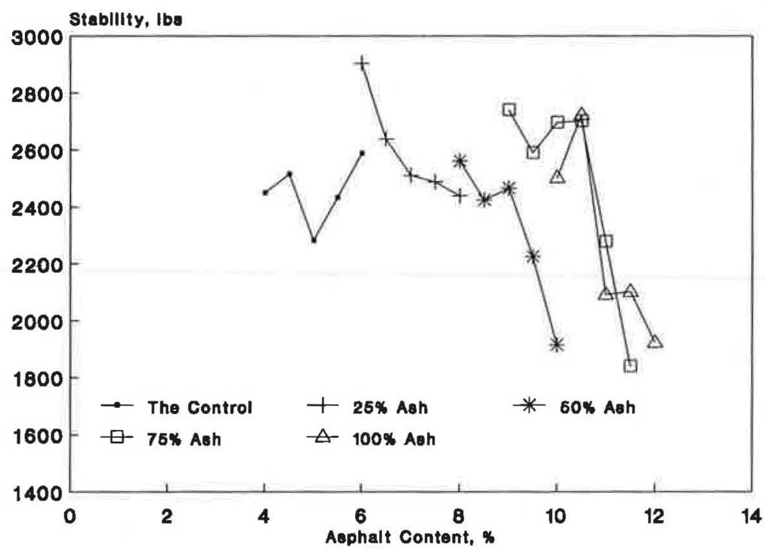

FIGURE 9 Stability versus asphalt content.

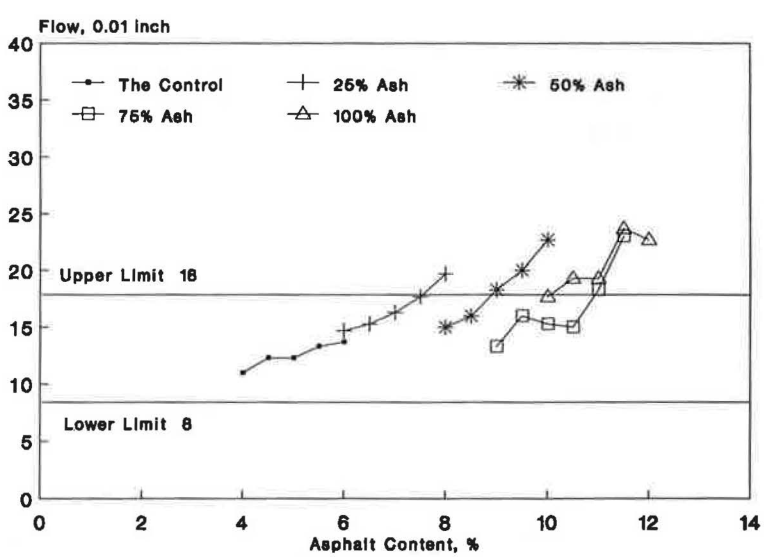

FIGURE 10 Flow versus asphalt content.

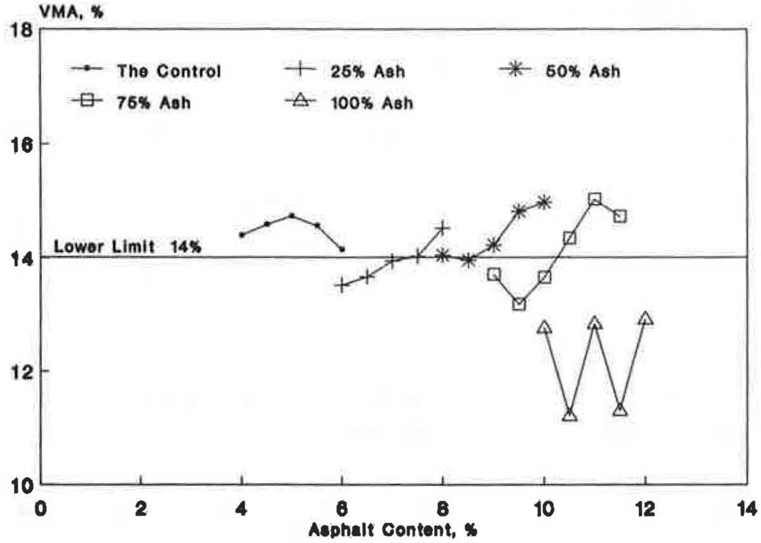

FIGURE 11 VMA versus asphalt content.

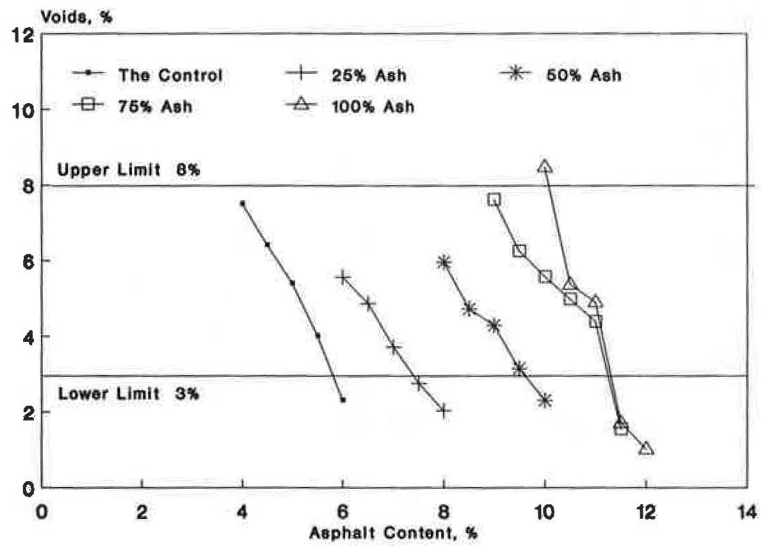

FIGURE 12 Total voids versus asphalt content.

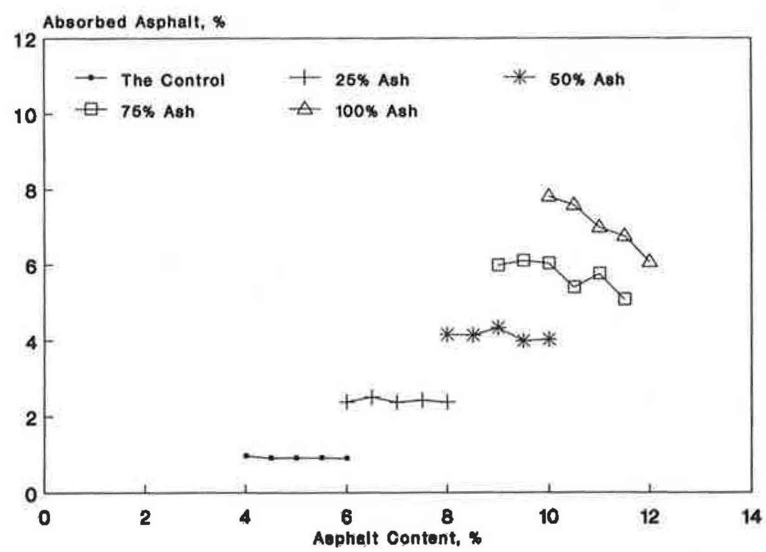

FIGURE 13 Absorbed asphalt versus asphalt content.

The voids in the mineral aggregate (VMA) relationship of the ash mixes is shown in Figure 11. The VMA significantly affects the performance of a mix because if it is too low, the mix may suffer durability problems, and if it is too high the mix may show stability and bleeding problems. The Asphalt Institute requires a minimum VMA of 14 percent for a nominal maximum particle size of ¾ in. All mixes containing up to 75 percent ash pass the VMA requirement of a minimum of 14 percent.

Figure 12 shows the void-asphalt content relationship of the Marshall mixes. The void content is based on the maximum theoretical specific gravity of the paving mix as determined by the Rice method. The void content criteria suggested by the Asphalt Institute for a base subject to medium traffic is between 3 and 8 percent. The asphalt content needed to meet the specification increases as the ash content increases. The reason that the ash mixes demand more asphalt is that the absorption of the ash is higher than the conventional aggregate. Some asphalt is absorbed into the ash particles, particularly the finer particles, increasing the amount of asphalt needed to attain complete coating of the aggregate particles in the mix.

Satisfying the Asphalt Institute design criteria as shown in the figures requires 5, 7.4, 8.6 and 10.5 percent asphalt cement for the 0, 25, 50 and 75 percent ash mixes. The 100 percent ash mixes do not satisfy the design criteria at any asphalt content.

The asphalt absorbed into the aggregate pores is shown in Figure 13. In concept, the amount of asphalt absorbed into the aggregate is not a function of asphalt content, as shown by the blends up to 50 percent ash. For reasons unknown at this time, the higher ash blends show a decrease in absorbed asphalt with increasing asphalt cement content. The effective asphalt, defined as the total asphalt content minus the absorbed portion, increases with increased asphalt content for both the ash mixes and the aggregate control. An extensive field test is planned to evaluate the long-term performance of the bottom ash mixes.

ENVIRONMENTAL TESTING

A number of methods were employed to evaluate the environmental properties of the bituminous blends. Lysimeters were used to evaluate leachate characteristics of a bottom ash pavement mix that was excavated and landfilled. A control lysimeter with bottom ash was used for comparative purposes. Batch laboratory leach tests were used to evaluate the effects of percent asphalt cement and percent bottom ash substitution on the encapsulating properties of bitumen, and a standard Environmental Protection Agency Toxicity Characteristic Leaching Procedure (EPA TCLP) test was run on the bottom ash.

Lysimeter Test Procedures

Approximately 30 yd^3 of bottom ash was collected at the waste-to-energy facility and processed to pass the ¾-in. sieve. Approximately 4 tons of this material was placed directly in a 20-yd^3 double-lined roll-off container. The remaining processed bottom ash was batched at a local hot mix plant (Pike Industries) to produce 12 tons of ¾-in. binder with 25 percent bottom ash (75 percent natural aggregate) at an asphalt cement content of 9 percent. The mix was paved, compacted, and broken up after a 7-day period with a backhoe into large pieces typical of what might be expected to be dumped into a landfill as construction debris. The broken up pavement, ranging in size from small palm size to large 2- by 3-ft plates, was put in a second double-lined roll-off container. These lysimeters generate time-dependent data on the leachate properties of the control bottom ash and the 25 percent ash asphalt pavement mix. The leachate, originating from natural precipitation, was collected and analyzed for analytes.

Regulatory Test Procedure

TCLP regulatory leach test was performed on composite bottom ash samples from material used in the control lysimeter. A number of additional inorganic analytes besides the specified regulatory analytes were analyzed to help develop a bottom ash leaching data base.

Results

The results of the lysimeter data for the first two collection events are given in Table 3. The cumulative liquid/solid ratio for the first event was 0.069 and 0.073 and for the second event was 0.174 and 0.184 for the ash and ash pavement lysimeters, respectively. Bottom ash releases significantly lower concentrations of contaminants compared with combined ashes because it does not contain the highly soluble $Ca(OH)_2$ added

TABLE 3 LYSIMETER LEACHATE DATA

	Bottom Ash		Bottom Ash Asphalt	
	First Event	Second Event	First Event	Second Event
L/S[a]	0.069	0.174	0.073	0.184
pH	6.41	6.75	7.15	7.32
COD[b]	310	400	22	15
NO_3^--N	<0.50[c]	<0.25	<0.050	<0.050
NO_2^--N	<0.50	<0.50	<0.050	<0.25
NH_4^+-N	5.0	16	0.20	0.44
SO_4^{2-}	1,700	1,600	31	68
Br^-	30	28	<1.0	2.1
PO_4^{3-}	<0.01	0.041	<0.01	<0.010
Cl^-	1,700	1,800	24	30
Al	0.20	0.16	<0.10	<0.10
Ba	<0.10	<0.10	<0.10	<0.10
Be	<0.0050	<0.50	<0.0050	<0.50
Cd	<0.0050	0.0007	<0.0050	0.0014
Ca	590	870	22	45
Cr	<0.010	<0.010	<0.010	<0.010
Cu	0.59	0.15	<0.020	0.024
Fe	0.050	7.3	<0.030	0.038
Pb	0.0053	0.028	<0.0050	<0.005
Mg	6.5	6.9	1.3	2.8
Mn	0.32	2.3	0.020	0.063
Hg	0.0006	0.0005	<0.0003	<0.0003
Mo	0.34	0.27	<0.10	<0.10
K	220	190	3.9	4.5
Si	2.2	1.4	1.2	2.7
Sr	4.4	4.3	0.15	0.21
Zn	0.068	0.031	<0.020	0.031

[a]L/S liquid to solid ratio weight of leachate to wet weight of ash
[b]Concentrations are expressed in mg/L
[c]Less than sign shows that the concentration was below the indicated detection limit.

TABLE 4 BOTTOM ASH TCLP DATA

Composite	1	2	3	Average	Regulated Limit
	Concentration, mg/L				
Al	3.9	1.7	1.1	2.2	-*
As	<0.2	<0.2	<0.2	<0.2	5.0
Ba	0.38	0.38	0.35	0.37	100.0
B	0.53	0.52	0.55	0.53	-
Cd	0.028	0.032	0.031	0.030	1.0
Ca	760	850	830	813	-
Cr	<0.01	<0.01	<0.01	<0.01	5.0
Cu	0.9	1.4	1.5	1.3	-
Fe	12	0.94	0.21	4.38	-
Pb	1.7	1.9	1.3	1.6	5.0
Mg	29	32	31	31	-
Mn	3.1	2.9	2.4	2.8	-
Hg	<0.0003	<0.0003	<0.0003	<0.0003	0.2
Mo	<0.10	<0.10	0.11	0.04	-
K	18	20	18	19	-
Se	<0.02	<0.02	<0.02	<0.02	1.0
Si	17	16	19	17	-
Ag	<0.02	<0.02	<0.02	<0.02	5.0
Sr	1.6	1.8	1.6	1.7	-
Zn	21	29	23	24	-

* - Not regulated

for air pollution control. The leachate from bottom ash contains relatively low concentrations of sulfate and chloride, and heavy metal release is nonproblematic. The encapsulating properties of bitumen in the ash pavement are readily apparent. Generally, there is more than a 10- to 20-fold decrease in salt leachability from bitumen encapsulated material as compared with unamended bottom ash.

The EPA TCLP test data are given in Table 4. These data indicate that the bottom ash easily passes the standard regulated limits. Results from these as well as other leach tests are being compiled to create an extensive leaching data base.

CONCLUSIONS

The following conclusions can be drawn from the work completed on this research project to date.

1. The variation of the physical properties of the ash produced during the 7-month test period is reasonably insignificant.
2. The physical properties of the ash are consistent with its use as a substitute for conventional aggregate in asphaltic concrete.
3. The properties of ash are typical of a lightweight aggregate.
4. Bottom ash mixes can be designed to meet NHDOT specifications with up to 75 percent ash substitution. The mixes have lower unit weights (increased volume with constant weight) and require more asphalt cement than conventional mixes.
5. Bitumen effectively encapsulates the bottom ash and significantly mitigates the release of low concentrations of soluble salts from the bottom ash.

A field pavement demonstration is planned after ongoing laboratory physical and field lysimeter work is completed.

ACKNOWLEDGMENTS

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