Research Report
KTC 92-14

DESIGN AND PERFORMANCE OF A BITUMINOUS SURFACE MIXTURE CONTAINING BOTTOM ASH AGGREGATE

by

David Q. Hunsucker
Research Engineer

Kentucky Transportation Center
College of Engineering
University of Kentucky

in cooperation with
Kentucky Transportation Cabinet

and

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16. Abstract

A one-mile experimental bituminous surface overlay was placed in October 1987 on State Route 3 in Lawrence County, Kentucky. The experimental section utilized bottom ash aggregate from the Kentucky Power Company's Big Sandy Power Plant, near Louisa, Kentucky. Bottom ashes are generally angular and have very porous surfaces. Approximately 539 tons of the experimental bituminous surface material, containing 40 percent bottom ash (dry weight), were placed. Reported herein are results of laboratory tests and performance evaluations of the experimental surface mixture.

Performance of the experimental bottom ash surface has been excellent. Skid resistance tests indicate the surface is highly skid resistant. Bottom ash represents a large potential source of high-friction, nonpolishing aggregate that may be successfully substituted for a portion of the coarse aggregate in a bituminous surface mixture.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in.	inches	25.40000	millimetres	mm
ft	feet	0.30480	metres	m
yd	yards	0.91440	metres	m
mi	miles	1.60934	kilometres	km
		AREA		
$in.^2$	square inches	645.16000	millimetres squared	mm^2
ft^2	square feet	0.09290	metres squared	m^2
yd^2	square yards	0.83613	metres squared	m^2
ac	acres	0.40469	hectares	ha
mi^2	square miles	2.58999	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57353	millilitres	ml
gal.	gallons	3.78541	litres	l
ft^3	cubic feet	0.02832	metres cubed	m^3
yd^3	cubic yards	0.76455	metres cubed	m^3
		MASS		
oz	ounces	28.34952	grams	g
lb	pounds	0.45359	kilograms	kg
T	short tons (2000 lb)	0.90718	megagrams	Mg
		FORCE AND PRESSURE		
lbf	pound-force	4.44822	newtons	N
psi	pound-force per square inch	6.89476	kilopascal	kPa
		ILLUMINATION		
fc	foot-candles	10.76426	lux	lx
fl	foot-Lamberts	3.42583	candela/m^2	cd/m^2
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.03937	inches	in.
m	metres	3.28084	feet	ft
m	metres	1.09361	yards	yd
km	kilometres	0.62137	miles	mi
		AREA		
mm^2	millimetres squared	0.00155	square inches	$in.^2$
m^2	metres squared	10.76392	square feet	ft^2
m^2	metres squared	1.19599	square yards	yd^2
ha	hectares	2.47103	acres	ac
km^2	kilometres squared	0.38610	square miles	mi^2
		VOLUME		
ml	millilitres	0.03381	fluid ounces	fl oz
l	litres	0.26417	gallons	gal.
m^3	metres cubed	35.31448	cubic feet	ft^3
m^3	metres cubed	1.30795	cubic yards	yd^3
		MASS		
g	grams	0.03527	ounces	oz
kg	kilograms	2.20462	pounds	lb
Mg	megagrams	1.10231	short tons (2000 lb)	T
		FORCE		
N	newtons	0.22481	pound-force	lbf
kPa	kilopascal	0.14504	pound-force per square inch	psi
		ILLUMINATION		
lx	lux	0.09290	foot-candles	fc
cd/m^2	candela/m^2	0.29190	foot-Lamberts	fl
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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ACKNOWLEDGEMENTS

The author wishes to express his appreciation and gratitude to Mr. Allen H. Myers, Special Projects Coordinator, Bituminous Section, Division of Materials, Kentucky Department of Highways and Mr. Edgar E. Courtney, former Engineering Technologist II with the Kentucky Transportation Center for providing their assistance in this endeavor.

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EXECUTIVE SUMMARY

This report summarizes available materials and construction information and performance evaluations of a waste bottom ash material utilized as an aggregate replacement in a bituminous surface mixture. A one-mile experimental bituminous overlay was placed in October 1987 on State Route 3 in Lawrence County, Kentucky. Approximately 539 tons of the experimental bituminous surface material were placed from Milepost 21.9 to Milepost 22.9. Bottom ash for the demonstration was supplied by Kentucky Power Company's Big Sandy Power Plant, located near Louisa, in Lawrence County.

Prior to placing the experimental bituminous surface, a complete array of tests were performed by the Division of Materials' Central Laboratory of the Kentucky Department of Highways to determine the physical attributes of the ponded bottom ash material. The physical tests included sieve analysis, specific gravity, soundness, absorption, wear, and sand equivalency value. Kentucky Department of Highways' methods were used to design a bituminous mixture that consisted of 40 percent bottom ash aggregate, 40 percent size No. 8 limestone aggregate, and 20 percent natural sand. Tests were conducted to determine levels of strength, stability, air void content and other design parameters of the bituminous mixture.

Performance evaluations included visual surveys to assess the condition of the experimental surface and that of a contiguous conventional Class I bituminous surface. Skid tests were performed to determine and compare the frictional characteristics of the experimental surface and the conventional bituminous surface. There were no observed performance deficiencies of the experimental surface when compared to the conventional surface. Skid numbers obtained for the experimental surface were found to be equivalent to the adjacent conventional section even though the average daily traffic was nearly three times greater for the experimental section.

This project has demonstrated that bottom ash aggregate may be successfully substituted for a portion of the coarse aggregate and performs well in a bituminous surface mixture. Bottom ash represents a large potential source of high-friction, nonpolishing aggregate for use as an aggregate substitute in bituminous surface mixtures.

INTRODUCTION AND BACKGROUND

Kentucky has traditionally been among the leading producers of coal in the United States. Kentucky is also a large consumer of coal. Approximately 30 million tons of coal are used annually for the generation of electricity within the state. Most of these facilities use pulverized coal boilers which have electrostatic precipitators for particulate removal. An abundance of by-product materials are produced as a result of burning coal. More than three million tons of fly ash are produced annually from Kentucky's coal-fired electric generation plants. In many instances, bottom ash is treated simply as a waste product that is normally disposed of in large landfills and has served no useful purpose. With the escalating costs of conventional road building materials, many agencies charged with the responsibility of designing and constructing highways are increasing their utilization of by-product ashes as alternate construction materials.

Crushed limestone is, and continues to be, the primary road building aggregate in Kentucky. The supply of quality limestone is abundant over approximately three-fourths of the state of Kentucky. In the remaining one-fourth however, it is necessary to use either locally obtainable aggregates or to import limestone aggregates. The latter is usually the case and transportation costs may equal or exceed the cost of the aggregate itself. The largest area so affected is Kentucky's Eastern Coal Field region. A small portion of this area may be economically supplied with limestone aggregate sources located along the western edge of the region, or from outcrops of the Pine Mountain Overthrust along the eastern edge of the region. Also, the northern extremity of the region may be supplied with river gravels or crushed slags. However, the lack of an abundance of good quality limestone aggregate located within the Eastern Coal Field region supports the search for alternative construction materials.

A primary factor influencing the nature of bottom ash is the type of boiler used to produce the ash. There are two basic types used; dry bottom boilers and wet bottom boilers. Ash produced from dry bottom boilers is usually referred to as bottom ash or dry bottom ash. Dry bottom ash is usually gray to black in color, has a porous surface texture and is highly angular. Ash from a wet bottom boiler is usually referred to as boiler slag. Boiler slag is composed of black angular particles having a glassy surface. The combination of bottom ash with limestone aggregate and natural sand would seem to offer improvement to the overall performance of a bituminous paving mixture with respect to skid resistance and structural stability. The supposition that bottom ash could improve the skid resistant performance of bituminous surface mixtures arises from the fact that dry bottom ashes are angular and have a very porous surface.

The primary objective of this research effort was to evaluate the design and performance of a bituminous surface mixture wherein a dry bottom ash was used as a substitute for a portion of the conventional limestone aggregate. The dry bottom ash used in this project was supplied by Kentucky Power Company's Big Sandy Plant located near Louisa, Kentucky. The Big Sandy Plant produces more than 225,000 tons of ash per year, 80 percent of which is bottom ash. The bottom ash typically is stored in large disposal ponds. A number of tests were performed by the Division of Materials' Central Laboratory of the Kentucky Department of Highways to determine the physical attributes of the ponded bottom ash material.

These physical tests included sieve analysis, specific gravity, soundness, absorption, wear, and sand equivalency value. Kentucky Department of Highways' methods were used to design a bituminous mixture containing bottom ash aggregate, limestone aggregate, and natural sand aggregate. Tests were conducted to determine levels of strength, stability, air void content and other design parameters of the bituminous mixture. Asphalt extractions and aggregate sieve analyses were performed on samples obtained during construction of the experimental surface course. Performance evaluations were made to assess the condition of the experimental surface and that of an adjacent conventional Class I bituminous surface. Skid tests were performed to compare the frictional characteristics of the experimental surface with those of the conventional bituminous surface.

MATERIALS INFORMATION

Seven samples were obtained from a stockpile at the Big Sandy Plant during April 1987. The samples were evaluated for specific gravity, absorption, sodium sulfate soundness, Los Angeles abrasion, gradation, and sand equivalency value. All tests were performed in accordance with applicable Kentucky Department of Highways Standard Test Methods. Table 1 contains results of tests conducted to evaluate the physical characteristics of the dry bottom ash material. The average saturated surface dry specific gravity was 2.10, the average absorption was 1.6 percent, and the average loss after completion of the sodium sulfate soundness test was four percent. Wear losses associated with the Los Angeles abrasion test were 20 percent after 200 revolutions and 40 percent after 500 revolutions on sample number two. Figure 1 illustrates the average gradation of sample numbers three, five and seven taken from the stockpiled material.

TABLE 1. RESULTS OF PHYSICAL TEST ON STOCKPILED BOTTOM ASH

	Sample Number						
	1	2	3	4	5	6	7
Specific Gravity (SSD)	2.04	2.05	NA	2.06	NA	2.03	2.32
Specific Gravity (BOD)	2.04	2.00	NA	2.02	NA	1.98	2.30
Specific Gravity (APP)	2.05	2.11	NA	2.10	NA	2.09	2.34
Absorption (%)	0.2	2.7	NA	1.8	NA	2.5	0.7
Soundness (%)	2	2	NA	5	NA	6	4
Wear (%) (200) (500)	NA	20 40	NA	NA	NA	NA	NA
Sand Equivalent Value	76	73	NA	79	NA	89	90

NA - Indicates sample not analyzed for that particular characteristic.

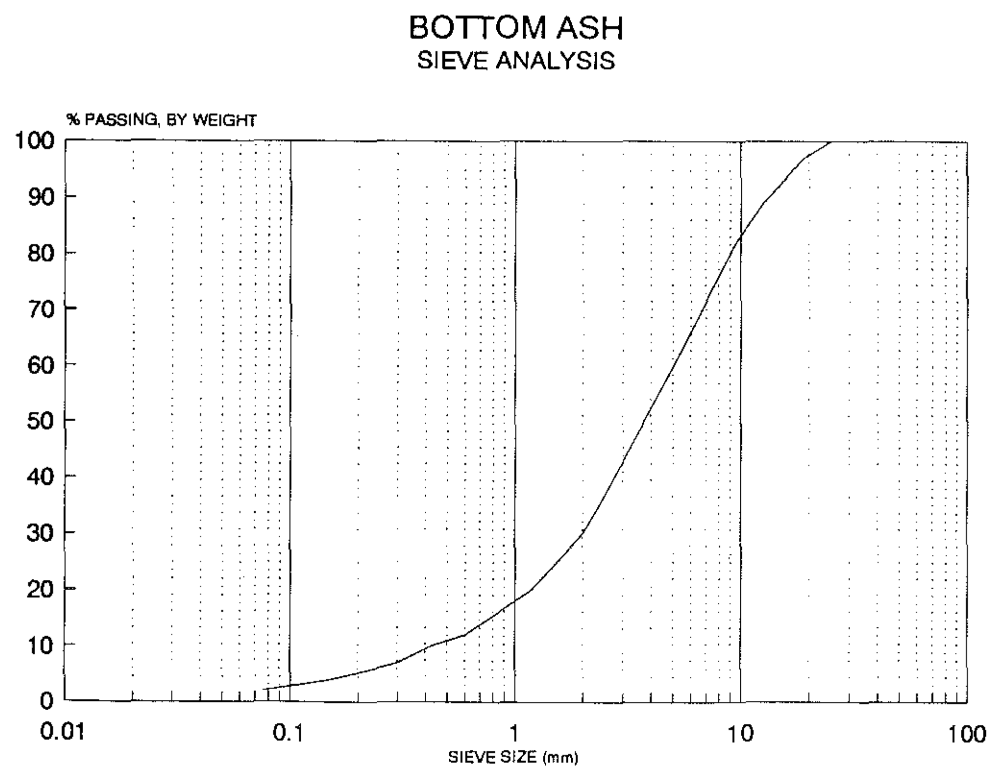

Figure 1. Average Gradation of Stockpiled Bottom Ash Samples.

The chemical analysis contained in Table 2 was performed and provided by the Ash Utilization and Research Section of American Electric Power Service Corporation, Kentucky Power Company's parent company. The primary constituents of the bottom ash were silica, aluminum oxide, and iron oxide. Minor quantities of potassium oxide, titanium oxide, calcium oxide, sulfur trioxide and other compounds were also present.

A second sample of the stockpiled bottom ash was obtained from the power plant in September. The bottom ash material was combined with size No. 8 limestone aggregate from Black River Mining Company and natural sand aggregate from Richards and Son. The Special Note for the experimental bituminous design required a mixture of 40 percent limestone aggregate, 40 percent bottom ash aggregate, and 20 percent natural sand.

Tests completed in September on the bottom ash by the Division of Materials' Central Laboratory in Frankfort indicated a saturated surface dry specific gravity of 2.00 and an absorption of 8.7 percent. The absorption was much greater for this bottom ash sample than previous samples. The limestone aggregate had a saturated surface dry specific gravity of 2.69 and an absorption of 0.6 percent. The natural sand aggregate had a saturated surface dry specific gravity of 2.65 and an absorption of 0.5 percent.

TABLE 2. CHEMICAL CHARACTERISTICS OF THE BOTTOM ASH

CHEMICAL COMPOSITION (wt %)		
Silicon Dioxide	SiO_2	54.0
Aluminum Oxide	Al_2O_3	26.7
Iron Oxide	Fe_2O_3	10.2
Magnesium Oxide	MgO	0.9
Sodium Oxide	Na_2O	0.3
Potassium Oxide	K_2O	2.6
Titanium Dioxide	TiO_2	1.6
Sulfur Trioxide	SO_3	1.8
Phosphorus Pentoxide	P_2O_5	0.1
Calcium Oxide	CaO	1.0

Marshall mix design tests were completed by the Division of Materials' Central Laboratory. The design mix gradation and gradation tolerances are given in Figure 2. An AC-20 bitumen was used in the experimental bituminous mixture. The laboratory mixing temperature was 300° F. The mixture was compacted at 50 blows per layer at a temperature of 265° F. Figures 3 through 12 contain results of the Marshall mix design.

Design test results indicated a unit weight of 130.5 lbs/ft^3. The optimum asphalt content was determined to be 8.5 percent and the effective asphalt content was 7.9 percent. The percent air voids in the mix was 3.8. Specific gravity of the bituminous mixture was 2.18. The flow was 0.08 inch. Stability, at the optimum asphalt content, was 1,900 pounds. Splitting tensile strength tests indicated a retained tensile strength value of 81.7 percent.

CONSTRUCTION INFORMATION

The application rate for a one-inch compacted thickness of the experimental surface was 98 lbs/yd^2. Because the bottom ash had a much lower specific gravity than the size No. 8 limestone and the natural sand, it was important to maintain the bottom ash at forty percent by weight (dry weight) of the total aggregate in the mix. If the proportion of bottom ash significantly exceeded forty percent of the total aggregate mixture, the amount of asphalt determined for the mixture would be insufficient to thoroughly coat the aggregate particles and ensure a durable pavement surface. Conversely, if the bottom ash was significantly less than forty percent of the total aggregate mixture, there would be excess asphalt which would promote flushing, or bleeding leading to slippery conditions when the pavement was wet. The Department recommended cold feeds be checked frequently to guarantee the bottom ash aggregate comprised only 40 percent of the total dry weight of the bituminous mixture.

Placement of the experimental bottom ash surface occurred October 13 and 14, 1987. Approximately 441 tons of the experimental surface were placed during the first day's production. An additional 98 tons of the experimental surface were placed the following day. Both the northbound and southbound lanes of State Route 3, from milepost 21.9 to 22.9, were overlaid with a one-inch thickness of the experimental bottom ash surface. The contractor for the work was the L. P. Cavett Company, of Lockland, Ohio. Production of the experimental mixture was at the United Asphalt Company in Proctorville, Ohio. The haul distance to the job site was approximately 38 miles. Mixing temperatures at the batch plant were recorded hourly and ranged from 310° F to 325° F. Four samples

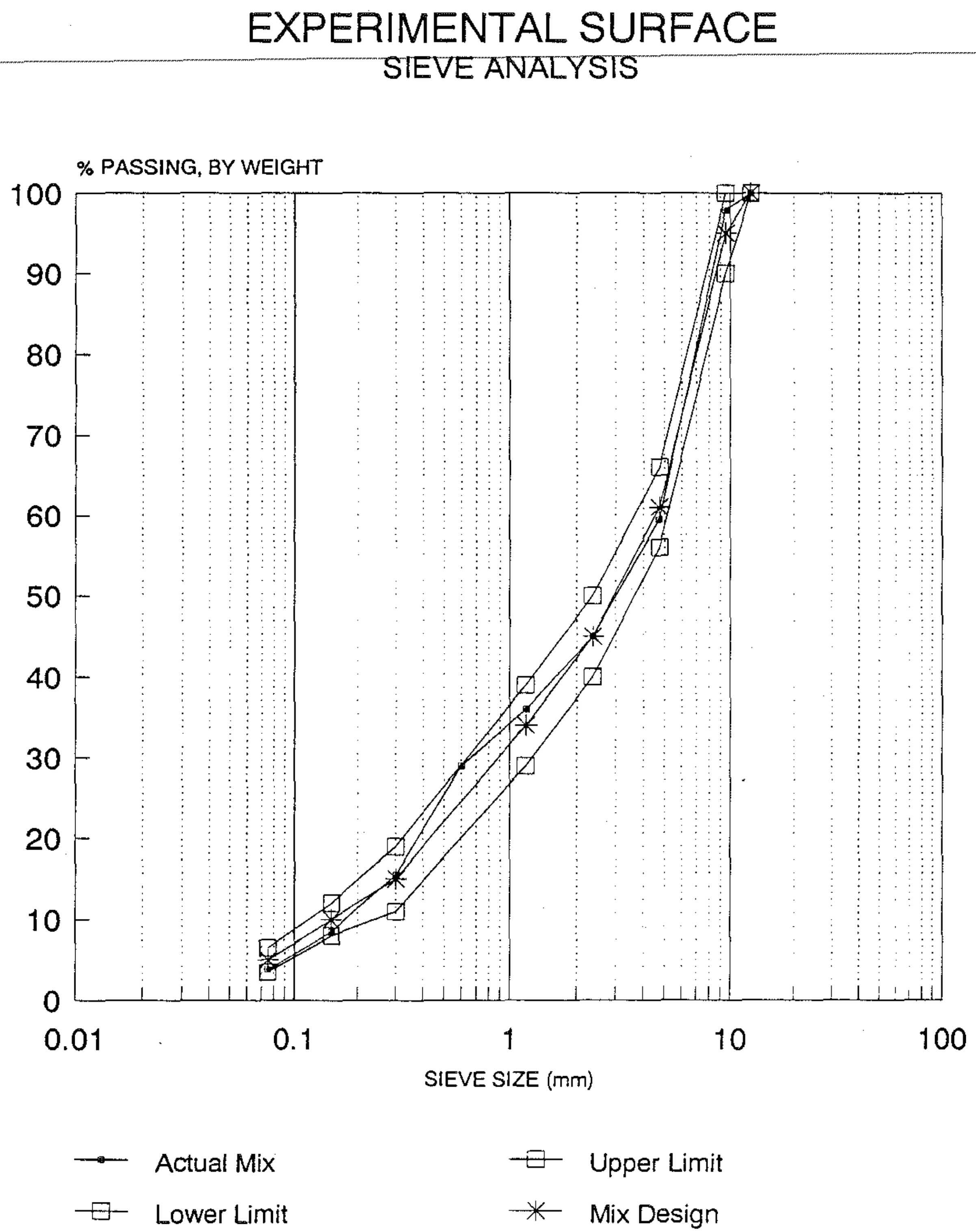

Figure 2. Mix Design Gradation, Job-Mix Formula Tolerances, and Extracted Gradation of the Experimental Surface Mixture.

Unit Wt. vs. %AC

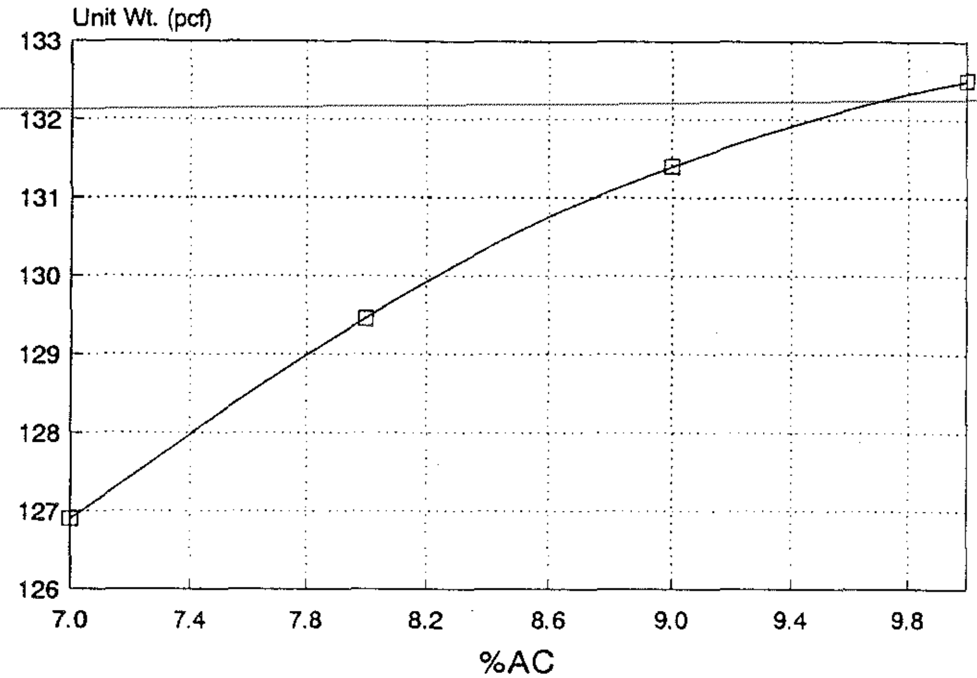

Figure 3. Unit Weight Versus Percent Asphalt for the Experimental Surface Mixture.

Stability vs. %AC

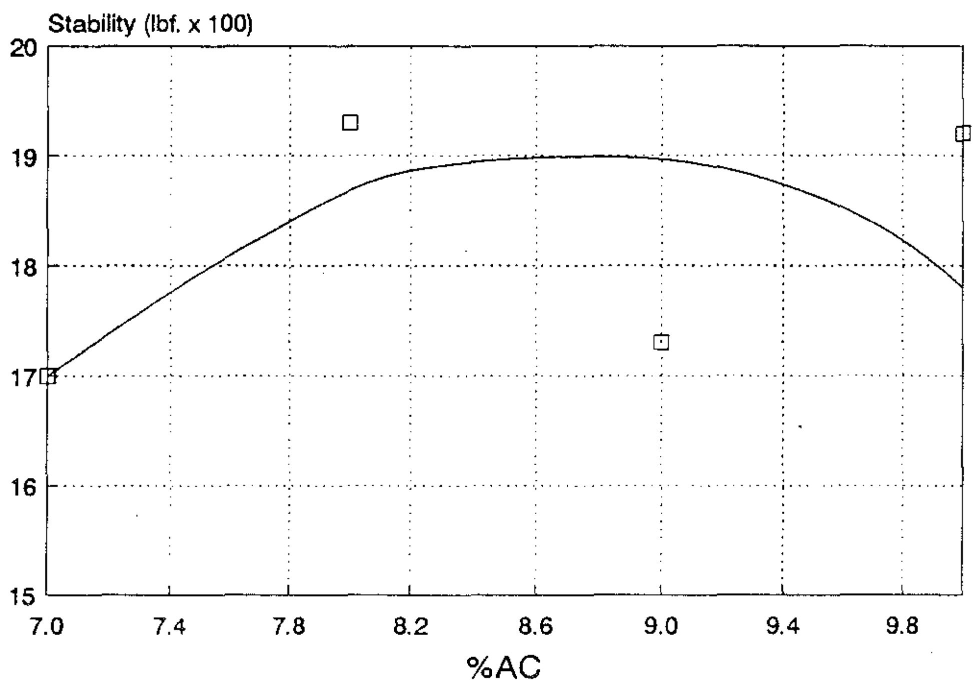

Figure 4. Stability Versus Percent Asphalt for the Experimental Surface Mixture.

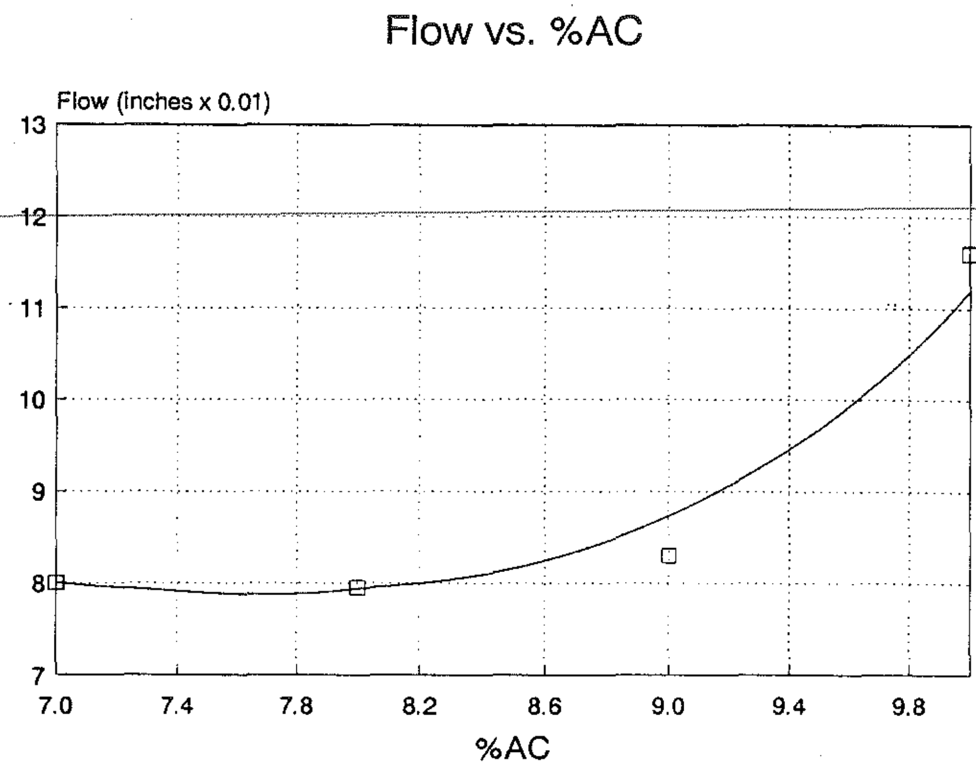

Figure 5. Flow Versus Percent Asphalt for the Experimental Surface Mixture.

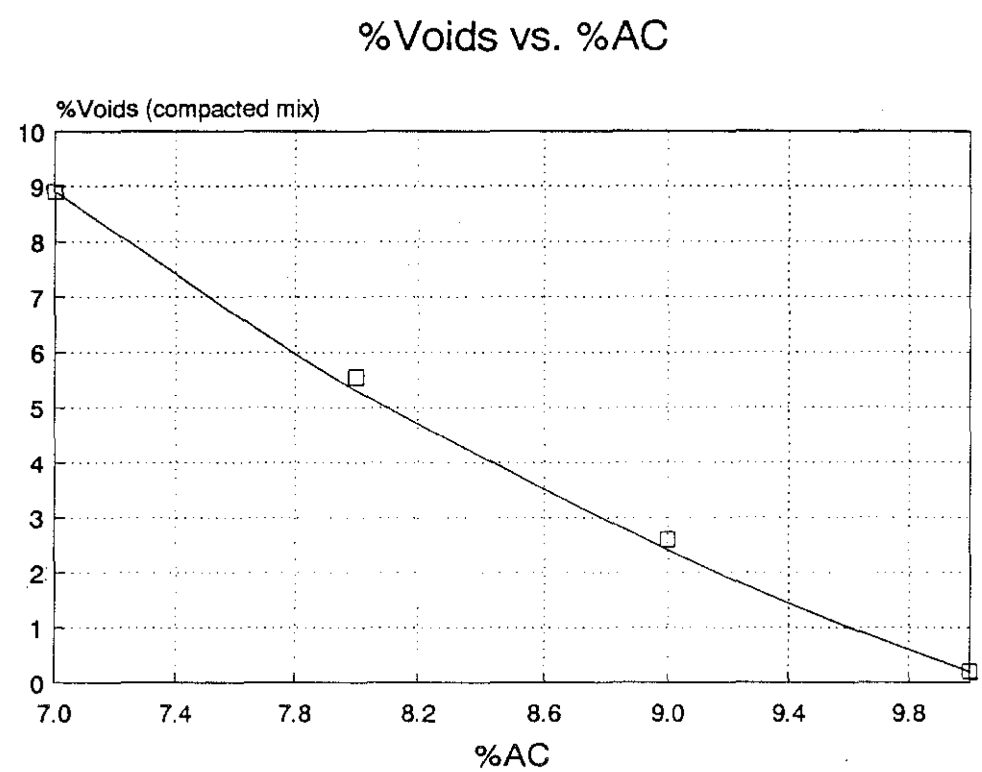

Figure 6. Percent Air Voids Versus Percent Asphalt for the Experimental Surface Mixture.

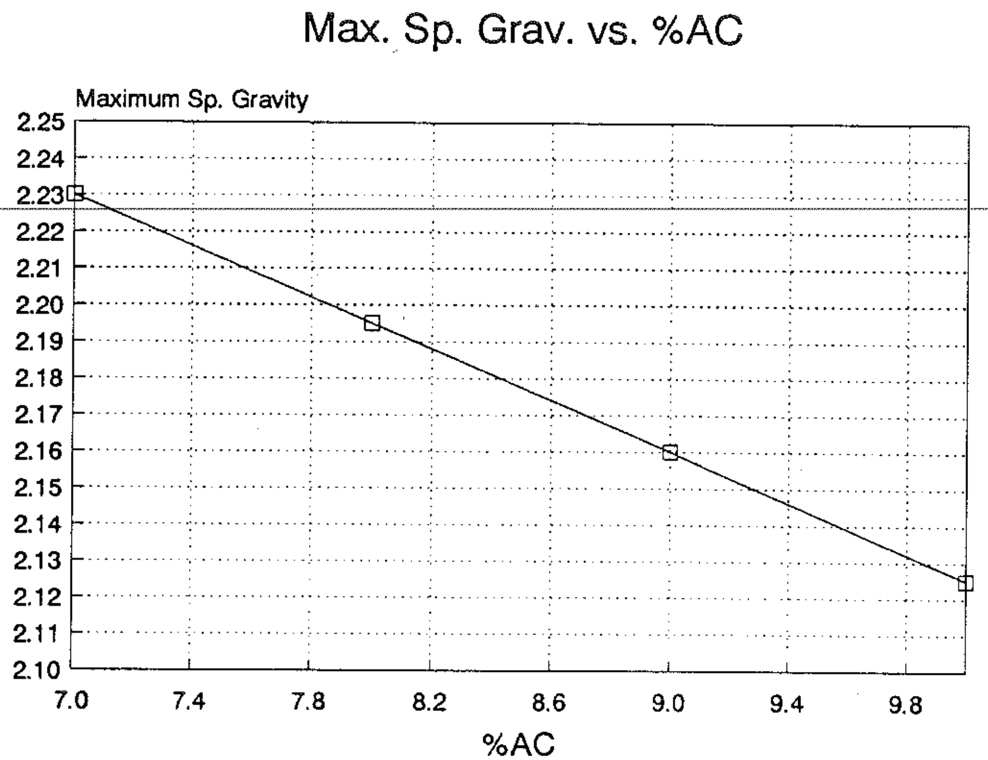

Figure 7. Maximum Specific Gravity Versus Percent Asphalt for the Experimental Surface Mixture.

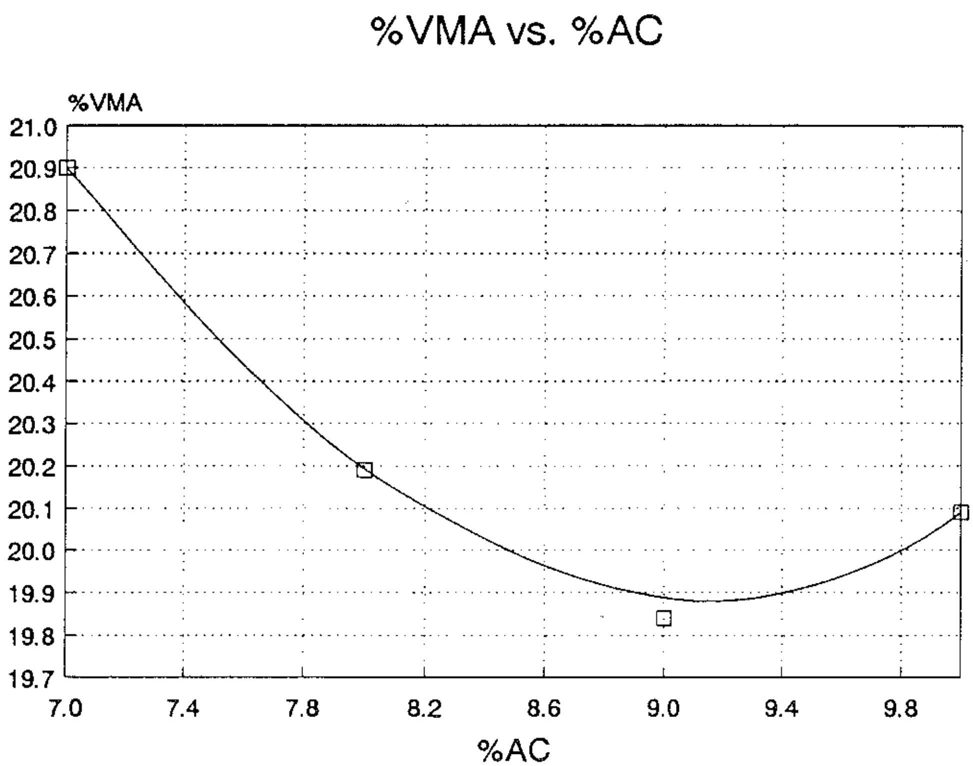

Figure 8. Percent Voids in the Mineral Aggregate Versus Percent Asphalt for the Experimental Surface Mixture.

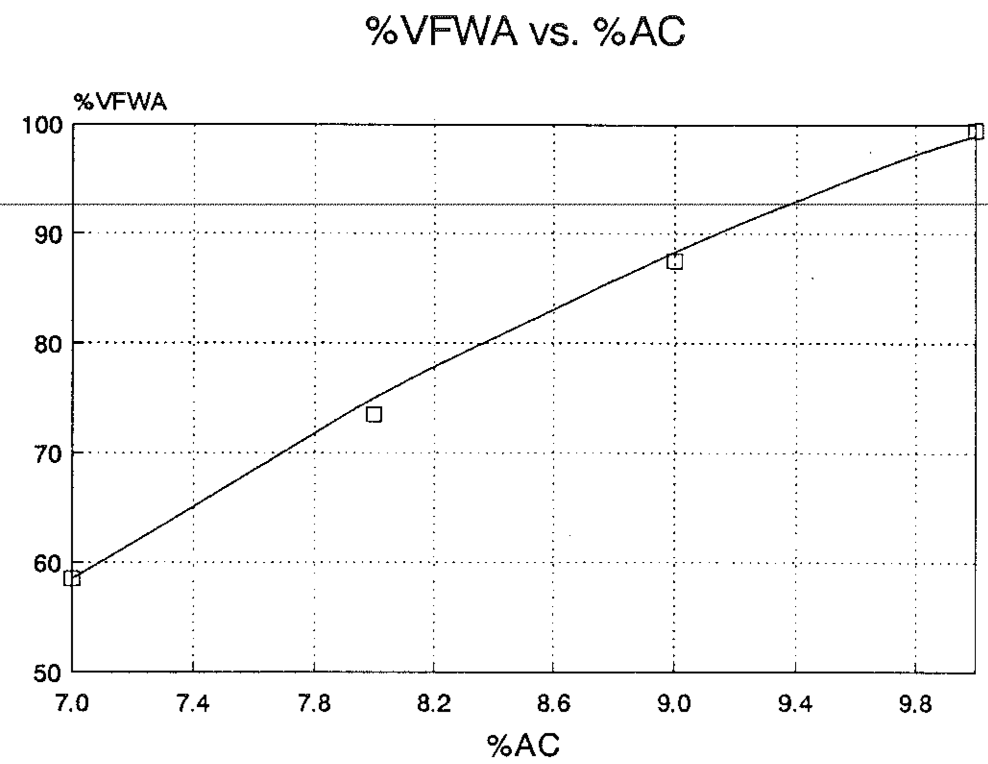

Figure 9. Percent Voids Filled with Asphalt Versus Percent Asphalt for the Experimental Surface Mixture.

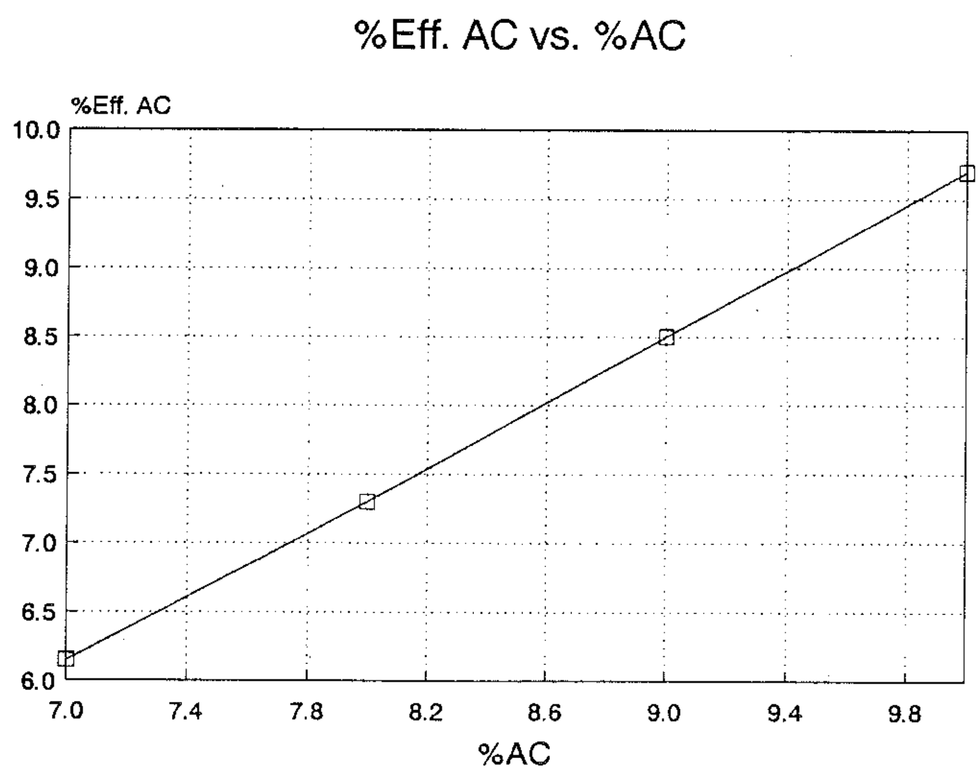

Figure 10. Percent Effective Asphalt Content Versus Percent Asphalt for the Experimental Surface Mixture.

Film Thickness vs. %AC

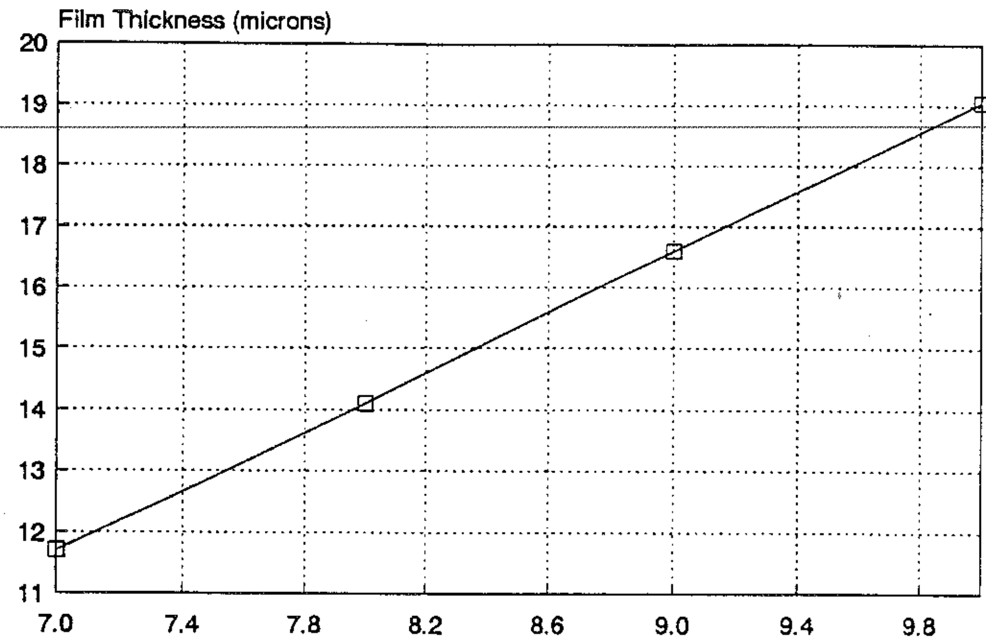

Figure 11. Film Thickness Versus Percent Asphalt for the Experimental Surface Mixture.

%Abs. AC (mix) vs. %AC

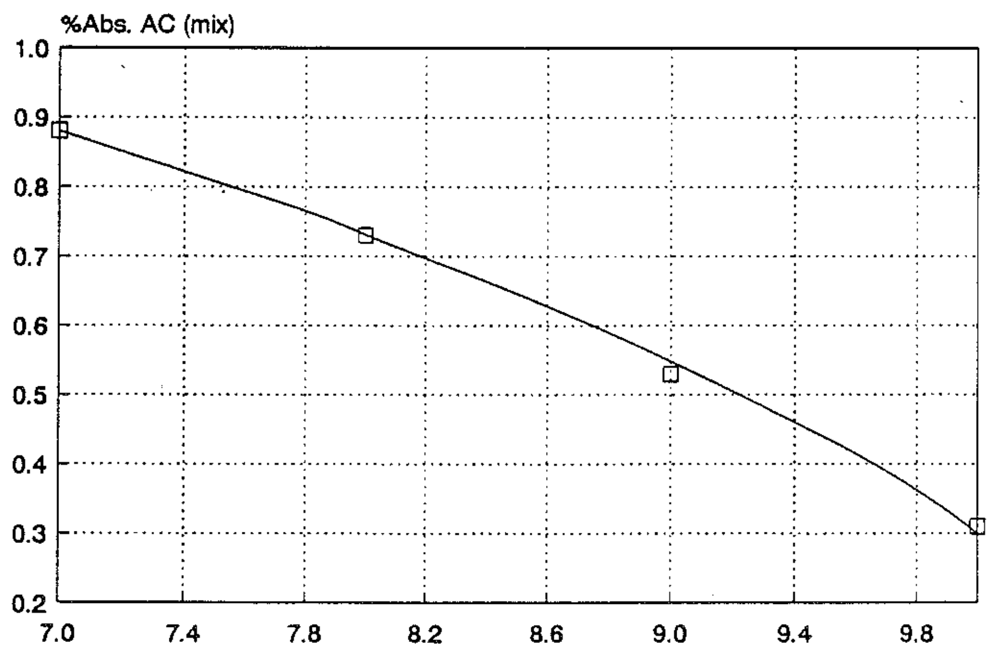

Figure 12. Percent Asphalt Absorption (Mix) Versus Percent Asphalt for the Experimental Surface Mixture.

were obtained, three on October 13 and one on October 14, for the purpose of determining asphalt content and aggregate gradation. The design asphalt content was 8.5 percent. Results of the asphalt extraction tests indicated extracted asphalt contents ranging from 8.5 percent to 8.7 percent and averaging 8.6 percent. Extracted aggregate gradations were within the tolerances allowed for the job-mix formula of the experimental bottom ash surface mixture. The average of the extracted aggregate gradations is shown in Figure 2 and is designated as the actual mix. There were no subsequent laboratory testing of the experimental bottom ash surface mixture performed by the Kentucky Department of Highways or the Kentucky Transportation Center.

Unfortunately, due to a lack of communication between Kentucky Transportation Center personnel and Kentucky Department of Highways personnel, construction of the experimental overlay was not observed by research personnel. Kentucky Department of Highways personnel indicated there were no significant difficulties with the production of the experimental bottom ash surface mixture or the placement of the material.

ECONOMIC CONSIDERATIONS

If economical utilization of the bottom ash aggregate was to be achieved, it was thought to be essential to have a source of the waste material near the project. Understandably, transportation costs might preclude any use of bottom ash aggregate in areas where it is not available as a waste product. Although Kentucky Power Company officials supplied the bottom ash materials to the contractor at no cost for this project, and the only costs incurred for the experimental bituminous surface mixture involved only transportation and associated mixing and placing costs, the unit bid price of the experimental surface was nearly 36 percent higher than the conventional Class I surface mixture. The unit bid price of the experimental Class I surface mixture containing bottom ash aggregate was $38.00 per ton. This compares to a unit bid price of the conventional Class I surface mixture of $28.00 per ton. The higher unit bid costs were thought to be attributable to the increased asphalt content (nearly fifty percent higher than the conventional mix) and the contractor's uncertainty about the use of the experimental material.

PERFORMANCE INFORMATION

Kentucky Transportation Center personnel conducted visual surveys to assess the condition and performance of the experimental bottom ash surface and to compare these aspects with the contiguous conventional Class I surface mixture. Principally, the inspections were performed annually one year after placement up through October 1991.

State Route 3 through Lawrence County was formerly US 23. The original pavement was a jointed portland cement concrete pavement. The original concrete pavement had been overlaid with a one-inch thickness of asphaltic concrete surface material prior to the October 1987 overlay. Because of the underlying concrete pavement, reflective cracks were visible above the existing portland cement concrete pavement joints in the asphaltic concrete surface of both the experimental and control sections (see Figure 13). Deterioration of the asphaltic concrete pavement in the vicinity of the reflective cracking appeared to be about the same in both the experimental and control sections. There were no instances of excess asphalt (bleeding or flushing) observed in the experimental section. No significant rutting was observed within either the experimental section or control section during the survey period.

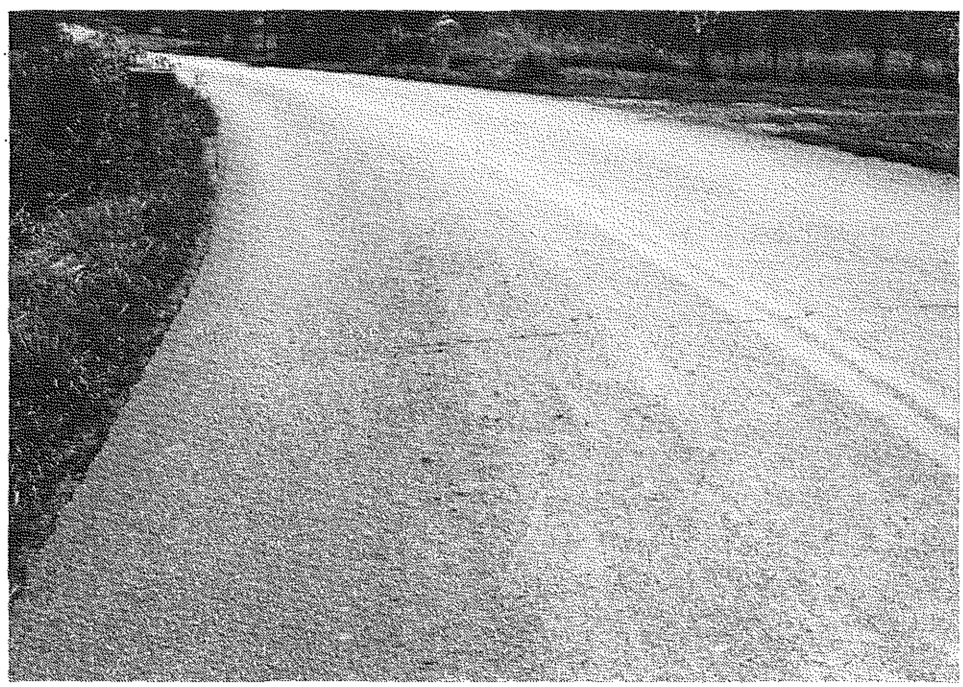

Figure 13. Reflective Cracking was Evident in Both Experimental and Control Sections.

The experimental bottom ash surface did exhibit considerable aggregate popouts (see Figures 14 and 15). Figure 14 shows a rather large piece (greater than 1/2 inch) of the bottom ash material that has been exposed and weathered. There is some ravelling of the experimental surface at this location, although this was not typical of the entire experimental section. Figure 15 depicts a more representative view of the experimental bottom ash surface. This photograph illustrates the observation of aggregate popouts and the general rough texture of the experimental surface. It did not appear that the quantity of aggregate popouts increased significantly during the survey period. The general appearance of the experimental surface remained fairly unchanged during the evaluation period. There were a number of instances where a bottom ash particle stained the pavement. An orange rust color could be seen on the pavement surface. This was attributed to the iron oxide present in the bottom ash aggregate. The staining was not detrimental to the experimental pavement's performance.

Skid testing of the experimental and control sections was conducted by the Pavement Management Unit of the Division of Specialized Programs of the Kentucky Department of Highways approximately three years after placement of the asphaltic concrete surface. Skid resistance testing was performed in both northbound and southbound lanes of the experimental section between milepost 21.9 and 22.9. The average annual daily traffic within the experimental section was estimated to be 1,100 vehicles per day. Skid numbers determined by the Pavement Management Unit as a result of the skid trailer test were 45 and 41 for the northbound and southbound lanes, respectively. Skid trailer testing was also performed in both northbound and southbound lanes of the control section between milepost 22.9 and 23.9. Average annual daily traffic within this section was estimated to be 400 vehicles per day. The reason for the disparate traffic volumes between the two contiguous sections is most likely due to the intersection of Blaine Creek Road with State Route 3 at milepost 22.9. Skid numbers determined by the Pavement Management Unit as a result of the skid test were 44 and 41 for the northbound and southbound lanes, respectively. The skid test results illustrate the excellent frictional characteristics of the experimental bottom ash surface. Although traffic volumes within the experimental section were nearly three times higher, the experimental bottom ash surface and the conventional Class I bituminous surface had similar skid numbers.

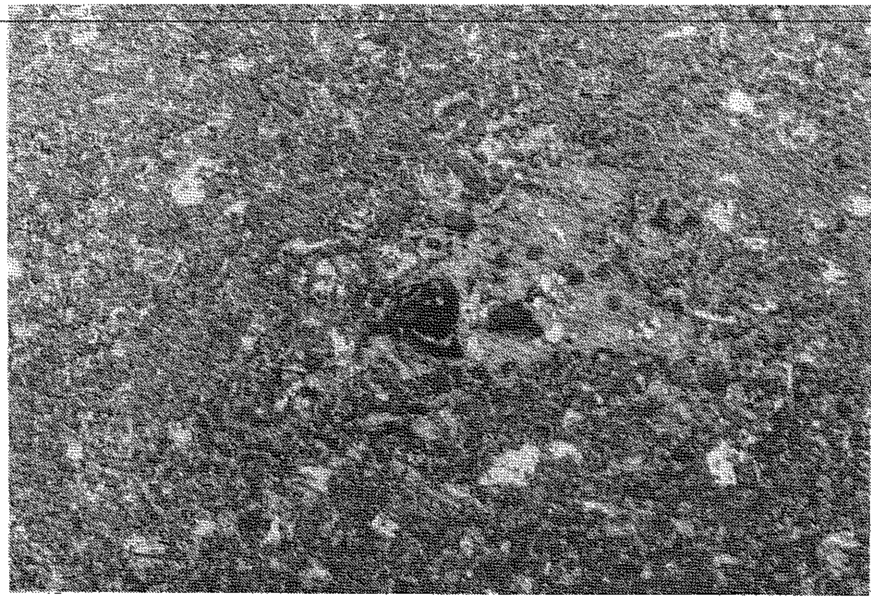

Figure 14. This Ravelled Area within the Experimental Section Was Not Typical of the Overall Surface Characteristics.

Figure 15. A Representative View Illustrating the General Rough Texture of the Experimental Bottom Ash Surface.

SUMMARY

The primary objective of the research effort was to evaluate the design and performance of a dry bottom ash used as a substitute for a portion of the limestone aggregate in a bituminous surface mixture. The dry bottom ash used in this project was supplied by Kentucky Power Company's Big Sandy Plant located near Louisa, Kentucky. A number of tests were performed by the Division of Materials' Central Laboratory of the Kentucky Department of Highways to determine the physical attributes of the ponded bottom ash material.

The physical tests performed on stockpiled bottom ash materials included sieve analysis, specific gravity, soundness, absorption, wear, and sand equivalent value. Sieve analyses indicated that 90 percent of the stockpiled bottom ash was finer than 1/2 inch. The Special Note developed for the experimental bituminous surface mixture required oversized material be scalped from the aggregate prior to entering the bituminous mixing plant. Saturated surface dry specific gravities ranged from 2.04 to 2.32. Losses of the bottom ash, determined by the sodium sulfate soundness test, ranged from two to six percent. Absorption of the bottom ash aggregate was variable and ranged from 0.2 percent to 2.7 percent. One bottom ash sample was evaluated for wear loss in the Los Angeles abrasion test. That sample had losses of 20 percent after 200 revolutions and 40 percent after 500 revolutions. The sand equivalency value of the bottom ash ranged from 73 to 90.

Kentucky Department of Highways' methods were used to design a bituminous mixture containing bottom ash aggregate, limestone aggregate, and natural sand. Tests were conducted to determine levels of strength, stability, air void content and other design parameters of the mixture. Aggregate tests performed on the bottom ash prior to combining the material with limestone aggregate and natural sand aggregate indicated a saturated surface dry specific gravity of 2.00 and an absorption of 8.7 percent. It is unknown why this sample had a higher absorption value than values determined previously. The Special Note required a mixture of 40 percent size No. 8 limestone aggregate, 40 percent bottom ash, with larger particles scalped from the aggregate, and 20 percent natural sand aggregate. Marshall mix design tests were completed by the Division of Materials' Central Laboratory. Results of the bituminous mix design indicated a unit weight of 130.5 lbs/ft^3 for the mixture. The optimum asphalt content was recommended to be 8.5 percent. The effective asphalt content was 7.9 percent. Air voids comprised 3.8 percent of the mixture. Specific gravity of the bituminous mixture was

2.18. The flow was 0.08 inches. Stability, at the optimum asphalt content, was 1,900 pounds. Splitting tensile strength tests indicated a retained tensile strength value of 81.7 percent.

The one-inch experimental bottom ash surface was placed on State Route 3 from milepost 21.9 to 22.9 on October 13 and 14, 1987. Approximately 539 tons of the experimental surface were placed. Due to a lack of communication between Kentucky Transportation Center personnel and Kentucky Department of Highways personnel, construction of the experimental overlay was not observed by research personnel. Kentucky Department of Highways personnel did not suggest any significant problems with the production of the experimental mixture or placement of the experimental material.

Asphalt extractions and aggregate sieve analyses were performed on samples obtained during construction. Results of those tests indicated extracted asphalt contents ranging from 8.5 percent to 8.7 percent and averaging 8.6 percent. Extracted aggregate gradations were within the tolerances allowed for the job-mix formula for the experimental bottom ash surface mixture. There were no subsequent laboratory testing of the experimental bottom ash surface mixture performed by the Kentucky Department of Highways or by the Kentucky Transportation Center.

Kentucky Transportation Center personnel conducted visual surveys to assess the condition and performance of the experimental bottom ash surface and to compare these aspects with the conventional Class I surface. Reflective cracks in the asphaltic concrete surface of both the experimental and control sections were visible above joints and cracks of the old portland cement concrete pavement. Deterioration of the experimental and control pavements in the vicinity of the reflective cracks appeared to be comparable in both sections. No significant rutting was observed in the experimental section during the survey period. The experimental bottom ash surface did exhibit considerable aggregate popouts and some ravelling throughout the section. Generally, the experimental surface exhibited a rough texture throughout the section which persisted during the evaluation period.

Skid tests were performed by the Pavement Management Unit of the Kentucky Department of Highways to compare the frictional characteristics of the experimental surface with the conventional bituminous surface. The skid test results demonstrated the excellent frictional characteristics of the experimental bottom ash surface. Although traffic volumes were nearly three times higher in the experimental section, the experimental bottom ash surface and the conventional Class I bituminous surface had similar skid numbers.

CONCLUSIONS AND RECOMMENDATIONS

The performance of this successful project has demonstrated that bottom ash aggregate may be effectively substituted for a portion of the coarse aggregate in a bituminous surface mixture. The combination of bottom ash aggregates with limestone and natural sand aggregate appears to improve the overall performance of a bituminous surface mixture, especially with respect to its skid resistant properties. Dry bottom ashes are angular and have a very porous surface which supports the concept that bottom ash used in a bituminous surface mixture course may improve its skid resistant properties. Because of the absorptive characteristics of bottom ash aggregate, nearly fifty percent more asphalt is required in the mixture. The increased asphalt content results in a higher unit bid price for the bituminous concrete material. Nevertheless, bottom ash represents a large potential source of high-friction, nonpolishing aggregates for use as an aggregate substitute in a bituminous surface mixture and increased utilization of bottom ash aggregate is recommended. With the success of this experimental application, it is quite probable that unit prices of bituminous concrete mixtures containing bottom ash aggregates will decrease to the point that the mixture is an economically viable alternative to conventional bituminous limestone mixtures especially in areas having abundant supplies of bottom ash.

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