Use of Power Plant Aggregate in Bituminous Construction

David A. Anderson, Department of Civil Engineering, Pennsylvania State University
Mumtaz Usmen and Lyle K. Moulton, Department of Civil Engineering, West Virginia University

Coal-fired power plant aggregates are the portion of the ash rejected by the stack and collected at the base as a waste product. Two aggregates are produced: boiler slag, a glasslike material, and bottom ash, more commonly called cinders. Approximately 16 percent of the annual ash production is used, and the remainder is disposed of as a waste product. This paper discusses engineering properties of power plant aggregates. Although they behave in many ways as conventional aggregates, they also differ in many ways from conventional aggregates. Consequently, new or modified test methods and specifications are needed before power plant aggregates can be used routinely in highway construction. Both field and laboratory data are given for bituminous mixtures using power plant aggregates. Based on these data and on limited service records, power plant aggregates can be used successfully in bituminous mixtures. Boiler slags are best used as partial replacements in conventional mixtures. Bottom ash is best used "as is" in stabilized base or shoulder construction.

Shortages of natural aggregates, increasing stockpiles of power plant ash, and the popularization of recycling have led to renewed interest in the use of power plant ash in highway construction.

ORIGIN OF POWER PLANT AGGREGATE

Coal-fired power plant aggregate is the portion of the ash rejected by the stack and collected at the base as a waste product. Two types of power plant aggregate are produced: dry bottom ash and wet bottom boiler slag (1). The term power plant aggregate includes both bottom ash and boiler slag.

Dry bottom ash, often referred to as cinders, is produced by burning pulverized coal over open grates. The ash that does not go up the stack falls as a solid to the ash hopper at the bottom of the furnace. The word dry refers to the solid state of the ash as it falls to the hopper. In a typical dry bottom furnace, 75 to 80 percent of the ash is fly ash and 20 to 25 percent is bottom ash. The newer and larger power plants are generally of the dry bottom type, and, therefore, production in the future will increasingly be of the dry bottom type.

Wet bottom boiler slag is produced by burning crushed or pulverized coal in a furnace where the bottom ash is kept molten and tapped off as a liquid. The molten slag is periodically drawn from the furnace and dropped into water where it is quenched and fractured to an angular glasslike material. The word wet is used to describe the molten state of the slag as it is drawn from the furnace. Depending on the type of furnace, from 50 to 85 percent of the total ash is boiler slag and the remainder is fly ash.

ANNUAL PRODUCTION AND USE OF POWER PLANT ASH

Annual ash production has increased from 23 Tg (25 million tons) in 1966 to 45 Tg (49 million tons) in 1973 (2). Annual ash production could easily increase to five times the 1973 figure by the year 2000 (3). The use of high-ash western coals and a switch to coal from other energy sources could further increase this figure. Although the percentage of ash being used has increased during the last few years (12 percent in 1967 versus 16 percent in 1973), in view of the increased production, the net amount of stockpiled ash is increasing each year. There is no reliable estimate of the quantity of ash that has been accumulated over the years in old stockpiles.

Of the 13.3 Tg (14.7 million tons) of bottom ash and boiler slag produced in 1973, 9.7 Tg (10.7 million tons) were dry bottom ash and 3.6 Tg (4.0 million tons) were boiler slag (2). Only 17 percent of the dry bottom ash was used whereas 45 percent of the boiler slag was used, and only 0.1 percent and 1.2 percent of the bottom ash and boiler slag were used in asphaltic concrete.

A large 1000-MW power plant may burn 2.7 Tg (3 million tons) or more of coal per year. With an ash content of 14 percent, approximately 0.38 Tg (420 000 tons) of ash, 0.08 Tg (80 000 tons) of dry bottom ash, and 0.30 Tg (340 000 tons) of fly ash would be produced each year. On the other hand, many of the smaller plants around the country produce only a few thousand megagrams of ash per year. Although some of this ash is of questionable economic value because of its limited quantity, most of the ash is produced at large plants. In fact, 80 percent

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of the coal is burned in plants that burn more than 0.9 Tg (1 million tons) of coal per year.

The production figures given above can be misleading, however. First, the production of ash may be interrupted when plants are occasionally shut down for unscheduled repairs, and, second, the quality and uniformity of the ash can vary. Ash quality and uniformity are controlled by a number of factors including coal source, degree of pulverization, load on plant, and burning temperature. These parameters are controlled to optimize power production, not ash production. Therefore, periodic and uncontrolled changes in ash quality and quantity may be expected, especially in plants that burn blended or multisource coals as necessitated by recent pollution regulations. These variations may or may not be significant in bituminous construction depending on the particular application of the ash.

STOCKPILING AND DISPOSAL

Because the production rate at a given plant is less than the rate at which the ash is used in a typical construction operation, the ash usually must be stockpiled. Although many plants do follow good stockpiling practice, stockpiling operations are generally designed not to maintain the quality of the ash but to facilitate handling and disposal. Often, the primary purpose of the stockpiling is to dispose of the ash, and only later is there an attempt to reclaim it.

Practices such as recombining pyrite with the ash and mixing fly ash or coal wash water with the ash are not uncommon. Because the stockpiled material is often transported hydraulically or end dumped from a large pile, it may be badly segregated. Old stockpiles are often very heterogeneous because of stockpiling practice and variations due to the operation of the power plant. Considerable care should be exercised before an existing stockpile of ash is accepted for potential use.

ENGINEERING PROPERTIES OF POWER PLANT AGGREGATE

Power plant aggregate is composed principally of silicon, aluminum, and iron and small percentages of calcium, magnesium, sodium, and other elements (4, 5). The composition of the ash is primarily controlled by the source of the coal and not by the type of the furnace. Chemical composition itself is of little practical importance in evaluating the engineering properties of power plant aggregates in bituminous mixtures.

Wet Bottom Steam Boiler Slags

Data from standard tests for several West Virginia wet bottom and dry bottom ashes are given in Table 1. Most boiler slags are predominately one size, and the bulk of the material occurs in the minus No. 4 to plus No. 16 range. This size range is typical of ash sampled from different sources in Kansas, Florida, West Virginia, Ohio, and Indiana. Traditional boiler slag is a hard, dense, black, glassy, angular material with a smooth surface texture, much like crushed glass.

Boiler slag can also be vesicular in nature, as if the molten slag was frothy prior to solidification. For example, the slag produced within the last few years at the Kammer, West Virginia, power station has been somewhat vesicular, but previously it was dense and nonvesicular. This change in the ash is apparently due to changing sources of coal.

As an extreme example, boiler slag from the Willow Island, West Virginia, power station was dramatically changed as the result of an experiment in which limestone was injected into the furnace to control sulfur emissions. The result was a frothy looking, greenish ash with little crushing resistance. Whereas the LA abrasion resistance (ASTM C 131-69) of the Willow Island ash had been consistently below 40, the limestone-injected slag had an LA value in excess of 50. The properties traditionally associated with wet bottom boiler slags—hard, angular, nonvesicular—may well be changed as the burning of western coal and the adoption of less traditional plant procedures become more prevalent.

Wet bottom boiler slags are fractured to size as a result of the thermal stresses created in the slag as it is quenched in water, and many of the particles are highly stressed internally. This fact is recognized in Germany, where wet bottom boiler slag is crushed before it is used in portland cement concrete (6). Wet bottom boiler slag is generally lacking in the coarser sizes (plus No. 4), and, except for the oversized material, it is not customary to crush boiler slag used for highway construction in the United States.

The presence of high residual stresses may account for the unexpectedly high soundness values (ASTM C 88-73) recorded for some of the dense, nonvesicular boiler slags (Table 1). The soundness losses may be partially due to thermal cycling during drying and not to the expansive forces of the sodium or magnesium sulfate. Boiler slag will often crackle and snap as it is suddenly heated or cooled.

LA abrasion values for wet bottom boiler slags are customarily in the 30 to 40 range. The data are indicative not necessarily of the hardness or wear resistance of the slag but of the fracture resistance. This is particularly true of the more vesicular or porous boiler slags that lack toughness. The more porous the slag is, the higher the percentage loss will be. The coarser fractions of wet bottom boiler slag tend to be more porous than the finer sand-size fractions. Consequently, LA abrasion data for the coarser fractions, on which the LA abrasion test is usually performed, may not be representative of the finer, sand-size fraction, which predominates in most boiler slags. The fines produced during the LA abrasion test are intermediate in size and are nonplastic.

Dry Bottom Ash

The physical and chemical properties of dry bottom ash are more variable than those of wet bottom boiler slag. This is true in terms of both plant to plant variation and daily or yearly variation. This is to be expected because dry bottom ash is the direct result of the burning process whereas wet bottom slag is solidified from the molten slag. Typical aggregate properties are given in Table 1. Gradation curves for two West Virginia dry bottom ashes are shown in Figure 1. Similar curves have been reported for other bottom ashes (4, 7) in which the ash was well graded from coarse to fine. The minus No. 200 sieve material is essentially coarse fly ash and is nonplastic.

Dry bottom ash contains hard boiler slaglike particles as well as popcornlike particles. The popcorn particles are essentially poorly sintered agglomerates of coarse fly ash. The softer of these agglomerates can be broken with the fingers to individual coarse fly ash particles. Dry bottom ash also contains hard boiler slaglike particles that accumulate and solidify on the super heaters or fall into the ash hopper in a molten state. These particles are hard, glassy, and vesicular. The popcorn and slaglike particles are found in both the coarse and fine fractions of the ash.

The specific gravity of dry bottom ash depends on the mineralogical composition of the ash as well as the porosity of the particles. A dense dry bottom ash may have a bulk specific gravity as high as 2.6 while a poor ash, with a large percentage of both porous and popcorn particles, may range as low as or even lower than 1.6. To some degree, specific gravity is an indicator of quality. The smaller the percentage is of popcornlike particles, the higher the specific gravity will be.

Water absorption data for dry bottom ash (ASTM C 127-73) are quite variable and depend on the porosity (surface texture) of the ash and the percentage of popcorn particles. The popcorn particles will invariably absorb water but not asphalt. Water absorption data are, therefore, not always a reliable indicator of how the ash will behave with asphalt.

Soundness data for dry bottom ashes tend to be on the high side but often meet specification limits for natural aggregates. Many of the pores in dry bottom ash are so large that the ash has no opportunity to build up stresses during the drying cycle. As a consequence, the soundness test does not discriminate ash quality, particularly with respect to the presence of popcorn particles.

A potentially serious problem can occur if the iron pyrite from the coal cleaning operation is recombined with the bottom ash. The pyritic particles are subject to degradation in the pavement and should be eliminated in ash that is to be used in bituminous construction. Further experience with other bottom ashes indicates that abnormally high sulfate contents can be caused by other than pyrite-contaminated ash. It appears that the sulfate can precipitate in the furnace as complex soluble sulfate salts. In the case of Hoot Lake bottom ash (Table 2), the water-soluble residue from the evaporation of ash leachate contained 28 800 mg/liter (216 oz/gal) of soluble sulfate, equivalent to 28.8 g of $SO_4^=$ ion per 1000 g (28.8 oz/1000 oz) of ash. Compacted samples of this ash stabilized with penetration grade asphalt were allowed to set in the laboratory. The samples subsequently expanded and produced cracking much like that produced by reactive aggregates in portland cement concrete. It is hypothesized that moisture absorbed by the salts caused volume changes sufficient to crack the specimens.

Leachate data for a number of other power plant ashes are given in Table 2. The data show that the pH of the leachate does not always correlate with sulfate content, nor is the pH of the fly ash necessarily that of the bottom ash. A high iron content may or may not be associated with a high sulfate content, depending on the source of the sulfate ion. The effect of the soluble salts on the durability of the bituminous binder is of questionable concern, but abnormally high sulfate contents are of concern to adjacent structures, particularly portland cement concrete (8).

BITUMINOUS MIXTURES CONTAINING WET BOTTOM BOILER SLAGS

The technical literature contains very little information on the use of power plant ash in bituminous mixtures, even though boiler slag has been used successfully at various locations in the United States. Much of the early work centered around the use of boiler slag as skid-resistant aggregate in finite graded mixtures, ostensibly because of the hardness and angularity of the aggregate.

Rockdale Slag Aggregate

Jimenez and Galloway (9, 10) reported on the design of mixtures using wet bottom boiler slag from lignite coal. The boiler slag was black, somewhat porous, and essentially of one size, ranging between the No. 30 and No. 8 sieves. The slag was combined with the fly ash in the disposal operation, and, therefore, the ash used in the mixtures contained about 5 percent fly ash.

Acceptable dense-graded wearing course mixtures with a top size of 9.5 mm (0.4 in) were obtained by blending 25 to 50 percent limestone screenings (50 percent minus No. 16) with the slag. The addition of limestone screenings was necessary to achieve adequate stabilities (Hveem stabilities of 35 to 50). When an immersion compression strength test was used, 90 percent of the strength was retained after 24 hours. Field results were favorable in terms of mixture and lay-down properties and resistance to weather and traffic. Acceptable skid resistance was reported.

Florida Wet Bottom Boiler Slag

The state of Florida evaluated wet bottom boiler slag as a surfacing aggregate (11). Adequate Marshall stabilities were obtained by blending the boiler slag with a stable, fine-graded sand. LA abrasion loss for the slag was reported as 43, exceeding the specification limit of 40. Approximately 95 percent of the bituminous coating was retained in a stripping test.

Wet bottom boiler slag has been used extensively in the past in the immediate Tampa area and by the city of Tampa. It was used extensively in paving the parking lot at Disney World. Since the conversion from coal to oil, boiler slag is no longer produced at the Tampa power station.

West Virginia Experience

Boiler slag has been used regularly in the northern panhandle of West Virginia as an aggregate in type 3 wearing course mixture (4, 7). The mixture is approximately 50 percent boiler slag, 39 percent river sand, 3 percent fly ash, and 8 percent asphalt cement. A great deal of this material has been placed during the last 10 years with a good record of service. In some cases it has been used under heavy traffic, such as on US-250 through Wheeling, West Virginia, which carries considerable heavy truck traffic. The mixes are not promoted as anti-skid mixtures; instead, boiler slag is used to upgrade a sand that is deficient in coarse fractions.

A similar mixture was used as a deslicking mixture on a hazardous stretch of road on Easton Hill in Morgantown, West Virginia. This mixture, placed in November 1969, was composed of 52 percent boiler slag, 23 percent limestone sand, 21 percent river sand, and 4 percent fly ash. Field skid data are not available, but the overlay did significantly reduce the accident frequency at the site (7). A problem in aggregate retention was encountered in the wheel tracks, and, by 1974, especially on the curves, the overlay had worn through to the old pavement. Some of the aggregate loss may be attributed to poor lay-down conditions (wet weather and the lateness of the season).

Special Considerations in Designing Boiler Slag Mixtures

The biggest difficulty in using wet bottom boiler slag is its smooth surface texture and tendency to be one size. To achieve acceptable stabilities and gradations requires that the slag be blended with other aggregates. The poor stability is due to the smooth glassy surface texture and lack of interparticle friction. The high angles of internal friction obtained in direct shear tests on boiler slags (Table 1) are due to particle interlock and are obtained only when the slag is confined. Data given in Table 3 show the effect on Marshall stability of replacing sand with constant gradation boiler slag and asphalt content. The stability is reduced as the percentage of boiler slag is increased.

Based on field experience and laboratory data, mixtures with more than 50 percent boiler slag will generally lead to unacceptable stabilities. This rule of thumb must vary according to the properties and gradation of the slag and the other aggregates in the blend. The more stable the other aggregates are and the more widely graded the slag is, the greater the allowable percentage of slag will be. Perhaps some of the more vesicular boiler slags may be used in greater percentages, but if excessively vesicular these slags tend to be weak and to lack crushing resistance. Boiler slag can be used without any special consideration in conventional mixtures if the percentage of boiler slag is limited to less than approximately 50 percent of the aggregate. The best use of boiler slag is as a partial replacement for the sand fraction in base and surface mixtures. Mixtures with acceptable skid resistance that use boiler slag as the top size aggregate can be designed by limiting the percentage of boiler slag in the mix and by avoiding open-graded mixtures with low filler content.

BITUMINOUS MIXTURES CONTAINING DRY BOTTOM ASH

Very little use has been made of dry bottom ash in bituminous construction. Ash from the Fort Martin and Mitchell power stations was used in cold mixes for maintenance work in West Virginia and in shoulder construction at the Fort Martin power station. The ash was used without beneficiation except for scalping on the 19-mm (¾-in) sieve.

Mixture Properties

Gradation curves for the Fort Martin and Mitchell ash (Figure 1) show considerable variation with sampling in 1972, 1973, and 1975. A set of Marshall design curves using the 1972 ash are shown in Figure 2.

As with conventional mixtures, the effect of kneading compaction instead of Marshall compaction is to increase the stability and density and decrease the optimum asphalt content. The effect of compaction method varies with different ashes and is more important with the more friable ashes, which are more easily degraded during compaction. For the Fort Martin ash, the density produced by kneading compaction was 160 Kg/m^3 (10 lb/ft^3) greater than that produced from the 50-blow Marshall compaction (Figure 2).

Kneading compaction more closely approximates field compaction. The rough surface texture and high angle of internal friction of the bottom ash apparently limit the amount of shear deformation in the compaction mold under drop hammer compaction, but kneading compaction breaks down the internal structure more the way field rolling does. Gyratory compaction may be more suitable and should be investigated relative to the compaction of dry bottom ash mixtures.

The low flow values shown in Figure 2 are typical of many dry bottom ash mixtures. This indicates a tendency toward brittle mixtures, and this has been observed in the field. With a loss in subgrade support, these mixtures appear to crack more readily and extensively than bituminous mixtures made with conventional aggregates.

Dry bottom ashes often exhibit high air void contents, even when well graded and compacted with the kneading compactor. The high air voids, relative to mixtures with similarly graded conventional aggregates, are due to the high angle of internal friction and the rough surface texture of the ash particles.

Special Considerations

A serious consideration with some dry bottom ash is the presence of popcorn particles. The popcorn particles invariably do not get coated throughout with asphalt. During field or laboratory compaction, the particles may be crushed and a void may be left that is essentially filled with crumbled, coarse fly ash particles. Because of these particles, using many of the dry bottom ashes as a surface aggregate is questionable. Instead, they can be more effectively used without beneficiation as stabilized base where aggregate quality and gradation requirements are less severe.

Immersion Marshall data for Mitchell and Fort Martin dry bottom ash show a 95 percent retention in stability after immersion. Retention of asphalt in the presence of water does not appear to be a problem with dry bottom ashes based on immersion data and field experience. As discussed previously, however, some pyritic or high sulfate ashes degrade when exposed to water over an extended period of time. The standard immersion tests are too short in duration to detect the sulfate problem. A test method, such as a water leachate test or a modified immersion test, should be developed to identify this problem. An upper limit on the soluble sulfates (leachate test) may provide an adequate criterion for identifying a potential sulfate problem.

Field Experience

Each summer since 1972, several hundred thousand megagrams of Fort Martin and Mitchell bottom ash have been used to upgrade secondary rural roads in northwestern West Virginia. Most of the ash was mixed with 6 to 7 percent residual asphalt by using both modified MS-2 and CMS-2 emulsions. Cost of the mix (at the plant) was \$10 to \$11 per megagram in 1975 (slightly more than half of the cost was attributed to the emulsion). The cost of equivalent hot mixes using conventional aggregate was \$17 to \$25 per megagram.

Field lay-down experience with this material was excellent. Although the material was a bit fluffy in the spreader, little or no difficulty was encountered whether the material was placed with a paver or spreader box or merely end dumped and leveled with a grader. The mix was very stable under a pneumatic-tired roller in depths up to 15 to 20 cm (6 to 8 in), although in the deeper lifts it had to be tracked with a grader before it could be successfully rolled. In general, the more satisfactory rolling was done with pneumatic-tired rollers. Compaction was essentially complete after 4 or 5 passes with the pneumatic-tired roller, and the mix was sufficiently stable to carry loaded dump trucks immediately after rolling.

Field densities for the Fort Martin ash were 1760 to 1810 kg/m^3 (110 to 113 lb/ft^3) at 10 to 12 percent air voids. These densities more closely approximate the densities achieved with kneading compaction than with the drop hammer or Marshall compaction. Although the data are not yet complete, preliminary results from research now in progress show that modified kneading compaction can be used to approximate the degradation that occurs during compaction. Sieve analyses of material entering the mixing plant may vary significantly from the material in the pavement after compaction; for example, compare the edge and conveyor graphs shown in Figure 3. Although the degradation is greater than that for conventional aggregates, it apparently has not adversely affected the performance of these pavements except in the one case noted below.

Table 1. Engineering properties of power plant aggregates.

Source of Ash	Type of Ash	Bulk Specific Gravity[a]	Percentage of Water Absorption[a]	LA Abrasion[b]	$MgSO_4$ Soundness[c]	Friable Particles[d]	Florida Bearing Value	Angle of Internal Friction (deg)
Fort Martin	Dry	2.31	2.0	30 to 45	15	Yes	196	40
Mitchell	Dry	2.68	0.3	30 to 40	10	No	—	43
Kammer	Wet	2.76	0.3	37	10	No	72	41
Willow Island	Wet	2.72	0.3	33	15	No	46	42

[a]ASTM C 127. [b]ASTM C 131. [c]ASTM C 88. [d]ASTM C 142.

Table 2. Chemical analyses of ash leachate.

Source	Type	pH	Ca^{++}	Fe^{++}	Mg^{++}	Na^{+}	$SO_4^{=}$
Fort Martin	Pyritic fly ash	8.2	1200	<20	30	42	3 500
Fort Martin	Pyritic bottom ash	3.0	960	7000	266	600	23 500
Fort Martin	Nonpyritic fly ash	10.3	700	<20	<2	156	2 460
Fort Martin	Nonpyritic bottom ash	8.4	100	<20	14	38	450
Harrison	Fly ash	12.1	1260	<20	<2	242	1 880
Harrison	Bottom ash	8.1	120	<20	14	20	520
Mitchell	Bottom ash	2.5	720	120	16	28	3 760
Big Sandy	Bottom ash	8.2	60	<20	4	60	250
Willow Island	Lime-injected boiler slag	12.5	1060	<20	<2	40	8
Hoot Lake, Minnesota	Bottom ash	10.8	800	<20	<2	9900	28 800
Montana	Bottom ash	9.6	520	<20	2	46	1 000
Ohio	Bottom ash	2.1	1260	2000	12	112	8 260

Note: Ion concentrations are reported as mg/liter (134 oz/gal) of ion soluble in water: 1:1 by weight, aggregate:water, agitated for 24 hours.

Figure 1. Gradation of dry bottom boiler ashes.

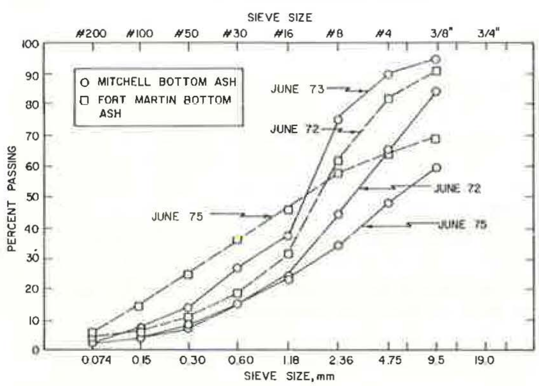


Table 3. Effect of percentage of boiler slag-sand on mixture stability.

Mixture	Marshall Stability (kg)	Flow (mm)
60% Kammer, 40% limestone sand 1	125	1.9
50% Kammer, 50% limestone sand 1	152	1.8
40% Kammer, 60% limestone sand 1	172	1.8
35% Kammer, 65% limestone sand 2	659	3.4
48% Kammer, 52% limestone sand 2	488	3.8

Note: 1 kg = 2.2 lb; 1 mm = 0.039 in.

Figure 2. Mixture design of Fort Martin and Mitchell, West Virginia, bottom ash.

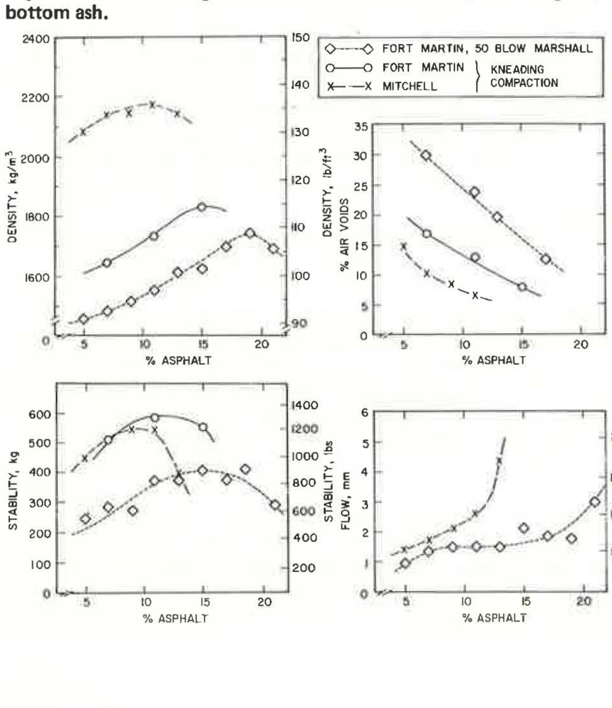
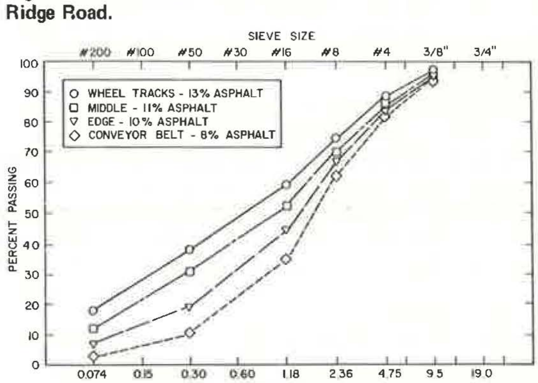


Figure 3. Gradation of Fort Martin ash for Baker's Ridge Road.



Service Behavior

The Mitchell bottom ash is representative of a good quality ash, has had an excellent service record with no reported problems, and demonstrates that bottom ash can be used successfully as an aggregate. The pyritic Fort Martin ash, placed in 1972, is representative of a poor quality ash and has brought out several potential problems as described in the following paragraphs.

Excessive pyrite and soluble sulfates present a durability problem. In spite of the asphalt coating, with time, the pyrite weathers throughout the depth of the pavement and forms weak pockets in the pavement. The weathered pyrite also tends to expand, causing popouts near the surface. This was especially severe on the shoulders of the access road to the Fort Martin power station (June 1975). In addition, the weathering of the pyrite also stained the pavement surface a deep, permanent, ferric oxide red color.

Disintegration of the popcorn particles at the pavement surface caused by compaction and traffic has left a pockmarked appearance. Below the surface these particles are crumbled and appear as voids filled with uncoated, loose, coarse fly ash. These voids could become a source of failure if they fill with water and freeze, but there is no evidence of this to date (June 1975).

Another problem was identified near Morgantown on Baker's Ridge Road, a rural road also paved in 1972 with Fort Martin ash. In the curves, the pavement in the wheel tracks has flushed badly with lateral shoving of 100 mm (39 in) or more. Gradation data and asphalt contents for samples taken from the wheel paths and the untrafficked part of the pavement (June 1975) are shown in Figure 3. The cornering forces of the traffic, some of which consists of loaded coal trucks, have caused severe degradation of the ash. The asphalt contents are higher than designed but still not sufficient to cause the flushing without the degradation.

With traffic, the surfaces paved with Fort Martin and Mitchell ash tend to skin over, giving a gritty but fine texture much like No. 80 grit sandpaper. This gritty surface is apparently maintained over a period of time. After 3 years of traffic, BPN skid numbers (ASTM E 303-74) have leveled at 60 to 80, depending on the level of traffic.

Except for the curves on Baker's Ridge Road, little if any additional densification of Fort Martin ash has occurred since it was placed. Density data from a variety of projects are relatively unchanged after 2 to 3 years, remaining at 1760 to 1810 kg/m^3 (110 to 113 lb/ft^3).

SUMMARY AND CONCLUSIONS

Based on prior usage and laboratory data, it is apparent that power plant aggregates can be successfully used in bituminous mixtures. Before this can be done on a routine basis, however, additional work must be done to develop test methods and specifications that are appropriate to power plant aggregate.

Need for New or Modified Test Methods and Specifications

In some cases the current test methods and specifications are too restrictive and exclude acceptable material. In other cases they are not sufficiently discriminating and allow material that is unacceptable. For example, the standard Los Angeles abrasion test does not sufficiently identify popcorn particles in dry bottom ash, nor is the test indicative of degradation that might occur under field compaction.

Still other questions can be raised: Are the high air voids associated with some dry bottom ashes acceptable? How significant is the soundness test for boiler slags, and what are acceptable test limits? Is specific gravity an adequate indicator of popcorn particles in dry bottom ashes, and, if so, what lower limit is acceptable? Clearly a test method is needed to identify potential sulfate problems in dry bottom ashes.

Potential Use

For power plant aggregates to be used successfully, they must be used properly. They should not, in general, be approached as conventional aggregates with the stock-in-trade question, "Do they meet specifications?"

Boiler slag can be used without special consideration in conventional mixtures if the percentage of boiler slag is limited to less than approximately 50 percent of the aggregate. The most favorable use of boiler slag is in base and surfacing mixtures through blending with other aggregates. Mixtures with acceptable skid resistance that use boiler slag as the top size aggregate are possible if careful attention is paid to mixture design.

Dry bottom ash is best used as is in base mixtures or for shoulder construction where gradation and toughness requirements are not so critical. Many bottom ashes are not acceptable in wearing courses. Although it may be feasible to blend bottom ash with other aggregates, extensive blending for beneficiation may be unacceptable economically.

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