plant operation is shown in Figure 4. The operating characteristics of the plant facilities are given in Table 1. The computer model set up for the plant is similar to the one proposed by Hancher (8). The basic input data for the feed to the plant are shown in Figure 5. Figure 6 shows the computer statement sequence required for the partial plant analysis. The results of the computer model analysis are shown in Figure 7.

Comparison between the proposed model (HONPI) and the existing model (HONDO) predictions for test samples collected at the plant has shown a certain degree of improvement of the HONPI model for aggregate plant analysis. Table 2 gives the results of the prediction of flow stream 7—the crushed product from a Telsmith 1.2-m (4-ft) standard cone crusher—and flow stream 3—the oversize material from the second deck of the first screen unit. Considerably more testing is required to evaluate the true capabilities of the model.

SUMMARY AND CONCLUSIONS

The primary objective of this research study was to develop a probabilistic prediction model for aggregate production plants. Through the use of available crushing and screening theories, Hancher's computer model (8) has been revised, and statistical devices have been added for the development of this proposed probabilistic model. Preliminary testing of the new proposed crushing and screening models has been confirmed by the manufacturer's recommended crushed product output and available screening data.

The probabilistic model proposed in this study will be a useful tool in the design and development of new aggregate plants as well as the expansion of existing plants. Although it does not purport to be a comprehensive model of the entire aggregate processing system, it does permit the user to seek, where appropriate, proper planning and optimization of his or her own design data for the data postulated in the basic model.

The analysis techniques used in the proposed model are compatible with those used in the aggregate industry in the United States. The use of such a model greatly facilitates the evaluation of many more plant arrangements, raw-feed compositions, and equipment settings than it is now possible to evaluate. It is also much easier, by using this model, to evaluate closed-circuit plant analyses (introduction of such material was omitted from this paper because of considerations of length).

Extensive experimental data would be required to ensure the validity of this model; however, collection of such data was not feasible in this study because of a lack of funding. It is believed that, after additional study and development, satisfactory, proven probabilistic prediction models might emerge.

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Applicability of Conventional Test Methods and Material Specifications to Coal-Associated Waste Aggregates

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The applicability of standard test procedures and specifications to nonconventional, coal-associated materials such as bottom ash, boiler slag, and coal mine refuse is evaluated. Test procedures for specific gravity, Los Angeles abrasion, degradation resistance, soundness, deleterious materials, weak particles, and leachate quality were performed. Asphaltic mixtures were analyzed for Marshall stability and flow, density, voids, and degradation. It was found that, because of the unique characteristics of bottom ash, boiler slag, and coal mine refuse, application of conventional test methods and specifications is often inappropriate and that effective use of such materials requires the development of new test methods or modifications to existing methods and specifications. Application of existing test methods and specifications may result in

the acceptance of a questionable material or arbitrary rejection of an acceptable material.

Natural aggregates such as crushed rock, sands, and gravels have been used in highway construction for many years. Based on extensive laboratory and field experience, a variety of test methods, specifications, and design and construction procedures have been developed to ensure that they provide adequate performance. In recent years, there has been considerable interest in the use of synthetic aggregates and waste materials, and it has been pointed out by several authors that these "new" materials exhibit properties and behavior that may be quite different from that of conventional aggregates (1, 2, 3).

Several approaches can be taken to test methods and specifications for these new materials:

1. They can be specified by applying the existing test methods and specifications and rejecting those materials that do not meet existing criteria.
2. Existing test methods and specifications can be modified to accommodate the new materials.
3. The unique properties of these new materials can be recognized and, where necessary, new test methods and specifications and design and construction procedures can be developed.

Research on coal-associated wastes has shown that the first approach given above is often inappropriate. Existing test methods and specifications developed for conventional aggregates often fall short of properly characterizing and evaluating coal-associated wastes. Adoption of standard test methods and specifications can lead to the acceptance of a questionable material or the arbitrary rejection of a suitable material. This implies that the second and third approaches are often more realistic for new materials such as coal-associated wastes.

In this paper, the applicability of selected test methods to coal-associated wastes is discussed in relation to the use of these materials in bituminous mixtures. Although the discussion in the paper applies to coal-associated wastes, similar problems may be encountered with other new materials such as incinerator residue, pyrolysis residue, various industrial slags, and recycled pavement materials.

MATERIALS

For the purposes of this paper, coal-associated wastes are defined as the solid wastes that arise from the mining, preparation, or burning of coal. Included in this definition are coal mine refuse, fly ash, bottom ash, and boiler slag (2, 4). To understand properly the nature and behavior of these materials, it is important to know how they are produced and subsequently handled. Factors such as coal source, plant production operations, and disposal practices exert a significant influence on material properties and behavior (2).

Power plant ashes are produced by burning coal at high temperatures in steam-generating boilers or furnaces. The finer portion of the ash residue that is carried up the stack by combustion gases is called fly ash, and the coarser portion of the ash that is rejected by the stack is called bottom ash (4). The bottom ash from "dry bottom" boilers that burn pulverized coal over open grates is called dry bottom ash, bottom ash, or cinders. The ash produced by "wet bottom" boilers is called wet bottom boiler slag or boiler slag. Whereas dry bottom ash solidifies before it drops from the furnace, boiler slag is tapped from the furnace as a molten slag and dropped into water where it is quenched to an angular, glasslike material. Dry bottom ash is typically well graded and may contain varying quantities of popcornlike particles, which are loosely sintered agglomerates of coarse fly ash. The individual particles are vesicular and irregularly shaped and have a rough, gritty texture. Boiler slag, in contrast, is one-sized [predominantly 4.75- to 1.18-mm (no. 4 to no. 16) mesh], smooth-textured, and angular. Some vesicularity may be present, particularly in the coarser sizes (2).

Coal mine refuse represents the rejected rock, carbonaceous and pyritic shales and slates, waste coal, and other impurities produced during mine development and operation and during the coal-cleaning process. The refuse is generally composed of dark grey, flat, angular, shalelike particles graded from 80 to 50 mm (3 to 2 in) to 0.075-mm (no. 200) mesh. Poor resistance to weathering—i.e., slaking—is also a prominent characteristic of coal mine refuse (5). Coal washings, or slurries, are typically less than 1 mm (0.04 in) and are not considered in this paper.

A description of the study materials is given in Tables 1 and 2. The materials were selected to represent typical bituminous coal sources, production operations, and disposal practices in the Appalachian region. Tests were performed on these materials in strict accordance with the standard American Society of Testing and Materials (ASTM) procedures to (a) evaluate the suitability of the test methods and (b) observe the behavior of the material during the testing procedures.

AGGREGATE TESTS

Specific Gravity

Hubbard and Jackson (6) discussed the early definitions and test methods for specific gravity that have remained relatively unchanged for the past 40 years (7). The currently used saturated, surface-dry concept (ASTM C 127) has long been used for coarse aggregates (6), but it was found to be unsatisfactory for sands and so the present "cone method" (ASTM C 128) was developed (7). Various researchers have disagreed about the appropriateness of these tests, particularly as a measure of absorption (8, 9).

Representative specific gravity and absorption values for coal-associated wastes are given in Table 1. A comparison of specific gravity data for coal-associated wastes with those for conventional materials indicates that the ash particles, because of their vesicular nature, tend to be lighter in weight than natural aggregates. The fine fraction of BS material is an exception because it is dense and nonvesicular. In general, the coarser ash fractions have a lower specific gravity than the fine fractions because they are more vesicular. The high absorption obtained for the BA-1 coarse aggregate is caused by the presence of soft, friable agglomerates that become saturated when soaked. It was found that, when saturated, such particles may contain in excess of 30 percent moisture. It was also noted that, because the pores are large, the absorbed water drained off fairly quickly when the particles were removed from water. Therefore, the actual water that can be held in the pores may be considerably in excess of the 13.1 percent given in Table 1. In terms of determining the saturated, surface-dry condition, it is difficult to observe the disappearance of the surface sheen on both the irregularly textured bottom ash surface and the black glassy boiler slag particles.

Achieving a true saturated, surface-dry condition in the sand-size BA-1 and BA-2 particles also presents

Table 1. Properties of coal-associated wastes selected for study and ASTM test methods.

Material	ASTM C 127 and C 128			ASTM C 88, Soundness Loss	ASTM C 131, Los Angeles Abrasion		pH	$SO_4^=$ (mg/L)	ASTM C 123, Lightweight Particles[b]	ASTM C 142, Clay Lumps and Friable Particles (%)
	G_{bulk}	G_{app}[a]	Water Absorption (%)		Value	Grading				
BA-1										
Coarse[b]	1.549	1.942	13.1	16.6	50	D	9.2	49	67	7
Fine[c]	2.192	2.225	0.7	24.4					80	7
BA-2										
Coarse	2.164	2.266	2.1	6.3	38	B	3.8	375	14	0.2
Fine	2.417	2.468	0.8	9.8					25	0.2
BS										
Coarse	2.210	2.301	1.8	29.1	46	B	9.4	31	13	0.2
Fine	2.575	2.654	1.2	7.1					1	0.4
CMR-1										
Coarse	-	2.549[c]	-	68.9	37	A	7.5	1750	16	27
Fine									17	37
CRM-2										
Coarse	-	2.459[c]	-	82.7	26	B	7.9	725	9	70
Fine									18	76

Notes: 1 mg/L = 0.000 13 oz/gal.
Coarse = passing 50.8 mm (2 in) and retained on 4.75 mm (no. 4); fine = passing 4.75 mm (no. 4) and retained on pan.
[a]Apparent specific gravity. [b]Liquid specific gravity = 2.0. [c]ASTM D 854.

Table 2. Gradation of as-sampled materials.

Material	Percentage Passing Sieve Size[a]									
	50.8 mm	25.4 mm	12.7 mm	4.75 mm	2.36 mm	1.18 mm	0.60 mm	0.30 mm	0.15 mm	0.075 mm
BA-1	100	100	98	90	79	65	50	35	19	7.0
BA-2	100	98	91	66	49	33	22	13	6	1.9
BS	100	98	90	71	38	9	3	2	1	0.4
CMR-1	100	86	61	35	23	13	9	6	4	3.2
CMR-2	100	78	46	7	-	2	-	1	-	0.3

[a]Corresponding U.S. sieve sizes: 2, 1, and 0.5 in and nos. 4, 8, 16, 30, 50, 100, and 200.

difficulties. The 25 tamps in the sand cone compacted the samples to a state in which, because of the rough, irregular surface texture, the particles would hold together without slumping despite a dry appearance. This effect, plus the draining of water from the larger pores, gives anomalously low values of water absorption. Therefore, the bulk specific gravity and absorption values given in Table 1 are suspect.

The values for specific gravity of solids reported in Table 1 for the samples of coal mine refuse (CMR-1 and CMR-2) were determined by the soils procedure (ASTM D 854). Bulk specific gravity and percentage absorption determined by standard aggregate procedures were found to be inappropriate for these materials because of the slaking tendency of the refuse. The low values of specific gravity reflect the porous nature of the unslaked particles and the presence of lightweight coal pieces.

Los Angeles Abrasion

The Los Angeles Abrasion test procedure (10) was devised by the city of Los Angeles in 1916 and subsequently adopted by the California Division of Highways. The specification limits (40 to 50) have changed little from those originally suggested in the late 1930s. The percentage of "wear" is considered to be an indicator of overall aggregate quality and is associated with mechanical strength and degradation during construction and service.

Values for percentage of wear for BA-1, BA-2, BS, CMR-1, and CMR-2 are given in Table 1. The test value reported for BA-1 is quite high and reflects the presence of a degradable "popcorn" type of material. On the other hand, BA-2 shows better toughness as indicated by the lower percentage value. BS has an intermediate percentage of wear.

The fines produced from the bottom ash and the boiler slag were intermediate in size and appeared as small, broken pieces of the larger particles with sharp edges and porous surfaces. This implied that the mechanism of degradation in the ash materials was primarily a fracturing process. In contrast, the fine material produced from the coal mine refuse was much finer and typical of abrasion or wearing action. This was verified by the rounded and smooth appearance of the refuse particles at the end of the test.

At the end of the test, it was possible to identify in the BA-1 material some popcorn particles that could be easily crushed between one's fingers. Two mechanisms are believed to contribute to this anomalous behavior. The first is a possible "cushioning effect" that results from degraded material and the relatively large volume of the test specimen that results from batching the lightweight bottom ash on a weight basis. A second mechanism may be the lower inertia of the lightweight particles, which causes them to roll more slowly to the bottom of the drum during the test.

The coarse fraction of the bottom ash and boiler slag is more vesicular than the fine fraction, and vesicularity affects strength. Therefore, the Los Angeles values obtained on the coarse fraction are not representative of the composite sample. This is especially true for the boiler slags. Although the standard Los Angeles test does not break down all the popcorn particles and in that sense is a mild test, it is perhaps too severe for the denser slaglike particles that degrade by fracturing (11). A modification of the test is needed—a reduced sample size adjusted for volume to account for the popcorn particles and fewer revolutions or lighter balls to account for the fracturing.

Because of its tendency to slake, the degradation of the coal mine refuse is much more pronounced in the presence of moisture than when it is dry. Thus, the standard Los Angeles abrasion test performed on a dry refuse will give a poor indication of the level of degradation that might occur under moist conditions in the field during construction or in service.

Figure 1. Gradations produced by degradation of mixture BA-1 by modified Los Angeles, mortar and pestle, and kneading compaction procedures.

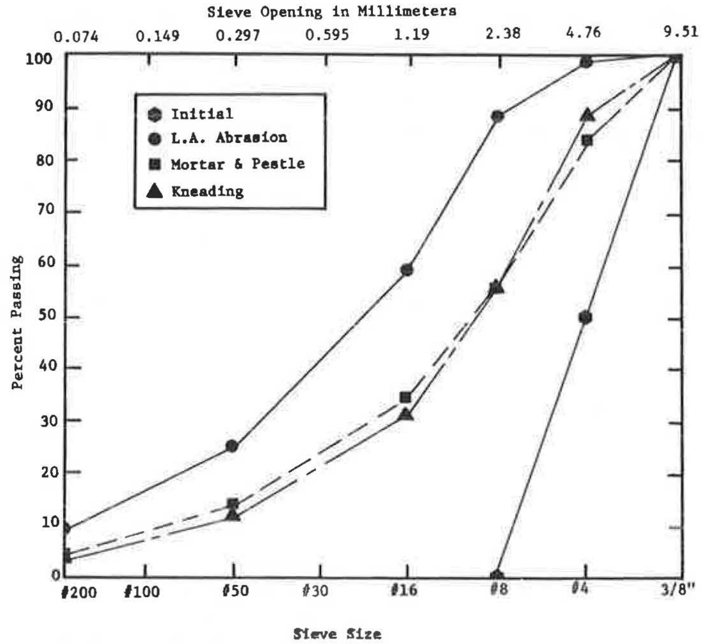
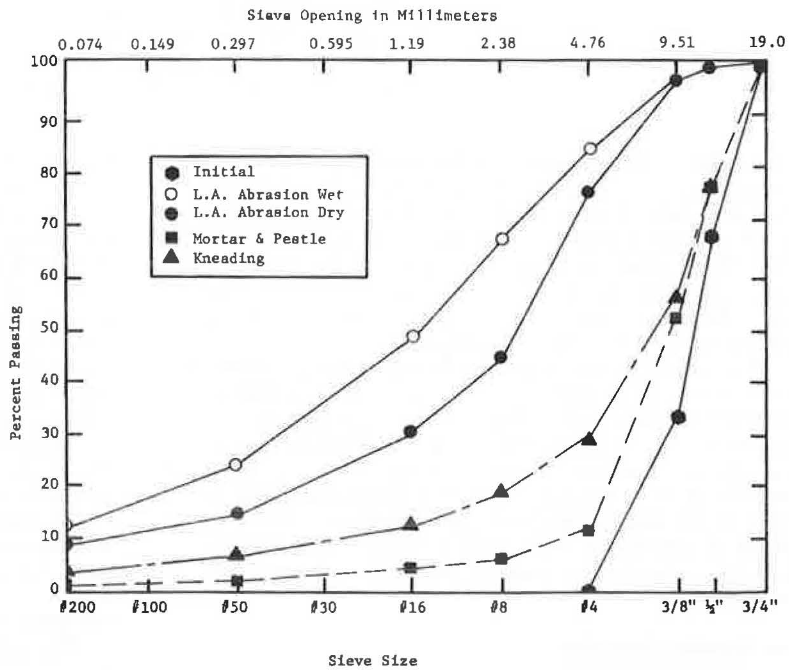


Figure 2. Gradations produced by degradation of mixture CMR-2 by modified Los Angeles, mortar and pestle, and kneading compaction procedures.



Nonstandard Degradation

The degradation characteristics of bottom ash, boiler slag, and coal mine refuse were studied by using three different testing procedures, performed both wet and dry: (a) a modified Los Angeles abrasion test, (b) a mortar and pestle test, and (c) a kneading compactor test. The test procedures, which are described elsewhere (12), were chosen to demonstrate different mechanisms of degradation. The Los Angeles test was modified by adjusting the weight of the specimen based on apparent specific gravity to give a constant sample volume. A washed sieve analysis and Atterberg limits test were performed at the end of each test. The mortar and pestle test was performed with 75 hand strokes of a rubber-tipped pestle for each 15- to 20-g portion of a 200- to 250-g sample. This level of effort was just sufficient to crush the friable popcorn particles in the BA-1 material. The kneading compaction was performed on a dry sample sandwiched between two 0.64-cm (0.25-in) rubber discs in a 10-cm (4-in) diameter mold by using 150 blows at a pressure of 3.45 MPa (500 lbf/in^2). The same gradation was used for each test but was chosen for each material to be representative of the as-produced materials.

The results of the degradation testing on the BA-1 material are shown in Figure 1. The modified Los Angeles test produced much severer degradation than the mortar and pestle and kneading compactor procedures. Although the level of degradation produced by the kneading and the mortar and pestle are very similar, the nature of the degradation is quite different. After testing, samples from the kneading and the modified Los Angeles abrasion tests contained soft and friable particles that could be crushed either by one's fingers or by the mortar and pestle. The fines produced in the Los Angeles and kneading tests included some of the crushed popcorn agglomerates as well as fractured corners from the more dense, slaglike particles. The fines produced by the mortar and pestle test contained mostly broken popcorn agglomerates.

Th mortar and pestle test adequately identifies the popcorn and highly vesicular friable particles. The Los Angeles and kneading tests reflect both fracture of corners from the denser, slaglike particles and the breaking of friable popcorn particles. As in the case of refuse, surface wear is not present because of the hard and brittle nature of the glass that comprises the ash. For bottom ash and boiler slag, the Los Angeles test is considered too severe to represent degradation as it might occur in the field because of the nature of the degradation mechanisms, the single-size gradation of the test sample, and the lack of confinement in the test. This is also true of the kneading test performed on a sample with a one-size gradation except that confinement is provided in the mold. Wet (versus dry) degradation had little effect on the bottom ash and boiler slag materials.

The results of degradation testing for CMR-2 material, including the modified Los Angeles abrasion test performed wet, are shown in Figure 2. Significant surface wearing of the refuse in the dry test is evident in the percentage of minus 0.075-mm (no. 200) mesh material produced and in the rounded appearance of the coarser particles. The wet degradation is significantly higher, principally because of slaking. The mortar and pestle is relatively ineffective in degrading the refuse. The Los Angeles abrasion test may be more representative of field degradation, but the quantity of water added to the specimen must be representative of field conditions.

Degradation in bottom ashes and refuse can also obscure the results of some of the other standard tests. One such test is the wet sieve analysis (ASTM C 117) in which constant degradation of the particles under rigorous agitation complicates the establishment of a termination point for the test.

Soundness

The use of salt crystallization tests to evaluate soundness dates back to 1826 when Brandt devised a test procedure in France that used a sodium sulfate solution (13). Sulfate tests of soundness have remained controversial over the years, particularly in relation to bituminous construction (14). The sulfate tests have been considered relatively ineffective for synthetic lightweight aggregates because of the presence of large pores in the coarse aggregate particles (15).

A summary of sodium sulfate soundness losses (ASTM C 88) is given in Table 1. The BA-1 material shows significantly higher losses than the BA-2 material. This is attributed to the presence of the highly porous and weak BA-1 popcorn particles, which disintegrate not only as a result of the expansive forces of the salt crystals but also as a result of rigorous shaking in the sieves after the soaking and drying cycles. In a comparison of the soundness losses for BA-1 and BA-2 materials with the associated absorption data, the more absorptive coarse particles exhibit a smaller loss of soundness. This reverse effect is caused by the drainage of the salt solution from the larger voids in the coarse particles. In fact, some of the coarse BA-1 particles that could be broken with the fingers still remained at the end of the soundness test.

The BS material behaved in the opposite manner: The coarser, more porous particles exhibited the greater loss of soundness. The voids in the coarse BS material are smaller than those in the BA-1 and BA-2 materials so that the salt solution was retained before drying. The coarser fraction of BS, which is necessary to make up the standard gradation for performing the test, is not representative of the larger portion [minus 4.76 mm (no. 4)] of the boiler slag, and its inclusion gives an anomalously high soundness value for the composite sample. For heterogeneous materials, the soundness or Los Angeles abrasion test samples must be representative of the grading of the material as it will be used if the test data are to be representative of the tested material.

The coal mine refuse exhibited very large soundness losses (Table 1). The severity of the standard sulfate soundness test on shale materials has been recognized by Shamburger, Patrick, and Lutton (16). This is caused in part by the slaking that occurs during wetting and drying, which overshadows the expansive forces produced by salt crystallization. Splitting along the bedding planes and complete disintegration into a fine powder were observed in the unsound particles of the refuse specimens.

Deleterious Materials

Various materials have been found to have an adverse effect on the performance of paving mixtures. Most of the literature that deals with deleterious materials emphasizes the effect of unsound and weak particles on the durability of portland cement concrete: e.g., soft and friable particles; clay lumps; coal and lignite (17, 18); chert and porous, absorbent sandstones (19, 20); and surface coatings (21). Thin and elongated pieces, vegetation, shale, soft particles, clay lumps, and clay coatings have been cited as objectionable substances in aggregates in bituminous mixtures (23). A number of different procedures for determining deleterious materials in aggregates are described in the literature (17, 18, 19, 20, 22). Currently, a wide variety of deleterious materials are covered in the material specifications.

Lightweight Particles

The results of an evaluation for clay lumps and friable particles (ASTM C 123 and C 146) are presented in Table 1. Because of its nonvesicularity, the fine fraction of the boiler slag contains few lightweight particles in contrast to its coarse fraction and ashes BA-1 and BA-2. The coal mine refuse contains relatively high percentages of lightweight particles—mostly coal fragments.

A visual examination of the particles that floated on the heavy liquid indicated that the major factor that affects the test results is particle vesicularity. Most of the popcorn particles in BA-1 material were floaters. Although the majority of the bottom ash particles that floated were vesicular and lightweight, not all of these particles were necessarily weak. A good portion of the refuse particles that floated were coal pieces, but appreciable quantities of shale pieces, which comprise the bulk of the material, also floated. No appreciable slaking was evident in the refuse specimen when it was agitated in the heavy liquid but, when it was brought in contact with water after testing, slaking occurred. The portions of the refuse that sank to the bottom were completely shalelike, but these pieces displayed as much slaking as the shale particles that floated. Although the test of lightweight particles is used to identify shale in conventional aggregates, the usefulness of this test on coal mine refuse, which is almost entirely composed of a carbonaceous shale, is open to question.

Weak Particles

The results of the tests for clay lumps and friable particles (Table 1) indicate that, although BA-2 material has minor quantities of soft, friable particles that can be crushed with the fingers, BA-1 material has appreciable amounts of such particles. The popcornlike agglomerates present in the BA-1 material showed little resistance to pressure applied with the fingers and disintegrated into individual grains of fly ash. The particles classified as friable in BS were thin and porous pieces. These pieces were brittle and could be easily broken between the fingers; however, this was not a disintegration phenomenon as in the case of bottom ashes. No clay lumps in the literal sense were encountered in any of the power plant aggregates tested.

The abnormally high percentages of clay lumps and friable particles reported for the coal mine refuse materials CMR-1 and CMR-2 reflect the slaking of these materials when they are soaked in water. The values given in Table 1 are arbitrary in that it was not possible to run the test on these materials in a meaningful manner because of continuous slaking and subsequent disintegration. In addition, most of the "nonfriable" pieces were coal fragments that had low resistance to breaking with the fingers but were still retained on the 0.075-mm (no. 200) sieve after washing.

The standard test procedure for clay lumps and friable particles (ASTM C 146) can be effectively performed on bottom ash and boiler slag. This test identifies the soft, popcornlike particles that are subject to degradation under compaction and traffic. Bottom ashes are free of clay lumps that can degrade into deleterious plastic fines, which suggests that higher percentages of friable particles than those customarily specified could be allowed in bottom ashes. However, excessive quantities of friable particles will undoubtedly hinder performance.

Leachate Tests

Although coal-associated wastes generally do not contain the types of deleterious materials that are found in conventional materials, in some instances they contain other deleterious elements that are potentially detrimental to their performance. For example, the presence of pyrites and other reactive salts in some of these materials can adversely affect pavement performance and may, in some extreme cases, be unacceptable from an environmental standpoint.

Table 1 gives pH values and the sulfate ($SO_4^=$) contents in milligrams per liter of water leachate. As previously reported by Anderson, Usmen, and Moulton (2), no direct correlation appears to exist between pH and sulfate content. All of the materials tested except BA-2 have leachates that are neutral or slightly alkaline in character. The acidic nature of the BA-2 leachate is attributable to the pyrite particles present in this material. The leachate water in this case was reddish-brown in color (iron oxide) and, on evaporation, left stains on the particle surfaces. The highest quantities of sulfate are observed in the CMR-1 and CMR-2 leachates. White salt crystals were seen on the particle surfaces of the refuse particles after the evaporation of the leachate water. Although they are not identified in Table 1, soluble salts other than sulfates are also present in ashes and refuse (2).

These considerations indicate that appropriate test methods and accompanying specification criteria designed to identify and exclude unacceptable material are definitely needed in the case of coal-associated wastes. A leachate analysis such as that reported in this paper and discussed by others (2, 12) should be considered if high pyrite contents are suspected. The sulfate content test suggested by Sherwood and Ryley (23) should also be considered.

INFLUENCE OF AGGREGATE PROPERTIES ON BITUMINOUS MIXTURES

The influence of the properties of bottom ash and boiler slag on bituminous mixtures was evaluated by Marshall mixture design procedures in which both Marshall (ASTM D 1559) and kneading compaction (ASTM D 1561) were used. The bottom ash was used at its as-sampled gradation (Table 2) but, based on earlier experience, the boiler slag was blended with a limestone sand to improve stability. Fly ash was added as a mineral filler, and an AC-20 asphalt cement was used in the mixture design. Gradations for the mixtures are given in Table 3.

Mixture Properties

Marshall stability and flow were measured in accordance with ASTM D 1560. Bulk specific gravity was determined by ASTM D 2726 by using saturated, surface-dry specimens, and the maximum specific gravity of the loose mixtures was determined by ASTM D 2041 by using the bowl method. Mixture properties are given in Table 3. The Marshall stability and flow values for mixtures prepared with BA-1, BA-2, and BS materials by using kneading compaction are shown in Figure 3.

The Marshall stabilities of the BA-1 and BA-2 materials peak at relatively high asphalt contents, which reflects the absorptive nature of the vesicular bottom ash particles. The BA-1 and BA-2 mixtures appeared extremely dry at lower asphalt contents because of incomplete particle coating. The BA-1 popcorn particles were difficult to coat except at high asphalt contents. This incomplete particle coating may account for the double peak in the Marshall stability curve of the BA-1 material (Figure 3), which is similar to the double peak encountered in the moisture density curve for clean sands. Bituminous mixtures of bottom ash generally yield low flow values, particularly at low asphalt contents, because of the irregular shape and gritty surface texture of the ash particles. More detailed discussions of the properties of bottom ash and boiler slag mixtures are given elsewhere (2, 12, 24, 25).

The specific gravities for the BA-1, BA-2, and BS mixtures are given in Table 4. The effective specific gravity is consistently greater than the apparent specific gravity. This is attributed to the difficulty in performing the tests for bulk specific gravity of the ash and the maximum specific gravity of the mixture. In the latter case, the difficulty is associated with the determination of the saturated, surface-dry condition on the "coated" (loose) mixtures, which absorb water during the test. It was observed that the large pores present in the coated particles allowed the drainage of water fairly quickly during the surface drying process. The effective specific gravity of the aggregate is calculated from the maximum specific gravity of the mixture, and any inconsistency in the effective specific gravity is

Table 3. Gradation of materials used in bituminous mixtures.

Material	Percentage Passing Sieve Size[a] 12.7 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	0.60 mm	0.30 mm	0.15 mm	0.075 mm
BA-1	100	100	93	83	68	53	38	22	9
BA-2	100	91	74	56	39	28	18	11	6
BS	100	96	74	51	27	17	11	7	6

[a]Corresponding U.S. sieve sizes: 0.5 and 0.375 in and nos. 4, 8, 16, 30, 50, 100, and 200.

Figure 3. Marshall stability and flow curves for mixtures BA-1, BA-2, and BS.

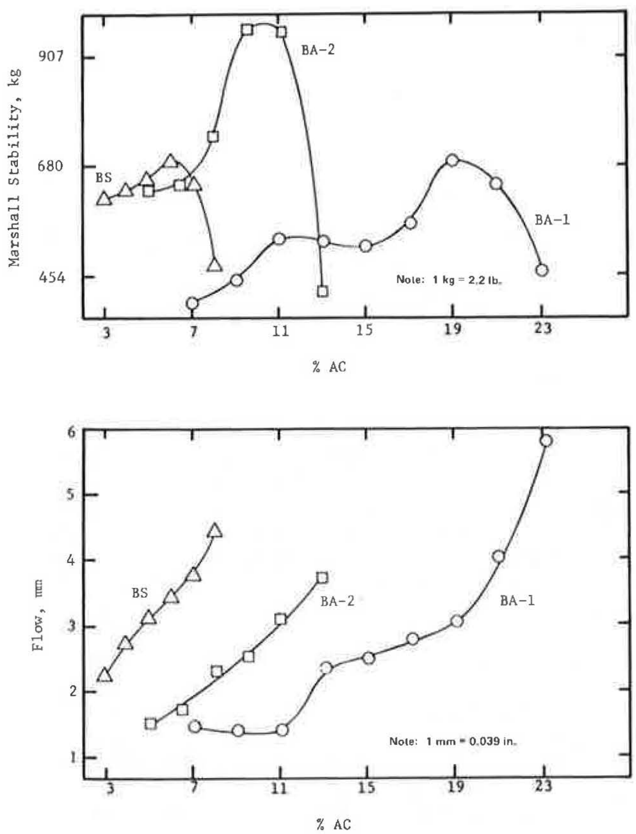


Table 4. Properties of bituminous mixtures that incorporate bottom ash and boiler slag.

Mixture	Aggregate G_{bulk}	G_{eff}	G_{app}	Mixture: Asphalt (%)	Air (%)	VMA (%)	R_r (%)[a] 24-h Soak	Five Wet-Dry Cycles
BA-1	2.134	2.235	2.205	9.0	28.6	38.5	-	-
				11.0	-	-	89.2	-
				13.0	22.0	38.4	-	-
				17.0	15.7	39.0	-	-
				23.7[b]	-	-	100+	-[c]
BA-2	2.341	2.421	2.404	6.5	13.9	23.6	-	-
				8.0	10.5	23.3	-	-
				9.5	-	-	84.7	72.1
				11.0	4.7	23.7	-	-
				11.3[b]	-	-	95.7	-
BS	2.561	2.652	2.643	4.0	9.8	15.7	-	-
				5.0	7.1	15.3	-	-
				6.0	-	-	85.7	83.1
				6.9[b]	-	-	98.0	-
				7.0	2.4	15.4	-	-

[a]Percentage retained stability at 60°C (140°F).
[b]Optimum asphalt content (Marshall).
[c]Too weak to test.

reflected in the calculated air voids and voids in mineral aggregate. Further, any degradation that occurs during compaction opens new pores, and this alters both the bulk specific gravity of the aggregate and the maximum specific gravity of the mixture. Based on these observations, the validity of customary voids analyses and the standard test procedures are suspect relative to the more vesicular bottom ash and boiler slag mixtures.

Effect of Water on Marshall Stability

Two tests were performed to determine the effect of water on the stability of the mixtures. The first test was the immersion-Marshall test, and the second was a modified immersion-Marshall test in which the 24 h of soaking were replaced by five wet-dry cycles. Each cycle consisted of 12 h of soaking at 60°C (140°F) followed by 12 h of air drying at room temperature. The results of the tests, which are given in Table 4, were performed at "optimum" asphalt contents and lower asphalt contents that were considered economically compatible with conventional mixtures. Only the lower asphalt contents were used in the modified immersion-Marshall tests.

The index of stability retention (R_r) values given in Table 4 indicates that all of the mixtures tested exhibited satisfactory moisture-durability characteristics (75 percent stability retention was considered adequate). Although it is not shown, kneading compaction generally improves resistance to water because of a reduction in voids.

The more severe exposure conditions in the wet-dry cycles have resulted in a reduction of stability retention (Table 4). The most drastic reduction is observed in mixture BA-1. Although this mixture retained 100 percent of its stability in the 24-h soak of the immersion-Marshall test, it was weakened considerably on extended immersion and drying. The weakening was manifested as cracking of the specimens after the third cycle and complete deterioration in the subsequent cycles. Although such deterioration was not observed in the specimens of the other mixtures, some reddish-brown stains were visible on the surfaces of the specimens of mixture BA-2 along with a few pop-outs. The presence of reactive elements, such as pyrite and other soluble salts, clearly explains the behavior of the specimens of mixtures BA-2 in the immersion tests. Although staining may or may not be significant with respect to stability retention on immersion, the pop-outs are believed to be detrimental to mixture durability.

The 24-h soak immersion-Marshall test can be applied to the compacted bituminous mixtures that incorporate bottom ash and boiler slag without any technical difficulties. However, the duration of the exposure in this test may be too short to identify some of the potential problems associated with bottom ash. This test must be modified so that it can identify the reactivity or stripping problems properly. A wet-dry cycle test should be used as a guideline for developing a proper set of exposure conditions, and test methods such as those suggested by Schmidt (26) and Lottman and others (27) should also be considered.

Mixture Degradation

Because of the inherently low particle strength of bottom ash and boiler slag, considerable degradation takes place under both laboratory and field compaction (2). The degradation of bituminous mixtures that incorporate bottom ashes BA-1 and BA-2 and boiler slag BS under

Figure 4. Extracted gradations of bituminous mixtures BA-1 and BS after drop-hammer compaction.

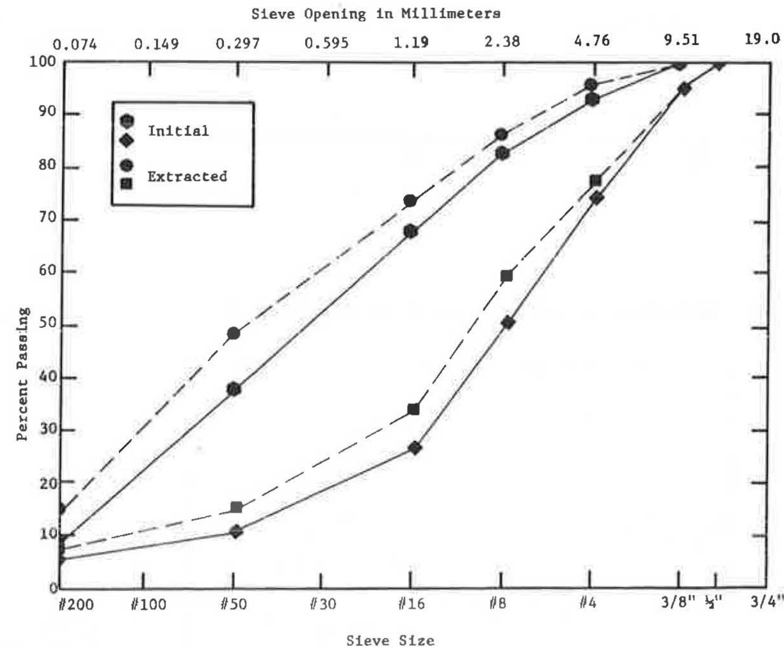


Table 5. Summary of applicability of conventional tests to coal-associated wastes.

Test Method	Bottom Ash	Boiler Slag	Coal Mine Refuse
Gradation			
ASTM C 136	A	A	A
ASTM C 117	NA	A	NA
Specific gravity			
ASTM C 127	NA	NA	NA
ASTM C 128	NA	Q	NA
Unit weight, ASTM C 29	A	A	A
Deleterious materials	I	I	I
ASTM C 123	Q	Q	Q
ASTM C 146	A	A	NA
Los Angeles abrasion, ASTM C 131	Q	Q	Q
Soundness, ASTM C 88	NA	Q	Q
Marshall method of mix design	NA	Q	-[a]
Bulk specific gravity, ASTM D 2726	A	A	-[a]
Marshall stability and flow, ASTM D 1560	A	A	-[a]
Maximum specific gravity, ASTM D 2041	NA	Q	-[a]

Note: A = applicable, NA = not applicable, Q = questionable applicability, and I = test results insufficient to characterize the material.

[a]Not studied.

drop-hammer and kneading compaction was studied by comparing the gradations of the mixture before and after compaction. Extraction tests were used to recover the aggregate. The results of the studies on mixtures BA-1 and BS in which drop-hammer compaction was used are shown in Figure 4. It was found that kneading compaction, which is not shown in the figure, results in slightly higher levels of degradation.

The degradation in the bituminous mixtures (Figure 4) is less severe than that in the previously discussed degradation tests performed on aggregate specimens (Figure 1). Some popcorn particles of the extracted BA-1 mixture did not experience excessive degradation during the laboratory compaction. Clearly, there is a potential for mechanical degradation in bottom ash and boiler slag, but a dense gradation and proper confinement will reduce this potential. As long as the stresses imposed by traffic do not break down the matrix of the mixture, the softer friable particles may escape degradation (2).

SUMMARY

A summary of the assessment of the applicability of selected conventional tests to three coal-associated wastes is given in Table 5. The surface texture and pore structure of bottom ash and boiler slag and the slaking of coal mine refuse complicate the determination of bulk specific gravity and absorption. The Los Angeles abrasion and sulfate soundness tests do not give a good indication of the mechanical integrity of the coal-associated wastes and fall short of representing the field conditions. The deleterious materials present in coal-associated wastes are not of the same origin and nature as those found in conventional materials and are thus not properly accounted for by the existing test methods and material specifications. The unit weight and dry sieve analysis are acceptable test procedures, but wet sieve analysis produces suspect test results because of degradation during sieving.

The unique properties of coal-associated wastes (i.e., pore structure and slaking) also obscure the test results on paving mixtures that incorporate these materials. An example of such a case is the voids analysis of bituminous mixtures prepared with power plant ashes. Existing methods of assessing moisture damage in bituminous mixtures are not sufficient to identify properly the potential problems associated with bottom ash. The degradation of the ash mixtures is also not properly evaluated by any of the current test methods.

CONCLUSIONS

Many of the existing test methods and associated specification criteria were not applicable to the three coal-associated wastes described in this paper, and modifications and additions to existing test methods and specification criteria are needed to enhance effective use of such materials. The considerations presented in this paper are not confined to coal-associated wastes but are pertinent to many other nonconventional materials. The specialized test methods and materials specifications developed for synthetic lightweight aggregates (28) illustrate this point. The following questions should be raised relative to the use of any new material in highway construction:

1. What are the physical and chemical properties of the product and what is its variability?
2. How do these properties affect design, construction, and performance?
3. How can the existing tests and specifications be used to assess properties and predict performance?
4. What modifications to the methods and criteria are needed?
5. What performance data are available as guidelines to modify or verify steps 1 through 4 above?

It should be clear from the information presented here that the assessment of new materials on the basis of conventional tests and specifications may lead to the approval of a questionable material or an arbitrary rejection of a suitable material. The experience and judgment of the materials engineer will be of increasing importance and value as new materials are proposed for use in highway construction.

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