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Publication of this paper sponsored by Committee on Mineral Aggregates, Committee on Soil-Portland Cement Stabilization, and Committee on Soil-Bituminous Stabilization.

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Use of Energy-Efficient Sintered Coal Refuse in Lightweight Aggregate

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The development and evaluation of a synthetic lightweight aggregate that has particular application to the building and transportation construction industries are described. Bituminous coal refuse, a waste product obtained from five coal-preparation plants in Kentucky, was successfully sintered on a pilot-sized traveling grate to produce lightweight construction aggregate. An improved sintering-grate process was used. A means is thus provided for using a waste product while gaining an economic advantage during processing from the inherent fuel value of the refuse. A thorough laboratory investigation of the aggregate as a material for use in bituminous concrete mixes and structural lightweight portland cement concrete indicated that a satisfactory aggregate for these construction materials was produced. Using lightweight aggregate from sintered coal-mine refuse in concrete construction offers significant technical and economic incentives from the standpoints of reduced weight and the greatly reduced thermal conductivity of the products formed.

The demand for quality aggregates for various construction applications has resulted in shortages of aggregate in many parts of this country. Some areas are experiencing a depletion of all quality natural aggregates (1,2). Environmental constraints and urban sprawl have curtailed production in some areas where aggregate supplies are abundant. Although U.S. reserves of natural aggregate are virtually inexhaustible, geographic distribution and quality do not necessarily coincide with need. This means high costs for transporting the heavy, bulky commodity.

The manufacture of synthetic aggregates and the use of by-product (waste) materials represent means that are being used to provide locally available aggregates and/or aggregates that have particular characteristics. Blast- and steel-furnace slag, power plant ash, and various mine tailings and wastes are by-product materials in current use. The most commonly manufactured synthetic aggregate is expanded lightweight shale (clay or slate), which is produced by heating the raw product to about 1040°C (2000°F) in a rotary kiln. At this elevated temperature, the gases generated expand (bloat) the material while the high temperatures stabilize it. A less commonly used method for producing synthetic lightweight aggregate is the continuous sintering-grate process, in which the raw material and an added fuel charge are placed on a traveling bed and ignited. As the product sinters (or burns), the particles fuse together and the carbon fuel burns, creating void spaces within the aggregate particles.

The Expanded Shale, Clay, and Slate Institute and the Lightweight Aggregate Producers Association promote the production and use of synthetic lightweight aggregates. All fuel requirements for rotary-kiln processing are provided from an external fuel source, whereas in the sintering operation only minimal external fuel is required and the bulk is contained in the raw feed material.

During the past four years, the Department of Civil Engineering at the University of Kentucky has been involved in research studies to develop uses for materials from bituminous coal refuse (3-9). Similar studies have been conducted in Great Britain, Pennsylvania, and elsewhere (10,11). In the Kentucky research, the possibilities of converting the refuse into high-quality lightweight aggregate were examined. To determine the technical competence of synthetic lightweight aggregate produced from the sintering of bituminous coal refuse, a thorough laboratory evaluation was conducted on the sintered material. The basic goal of the research was to determine the suitability of the material for use as an aggregate in construction products.

The purpose of this paper is to briefly discuss the origin of coal refuse and the production of lightweight aggregate from sintered coal refuse and to more fully describe laboratory studies conducted on the sintered aggregate to determine its suitability for use in construction products.

COAL REFUSE

Coal refuse is a mixture of fragmented materials that are removed from run-of-mine coal during the cleaning and preparation process so that the quality of the coal will be improved. Sources of refuse materials include thin bands of shale and clay and other impurities and minerals inherent in or adjacent to the coal seam. It is easier and cheaper, with mechanized equipment, to extract a seam of coal with its unwanted impurities than to try to mine only the pure coal (9).

The processing is accomplished in preparation plants, some of which process as much as 18 000 Mg (20 000 tons) of coal a day. Since the coal has a lower specific gravity than the refuse materials, the coarser fractions are normally separated by heavy-media methods. Special frothing agents that attach to and float the coal are com-

monly used as a medium to separate the fine coal and the refuse (4).

Approximately 50 percent of the coal mined in the United States is processed in preparation plants. About 25 percent of the 272 million Mg (300 million tons) of coal is rejected, which produces 68 million Mg (75 million tons) of refuse annually. At present production rates in Kentucky, approximately 18 million Mg (20 million tons) of refuse are being produced each year (4,9). As the demand for coal increases during the coming years, it is anticipated that production of refuse will increase at an even greater rate because a larger percentage of the coal will be processed.

Environmental standards are demanding higher-quality, cleaner-burning coals that will require more intensive cleaning. This is particularly true in areas where lower-quality seams are now being worked because the higher-quality seams have already been mined. In addition, modern automated mines produce larger percentages of rejected materials because of the lack of selective mining. In addition, cleaned and processed coal results in a constant-quality product, lower transportation cost since the nonburning fraction is removed at the mine site, and an increase in the market price of several dollars per megagram over the price of run-of-mine coal.

An issue that currently faces the coal industry is how to dispose of the increasing quantity of refuse in an economically and environmentally acceptable manner (12). Conventional disposal practices involve either placing the refuse in large waste piles or pumping it behind retaining structures. Currently, it costs \$0.55-\$1.10/Mg (\$0.50-\$1.00/ton) to dispose of the refuse, or an industry cost in this country of over \$50 million/year. The per-megagram disposal costs are increasing because of the higher costs associated with more stringent environmental controls (9). Obviously, making use of coal refuse would eliminate the need for complex, permanent disposal facilities.

PROCESSING OF SINTERED AGGREGATE

Preliminary Processing

Preliminary pilot-scale rotary-kiln firings and bench-scale sinter-pot firings were conducted by using small samples of coal refuse (13). Rotary-kiln tests at the Texas Transportation Institute Research Center indicated that bituminous coal refuse responded to rotary-kiln processing and that, in spite of some handling problems, a lightweight product could be produced. However, no fuel benefit was obtained from the carbon content in the refuse because the generated heat exited through the stack and did not assist in further heating of the product. Environmental problems were also encountered because of the high sulfur content of the bituminous coal in the refuse.

Bituminous coal refuse was used in sinter-pot firings at McDowell-Wellman Engineering Company in Cleveland, Ohio. The test apparatus consisted of a balling disc and a sinter test pot, to which the refuse responded favorably. Laboratory analyses of the small quantity of sintered aggregate that was produced indicated a high-quality, lightweight product. As expected, exhaust gases from the batch sintering tests contained considerable smoke-sulfur emissions in the form of particulates of carbon and condensable hydrocarbons from the bituminous coal in the refuse. However, several tests in which simulated recycle draft was used within designed time-temperature cycles indicated that the raw materials should respond to a sintering system that involves multipass recycle draft.

Pilot Plant Processing

After the favorable preliminary results, pilot plant tests were conducted by using an improved sintering process to minimize exhaust draft quantities and to arrest combustibles in the draft stream through recycling and post-bed combustion. The intent of the pilot plant program was to demonstrate the feasibility of the process on a practical scale and to provide tonnage samples of aggregate for large-scale product evaluation.

The basic sintering process has been described as follows (14):

In principle, the sintering process consists of charging a bed of fine moistened materials, which are then subjected to heat developed by combustion of fuel within the bed while individual particles are kept in quiescent state. An air draft is induced through the bed, made porous for the operation, and this draft combined with an ignited solid fuel provides combustion. Through heat transfer the sintering process is completed. Usually mixing, igniting, burning, and cooling are the main phases of the generic term "sintering".

When it was first developed, the sintering process was performed in a large vessel, but in 1906 the continuous sintering process was invented by A. S. Dwight and R. L. Lloyd. Although it has primarily been used for beneficiating metallic ores, this process has also been used for other purposes, including the processing of lightweight aggregate.

Refuse samples were obtained from five large coal-preparation plants in eastern Kentucky (see Figure 1). These plants are typical of "total cleaning" plants in the coal fields of that region. The plants are identified as follows: South-East Coal Company, Irvine plant—SEI; Island Creek Coal Company, Pevler plant—ICP; Beth-Elkhorn Corporation, Pike plant—BEP; Eastover Mining Company, Brookside plant—EOB; and U.S. Steel Corporation, Corbin plant—USSC.

A typical refuse sample is shown in Figure 2. The >25.4-mm (>1-in) material was initially screened from the samples. Bulk density, moisture content, and typical coal analyses of the raw refuse, as sampled, are given in Table 1. Before the refuse was processed on the traveling grate, it was permitted to dry to about 4.0 percent moisture content and hammer-milled until more than 90 percent passed a 9.5-mm ($\frac{3}{8}$ -in) screen.

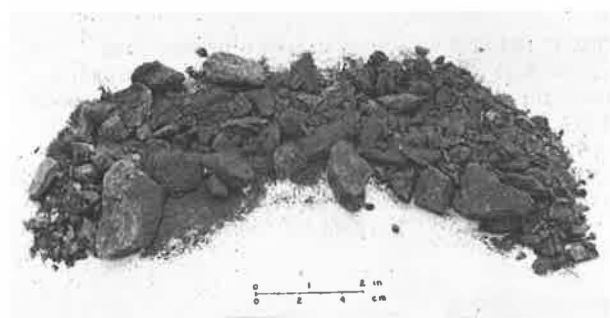
An extensive evaluation of processing conditions was made on the refuse obtained from the South-East Coal Company plant at Irvine (SEI). Fourteen materials-balance tests were conducted during the pilot plant program, not including a preliminary run. Sufficient data were acquired during the tests to establish a materials balance (optimum bed content of materials to be sintered), a draft flow circuit, and product analyses. The data collected were analyzed after each pilot plant test, and this information was used to establish processing conditions for subsequent tests.

The operation of the pilot plant involved delivering the crushed raw refuse and a selected amount of return (partially sintered material from previous runs) to a nodulizing-balling disc. This device used an inclined rotary pan and blended and nodulized the raw feed, particularly the fine material. The raw feed was discharged onto a 0.61-m (2-ft) wide by 5.5-m (18-ft) long traveling-grate machine positioned over active wind boxes, as shown in Figure 3. Ignition of the nodulized feed was accomplished by using natural-gas ignition torches. Various feed rates, percentages of returns, bed depths, machine speeds, ignition times, and recycle and exhaust wind-box flows were investigated. When the pilot plant was stabilized, as evidenced by relatively uniform conditions of operation, the >25.4-mm (>1-in) product (sinter cake) produced during the specific period was

Figure 1. Sites of Kentucky coal-preparation plants from which sample refuse was obtained.



Figure 2. Raw refuse as sampled.



collected and saved for subsequent evaluations. The <9.5-mm (<3/8-in) size was used for returns, as was a portion of the <25.4- to >9.5-mm size. The draft was incinerated in an afterburner, then exhausted to a scrubber, and finally to a stack (3).

Less extensive evaluations were made on samples obtained from the other four plants, and only small quantities of these were sintered. In addition, a sample that consisted of 70 percent SEI refuse and 30 percent non-carbonaceous (blue) clay was also sintered. The blue clay came from a location adjacent to the plant.

It was concluded that the improved sintering process, embodying strand cooling and draft recycling, could be favorably applied to the sintering of coal-mine waste materials. The sinter quality appeared satisfactory, and relatively low quantities of draft were available in a hot stream for final decomposition to produce a stack exhaust that was clear of visible emissions. The raw materials were relatively high in fuel content and had strong bloating characteristics. This necessitated the use of high return-bed permeability. These raw material factors limited the benefits of the improved sintering process because the high fuel content did not consistently enable complete strand cooling of the product. It was believed that the effect of these factors could be minimized by using refuse that contained a lower fuel value or a blend of inert materials, such as clay or sand, within the sinter charge.

EVALUATION OF AGGREGATE PRODUCT

Bulk quantities of the sinter cake material retained on the 25.4-mm (1-in) sieve were processed in the laboratory for use as graded aggregate in bituminous concrete and portland cement concrete. Figure 4 shows the sinter cake, which was crushed to a maximum size of 19 mm (0.75 in) by a laboratory jaw crusher and screened

into various size ranges, as given below (1 mm = 0.039 in):

Sieve Size (mm)	Percentage Passing (by weight)		
	Concrete Grading	2.36-mm Grading	Open Grading
19.0	90-100	-	-
12.7	50-80	100	-
9.52	20-60	85-100	100
4.75	0-10	10-30	30-50
2.36	-	0-10	5-15
1.18	-	0-5	-
0.300	-	-	-
0.150	-	-	-
0.075	-	-	2-5

The 2.36-mm (no. 8) and open gradings are those used in bituminous mixes.

Laboratory tests were conducted on the discrete aggregate particles. Standard American Society for Testing and Materials (ASTM) procedures and specifications (15-19) were used unless otherwise noted. The test data are given in Table 2.

Dry-Loose Unit Weight

Unit weight was determined in accordance with ASTM C29 by using the shoveling procedure (16). The concrete grading averaged 506 kg/m³ (31.4 lb/ft³). ASTM C331 permits this value to be as high as 880 kg/m³ (55 lb/ft³) for concrete-graded lightweight coarse aggregate (16). The unit weight of the asphalt-mix-graded aggregates was around 550 kg/m³ (34 lb/ft³).

The low values are caused by a combination of low specific gravity of the sintered aggregate and a rough surface texture that prevents a tight packing condition. Most rotary-kiln-produced lightweight aggregates are slightly heavier and have smoother surface texture.

Bulk Specific Gravity and Water Absorption

Since the absorption of sintered aggregate is higher and more variable than that of conventional aggregate, a select procedure standardized by the Texas Highway Department as test method Tex-433-A (20, 21) was used. This method of testing is intended for use in determining the bulk specific gravity (both dry and saturated surface dry), apparent specific gravity, absorption, and rate of absorption of both fine and coarse lightweight aggregates.

As Table 2 notes, average dry bulk specific gravities ranged from 1.27 to 1.42 for the various gradings. After 100-min and 24-h soaks, the average bulk specific gravities ranged from 1.34 to 1.48 and 1.38 to 1.53, respectively. The average 100-min absorptions ranged from 4.26 to 5.07 percent and increased from 7.92 to 8.49 percent after 24 h. Specific gravities were slightly be-

Table 1. Data for as-sampled raw refuse.

Property or Material	SEI Sample					
	Raw Refuse	Blue Clay	ICP Sample	BEP Sample	EOB Sample	USSC Sample
Bulk density (kg/m ³)	1240	-	-	-	-	-
Moisture content (%)	8.1	10.6	12.5	-	9.1	11.6
Size (mm)	-25.4	-9.5	-9.5	-9.5	-9.5	-9.5
Ash* (%)	80.2	86.1	57.6	74.5	77.0	71.6
Volatile matter* (%)	12.0	8.4	19.3	13.5	13.8	14.2
Fixed carbon* (%)	7.8	5.5	22.8	12.0	8.7	14.2
Total sulfur* (%)	2.3	1.6	1.1	0.8	1.1	1.3
Heating value* (kJ/kg)	3220	2260	11 420	5820	5730	7990

Note: 1 kg/m³ = 0.062 lb/ft³; 1 mm = 0.039 in; 1 kJ/kg = 0.43 Btu/lb.

* Moisture-free condition.

Figure 3. Traveling-grate sintering process.

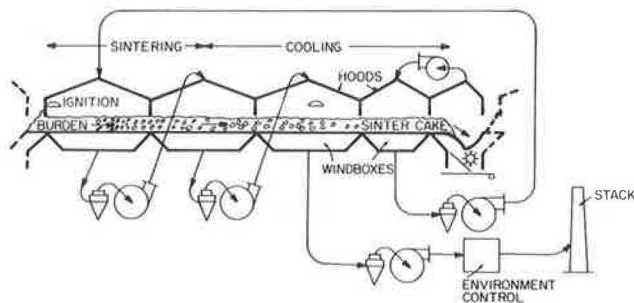


Figure 4. Sinter cake and crushed material.



low average in comparison with those of typical lightweight aggregates. Absorption values were average to slightly above average.

Soundness

ASTM standard test C 88 (16) was used to evaluate the soundness of aggregate; magnesium sulfate and five cycles of alternate immersion and drying were used. Loss values of approximately 20 percent were obtained (Table 2). ASTM C 33 specifications (16) permit the value to be as high as 18 percent for concrete-graded, normal-weight aggregate. The applicability of this test to lightweight aggregate is questionable.

Freeze-Thaw Durability

Test method Tex-432-A (21) was used to evaluate the resistance of the sintered aggregate to breakdown during alternate freezing and thawing. The samples were first saturated in water for 100 min and then subjected to 50 freeze-thaw cycles. Average losses for the asphalt-graded aggregates were approximately 5 percent; these

increased to 30.5 percent for the coarser-graded concrete aggregate.

Los Angeles Abrasion

ASTM C 131 (16) was used to test abrasion loss. The coarser B grading represented the concrete-grading sizes, whereas the C grading was used for the asphalt gradings (Table 2). Average losses ranged from 43 percent for the concrete grading to 35 percent for the asphalt grading. Most specifications for normal-weight aggregate limit the loss to 40-50 percent for concrete aggregate and 35-40 percent for asphalt-graded aggregate.

Pressure Slaking

The test to determine the pressure-slaking tendency of synthetic coarse aggregate, Tex-431-A (21), is intended to be used to evaluate the amount of dehydration that has occurred in the production of synthetic aggregates fired in a rotary kiln. An average value of 8.0 percent was obtained for the sintered aggregate (Table 2). Six percent is generally considered a maximum value for rotary-kiln-fired lightweight aggregate.

Absolute Specific Gravity and 100-Min Saturation

The absolute specific gravity of the various gradings was obtained by using test method Tex 109-E, part 1 (21), and a pressure pycnometer. The 100-min saturation was calculated, by using test method Tex-433-A (21), from the 100-min absorption, dry bulk specific gravity, and absolute specific gravity. The value, expressed as a percentage, is the volume of voids in the aggregate filled with water divided by the total volume of voids available, after 100 min of soaking in water. An average value of 16 percent was obtained for the concrete grading (Table 2). About 15 percent has been established as a maximum value to ensure adequate freeze-thaw resistance for rotary-kiln-produced lightweight aggregate.

Loss on Ignition

Loss on ignition was tested to determine whether the material had been completely fired during the sintering process. Values were determined in accordance with ASTM C 114 (15) (referee method). Samples were heated to 950°C (1775°F). Average values were about 4-5 percent (Table 2). ASTM specifies that loss on ignition shall not exceed 5 percent.

Clay Lumps

The clay-lumps test was conducted as outlined in ASTM C 142 (16). The percentage values were all less than the

Table 2. Test values for sintered aggregate.

Test	Concrete Grading		2.36-mm Grading		Open Grading	
	Value	Range	Value	Range	Value	Range
Dry-loose unit weight (kg/m ³)	506	463-553	539	429-587	563	518-614
Dry bulk specific gravity	1.27	1.16-1.45	1.36	1.24-1.53	1.42	1.32-1.55
Bulk specific gravity						
100 min	1.34	1.22-1.52	1.43	1.30-1.60	1.48	1.38-1.61
24 h	1.38	1.26-1.56	1.48	1.36-1.64	1.53	1.44-1.64
Absorption						
100 min	5.03	4.61-5.48	5.07	4.05-7.18	4.26	3.81-4.59
24 h	8.49	7.71-9.43	8.42	7.48-9.64	7.92	6.67-8.86
MgSO ₄ soundness loss (%)	22.7	5.3-44.2	21.5	7.0-46.9	21.1	8.9-46.6
Freeze-thaw loss (%)	30.5	12.3-41.2	5.1	3.2-7.4	5.0	2.4-8.3
Los Angeles abrasion loss ^a (%)	43.0 ^a	40.0-47.2	34.6 ^b	32.6-37.2	34.6 ^b	32.6-37.2
Pressure slaking value			8.0	4.6-10.2		
Absolute specific gravity	2.10	2.02-2.18	2.14	2.11-2.19	2.09	2.04-2.13
Saturation, 100 min (%)	16.37	13.00-22.52	18.82	15.75-23.86	19.46	16.79-27.81
Loss on ignition (%)	3.96	2.55-3.55	4.09	1.75-8.23	5.13	2.20-10.30
Clay lumps (%)	0.59	0.36-0.79	0.99	0.58-1.55	1.15	0.73-1.69
Organic impurities			None			
Staining materials index			Light Very light-moderate			

Note: 1 kg/m³ = 0.062 lb/ft³.

^aB grading. ^bC grading.

2 percent specified by ASTM (Table 2).

Organic Impurities

The organic-impurities test is used to detect the presence in natural sands of materials that might cause harmful effects in concrete products. The procedure followed was ASTM C 40 (16) (alternate procedure B). No organic impurities were indicated in any of the aggregate gradings (Table 2).

Staining Materials

ASTM test C 641 (16) is used to indicate the presence of iron compounds that produce staining in concrete products. Values ranged from very light to moderate (Table 2). ASTM specifications state that stain in aggregate must be classified as lighter than heavy, and all samples met that criterion.

BITUMINOUS CONCRETE

Bituminous (or asphalt) mixes that contained the sintered aggregate from the five plants were made and evaluated in the laboratory. The main attribute of this material in bituminous mixes is its skid-resistant characteristics and, to some extent, its lightweight characteristics. Both dense-graded and open-graded surfacing mixes were evaluated.

Asphalt Absorption

The percentage asphalt absorbed by the sintered aggregate was calculated according to the procedure outlined in Chapter 5 of the Asphalt Institute Manual, Series 2 (22). The percentage absorptions were based on the weight of the total aggregate. A sample composed of AC-20 viscosity-graded asphalt cement was used in the mixes.

Values of 5.4 and 6.4 percent were obtained for the open-graded and 2.36-mm (no. 8) gradings, respectively. These compare with water absorptions of 4.1 percent at 100 min and approximately 8 percent at 24 h. Asphalt absorption decreased as particle size decreased.

An examination of the coated aggregate under ultra-violet black light failed to reveal that selective absorption was occurring. Aggregate freshly mixed with asphalt and aggregate that had been coated with asphalt several months before were examined.

Evaluation of Dense-Graded Mix

Two dense-graded asphalt mixes were evaluated for medium traffic by using the Marshall design procedure of ASTM D 1559 (17). Sintered aggregate was used for the coarse-aggregate fraction in each mix. Natural sand was used as fine aggregate in one mix, and manufactured limestone sand was used in the other mix. Agricultural limestone was used as mineral filler in both mixes.

The aggregates were combined to meet gradation requirements for Kentucky Department of Transportation (DOT) type B surface mix (23). The gradation limits are given below (1 mm = 0.039 in):

Sieve Size (mm)	Percentage Passing
12.5	100
9.5	85-100
4.75	60-80
2.36	40-60
1.18	25-50
0.300	5-20
0.150	3-12
0.075	2-6

The mix is similar to Asphalt Institute 6A mix. Since aggregates of widely varying specific gravities were used in the blend, it was necessary to use a volumetric proportioning procedure. A typical blend of normal-weight aggregates that meet the grading specification requires approximately 40 percent (by weight) of 2.36-mm-graded (no. 8-graded) crushed limestone aggregate for the coarse fraction. The percentage by volume is nearly the same. However, when the lightweight sintered aggregate (graded as 2.36 mm) was blended, a much lower percentage by weight was required to effect the approximately 40 percent by volume coarse fraction. Actually, the same volume of sintered aggregate could be obtained by using only 55 percent the weight of limestone required for the same volume. The volumetric blends of aggregates are given below:

Type of Aggregate	Volumetric Blend (%)	
	Mix 1	Mix 2
2.36-mm-graded sintered aggregate	35	40
Manufactured limestone sand	55	-
Natural river sand	-	40
Agricultural limestone	10	20

Since the coarse-aggregate fraction is generally con-

Table 3. Test results for dense-graded sintered aggregate mixes.

Marshall Design Value	Design Results at Optimum			Asphalt Institute Criteria ^a	
	Mix 1	Mix 2		Minimum	Maximum
		Value	Range		
Stability ^b (kN)				2.225	-
Unsoaked	9.210	8.245	6.676-9.6		
Soaked	8.455	7.105	6.265-8.4		
Flow (mm)				2.0	4.6
Unsoaked	3.35	2.90	2.34-3.33		
Soaked	4.19	3.00	2.64-3.38		
Air voids (%)	9.0	7.8	5.7-10.1	3.0	5.0
Voids in mineral aggregate (%)	19.6	21.5	20.0-23.8	16.0	-
Unit weight (kg/m ³)	1910	1860	1800-1940	-	-
Optimum asphalt content by weight of mix (%)	8.5	10.2	10.0-10.5	-	-
Bitumen absorption by weight of aggregate (%)	3.12	3.11	2.63-4.33	-	-
Combined oven-dried bulk specific gravity of aggregate	2.167	2.113	2.064-2.187	-	-

Note: 1 kN = 225 lbf; 1 mm = 0.039 in; 1 kg/m³ = 0.062 lb/ft³.

^aSuggested criteria for test limits for medium-traffic surfaces (24).

^bAt 60°C (140°F).

Table 4. Mix design test results for open-graded mixes.

Mix Parameter	Value by Percentage Asphalt Content (by weight of total mix)							
	14 Percent		16 Percent		18 Percent		20 Percent	
	Average	Range	Average	Range	Average	Range	Average	Range
Unit weight (kg/m ³)	960	905-1035	1010	925-1135	1025	955-1135	1035	955-1125
Air voids (%)	34.9	30.4-36.8	30.7	25.6-33.8	28.8	23.3-31	27.5	22.3-30.4
Voids in mineral aggregate (%)	42.3	40.4-43.7	40.9	38.7-43.6	41.2	39.1-42.9	42.2	40.7-44.5
Marshall stability ^a (kN)								
Unsoaked	3.395	2.91-3.94	3.64	3.135-4.235	3.875	3.422-4.545	3.79	3.465-4.36
Soaked	3.345	3.2-3.51	3.415	3-3.77	3.715	3.311-4.34	3.420	3.135-3.645
Loss in stability after soaking (%)	1.5	-14.5-11	6.2	-0.6-10.9	4.1	0.6-12.1	9.8	-0.6-22.1
Effective asphalt content by volume of total mix (%)	7.5	5.9-10.2	10.1	7.9-12.6	12.3	10.2-15	14.6	12.5-17.4

Note: 1 kg/m³ = 0.062 lb/ft³; 1 kN = 225 lb.

^aAt 49°C (120°F).

sidered to influence the frictional properties of dense-graded asphalt mixes more than the fine fraction, it was believed that the blends would provide a satisfactory frictional level as a result of incorporating the highly skid-resistant coarse sintered aggregate and also permit use of locally available sands and mineral fillers.

Six Marshall specimens were made from each of four asphalt contents for both mixes. After measurements of bulk density, three of the specimens were evaluated for stability and flow by using the standard procedure of a 20- to 30-min water soak at 60°C (140°F) before testing. The other three specimens were soaked at 49°C (120°F) for 96 h before the 60°C stability and flow evaluations to determine the water sensitivity of the mixes. Measurements of maximum specific gravity were made on the loose mixtures according to ASTM D2041 (17), and voids and asphalt absorptions were calculated for each asphalt content.

Table 3 gives the design results at optimum asphalt content and the Asphalt Institute's suggested criteria for test limits for medium-traffic surface mixes (24). All of the suggested criteria for test limits were met with the exception of percentage air voids, which was slightly higher than the recommended content. This may be desirable, although the air voids content could probably be reduced to the 3-5 percent range by adding more mineral filler. But the rough, rugose texture of the sintered aggregate may preclude the attainment of extremely dense mixes.

Marshall stability values greatly exceeded the mini-

mum suggested value, and flow units were within the suggested range. This indicates that very stable, workable mixes were produced.

The mixes were not sensitive to the effects of soaking in water. Moderate losses in stability were noted for the specimens with the lowest asphalt content for each mix (underasphalted), but only about 12 percent losses in stability occurred in the optimum and higher-asphalt-content specimens.

Evaluation of Open-Graded Mix

An open-graded asphalt mix was evaluated by using substantially the design procedures recommended by the Federal Highway Administration (FHWA) (25) and the Asphalt Institute (26). The grading used was the mid-point of the recommended aggregate gradation given below (1 mm = 0.039 in):

Sieve Size (mm)	Percentage Passing
9.5	100
4.75	30-50
2.36	5-15
0.075	2-5

The apparent optimum asphalt content was selected based on observation of asphalt drainage on the bottom of a clear glass dish; it was judged to be approximately 18 percent by weight of total mix. The AC-20 asphalt cement and sintered aggregate were mixed at 116°C

(240°F). No antistripping additives were used. Marshall-sized specimens were made at four different asphalt contents. The specimens were compacted at 104°C (220°F) by using 35 blows of a Marshall hammer on one end. This compactive effort is used by the Kentucky DOT in designing open-graded mixes and has been judged to be satisfactory. Three of the specimens at each asphalt content were tested by using the Marshall procedure after a 30-min soak at 49°C (120°F). The other three specimens at each asphalt content were soaked for 96 h at 49°C (120°F) before they were tested.

Table 4 gives the mix design results at the various asphalt contents for both the unsoaked and soaked specimens. Based on stability data, an asphalt content of about 16–18 percent is optimum, which is close to that estimated from appearance and drainage characteristics.

The soaked specimens averaged 5.4 percent loss in stability compared with the unsoaked specimens. At 18 percent asphalt content, the loss was only 4.1 percent. These values are well below the 50 percent maximum loss in unconfined compression permitted by the FHWA design procedure (25). Although the Marshall procedure is normally not used in designing open-graded mixes, it is believed that the index of retained Marshall stability after soaking is an applicable criterion for evaluating the resistance of open-graded mixes to the effects of water.

Voids parameters were quite high, as expected for open-graded mixes. Compacted unit weights were very low; this reflects the lightweight effects of the aggregate and high asphalt and voids contents of the mixes.

Skid Resistance

Skid resistance was evaluated in the laboratory by using a procedure developed by the Georgia DOT (27) [ASTM E 510 (17)]. Test samples were subjected to 5 million passes of the circular action of rubber wheels. At various intervals the brakes could be applied and the torque measured, and thus the polishing effect and the skid number could be derived. The results indicated that these mixes are as good as and compare well with the skid-resistant granites used in Georgia.

PORTLAND CEMENT CONCRETE

Typical concrete made in the Kentucky area contains a coarse aggregate that is normally limestone, siliceous river sand, portland cement, and water. Several mixes were made in the laboratory by using standard mixing conditions. Control mixes that contained limestone and experimental mixes that substituted sintered lightweight aggregate for the limestone were made. The purpose of the limestone mixes was to establish a control data base for comparison. Siliceous river sand was used in all mixes as the fine-aggregate fraction. Type 1 cement was used throughout the investigation. Cement factors of 7.8 and 9.2 bags/m³ (6 and 7 bags/yd³) were used.

Mix Design and Procedure

The limestone control mixes were designed by following the ACI 211.1 procedure of the American Concrete Institute (28). Fifty-five percent of the total volume of the aggregate was coarse limestone (no. 57s), which produced the best workable mix. In the sintered aggregate mix design, an equal volume of coarse lightweight aggregate [19 mm (0.75 in) maximum size] was substituted for the coarse limestone aggregate. The sintered aggregate was permitted to soak for 24 h before mixing.

After the 0.057-m³ (2-ft³) batches of concrete were thoroughly mixed, tests for slump (ASTM C 143), air

content (ASTM C 173, volumetric method), and unit weight (ASTM C 138) were made on the fresh concrete (16). Slumps were in the 75- to 100-mm (3- to 4-in) range, and air contents were between 5 and 6 percent. Wet unit weights for the sintered aggregate mixes ranged from 1740 to 1850 kg/m³ (109–116 lb/ft³) compared with 2330 kg/m³ (145 lb/ft³) for the control mixes.

Quality Evaluations

Test specimens were made to determine the properties of the hardened concrete. Six standard 152.4-mm (6-in) diameter cylinders were made for evaluating dry unit weight, compressive strength, and static Young's modulus of elasticity. Four prisms for freeze-thaw testing, two prisms for length-change determinations, and one prism to test for popout materials were made from each mix.

The normal-weight and lightweight specimens were made in accordance with ASTM C 192 and cured as described in ASTM C 330 (16). This necessitated removing the strength and length-change specimens from the moist room after seven days and storing them at a relative humidity of 50 percent until the time of testing.

Unit Weight

The unit weight of the hardened concrete was calculated in accordance with ASTM C 567 (16). The cylinders were initially moist cured for 7 days and subsequently cured at 50 percent relative humidity for 21 days before testing. Unit weights for the sintered aggregate mixes ranged from 1700 to 1800 kg/m³ (107–113 lb/ft³) compared with a value of 2270 kg/m³ (142 lb/ft³) for the limestone mixes, a difference of 22 percent. ASTM C 330 (16) permits unit weights of structural lightweight concrete of as much as 1840 kg/m³ (115 lb/ft³). Low unit weight is a significant feature of lightweight concrete.

Compressive Strength

The compressive strength of the concrete cylinders was determined as outlined in ASTM C 39 (16). Three of the cylinders were tested at 28 days and the other three at 56 days.

Although 28 days is the standard curing period, 56 days is also used as a curing period for some lightweight applications. On the average, after 28 days of curing, a concrete mix that contained 7.8 bags/m³ (6 bags/yd³) of cement and was made with the control limestone had a strength of 35.8 MPa (5180 lbf/in²) (see Table 5). A strength of about 28.3 MPa (4100 lbf/in²) was obtained after 28 days by using the sintered concrete with the same cement factor. Generally, some strength is sacrificed when lightweight aggregate is used, particularly if it is as light as this material. But, with the 9.2-bags/m³ (7-bags/yd³) mixes, the lightweight aggregate at 28 days had on the average a strength nearly comparable to that of the typical 7.8-bags/m³ limestone mix. After 56 days, the 7.8-bag limestone mix increased in strength to 36.9 MPa (5350 lbf/in²); the 9.2-bag mixes of sintered lightweight aggregate increased in strength to an average of 35.2 MPa (5100 lbf/in²). Because the sintered material has greater absorption, it releases water over a longer period of time. The water is thus available to continue hydration over the longer curing period. This phenomenon is quite common with lightweight concrete.

Table 5. Compressive strength of air-entrained concrete.

Days of Curing ^a	Cement (bags/m ³)	Compressive Strength (MPa)							
		Limestone Control Mixes		Sintered Experimental Mixes					
				SEI		Raw Refuse	Blue Clay	ICP	BEP
		Average	Range						
28	7.8	35.8	32.9-38.6	28.3	-	-	-	-	-
28	9.2	-	-	32.8	35.7	33.6	33.8	31.1	31.6
56	7.8	36.9	34.1-39.8	31.8	-	-	-	-	-
56	9.2	-	-	-	39.0	35.3	35.0	32.9	34.0

Note: 1 MPa = 144.8 lbf/in²; 1 bag/m³ = 0.76 bag/yd³.

^aMoist cure for first seven days.

Static Modulus of Elasticity

Testing to determine Young's static modulus of elasticity was accomplished as outlined in ASTM C 469 (16) at a concrete age of 28 days. The modulus for the 7.8-bags/m³ (6-bags/yd³) control mixes averaged 29 300 MPa (4 240 000 lbf/in²), whereas the modulus for the 9.2-bags/m³ (7-bags/yd³) sintered mixes ranged from 16 700 to 18 300 MPa (2 420 000-2 650 000 lbf/in²). As expected, values for the normal-weight mixes were higher than those for the sintered mixes.

Freeze-Thaw Durability

The specimens for the freeze-thaw test were prepared as specified in ASTM C 331 (16) by using air-entrained concrete. The resistance of the concrete to rapidly repeated cycles of freezing and thawing was determined in accordance with ASTM C 666 (16). The apparatus used followed procedure B—freezing in air and thawing in water. The process of weighing and testing for fundamental frequency was repeated at various cycle intervals. The freeze-thaw cycling is normally continued until the specimen falls below 60 percent of its initial dynamic modulus of elasticity or withstands 300 cycles of freezing and thawing, whichever comes first. All specimens exhibited excellent freeze-thaw durability. The test was discontinued after 350 cycles. All control and sintered specimens had durability factors of 100 percent.

Shrinkage

The determination of the change in the length of the hardened concrete was made in accordance with ASTM C 331 (16) and ASTM C 157 (16) by using 100 percent sintered aggregate. Measurements were taken after 28 and 100 days of curing. Shrinkage of the sintered mixes ranged from 0.023 to 0.036 percent after 28 days and from 0.056 to 0.066 after 100 days. Shrinkage of the control mixes averaged 0.040 percent after 28 days and increased to 0.048 percent after 100 days. ASTM specifications for lightweight concrete aggregate permit shrinkage of 0.10 percent. All specimens met this requirement and should not experience excessive shrinkage or expansion with curing.

Popouts

The tendency of aggregate to absorb water at high temperature and pressure was also evaluated by the so-called soundness, or popout, test in an autoclave soundness chamber. Specimens of 100 percent sintered aggregate were evaluated according to procedures described in ASTM C 331 (16) and ASTM C 151 (15). No popouts or other detrimental effects were observed in any of the specimens.

THERMAL ASPECTS

Materials that will be used in the future to construct buildings and other containments will have to be closely analyzed for their characteristics of thermal resistance. Aside from the energy conservation aspects of construction, the overall economics of construction must be carefully analyzed to establish acceptable lifetime costs.

Test specimens of structural concrete that contained the sintered aggregate and control specimens that contained limestone aggregate were evaluated. The specific mechanism used in the measurement of heat flow through the concrete section was the guarded hot plate [ASTM C 177 (19)]. The basic procedure is based on steady-state heat transfer between a hot (warm) plate and a cold plate (flat surface). When sintered aggregate was substituted for the normal-weight limestone aggregate, the overall heat-transfer coefficients decreased 55 percent for the concrete slab specimens.

More detailed information on the thermal aspects of the products is given elsewhere (3).

FINDINGS AND CONCLUSIONS

Bituminous coal refuse, a waste product obtained from five coal-preparation plants in Kentucky, was successfully sintered on a pilot-sized traveling grate to produce lightweight construction aggregate. An improved sintering-grate process that incorporates a sealed sintering facility with a multipass recycle draft was used. The process is particularly applicable to processing bituminous coal refuse because it alleviates some prominent air pollution problems and provides an environmentally acceptable process. The process provides a means for making use of a waste product while gaining an economic advantage from the inherent fuel value of the refuse. Using coal refuse as a raw material requires less than one-third the amount of added fuel required when native clays and shales are sintered conventionally.

Both dense-graded bituminous concrete mixes that contained sintered material as the coarse fraction and open-graded mixes that contained only sintered aggregate exhibited acceptable levels of stability, water sensitivity, and other design parameters. The mixes performed well in laboratory polishing tests, and the results indicate a high-friction, nonpolishing aggregate. Skid-resistant qualities are particularly important and timely, since increased emphasis is expected to be placed in the future on developing and using more highly skid-resistant paving materials.

The sintered aggregate performed very well in the portland cement concrete mixes. The test values indicated good compressive strength, excellent freeze-thaw durability, and no autoclave popouts with a unit weight in the range of 1760 kg/m³ (110 lb/ft³).

Using lightweight aggregate from sintered coal-mine

refuse in concrete construction offers significant technical and economic incentives from the standpoints of reduced weight and the greatly reduced thermal conductivity of the products formed. In the thermal conductivity tests performed in this research, slab concrete with lightweight aggregate showed a 55 percent reduction in thermal conductivity over similar shapes made with normal-weight aggregate.

Bituminous coal refuse represents an essentially unlimited source of raw material for the production of lightweight sintered aggregate in the coal-producing areas of the United States. The lightweight properties and economical production costs of the synthetic aggregate will provide for relatively wide marketing areas. In view of the high costs and scarcity of fuels predicted for the future, the relatively low energy requirements of processing coal refuse will be even more attractive. In addition, the uncertainty of natural aggregate supplies in some areas and the desirability of more insulative building products and skid-resistant paving materials are apparent.

ACKNOWLEDGMENT

The research reported here was sponsored by grants from the Institute for Mining and Minerals Research of the University of Kentucky and the Appalachian Regional Commission (Bluegrass Area Development District). I wish to especially acknowledge research assistants Dale S. Decker, Norman R. Simon, R. Kevin Floyd, and Jeffrey A. Lowe for their assistance in conducting the laboratory analyses. The cooperation of the Kentucky and Georgia Departments of Transportation and the Kentucky coal industry is appreciated. The projects were administered by the College of Engineering, University of Kentucky.

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Publication of this paper sponsored by Task Force on Optimizing the Use of Materials and Energy in Construction.

Industrial Waste Products in Pavements: Potential for Energy Conservation

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Criteria for evaluating the potential performance of industrial waste products as pavement materials are outlined. It is shown that a net energy saving is realized over a selected analysis period whenever the energy saved in the production of raw materials for a pavement that contains waste products (in comparison with a conventional pavement design) is equal to or greater than a function of the energy cost of resurfacing and the times required for both the conventional and waste-product pavements to reach a present serviceability index of 2.5. The "marginal waste product" is (a) in energy terms, that material for which the energy saved in production of raw material is just equal to the additional energy cost of resurfacing over the analysis period, and (b) in economic terms, that product for which the cost per unit of energy saved is equal to the current unit price of energy. Potentially useful industrial waste products can be ranked according to these criteria. A performance criterion for waste materials requires that data be available on which to base reasonable estimates of serviceability history. Several examples of waste products that are currently used as paving materials are discussed, and a statistical study of the compressive strength of pozzolanic concrete correlated with available data on pavement performance is examined.

Certain industrial waste products such as fly ash and blast-furnace slag have long been known to the construction industry as useful ingredients for paving mixtures and other purposes. The use of such products has generally resulted from a combination of their low cost and the high-quality products attainable. It is quite probable that such waste materials would be used in construction even in the absence of environmental or energy considerations.

Environmental enhancement has provided some incentive for greater use of industrial waste products in construction. Previous studies of the use of such waste products have generally focused on particular materials and have usually emphasized the environmental advantages of removing those materials from stockpiles. But, if any significant environmental advantage is to accrue from the use of industrial waste products, the material in question must exist in large quantities within a large geographic area. Otherwise, such environmental effects as enhancement of the landscape and pollution reduction are not sufficient to justify the expense of research and testing. The number of industrial waste products that offer real potential for environmental improvement and have properties suitable for use in construction is therefore quite limited.

Energy conservation has recently emerged as a specific consideration in the design and construction of pavement projects, and the potential of industrial waste

products in relation to energy conservation has not been fully explored. The waste materials that result from essential industrial processes and that then exist in a form that makes them useful for incorporation into construction projects with little or no additional processing offer opportunities for substantial savings in the energy required to produce the raw ingredients of a paving mixture.

It is the purpose of this paper to outline criteria that could be used to evaluate the potential usefulness of industrial waste products as paving materials. The application of the criteria proposed here should make it easier to identify waste products that are usable for pavement construction and to rank such products on a quantitative scale according to the energy they save.

ENERGY CONSUMPTION IN PAVEMENT CONSTRUCTION

The energy required to construct and maintain a pavement can be summarized as follows:

$$E = M + T + C + R + A + S \quad (1)$$

where

- E = energy consumption per unit area of pavement for some analysis period in years;
- M = energy required to produce materials for a unit area of pavement;
- T = energy required to transport materials to the job;
- C = energy required to mix, place, and compact materials for a unit area of pavement;
- R = energy consumption by road users during the analysis period;
- A = energy required to construct overlay on a unit area of pavement; and
- S = energy required for maintenance of a unit area of pavement during the analysis period.

Subscripts c and w are used in the following discussion to denote terms in Equation 1 associated, respectively, with conventional materials and waste materials. If it is then assumed that the energy expenditures for transportation of material, mixing, placing, compacting, and maintenance are about equal for all