FHWA/RD-81/136

Ceramic Roadway Aggregates With Improved Polish- and Wear-Resistance

August 1981

Offices of Research and Development
Federal Highway Administration
U.S. Department of Transportation

FOREWORD

This report summarizes an investigation of the production and testing of a series of synthetic aggregates made ceramically using various waste materials. The one and two component aggregates produced were evaluated for their wear and polish resistance using the Los Angeles Abrasion Machine and the British Polishing Wheel. Their production costs were compared with those of natural aggregates and specialized aggregates such as Guyana bauxite.

This report is available only through the National Technical Information Service because it is not being formally printed by the Federal Highway Administration.

Charles F. Scheffey
Charles F. Scheffey
Director, Office of Research

NOTICE

Technical Report Documentation Page

1. Report No. FHWA/RD-81/136	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Ceramic Roadway Aggregates With Improved Polish- and Wear-Resistance		5. Report Date August 1981
		6. Performing Organization Code
7. Author(s) Arthur V. Petty, Jr.		8. Performing Organization Report No.
9. Performing Organization Name and Address U.S. Bureau of Mines Tuscaloosa Research Center P. O. Box L University, Alabama 35486		10. Work Unit No. (TRAIS) 34G2053
		11. Contract or Grant No. 7-3-0046
12. Sponsoring Agency Name and Address Offices of Research and Development Federal Highway Administration U.S. Department of Transportation Washington, D.C. 20590		13. Type of Report and Period Covered March 1977 - Dec. 1980 Final Report
		14. Sponsoring Agency Code M/0709

15. Supplementary Notes

FHWA Contract Manager: S. W. Forster (HRS-22)

16. Abstract

Through a cooperative program between the Bureau of Mines, Tuscaloosa Research Center and the Federal Highway Administration, synthetic ceramic aggregates having high wear- and polish-resistance were developed. Three hundred aggregate compositions, incorporating a variety of low-cost "waste" materials were evaluated over a 30-month period. Aggregates were produced using conventional ceramic processing techniques and fired at temperatures ranging from 900° - 1,500° C. British Wheel and L. A. Abrasion tests were used for initial screening of the aggregates. These data, in addition to raw material costs, availability, and energy requirements, were used to select nine compositions for circular track tests at Maryland DOT and North Carolina Department of Transportation and Highway Safety facilities. Economic evaluations showed that present production costs, based on a 1,000 ton-per-day operation ranged from $10 to $120 per ton of material produced. Guyana bauxite was used as a standard and several of the selected compositions developed surpassed the bauxite in performance and were lower in cost.

17. Key Words Aggregates, Synthetic Aggregates, Ceramic Aggregates, Polish Resistance, Wear Resistance, Mining Wastes, Metallurgical Wastes, Mineral Wastes	18. Distribution Statement No original distribution by the sponsoring agency. This documentation is available to the public only through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	104	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

FIGURES

Title

LIST OF TABLES

INTRODUCTION

With the objective to conserve the Nation's mineral resources, the Bureau of Mines' Tuscaloosa Research Center has for several years been engaged in research to utilize various industrial and mining wastes as potential raw materials for producing ceramic products. In 1977, a program was undertaken to develop synthetic aggregates that were resistant to wear but able to maintain a high level of skid resistance under severe traffic conditions. Primary emphasis was given to laboratory investigations of raw materials and processing parameters and measurements were made to determine the physical and mechanical properties of the aggregates produced. This research, entitled, "Ceramic Processes for Production of Wear-Resistant and Polish-Resistant Aggregates for Pavement Surfaces," was a cooperative effort with the FHWA under Task 2 of the Federally Coordinated Program (FCP) Project 4G.

Advantages of synthetic aggregate over natural mineral aggregate include the potential for improved skid- and wear-resistance, the ability to produce aggregate in areas lacking suitable natural materials, and the utilization of low-cost "waste" materials. For these reasons, a variety of raw materials from differing geographic locations were considered.

A problem with many naturally occurring aggregates, particularly carbonate rocks which are widely used where available, is that they are composed of minerals fine in grain size, tightly bonded, uniform in hardness, and thus wear at an even rate. This eventually results in polishing of exposed surfaces. Other rocks like some sandstones are composed of minerals with coarse angular grains, variable hardness, and relatively weak bonding. Wear takes place differentially with the dislodgement of individual crystals before the exposed surface becomes polished. Abrasion of the surface however may be excessive. Aggregates such as expanded clays and shales have a vesicular structure which does not polish but is susceptible to wear.

As described by J. R. Hosking[1], acceptable aggregate materials can be classified into five categories: (1) very hard materials, (2) conglomerations of small hard particles, (3) dispersions of hard particles in a softer matrix, (4) materials which fracture in an irregular, angular manner, and (5) vesicular materials. Aggregates representing each of these categories were evaluated.

DESCRIPTION OF RAW MATERIALS

Calcined Guyana bauxite, although limited by its high cost, has been evaluated for skid- and wear-resistance in both the U.S. and Great Britain. British Wheel test data are available in the literature.[1] A sample of kiln-run RASC (Refractory A-Grade Super-Calcined) bauxite, the only grade presently being imported by the U.S., was obtained and used for comparison throughout the laboratory experimental stage.

Other commercial materials evaluated or used in the development of composite mixtures included calcined domestic high alumina clays (Al_2O_3 content ranging from 45 to 70 percent), ball clays, low PCE (pyrometric cone equivalency) ASTM C24-72[2] clays and shales used in the manufacture of structural clay products, silicon carbide, Al_2O_3 fused grain, bubbled Al_2O_3, a variety of crushed commercial refractory bricks, tabular Al_2O_3, and calcined seawater periclase.

Waste materials evaluated, either alone or in combination with other wastes or commercial materials, included slate mining waste and slate mining overburden, copper mill tailings, serpentine waste (asbestos mining waste), fly ash, phosphate slime, aluminum processing wastes, waste glass from municipal incinerators, metallurgical slags and sands.

CERAMIC PROCESSING TECHNIQUES

The ceramic industry has for years been involved with the production of aggregate materials, including prefired grog and lightweight aggregate for use in structural clay products and as admixtures for portland cement and dense, highly refractory grogs used to control shrinkage and warpage in bonded refractories and castables. As a result a wide variety of processing techniques have been developed to produce aggregate from numerous raw materials. Basically these processing techniques include five basic steps:

1. grinding (may not be required depending on the state of the raw material(s) used)
2. mixing (required if more than one raw material is used or if a single raw material is inhomogeneous)
3. forming (for economic reasons, in large scale production this would primarily involve extrusion, pelletization, or briquetting)
4. firing (the temperatures required varies over a wide range depending on the raw material composition and the fired properties desired)
5. crushing (primarily the mechanical breakdown of oversized calcined material to the desired aggregate size distribution)

A typical flowsheet describing the procedures used in producing synthetic aggregate is shown in figure 1.

The production of ceramic materials, involving processing at elevated temperatures, is obviously an energy intensive one. In producing synthetic aggregate, particularly if emphasis is given to waste and other low-cost raw materials, the energy may well represent the largest single cost involved in the process. The actual energy required will depend primarily on the chemical composition of the starting materials, the length of time required at temperature to

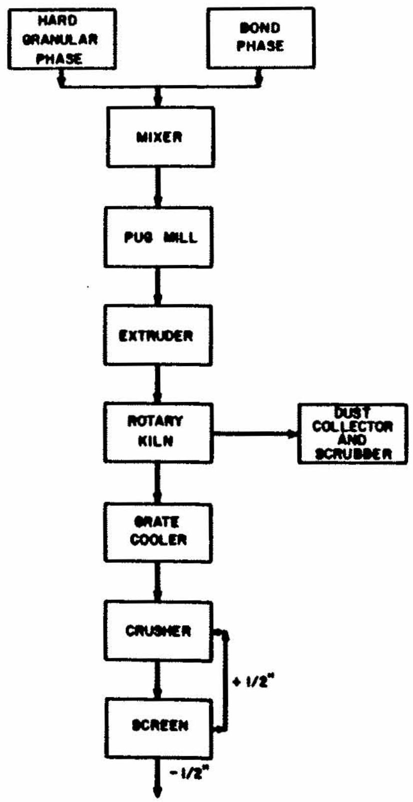

FIGURE 1. Typical process flowsheet

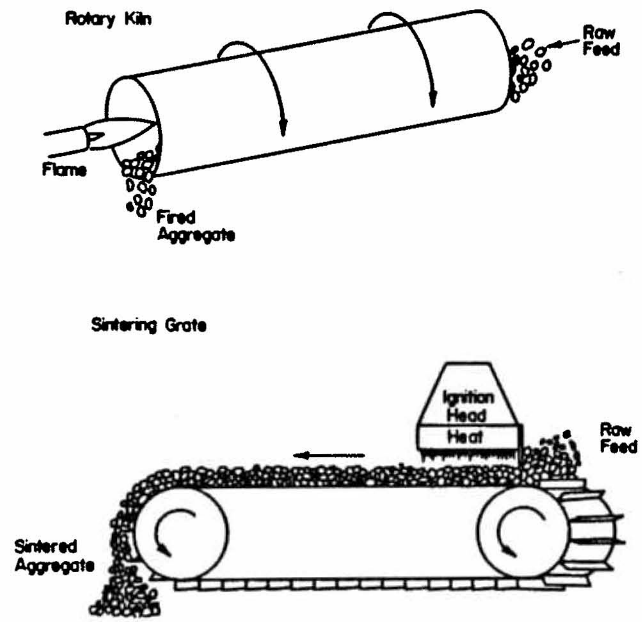

FIGURE 2. Lightweight (Synthetic) Aggregate Production Methods

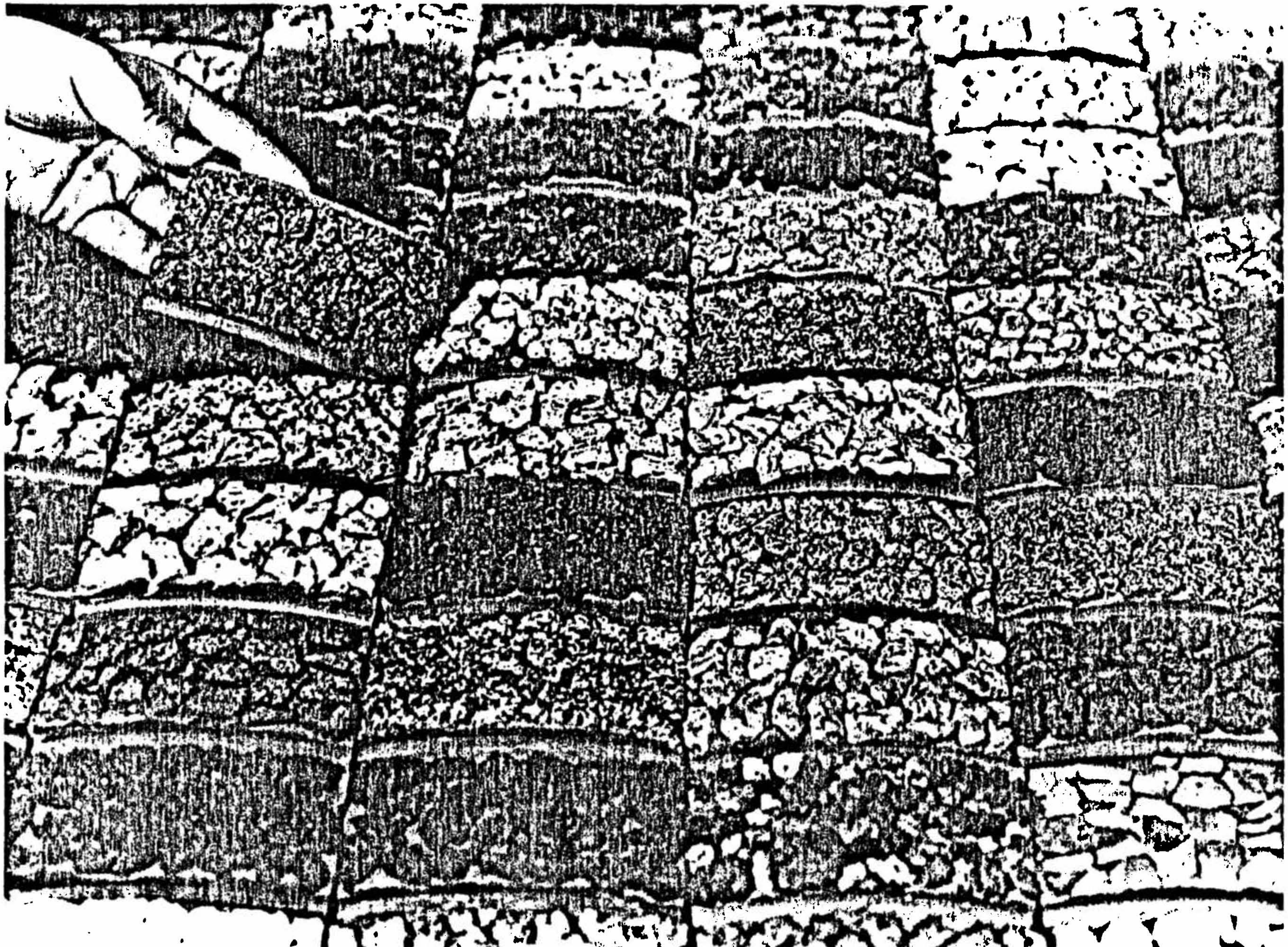

FIGURE 3. Examples of aggregate compositions evaluated

develop the desired properties, and the method of processing (type of furnace) used.

The two primary types of furnaces used in the production of aggregate are the rotary kiln (rotary calciner) and the sintering-grate. Illustrations of these are shown in figure 2.[3] All fuel requirements of the raw material for processing in the rotary kiln are provided from an external fuel source. However, the sintering-grate operation requires some form of solid fuel in the raw feed material in order to sustain combustion after ignition. If the raw material contains some form of naturally occurring fuel such as found in coal refuse and certain types of fly ash, significant fuel savings can be achieved using the sinter-grate approach. An annotated bibliography describing ceramic processing techniques is included as Appendix I.

PROCEDURES FOR ANALYSIS AND CHARACTERIZATION

Chemical analyses and characterization studies included wet chemical analysis, X-ray diffraction, petrographic microscopy, SEM, and TEM. Physical testing included bulk density and apparent porosity (ASTM C67-78, Part 16, Sampling and Testing Brick and Structural Clay Tile)[4] unit weight (ASTM C29-78 Part 14, Unit Weight of Aggregate), British Wheel Test (ASTM D3319-74T, Part 15, Accelerated Polishing of Aggregates Using the British Wheel, with modifications to: (a) time of run, (b) feed rate of SiC, and (c) flow rate of water, to meet Texas Dept. of Highways and Public Trans. specification TEX-438-A),[5,6] British Portable Tester (ASTM E 303-74, Part 15, Measuring Pavement Surface Frictional Properties Using the British Portable Tester)[5], Los Angeles Abrasion Test (ASTM C131-76, Part 15, Resistance to Abrasion of Small Size Coarse Aggregate by Use of the Los Angeles Machine)[5], and Circular Track Tests (Maryland [FHWA-MD-R-77-1][7] and North Carolina [ASTM E660, Part 15, Accelerated Polishing of Aggregates or Pavement Surfaces Using a Small-Wheel Circular Track][5] Depts. of Transportation). Surface microtexture measurements were made on selected aggregate materials by the Federal Highway Administration, Langley, Va.

DESCRIPTION OF AGGREGATE PRODUCTION

Throughout the program conventional ceramic processing equipment was used. Raw materials which required mixing were dry mixed and water added based on the forming method selected. The material was then either pelletized, extruded and chopped to size, or briquetted. Firing involved periodic gas-fired furnaces, rotary calciners, or moving-grate type furnaces. The calcined material was then crushed using a jaw crusher and sized. Exceptions to the above procedure are noted in cases where the raw materials were melted, foamed, and heat-treated to produce crystalline glass-ceramics and in cases where only calcination of "as-produced" waste material and crushing and sizing were required.

In cases involving composite mixtures of calcined clay and other soft bond phases, various fire clays from Pennsylvania, Missouri, California, Georgia, and Alabama were added as pre-calcined material or extruded, calcined and crushed to size prior to mixing with the softer bond phase material.

EXPERIMENTAL RESULTS

Approximately 300 aggregate compositions were produced and evaluated (figure 3). Some compositions were rejected immediately after firing if no bond developed to consolidate the material. For those aggregate materials having enough strength to show some potential, British Wheel Tests were used for initial screening. The cost and availability of raw materials[8-32] and the energy requirements (final temperature and time at temperature required) to produce the aggregates were also considered. Appendix II summarized the initial data for all the compositions.

A number of two component aggregate materials, having a hard angular material bonded with a softer phase, were investigated. Although several mixtures incorporating tabular alumina, silicon carbide, or bubbled alumina gave high polish values (PV's) little consideration was given to the results due to the prohibitively high cost of the raw materials required. Other hard phase materials, that were evaluated included periclase, sand, and calcined fire clays or high alumina clays. Excellent results were obtained on several composite aggregates containing periclase, but the high cost of the raw material would be a limiting factor.

Experimental results indicated that for composite materials, mixtures of 60 weight-percent hard phase material finer than the 300-μm (50 mesh) particle size distribution and 40 weight-percent softer bond phase gave optimum results.

A number of samples in which angular sand was bonded together with materials such as fly ash, low PCE clays and shales, waste glass and phosphate slime were evaluated. Several of these showed high PV's, but very poor bonding between the sand grains and the bonding matrix. Many of these materials showed low strength and friability resulting in very poor wear-resistance.

Promising results were obtained for two phase composite aggregates containing pre-calcined fire clays as the hard phase material. The raw material costs of the calcined fire clays are considerably lower than those of the tabular alumina but comparable results were obtained. The fire clays are readily available and widely distributed geographically. Clays from Alabama, Georgia, Missouri, Pennsylvania, and California were evaluated and similar results were obtained for all.

Generally aggregates composed of glass-ceramic material were rejected because of the high energy cost required in producing this material. This included composite materials in which the hard angular phase was bonded together with a glass-ceramic or vesicular single component aggregates produced from a foamed glass which was subsequently heat-treated to cause controlled devitrification into a partially crystalline material. Frictional measurements made on these glass-ceramic aggregates were only marginally acceptable.

A number of waste commercial refractories such as would result from production defects or when linings are replaced in large industrial furnaces or smelters were evaluated. A variety of refractory compositions were evaluated. The very localized and low-volume availability of these materials and their general high density making transportation expensive, indicate a poor potential for using these materials for roadway aggregate, even where excellent frictional properties were determined. Several composite aggregate materials containing brucite gave high PV's, but again little consideration should be given to them due to limited availability and a very competitive market for this material.

Metallurgical slags of several types were considered. Although these materials are already used extensively as highway aggregate, where available, the potential exists that an improved, more skid-resistant aggregate could be produced in many cases by improving the heat-treatment (cooling rate) of these slags as they are removed from furnaces and smelters. Some very limited work with these materials during the investigation resulted in only marginal improvement in the frictional properties and since the composition of slags varies considerably, substantial research would be required to determine the optimum treatment for each slag composition to yield significant improvement.

Several aggregates which showed fairly high PV's were eliminated because they possessed such low strength or poor bonding that simple visual observation and/or handling indicated sub-marginal abrasion-resistance. These included bottom ash, boiler slag, composite materials in which the hard phase represented more than 70 percent of the mixture or were larger than 2.36mm (8 mesh) in size, several mixtures in which waste glass or fly ash were used as a bond phase, and compositions where rice hulls were added in order to increase porosity.

Table 1 summarizes aggregate compositions which were rejected because of poor performance, cost and/or availability of raw materials, or high energy requirements.

The aggregate compositions shown in table 2 were further evaluated using the Los Angeles Abrasion Test. Samples having PV's below 30 and L.A. Abrasion numbers above 40 were not considered for further study. This led to the selection of 11 final potential candidate materials. Physical and mineralogical data for these aggregate materials are summarized in table 3. A detailed discussion and characterization of the individual aggregates follows.

Sintered Coal Refuse

Coal refuse, designated as sample numbers 79 through 84, is a mixture of rock (mainly shale), clay, and carbonaceous materials which are mined along with coal and are removed from the coal during beneficiation or washing operations. An estimated 3 billion tons of bituminous and anthracite coal refuse are presently stockpiled throughout the United States, with 110 million tons being produced annually.[3] The use of sintered coal refuse as a highway aggregate has been investigated by others [19,33]; samples were obtained through the University of Kentucky Research Foundation for evaluation of skid-resistant properties. These samples had been produced by McDowell-Wellman Engineering, Co., using a sinter-grate process. As described by McDowell-Wellman [34] 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. An air draft is introduced through the bed. Through heat transfer the sintering process is completed. Usually mixing, igniting, burning and cooling are the main phases of the generic term "sintering." In work done on coal refuse, the material was first pelletized to provide a uniform feed to the sintering machine and to insure a uniform product.

Since the coal refuse contains residual carbonaceous material, a large portion of the energy required for sintering was supplied by the raw material itself. Since excessive carbon was contained in the coal refuse, previously sintered material had to be added to the raw material prior to pelletization in order to lower the overall carbon level in the feed. This resulted in the recycling of a large portion of the product thus requiring additional energy to reheat the previously sintered material. A technique which has not as yet been evaluated would be to add an inorganic filler to the coal refuse prior to pelletization. This would reduce the overall carbon content to an acceptable level and allow the material to undergo a single pass through the sintering furnace. This could substantially reduce the energy requirements and overall production costs of the operation.

The sintered coal refuse was evaluated for polish- and wear-resistance and gave excellent results. The physical and mineralogical properties are found in table 3. Figure 4 shows the aggregate and figure 5 the porous internal structure.

Waste Slate Overburden

Waste slate overburden, designated as sample number 122A, occur over slate deposits in Vermont and other northeastern areas. It has the appearance of a clay, and X-ray diffraction of the material shows it to be slate having a mineralogical composition of chlorite, muscovite, quartz, and oligoclase, very similar to the underlying massive slate.[35] When the material is pelletized, briquetted, or extruded and quick-fired in a rotary calciner, a lightweight

TABLE 1. -- AGGREGATE COMPOSITIONS REJECTED BECAUSE OF POOR PERFORMANCE, COST AND/OR AVAILABILITY OF RAW MATERIALS, OR HIGH ENERGY PROCESSING REQUIREMENTS

AGGREGATE TYPE	RAW MATERIAL	LIMITATION
Composite mixtures of a hard, angular material and softer bond phase	Tabular alumina[1]	High cost
	Bubbled alumina[1]	High cost
	Fused alumina grain[1]	High cost
	Calcined periclase[1]	High cost
	Silicon carbide[1]	High cost
	Calcined bauxite[1]	High cost, imported
	Brucite[1]	High cost, availability
	Sand[1]/Waste glass[2]	Poor bond
	Phosphate slime[2]	Poor bond
Crushed commercial refractories	All types	High cost, availability
Glass-ceramics	...	High energy requirements, low polish numbers
Metallurgical slags	...	Availability

1 Hard phase material.

2 Bond phase.

TABLE 2. SUMMARY OF L.A. ABRASION AND BRITISH WHEEL TEST RESULTS OF PROMISING AGGREGATES

SAMPLE NO.	AGGREGATE DESCRIPTION	L.A. ABRASION NO. (PCT - WT LOSS)	POLISH VALUE (PV)
79	Sintered coal refuse	32.4	54
81	Sintered coal refuse	32.0	53
82	Sintered coal refuse	30.7	53
83	Sintered coal refuse	33.4	54
108	Calcined fire clay and waste glass	40.4	50
114	Sand and waste glass	68.8	48
122A	Expanded slate overburden	24.2	45
138	Clay/sand mix with rice hulls	64.3	50
150	Calcined high Al_2O_3 clay	31.4	57
159	Calcined high Al_2O_3 clay	34.8	48
203	Aluminum smelter waste and high Al_2O_3 clay	24.8	50
204	Aluminum smelter waste and fire clay	19.4	46
262	Sintered copper mill tailings	28.4	46
264	Sintered copper mill tailings	62.1	49
269	Sand and fly ash	50.3	40
271	Calcined clay and fly ash	31.4	43
272	Sand and waste glass	51.5	35
273	Periclase and waste glass	36.9	38
274	Calcined clay and waste glass	19.1	44
277	Calcined clay and copper mill tailings	31.9	36
289	Calcined clay and low PCE shale	25.1	30
290	Calcined serpentine waste	19.8	34

TABLE 3. -- SUMMARY OF MINERALOGICAL AND PHYSICAL DATA FOR FINAL SELECTED AGGREGATE SAMPLES

SAMPLE NO.	AGGREGATE DESCRIPTION	BUCKET DENSITY, kg/m^3	BULK DENSITY, gm/cc	PCT APPARENT POROSITY	PCT ABSORPTION	PRIMARY MINERAL CONTENT
Control	RASC bauxite	NA	3.1	NA	NA	α- Al_2O_3
82	Sintered coal refuse	869.9	1.09	43.28	36.60	Amorphous
122A	Waste slate overburden	871.5	1.60	15.81	9.87	Quartz, amorphous
150	Calcined high Al_2O_3 clay	942.0	NA	NA	NA	Mullite
203	Aluminum waste + fire clay	812.2	2.11	20.62	9.78	α- Al_2O_3
204	Aluminum waste + high Al_2O_3 clay	483.8	1.67	38.68	23.16	Mullite
262	Copper mill tailings	996.4	3.24	6.53	2.01	Garnet structure
271	Calcined clay + fly ash	900.3	1.98	26.01	13.16	Mullite, cristobalite
273	Periclase + waste glass	1,012.5	NA	NA	NA	Periclase, amorphous
274	Calcined clay + waste glass	860.3	1.96	23.00	11.77	Mullite, cristobalite, amorphous
289	Calcined clay + low PCE shale	1,047.7	2.07	15.81	7.63	Mullite, cristobalite
290	Calcined serpentine wastes	1,337.7	2.66	11.98	4.50	Forsterite, clino-enstatite

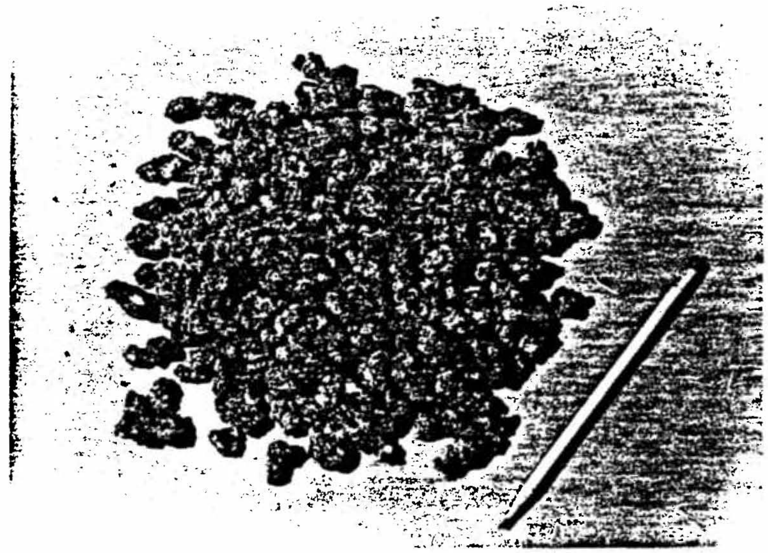

FIGURE 4. Sintered coal refuse

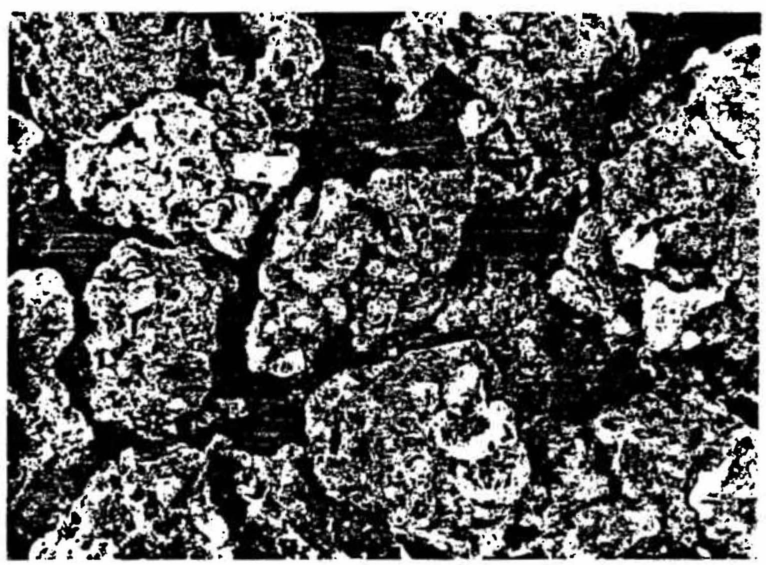

FIGURE 5. Morphology of sintered coal refuse

porous aggregate is formed. This results from the rapid heating of the outer surface of each piece during which a thin, highly viscous, impervious layer is formed, thus trapping water and other volatiles inside. As the material continues to be heated, pressure builds up inside each piece causing a swelling to occur. Chracteristics of a good lightweight aggregate include high strength, and a closed pore structure of uniform pore size. The aggregate produced from the slate overburden contains small uniform pores. Physical and mineralogical data for the calcined material are shown in table 3. The aggregate is shown in figure 6 and figure 7 shows the internal pore structure.

Aggregate produced from crushed massive slate contains larger and various sized pores. The larger pores develop along the natural lamination planes of the slate particles. The wear resistance of the aggregate formed from the massive slate is not as good as for the aggregate produced from the slate overburden.

Calcined High Alumina Fire Clay

Calcined fire clay, represented by sample numbers 150 and 159, is a finely divided kaolinitic clay found in many locations throughout the United States. Several clays were evaluated including samples from Alabama and Georgia having alumina contents of approximately 70 percent. This domestic material when calcined is similar to calcined Guyana bauxite except that it contains more silica and less alumina. When produced for refractory applications in the ceramic industry the material is generally extruded, dried, and fired in a rotary calcining furnace to high temperature (~1,700° C) to yield a high density refractory grog. Research showed that similar procedures could be followed in producing a high friction highway aggregate, however, by firing to a somewhat lower temperature (1,350-1,450° C), a more porous and granular material resulted with improved frictional properties. Although this would be considered a high-cost raw material, it is considerably less expensive than imported refractory grade calcined bauxite and seems to have similar frictional properties. Physical and mineralogical data for the calcined material (sample No. 150) are shown in table 3. The aggregate depicted in figure 8 and figure 9 shows the internal structure. The calcined material of sample No. 159 was identical in appearance.

Aluminum Smelter Waste and High Alumina Clay

Aluminum smelter waste and high alumina clay were combined in sample No. 203. The aluminum smelter waste is a finely ground material, minus 30-mesh, produced during the processing of aluminum smelting drosses/residues. In the reclamation of metallic aluminum from melting furnace drosses, the residue is processed by crushing and grinding through a comminution circuit consisting of crusher, several ball mills and multdeck vibrating screens. The metallic aluminum is collected at several points as a concentrated furnace feed to be remelted and cast into ingot. The waste material separated from the metallic aluminum has a chemical composition as shown in table 4. This material has been used in the production of portland cement as a replacement for clay, fly ash, or shale.

TABLE 4. TYPICAL ANALYSIS OF PROCESSED ALUMINUM SMELTER WASTE

FREE ALUMINUM	3-5 PCT
Al_2O_3	75-85 pct
SiO_2	7.5 pct
Fe_2O_3	2.5 pct
CaO	5.5 pct
MgO	5.5 pct
K_2O	1.0 pct
Na_2O	1.0 pct
TiO_2	.2 pct
Chlorides	3-5 pct

This material was mixed with a high alumina clay containing 70 percent Al_2O_3 and pelletized. The finely divided aluminum waste is somewhat pozzolanic and the addition of water causes the material to hydrate, resulting in a hard pellet suitable for feed directly into a rotary calciner. No binders were required.

Rather high sintering temperatures, approximately 1,500° C, were required but the resulting aggregate was an extremely hard, vesicular material, containing primarily alpha-alumina and having excellent frictional and wear-resistant properties. The physical and mineralogical properties are shown in table 3. Figure 10 shows the aggregate and figure 11 the internal pore structure of the material.

Aluminum Smelter Waste and Fire Clay

Aluminum smelter waste and fire clay were combined in sample No. 204. The smelter wastes, as described in the previous section was combined with a fire clay containing 45 percent alumina, pelletized, and fed into a rotary calciner. As with sample No. 203, no binder was required and the maximum firing temperature was 1,500° C. Calcining again produced an extremely hard, vesicular material, in this case composed primarily of mullite, and having excellent frictional and wear-resistant properties. The physical and mineralogical properties are shown in table 3. Figure 12 shows the aggregate and figure 13 the internal pore structure of the material.

Sintered Copper Mill Tailings

Copper mill tailings are a processing waste resulting from the recovery of copper from porphyry copper ores in the western United States. The ore is ground to approximately minus 35-mesh, and through flotation, the copper and molybdenum sulfides are separated. The waste material may or may not be run through a magnetic separator to remove iron-containing minerals.

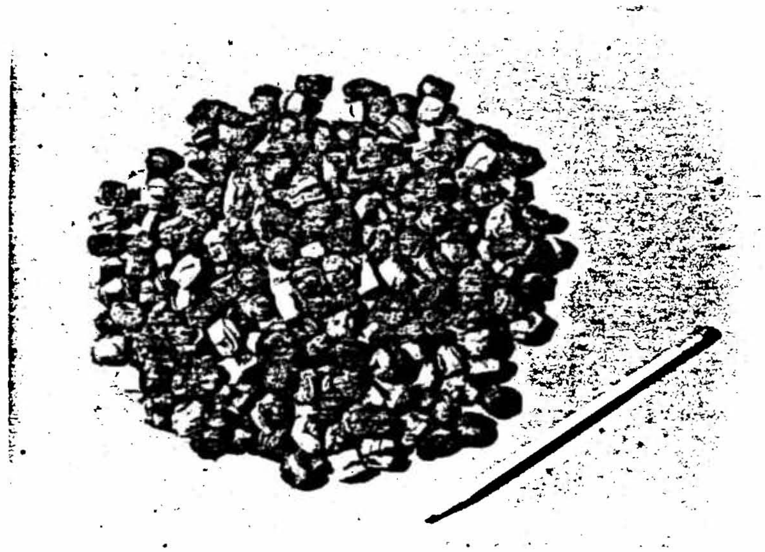

FIGURE 6. Waste slate overburden

FIGURE 7. Morphology of waste slate overburden

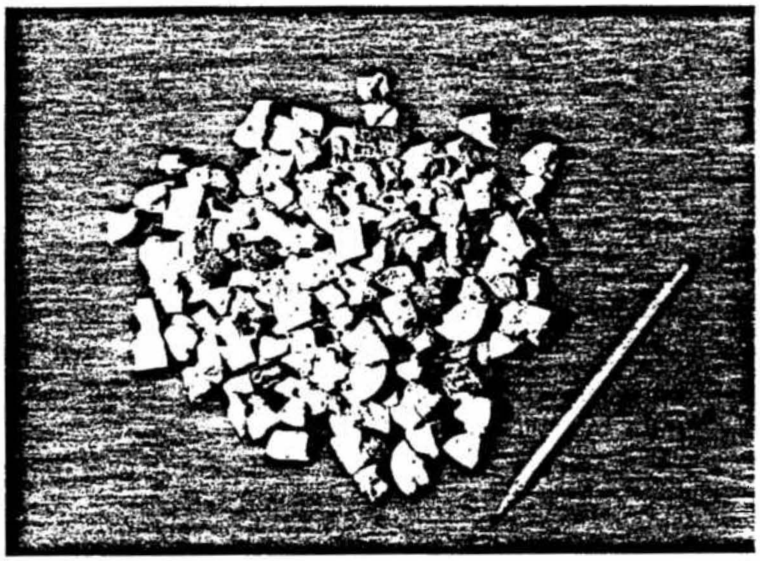

FIGURE 8. Calcined high Al_2O_3 clay

FIGURE 9. Morphology of calcined high Al_2O_3 clay

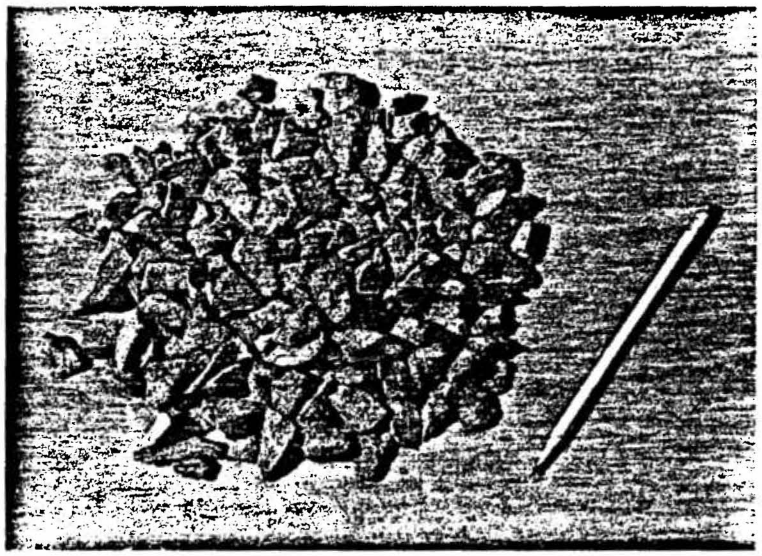

FIGURE 10. Aluminum waste and refractory fire clay

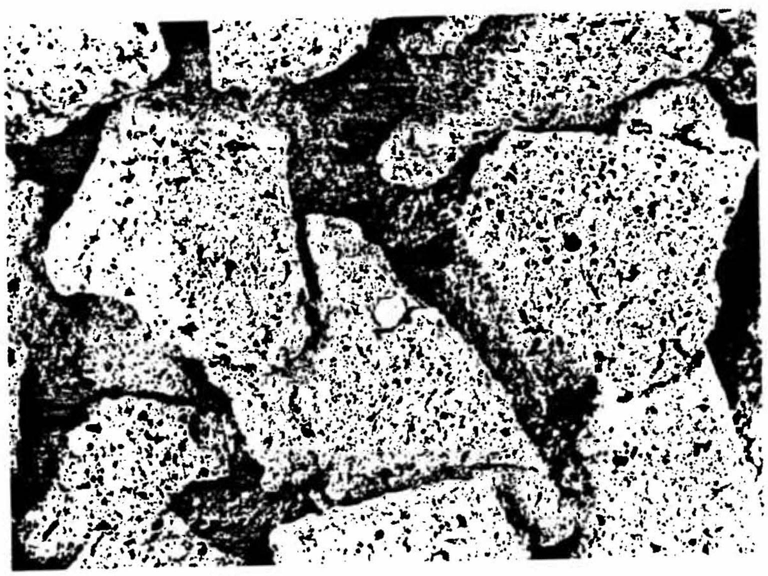

FIGURE 11. Morphology of aluminum waste and refractory fire clay

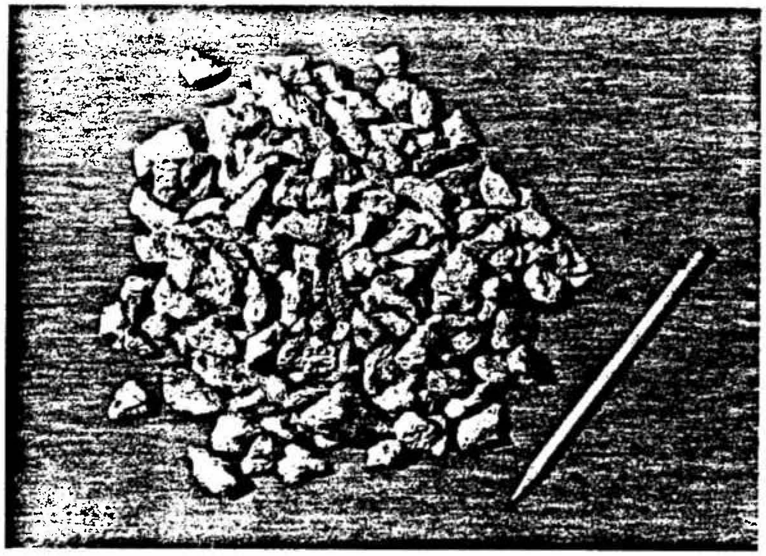

FIGURE 12. Aluminum waste and high Al_2O_3 clay

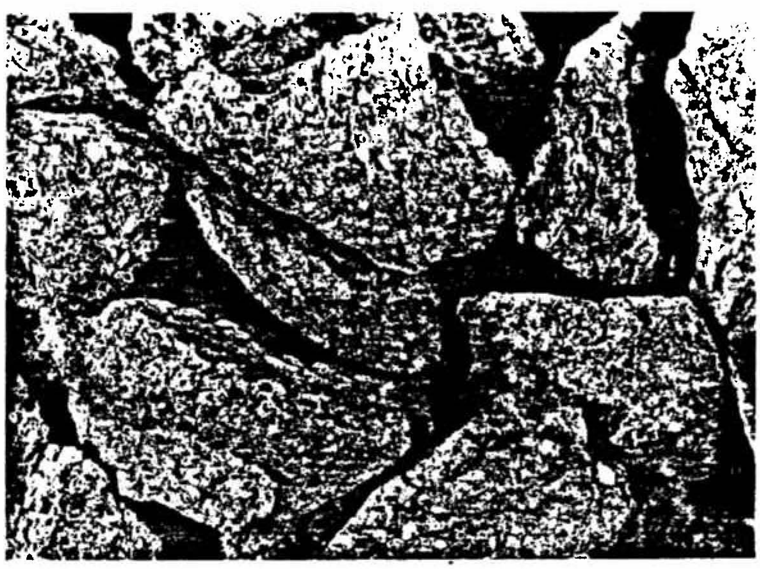

FIGURE 13. Morphology of aluminum waste and high Al_2O_3 clay

These wastes are produced at approximately 1 million tons per day in the United States. In this investigation, tailings from three different mills were evaluated; ores numbered 2388, 2401, and 2403. The mineralogy of these ores is shown in table 5.

TABLE 5. MINERALOGICAL CONTENT OF THREE COPPER MILL TAILINGS

ORE No.	QUARTZ	GARNET	ORTHO-CLASE	PLAGIO-CLASE	OTHER
2388	X	X	-	-	Diopside
2401	X	-	X	X	Mica
2403	X	-	X	X	Mica

Sample No. 262 was produced by pelletizing ore No. 2388 with 2 percent western bentonite added as a binder. The material was then fired to 1,150° C in a rotary calciner, resulting in a porous aggregate with a garnet structure and showing excellent polish-and wear-resistance. Physical and mineralogical data for the calcined material are shown in table 3. The aggregate is shown in figure 14 and the internal pore structure in figure 15.

Calcined Clay and Fly Ash

Calcined clay and fly ash were combined to produce a two-phase aggregate, sample No. 271. The clay, containing 45 percent alumina, was purchased in calcined form and crushed to minus 48-mesh. Clays of this type are available in Georgia, Alabama, Pennsylvania, Missouri, and California. Sixty percent of this hard phase calcined clay was mixed with 40 percent fly ash. Fly ash is widely available as a waste by-product in the burning of coal. Two percent western bentonite was added as a binder and the mixture pelletized and fired to 1,260° C in a rotary calciner. The fired product was primarily a mixture of mullite and cristobalite. The phyical and mineralogical properties for the calcined material are shown in table 3 and the aggregate shown in figure 16. The internal structure shown in figure 17 indicates the uniform distribution of hard, angular calcined clay in a porous matrix. This combines the benefits of a two-phase aggregate with those of a vesicular structure, to yield a high friction and wear-resistant material.

Periclase and Waste Glass

Periclase and waste glass were combined to produce a two-phase aggregate, sample No. 273. The calcined periclase was obtained from a commercial producer and crushed to minus 48-mesh. Sixty percent of this hard phase material was mixed with 40 percent waste glass (obtained from a municipal incinerator) that was ground to minus 200-mesh. Two percent western bentonite was added as a binder, the mixture pelletized, and fired to 900° C in a rotary calciner. A porous two-phase aggregate resulted having good frictional properties and wear-resistance. Analysis of the fired aggregate showed only periclase and an amorphous glassy phase bonding the grains together. Although periclase is a relatively expensive raw material, this is somewhat compensated for by the low firing temperature required to melt the waste glass and bond the hard grains together. The physical and mineralogical properties are summarized in table 3. The aggregate shown in figure 18 and figure 19 again indicates a uniform distribution of the periclase in a porous glassy matrix.

Calcined Clay and Waste Glass

Calcined clay containing 45 percent alumina was combined with waste glass to produce a two-phase aggregate, sample No. 274. Production was similar to that described in the previous section with 60 percent calcined clay [minus 300-μm (50 mesh)] being combined with 40 percent waste glass [minus 75-μm (200 mesh)] two percent western bentonite added as a binder, and the mixture pelletized. The material was fired to 900° C in a rotary calciner to produce a porous two-phase aggregate. The substitution of calcined clay for periclase as the hard-phase component results in a considerable savings of raw material costs. The resulting aggregate also shows better skid-resistance and considerably improved wear-resistance due to the improved bond between the hard-phase and matrix. Physical and mineralogical data are shown in table 3 and the aggregate in figure 20. Figure 21 shows the uniform distribution of the hard angular calcined clay in the porous, glassy matrix.

Calcined Clay and Shale

Calcined clay containing 45 percent alumina was combined with low PCE shale to produce a two-phase aggregate, sample No. 289. Production of the aggregate was again similar to the procedure described in the previous sections. The pelletized aggregate was fired in a rotary calciner to 1,375° C, resulting in a porous two-phase aggregate. Figure 22 shows the crushed and sized, fired aggregate and figure 23 indicates the uniform distribution of the calcined clay in the porous matrix. The fired aggregate, composed primarily of mullite and cristobalite, had somewhat lower frictional level than the two-phase aggregates previously described. Again the wear-resistance was excellent. The physical and minerogical data are shown in table 3.

Calcined Serpentine Waste

Serpentine waste tailings, a by-product in the mining and processing of asbestos, was used to produce an aggregate, sample No. 290. The waste material contains residual amounts of fibrous asbestos and at present the Environmental Protection Agency prohibits the surfacing of any roadway with asbestos tailings. [36] However, these regulations do not consider the use of thermally altered materials. Mineralogical analysis of the starting material showed primarily antigorite and minor amounts of carbonates and opaques and traces of chrysotile (asbestos) and fibrous serpentine. However, examination by the

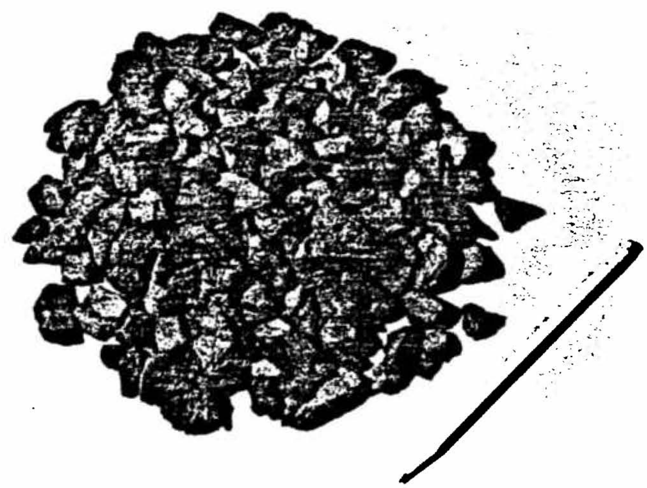

FIGURE 14. Copper mill tailings

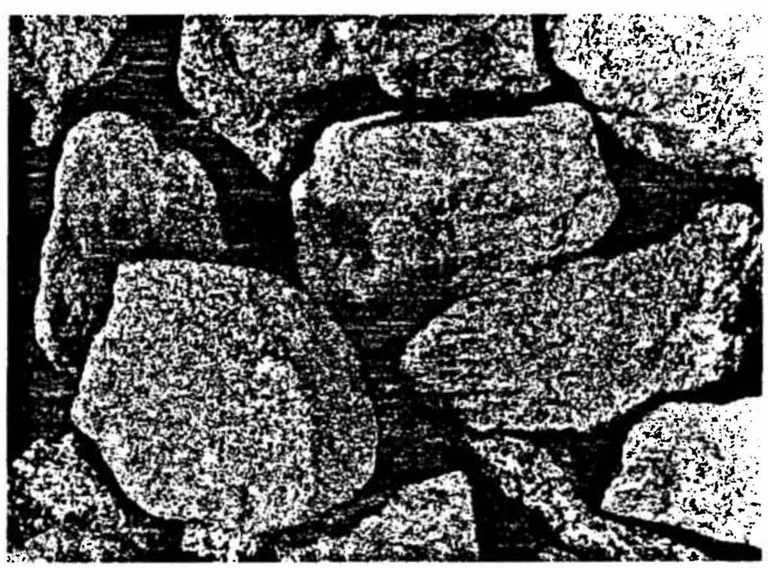

FIGURE 15. Morphology of copper mill tailings

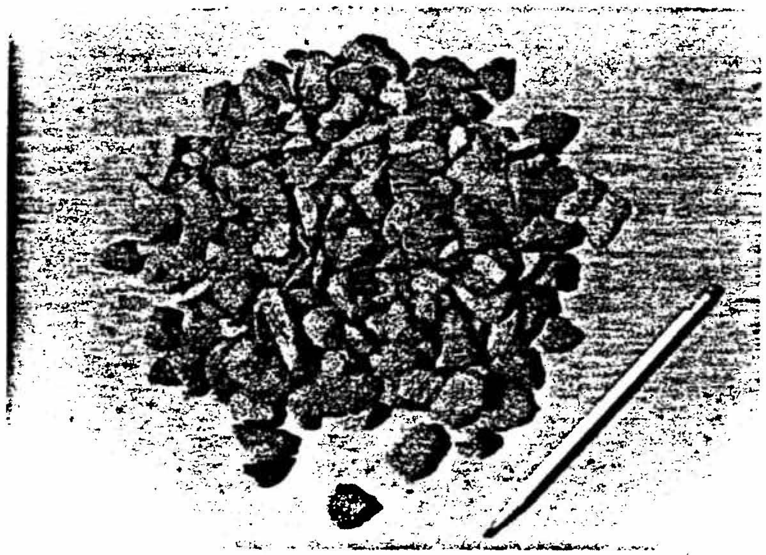

FIGURE 16. Calcined clay and fly ash

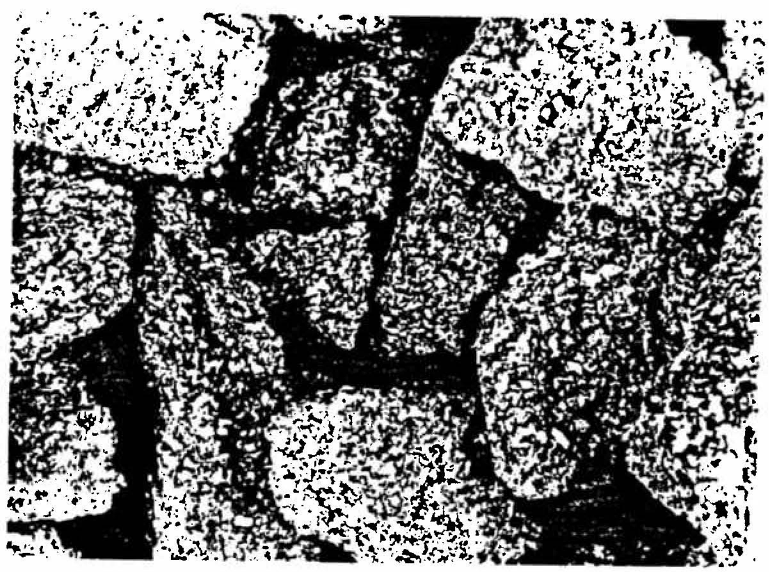

FIGURE 17. Morphology of calcined clay and fly ash

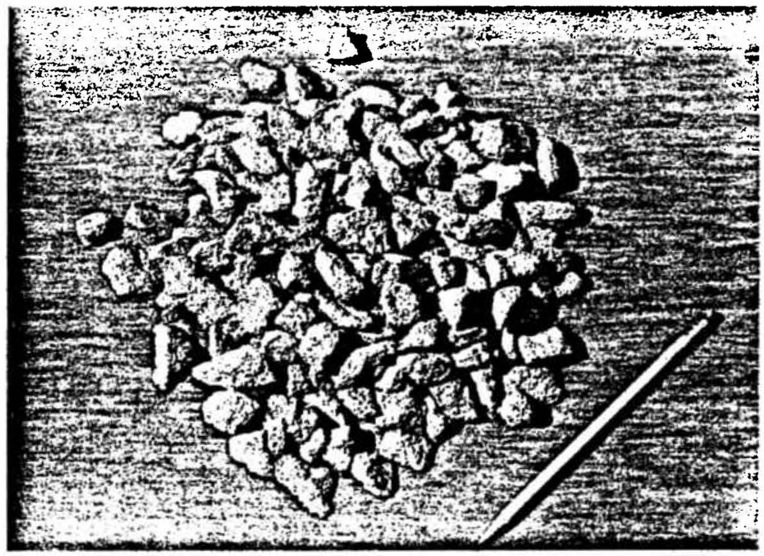

FIGURE 18. Periclase and waste glass

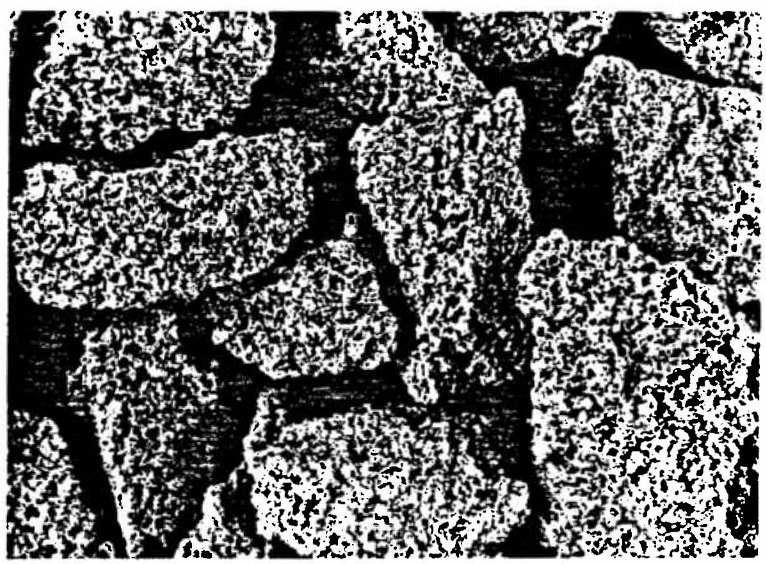

FIGURE 19. Morphology of periclase and waste glass

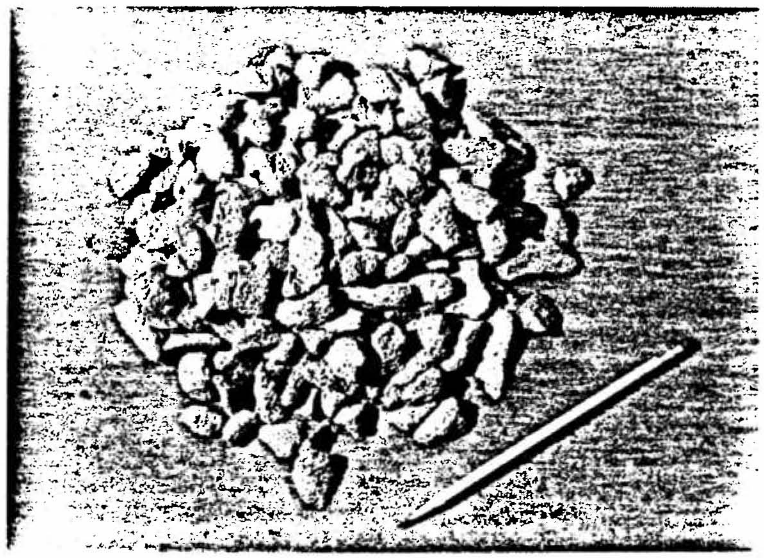

FIGURE 20. Calcined clay and waste glass

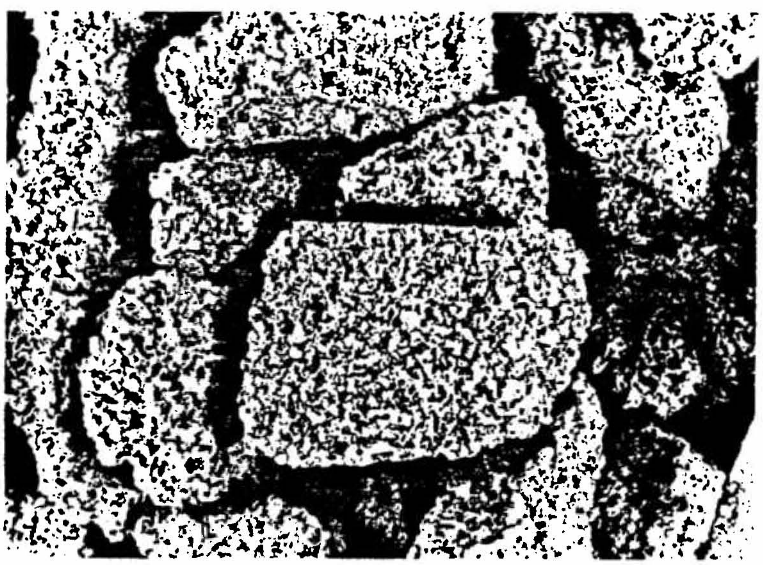

FIGURE 21. Morphology of calcined clay and waste glass

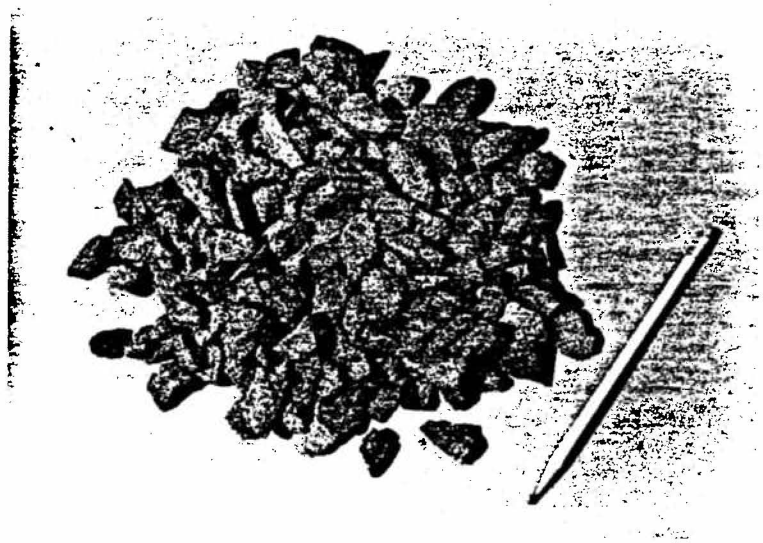

FIGURE 22. Calcined clay and low PCE clays

FIGURE 23. Morphology of calcined clay and low PCE clays

U.S. Bureau of Mines, Particulate Mineralogy Unit, Avondale, Maryland, using optical microscopy, transmission electron microscopy and X-ray diffractometry of the aggregate following calcination (thermal treatment) at 1,350° C showed the material to be composed of enstatite and forsterite. No particles were observed which exceeded 5 to 1 in aspect ratio and no skeletal remains of chrysotile were observed.

The production of aggregate from the serpentine waste simply involved the firing of the waste in a rotary calciner to 1,350° C and crushing the fired material to size. The frictional level of the resultant crushed aggregate was moderately good and the wear-resistance excellent. This material and process also resulted in the lowest production costs of any of the synthetic aggregates evaluated. The physical and mineralogical data are shown in table 3 and the aggregate shown in figures 24 and 25.

Summary of Selected Aggregate Systems

Characterization of these aggregates is summarized in table 6. These materials fall into three of the five categories of aggregates outlined by Hosking - very hard materials (sample Nos. 150, 262, and 290); dispersions of hard particles in a softer matrix (sample Nos. 271, 273, 274, and 289) and vesicular materials (sample Nos. 82, 122A, 203, and 204). Sample Nos. 271, 273, 274, and 289 combine the properties of (1) a hard phase material distributed in a softer matrix and (2) a vesicular structure.

Sample Nos. 203 and 204, mixtures of aluminum processing wastes and high Al_2O_3 bauxitic clay or low Al_2O_3 fire clay, combine the properties of very hard materials with vesicular structures.

Production processes, along with PV's and L.A. Abrasion Test results, are given in table 6. The high PV's and low L.A. Abrasion numbers should be noted. PV's ranged from 30 to 54 with five ranking higher than average values obtained on Guyana RASC bauxite. The L.A. Abrasion numbers ranged from a high value of 36.9 to a low of 19.1.

Economic and Process Evaluation

An economic and process evaluation was made by the Bureau of Mines, Process Evaluation Group, Avondale, Maryland, based on a production rate of 1,000 tons-per-day. A summary of this evaluation is shown in table 7 where the fixed capital cost (including all currently required pollution control equipment), production costs per ton of aggregate produced, and the thermal requirements per 1,000 tons of aggregate produced are given for each of the 11 aggregate compositions. The production costs per ton of aggregate produced ranged from \$10.62 to \$120.09 per ton. It should be noted that for those nine materials submitted for circuclar track tests the cost range is from \$10.62 to \$53/ton as compared to the present cost for Guyana bauxite of \$235/ton FOB, port of entry.

The high fixed capital cost for samples 79-83, sintered coal refuse, is due to the cost of pollution control equipment for the sintergrate furnace. The high fixed capital cost is offset by low energy requirements and the actual production cost ranks this as one of the less expensive synthetic aggregates. The report is included as Appendix III.

Circular Track Tests

Seven and nine of the selected aggregates were sent to the Maryland and North Carolina Departments of Transportation, respectively, for circular track testing. The remaining two aggregate compositions listed in table 3, sample Nos. 150 and 273, were not included in the circular track tests due to the high cost of producing these materials. The Maryland and North Carolina tests differ basically in that the Maryland method evaluated only the aggregate whereas the North Carolina test evaluated an open-graded bituminous/aggregate mix.[5,7,37] The results of these tests are summarized in table 8. As stated in the report submitted by the Maryland Department of Transportation polish values for the seven synthetic aggregates indicate higher frictional levels than all previously tested carbonate and serpentinite rock-types. Also, four reported polish values are higher than any natural aggregate previously tested. The report from the Maryland State Highway Administration is included as Appendix IV.

The North Carolina Department of Transportation reported that problems were encountered in obtaining an adequate bond and coating with AC 20 asphalt. Based on results of initial trial runs, the asphalt content was increased and 1/2 percent by weight anti-strip additive was used to improve the adherence of asphalt to the synthetic materials. The copper mill tailings were especially difficult to coat relative to unit weight. Based upon the plotted curves at VSN (Variable Speed Number, 40 mph, ASTM E707) the aggregates could be ranked for 4-hour polish as follows:

- Aluminum waste and refractory clay
- Calcined clay and low PCE clay
- Aluminum waste and high Al_2O_3 clay
- Calcined serpentine waste
- Copper mill tailings
- Sintered coal refuse
- Calcined clay and waste glass
- Calcined clay and fly ash
- Expanded waste slate overburden

Four of the aggregates ranked equal to or higher than the control aggregate while five ranked lower.[1] The report from W. G. Mullen, Coordinator,

1 The control aggregate was a medium to low skid-resistant aggregate when polished.

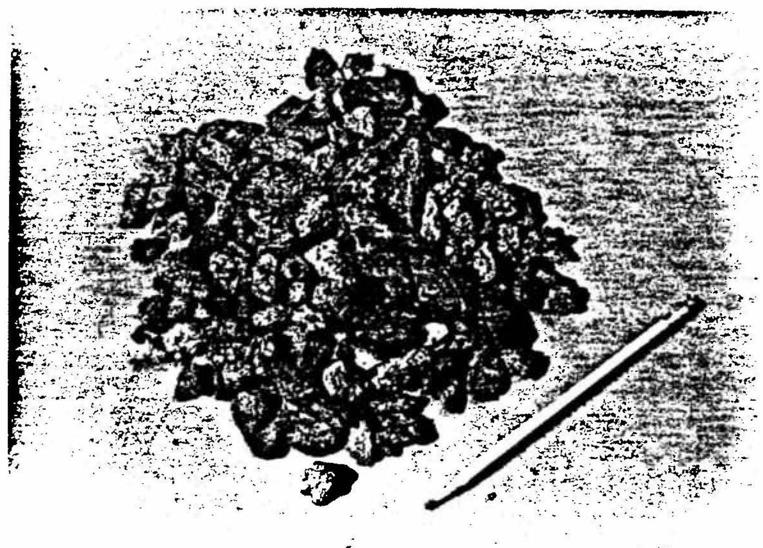

FIGURE 24. Calcined serpentine wastes

FIGURE 25. Morphology of calcined serpentine wastes

TABLE 6. - EVALUATION SUMMARY FOR SELECTED AGGREGATE SYSTEMS

SAMPLE NO.	AGGREGATE DESCRIPTION	BINDER REQUIRED	AGGREGATE FABRICATION	FURNACE TYPE	SINTERING TEMP., °C	PV	L.A. ABRASION VALUE
Control	RASC Guyana bauxite	None	Crush	Rotary calciner	>1,600	46	ND
82	Sintered coal refuse	None	Pelletize	Sinter grate	1,100	54	32
122A	Waste slate overburden	None	Extrude	Rotary calciner	1,150	45	24.2
150	Calcined high Al_2O_3 clay	None	Extrude	Rotary calciner	1,400	53	32.5
203	Aluminum waste + fire clay	None	Extrude or pelletize	Rotary calciner or sinter grade	1,500	50	24.8
204	Aluminum waste + high Al_2O_3 clay	None	Extrude	Rotary calciner or sinter grate	1,500	46	19.4
262	Copper mill tailings	-2 pct bentonite	Extrude	Rotary calciner	1,150	46	28.4
271	Calcined clay + fly ash	-2 pct bentonite	Pelletize	Rotary calciner	1,260	43	31.4
273	Periclase + waste glass	-2 pct bentonite	Pelletize	Rotary calciner	900	38	36.9
274	Calcined clay + waste glass	-2 pct bentonite	Pelletize	Rotary calciner	900	44	19.1
289	Calcined clay + low PCE clay	None	Extrude or pelletize	Rotary calciner	1,375	30	25.1
290	Calcined serpentine waste	None	Crush	Rotary calciner	1,350	34	19.8

TABLE 7. — FIXED CAPITAL COSTS, PRODUCTION COSTS AND THERMAL REQUIREMENTS FOR 11 PROCESSES FOR PRODUCING ROADWAY AGGREGATES

SAMPLE NO.	AGGREGATE DESCRIPTION	FIXED CAPITAL COST	PRODUCTION COST[1] PER TON AGGREGATE	DAILY THERMAL REQUIREMENTS, MMBTU COAL
82	Coal refuse aggregate	$32,694,600	$18.56	604.9
122A	Slate waste aggregate	15,665,900	13.05	3,050.0
150	High alumina clay aggregate	15,697,500	71.08	3,410.0
203	Sixty pct aluminum dross and 40 pct refractory clay aggregate	16,017,000	35.98	3,250.0
204	Forty pct aluminum dross and 60 pct refractory clay aggregate	16,556,400	34.25	4,290.0
262	Copper mill tailings aggregate	16,005,000	13.58	2,654.2
271	Calcined clay and fly ash aggregate	16,152,800	44.63	2,470.0
273	Periclase and waste glass aggregate	15,457,400	120.09	1,870.0
274	Calcined clay and waste glass aggregate	16,608,300	43.51	2,310.0
289	Calcined clay and low PCE clay aggregate	15,844,800	53.01	2,750.0
290	Serpentine waste aggregate	13,365,100	10.62	2,050.0

[1] Production costs include fixed capital costs, raw materials, utilities, direct labor, plant maintenance overhead, and fixed costs including taxes, insurance, and depreciation over 20 years.

TABLE 8. -- RESULTS OF THE MARYLAND AND NORTH CAROLINA CIRCULAR TRACK TESTS

SAMPLE NO.	AGGREGATE DESCRIPTION	MARYLAND POLISH VALUE STRAIN	MARYLAND POLISH VALUE BPN	NORTH CAROLINA ASTM E660 CIRCULAR TRACK
82	Sintered coal refuse	22	78	a
122A	Waste slate overburden	11	45	a
203	Aluminum waste + fire clay	NA	NA	b
204	Aluminum waste + high Al_2O_3 clay	19	70	b
262	Copper mill tailings	19	63	a
271	Calcined clay + fly ash	NA	NA	a
274	Calcined clay + waste glass	18	57	a
289	Calcined clay + low PCE clay	14	46	b
290	Calcined serpentine waste	14	50	b
	Control	6	28[c]	d

[a] Lower than control (4-hour polish)
[b] Higher than control (4-hour polish)
[c] Dolomitic marble
[d] Crabtree granite open-graded mix

Highway Research Program, North Carolina State University and Durwood Barbour, North Carolina Department of Transportation Materials Laboratory is included as Appendix V.

Surface Microtexture Analysis

Sample coupons like those prepared for British Wheel Testing were prepared for each of the aggregate materials included in table 3. These coupons were submitted to the Federal Highway Administration, Langley, Virgina, for surface microtexture analysis. The theory and procedure used in evaluating microtexture have been described by S. W. Forster.[38] Following this the samples were abraded using the standard procedure used for the British Wheel Test and returned to the FHWA for subsequent microtexture anlaysis. The test results are summarized in table 9.

In general, when acting on natural aggregates, the British Wheel Polishing Test has the effect of a decrease in the average asperity density (peaks/μm) and the average asperity height (μm). This results because the microtexture on these materials usually consists of mineral grains or crystals protruding above a matrix material. Under the action of the wheel, these peaks become rounded and smoothed, thereby decreasing the average peak density and average peak height. For the artificial materials examined here (see attached table), although the average peak height decreased in nearly all cases, the average density was found to remain about the same for 4 of the 9 specimens which retained, intact the stones measured for microtexture, after the British Wheel Test. This may be due to the fact that these materials are often foamed or expanded and therefore vesicular. These surfaces are, as a result, a system of voids with intervening ridges. While the height of the ridges may be decreased somewhat (thereby decreasing the average asperity height measurement), apparently their average spacing is not significantly decreased by the action of the British Wheel. If the voids are evenly distributed throughout the material this should indeed be the case since any planar section through an aggregate piece would then intersect an equal number of void boundaries (ridges).

The average shape factor (which combines the average density and average peak height measurements) decreased for all these aggregates, whether of the vesicular type or not. This occurred because a decrease in either density or height will cause a decrease in shape factor if the other characteristic remains the same. The polish value decreased for all samples also.

In general these artificial materials retained higher shape factors at the end of the British Wheel Test than most natural aggregates tested. This indicates they may also retain their skid-resistance better in the field, although enough correlations between these microtexture parameters and skid measurements have not been attempted to state this conclusion definitely. The fact that these artificial materials also achieve generally higher ultimate polish values than natural materials reinforces this premise.[39]

SUMMARY

In summary, of the almost 300 aggregate compositions evaluated during this study, a large number showed potential for improved skid- and wear-resistance on roadway surfaces. Many of the aggregates tested demonstrated wear-resistance greater than or equal to calcined Guyana bauxite and showed superior polish resistance based on British Wheel and British Pendulum test data.

Based on the production costs, it is obvious that synthetic aggregate materials cannot compete with natural mineral aggregates when based on cost alone. However, in areas lacking suitable natural mineral aggregate, in areas exposed to extreme wear, in areas where downtime required for maintainance cannot be tolerated, or in areas where improved safety due to skid-resistant aggregate could justify the costs, synthetic aggregates should be considered.

All of the aggregates described in this report were produced using conventional and proven equipment and processing techniques, common within the ceramic industry. If and when larger scale field testing can be justified, numerous ceramic material processing facilities are available throughout the country where sufficient quantities of synthetic material required for field tests could be produced. This would eliminate the need for capital investment in pilot plant facilities and greatly reduce the cost for such continued experimental work.

CONCLUSIONS

1. Synthetic roadway aggregate can be produced using standard ceramic processing techniques and equipment.

2. Synthetic aggregate offers improved frictional levels over natural mineral aggregate. Polish Values ranged from 30 to 54.

3. Based on excellent wear- and polish-resistance and the lowest processing costs, aggregate produced from calcined serpentine waste was rated best of those materials evaluated.

4. Other aggregate materials showing excellent polish- and wear-resistance and relatively low production costs included expanded waste slate overburden, calcined copper mill tailings, sintered coal refuse, and mixtures of aluminum processing waste and high alumina clays or fire clays.

5. Production costs for the aggregates tested ranged from $10.62/ton for calcined serpentine waste to $120.09/ton for mixtures of periclase and waste glass. Other materials showing low production costs included calcined copper mill tailings ($13.58/ton), expanded waste slate overburden ($13.05/ton), sintered coal refuse ($18.56/ton) and mixtures of aluminum processing wastes and high A_2O_3 clays ($34.25/ton) or refractory fire clays ($35.98/ton).

TABLE 9. -- MICROTEXTURE MEASUREMENTS OF SYNTHETIC CERAMIC ROADWAY AGGREGATES

SAMPLE NO.	P.V.	BEFORE POLISHING DENSITY (PEAKS μm)	HEIGHT (μm)	SHAPE FACTOR	P.V.	AFTER POLISHING DENSITY (PEAKS μm)	HEIGHT (μm)	SHAPE FACTOR
82	55	0.0051	50	0.256	46	0.0052	38	0.197
122A	57	.0065	38	.247	45	.005	33	.171
150	55	.0029	55	.160	-	.003	48	.142
203	60	.004	45	.180	42	.0041	37	.150
262	55	.0056	32	.180	43*	.0055**	28**	.150**
271	54	.0052	36	.184	43*	.0044**	35**	.155**
273	60	.0047	41	.191	44*	.005	32	.159
274	53	.0047	40	.189	39	.004	36	.142
277	51	.0051	43	.220	34	.0043	47	.203
289	48	.0046	41	.186	30	.0037	34	.123
290B	49	.0033	39	.128	32	.0029	30	.086

* One or more stones plucked during the polishing test.
** One or more stone measured for microtexture plucked during the polishing test.

REFERENCES

1. Hosking, J. R. Aggregates for Skid-Resistant Roads. Materials Division, Highway Department, Transportation and Road Research Laboratory, (Crowthorne, Berkshire, England), Report No. LR 693, 1976, 30 pp.

2. 1976 Annual Book of ASTM Standards, Part 17, Standard Specifications for Refractories, Glass, Ceramic Materials; Carbon and Graphite Products (C24-72), American Society for Testing and Materials, Philadelphia, PA, 1976.

3. University of Kentucky Research Foundation. An Implementation Plan for Industrial Development Related to Coal Refuse Utilization in Estill County, Kentucky. Contract No. 76-143/NY-4567-76, Dec. 1977, IV pp. II-1 - III-6.

4. 1978 Annual Book of ASTM Standards, Part 16, Standard Specifications for Sampling and Testing Brick and Structural Clay Tile (C67-78), American Society for Testing and Materials,Philadelphia, PA, 1978.

5. 1978 Annual Book of ASTM Standards, Part 15, Standard Specification for Road, Paving, Bituminous Materials; Skid Resistance (D3319-74T, E303-74, C-131-76, E660), American Society for Testing and Materials, Philadelphia, PA, 1978.

6. Patty, T. S. Accelerated Polish Test for Coarse Aggregate. Materials and Tests Division, Texas Highway Department, (Austin, TX), August 1973, 13 pp.

7. Development of Laboratory Method of Predicting Wear-Resistance of Aggregates; Report No. FHWA MD-R-77-1, Maryland State Highway Administration, Brooklandville, MD.

8. Aleshin, E. Utilization of Waste By-Products. American Foundrymen's Society Transactions, v. 73, 1968, pp. 313-322.

9. Abrahams, Jr., J. H. Recycling Container Glass - An Overview. Proc. of the 3rd Mineral Waste Utilization Symp., Mar. 14-16, 1972, Chicago, ILL, edited by M. A. Schwartz, pp. 35-44.

10. Carlson, J. W. Granulated and Air Cooled Slag for Road Construction. Public Works, v. 89, No. 12, Dec. 1958, pp. 82-83.

11. Charmbury, H. B. Panel Discussion on Utilization of Coal Mining Wastes. 2nd Mineral Waste Utilization Symp. Proc., IIT Research Institute, Chicago, ILL, 1970, pp. 225-227.

12. Charmbury, H. B. and Maneval, D. R. The Utilization of Incinerated Anthracite Mine Refuse as Anti-Skid Highway Material. 3rd Mineral Waste Utilization Symp. Proc., IIT Research Institute, Chicago, ILL, 1972, pp. 123-128.

13. Clifton, J. R., P. W. Brown, and G. Frohnsdorff. Survey of Uses of Waste Materials in Construction in the United States. National Bureau of Standards, Materials and Composites Section, Washington, D.C., July 1977, 55 pp.

14. Collins, R. J. Availability of Mining Wastes and Their Potential for Use as Highway Material: Volume II, Location of Mining and Metallurgical Wastes and Mining Industry Trends. Report No. FHWA-RD-76-107, 1976, U.S. Dept. of Transportation, Federal Highway Administration, Offices of Research and Development, Washington, D.C., 138 pp.

15. Collins, R. J. and R. H. Miller. Availability of Mining Wastes and Their Potential for Use as Highway Material: Volume I, Classification and Technical and Environmental Analysis, Report No. FHWA-RD-76-106, 1976, U.S. Dept. of Transportation, Federal Highway Administration, Offices of Research and Development, Washington, D.C., 308 pp.

16. Cutler, I. B. and P. Nicholson. Ceramic Products from Mineral Wastes. Proc. of the 2nd Mineral Waste Utilization Symp., Mar. 18-19, 1970, Chicago, ILL, edited by M. A. Schwartz, pp. 149-154.

17. Fly Ash Utilization. U.S. Dept. of Interior. BuMines IC 8483, Washington, D.C., 1970.

18. Fondriest, F. F. and Synder, M. J. Synthetic Aggregates for Highway Construction. NCHRP Report No. 8, Highway Research Board, 1964.

19. Gutt, W. Aggregates From Waste Materials. Chemistry and Industry, No. 11, June 3, 1972, pp. 439-447.

20. Gutt, W. and P. J. Nixon. Use of Waste Materials in the Construction Industry (Analysis of the RILEM Symp. by Correspondence), Materiaux et Constructions, v. 12, No. 70, 1979, pp. 255-305.

21. Lenhart, W. B. Aggregates from Mine Wastes. Rock Products, v. 53, No. 5, May 1950, pp. 94-95.

22. Marek, C. R., M. Herrin, C. E. Kesler, and E. J. Barenberg. Promising Replacements for Conventional Aggregates for Highway Use National Cooperative Highway Research Program Report No. 135, Highway Research Board, Washington, D.C., 1972

23. Miller, R. H. and R. J. Collins. Waste Materials as Potential Replacement for Highway Aggregates. Proc. of the 4th Mineral Waste Utilization Symp., May 7-8, 1974, Chicago, ILL, edited by E. Aleshin, pp. 50-61.

24. _____. Wastes Materials as Potential Replacements for Highway Aggregates. National Cooperative Highway Resource Program Report

No. 166, Highway Research Board, Washington, D.C., 1976

25. Moulton, L. K. Bottom Ash and Boiler Slag, Ash Utilization. Proc. 3rd Internat. Ash Utilization Symp. Sponsored by National Coal Assoc., Edison Electric Institute; American Public Power Assoc.; National Ash Assoc.; and Bureau of Mines, Pittsburgh, PA, March 13-14, 1973, BuMines IC 8640, Washington, D.C., 1974, pp. 148-169.

26. Nakamura, H. H., E. Aleshin, and M. A. Schwartz. Utilization of Copper, Lead, Zinc, and Iron Ore Tailings. 2nd Mineral Waste Utilization Symp. Proc, IIT Research Institute, 1970, pp. 139-148.

27. Nakamura, H. H., and M. A. Schwartz. Utilization of Mining and Milling Wastes. Illinois Institute of Technology, Research Institute, Project No. G6027, May 15, 1970.

28. Patankar, U. M., E. Palermo, G. D. Gindlesperger, and M. R. Taylor. Evaluation of the Economic and Environmental Feasibility of Using Fused and Unfused Incinerator Residue in Highway Construction. Report No. FHWA-RD-79-83, 1979, U.S. Dept. of Transportation, Federal Highway Administration, Offices of Research and Development, Washington, D.C., 131 pp.

29. Road Research: Use of Waste Materials and By-Products in Road Construction. Prepared by an OECD Road Research Group, Sept. 1977, pp. 21-28 and 158-164.

30. Toyabe, Y. and G. Matsumoto. Manufacturing Ceramic Goods Out of Mining Wastes. Proc. of the 4th Mineral Waste Utilization Symp., May 7-8, 1974, Chicago, ILL, edited by E. Aleshin, pp. 240-244.

31. Utley, R. W., H. L. Lovell, and T. C. Spicer. The Utilization of Coal Refuse for the Manufacture of Lightweight Aggregate. Penn. State Univ., Special Research Report No. SR-46, Sept. 1, 1964, 110 pp.

32. Vogley, W. A. The Economic Factors of Mineral Waste Utilization. 1st Mineral Waste Utilization Symp. Proc., IIT Research Institute, Chicago, ILL, 1968, pp. 7-19.

33. Maneval, D. R. Coal Refuse Utilization Prospects - An Update of Recent Work, Proceedings of the 2nd Symp. on Coal Preparation, NCA/BCR Coal Conf. and Expo. III, Louisville, KY, Oct. 1976.

34. The Cake That Dwight and Lloyd Baked. McDowell-Wellman Engineering Co., Cleveland, OH, 1958.

35. Brownell, W. E., Professor, New York State College of Ceramics, Alfred University, Alfred, NY. X-ray Examination of Clay-Like Material from West Pawlet, Vermont. Nov. 14, 1977 (available through the State of Vermont, Agency of Environmental Conservation, Montpelier, VT.)

36. Federal Register, Vol. 38, No. 66, April 6, 1973, p. 8,822.

37. Mullen, W. G. Skid Resistance Laboratory Procedures and Equipment at North Carolina State University. Presented to the Canadian Technical Asphalt Association, Toronto, Canada, Nov. 24-26, 1975.

38. Forster, S. W.. Automated Aggregated Microtexture Measurement: Description and Procedures, Oct. 4, 1978. Available through the Federal Highway Administration, Office of Research, Materials Division, Langley, VA.

39. ____. Federal Highway Administration, Office of Research, Materials Division, Langley, VA (personal correspondence).

APPENDIX I

ANNOTATED BIBLIOGRAPHY

The following annotated bibliography covers references dealing with the production of synthetic ceramic aggregate. Aggregate manufacture is not limited to highway usage, since this comprises only a small portion of total aggregate production. Emphasis is placed on raw materials and the equipment required for fabrication. Raw materials, which can vary greatly with time and location, have a significant influence on aggregate final properties. Equipment and process variables, however, remain essentially the same.

1. Bell, W. C. Proper Pelletizing Technique-Key to Efficient Sintering of Aggregate. Brick and Clay Record, v. 120, Jan 1952, pp. 46, 49, and 52.

Pelletization, extrusion, and briquetting as techniques for the formation of an aggregate are discussed. Particle sizing, pellet packing density, fuels, and fuel ratios are analyzed.

2. Bell, W. C., and O. H. McGinnis. The Development of Large Lightweight Structural Clay Building Units (I. Development of Lightweight Clay Aggregates by the Sintering Method). Am. Ceram. Soc. Bull., v. 30, Oct. 1951, pp. 333-436.

The manufacture of lightweight aggregates using a sinter grate furnace was studied. Shales, clays, and coke were agglomerated and sintered at temperatures ranging from 2,000° to 2,670° F. Process variables such as pelletization, packing density, loading procedures, and fuel requirements are analyzed.

3. Bergstrom, J. H. Lightweight Launched in New England. Rock Products, v. 65, Oct. 1962, pp. 54-58.

The manufacture of expanded shale from mine to the finished product at Masslite, Inc., is described. Seventy pct shale, 23 pct sinter returns, and 7 pct coal are mixed and used as feed to a 1,000 tpd sinter hearth furnace. The sintered product is crushed and ground to the desired particle size. Flowsheet giving equipment and its plant location are included in the article.

4. Bergstrom, J. H. Nytralite is Newest Contender in Lightweight Scramble. Rock Products, v. 65, Dec. 1962, pp. 58-62.

Nytralite is a 1,000 tpd expanded shale plant. Shale is mined, crushed, screened, and fired in a rotary kiln at 2,100° F. Kiln feed allows for 10 pct dust, moisture, and ignition losses. A rotary cooler is used to recover heat from the fired product. The fired material is screened and shipped from the plant by barge. A process flowsheet, feed rates, and major equipment list are included.

5. Biege, H. W., and S. M. Cohen. Cut Fuel Costs in the Lightweight Aggregate Industry. Am. Ceram. Soc. Bull., v. 54, June 1975, pp. 569-70.

An analysis is made of ways to conserve fuel in a rotary kiln while manufacturing lightweight aggregate. Three areas of heat losses in a rotary system are examined: the kiln product, the exit gases, and the production volume. A 1,000 tpd rotary kiln is used to analyze Btu consumption for various raw material feed rates. Lifters, quandrants, and a grate cooler are also investigated for their effect on fuel consumption.

6. Bonifay, P. W., W. W. Scott, J. A. Epps, and B. M. Gallaway. Rotary Kiln-Fired Synthetic Aggregates Manufactured from Texas Lignite Fly Ash. Texas Transportation Institute (College Station, Texas), Highway Research Record No. 355, 1977, pp. 25-30.

Six types of aggregates were manufactured from fly ash and evaluated as potential highway aggregate material. Different firing times were investigated for their influence on finished product properties.

7. Boux, J. F. Development of a Process for the Production of Lightweight Aggregate and Pozzolan from Lakeview Generating Station Fly Ash. The Canadian Min. and Met. Bull., v. 63, No. 700, Aug. 1970, pp. 921-26.

Fly ash from the Lakeview Power Station in Canada is processed into a lightweight aggregate. The ash is pelletized, sintered in a hearth furnace, and crushed to the desired particle size. A description and flowsheet of the process are included.

8. Brick and Clay Record. Continuity Key to Shalite's High Production. v. 129, No. 5, Nov. 1956, pp. 40-43.

Shalite Corp. produces 400 cu yd of aggregate per day from shale which is mined, aged, crushed, screened, mixed with fly ash and sinter returns, and fired in a sinter hearth furnace at 2,400° F. The fired material is crushed and screened to the desired particle size. Fuel consumption for the process and a list of equipment and suppliers are included in the article. Reasons for the choice of a sinter hearth furnace over a rotary kiln are also included.

9. Brick and Clay Record. Factors in Making Light-weight Aggregate by Sintering Process. v. 116, No. 6, June 1950, pp. 48, 84, and 86.

An explanation is given of the sinter hearth process for manufacturing lightweight aggregate. A comparison is made of the sinter hearth furnace to other manufacturing processes, including estimates for equipment, plant and finished product costs.

10. Brick and Clay Record. Onondaga Successfully Converts to Lightweight Aggregate. v. 129, No. 4, Oct. 1956, pp. 73-75.

Onondaga Brick Co. opened a lightweight aggregate plant producing 600 cu yd of aggregate per day from shale. Equipment from their old brick plant was modified and utilized in the aggregate plant. Seventy pct shale, 5 pct coal fines, and 25 pct sinter returns are pelletized with a small amount of water for furnace feed. The material is sintered in a sinter hearth furnace, cooled, and crushed to the desired size fractions. Equipment lists and suppliers are included in the article.

11. Brick and Clay Record. Sintering Machine Makes Aggregate from a Variety of Clays. v. 116, No. 5, May 1950, pp. 52-55.

Marietta Concrete Corp. produces 250 cu yd of lightweight aggregate per 8 hour shift from a mixture of clay, shale, and coal. Clay and shale are mined near the plant, crushed, screened, and fed to a pug mill where the material is agglomerated with fuel and sinter returns. The material is then sintered in a sinter grate furnace, crushed, and screened to the desired particle sizes. Plant operation and capabilities are discussed.

12. Capp, J. P. and J. D. Spencer. Fly Ash Utilization, A Summary of Applications and Technology. BuMines IC 8483, 1970, 72 pp.

The pelletization, sintering, and processing of fly ash into a lightweight aggregate and the potential areas of utilization of the aggregate are analyzed. An economic evaluation for a 1,000 tpd plant making aggregate and an evaluation of finished product properties are reviewed.

13. Catchpole, F. Production of Lightweight Aggregate by the Sinter-Hearth Process. Trans. Brit. Ceram. Soc., v. 56, No. 10, Nov. 19pp. 519-28.

The use of the sinter hearth furnace to manufacture lightweight aggregate is discussed. All phases of processing a shale into a lightweight aggregate, including pollution control equipment, are analyzed.

14. Cohen, S. M. How to Make Lightweight Aggregate Production Fuel Efficient. Rock Products, v. 81, No. 12, Dec. 1978, pp. 68-72.

Ways to lower the fuel costs in a rotary kiln and make its operation more efficient are discussed. High fuel consumption due to raw materials properties, poor firing practices, and inadequate equipment are analyzed. Techniques to improve heat losses caused by convection and radiation in the kiln shell, the product, and the exit gases are discussed. Four types of coolers to recover heat from the fired product are compared. The influence of excess air and kiln internals is also discussed. Fuel savings and cost breakdowns are given in the several systems.

15. Cohen, S. M. and N. W. Biege. Lightweight Aggregate Designing and Operating for Quality Product. Pres. Ann. Meet. of Am. Ceram. Soc., Washington, D.C., May 8-11, 1972; available upon request from Fuller Company, Catasauqua, PA.

An explanation of raw material properties and processing conditions necessary for the production of a lightweight aggregate are given. The finished properties of highway aggregates are related to kiln operating conditions. Future trends in lightweight aggregate production are predicted.

16. Dehir, S. H., and J. J. Henry. Alternatives for the Optimization of Aggregate and Pavement Properties Related to Friction and Wear Resistance. The Pennsylvania State University. Report No. FHWA-RD78209, Apr. 1978, 284 pp; available from National Technical Information Service, Springfield, VA.

An investigation was made into highway road aggregates and their performance. Energy necessary for firing fly ash, shale, and coal refuse into aggregates and the process variables for the manufacture of aggregates in tunnel kilns, rotary kilns, electric furnaces, and other firing systems are presented. Present and past usage of highway aggregates and fabrication techniques, such as those for manufacturing Synopal and calcined bauxite, are detailed. Phase diagram analysis of aggregate systems is done in an attempt to predict means of making quality aggregates.

17. Davies, W. (assigned to John G. Stein and Co. Ltd, Bonnybridge, Scotland). Sintered Aggregates. U.S. Pat. 3,607,339, Sept. 21, 1971.

The composition and manufacture of a highway road aggregate using cheap, available raw materials is discussed. The cellular structure of the finished product along with the ability of some grains to tear out gives the aggregate its good skid resistance. Raw materials, types of processing equipment, and formulation variations are discussed.

18. Flint, E. P. Select Proper Burning Equipment. Brick and Clay Record, v. 116, No. 4, Apr. 1950, pp. 65-66, and 69.

The rotary kiln and sinter hearth furnaces were evaluated for manufacturing lightweight aggregates. The rotary kiln was felt to give higher quality aggregates while the sinter hearth was able to treat a wider variety of raw materials. The sinter hearth furnace was also felt to be of more use in processing materials with a short firing range. Additives that promote bloating of the materials are discussed. Fixed-grate and fixed-grate updraft sintering machines were compared. Equipment costs and modifications for all systems are analyzed.

19. Gallaway, B. M., J. A. Epps, and W. W. Scott, Jr. A Study of the Feasibility of Producing Lightweight Aggregate from Texas Lignite Fly Ash. Texas A&M Research Foundation, (College Station, Texas), Sept. 1969, 27 pp. (prepared for Industrial Generating Co., Gifford-Hill & Co., Inc,; Aluminum Co. of America; Texas Power and Light Co.

Techniques for processing fly ash into a lightweight aggregate were examined. Pelletization, moisture levels, additives, bloating times, and firing temperature were discussed.

20. Gutt, W. Aggregates from Waste Materials. Chemistry & Industry, (London), June 3, 1972, pp. 439-447.

Techniques for processing waste material into an aggregate in Britain are discussed. These wastes include blast furnace slag, steel slag, coal wastes, and slate. Processing equipment includes the sinter hearth furnace and the rotary kiln.

21. Herod, B. C. Lightweight Aggregate Operation with Heavyweight Capability...Masslite Inc. Pit and Quarry, v. 55, No. 4, Oct. 1962, pp. 78-83, 115-116.

Production facilities for the manufacture of lightweight aggregate from shale at Masslite, Inc., are described. Present production capacity is 1,000 tpd. Feed to the sinter grate furnace is composed of 70 pct shale, 7 pct coal, and 23 pct sinter returns. Flowsheets for the overall process are given.

22. Hosking, J. R. Synthetic Aggregates of High Resistance to Polishing. Part I, Gritty Aggregates. Materials Section, Road Research Laboratory (Crowthorne, Berkshire, England), Report No. LR 350, 1970, 35 pp.

This report analyzed highway road aggregates for high wear sites requiring good skid resistance. Emphasis is directed toward those aggregates which are a hard grit in a soft matrix. Both natural and synthetic aggregates were evaluted. Processing techniques for commercial production of sintered aggregates are discussed.

23. Industrial Minerals. CE Minerals: Georgian Bauxite and Kaolin Calcined for Refractory Grog. May 1972, pp. 17, 19-22.

The operation of CE Minerals plant for calcining kaolin and bauxite into three grades of calcined kaolin is described. Production volume is 250,000 tpa. Mining, mixing, firing, and shipping are some of the operations described.

24. Jeffers, P. E. Expanding Slate for Lightweight Aggregate. Brick and Clay Record, v. 164, No. 4, Apr. 1974, pp. 28-31.

Hercules Inc. expands slate into lightweight aggregate. Black slate is mined, transported to the plant, crushed, ground and fed to the rotary kiln. Methods of improving heat transfer in the rotary kiln during firing are described. The sintered aggregate is cooled, crushed, and screened to the desired particle size. An equipment list and a list of suppliers are included.

25. Jeffers, P. E. New Plant Streamlines Production at Weblite. Brick and Clay Record, v. 164, No. 2, Feb. 1974, pp. 28-30.

The plant expansion of Weblite Corp., a lightweight aggregate manufacturer, is described. In their manufacturing process, shale and coal are mined, crushed, mixed with 30 to 40 pct sinter returns, pelletized, and sintered in a sinter hearth furnace to form a lightweight aggregate. The material is then processed to the desired particle size. A list of equipment suppliers is included in the article.

26. Jeffers, P. E. Shalite: Success Story for Lightweight Aggregate. Brick and Clay Record, v. 166, No. 2, Feb. 1975, pp. 23-25.

The processing of shale into an expanded aggregate at Shalite Corp. is explained. Shale is mined, crushed, screened, and mixed with coke breeze, fly ash residue, and sinter returns. Water is added to the mixture causing agglomeration, and the agglomerated material is fed to a sinter grate furnace. After firing, the material is crushed, screened, and stored. Flowsheets and equipment supplier lists are included.

27. Josephson, G. W., F. Sillers, and D. G. Runner. Iron Blast-Furnace Slag Production, Processing, Properties, and Uses. BuMines Bull. 479, 1949, 304 pp.

Blast furnace slag manufacture, use, and history are discussed. Details are given of different methods of processing blast furnace slag, of its handling, and of its finished properties. A plant layout is described.

28. Kroyer, K. K. K. Aggregate Material for Construction Materials, Particularly Road Construction Materials, and Process for Producing Same. British Pat. 897,125, May 23, 1962.

The manufacture of a highway road aggregate consisting of hard, white, non-absorbent grains of devitrified glass is described. A composition range for the glass and manufacturing processes using a rotary kiln, a batch rotary drum, a glass melting tank, and molding blocks are described. A flowsheet, operating conditions, and necessary equipment for the aggregate production are given.

29. Levine, S. Sintering Control for Lightweight Aggregate Processing at Masslite. Nonmetallic Minerals Processing, v. 3, No. 10, Oct. 1962, pp. 20-24.

Masslite Inc., produces 1000 tpd of an expanded shale lightweight aggregate. Mix composition is 44 pct shale, 6 pct coal, and 50 pct sinter returns with water added as a binder. A disc pelletizer agglomerates these materials and feeds them to a sinter grate furnace. After firing, the material is crushed and screened to a desired particle size. Equipment lists and a process flowsheet are included.

30. Milas, J. E. Sintering Machine Expands Clay at 50-tph Rate. Rock Products, v. 73, No. 6, June 1970, pp. 48-51, and 96.

Construction Aggregates Corp. produces an expanded clay aggregate at the rate of 50 tph. Market evaluation before plant startup and an investigation into types of furnace for aggregate production are included. Operation of the plant for aggregate manufacture, plant layout, flowsheets, and equipment references are given.

31. Miller, R. H. and R. J. Collins. Waste Materials as Potential Replacements for Highway Aggregates. National Cooperative Highway Research Program Report No. 166, Transportation Research Board, National Research Council, 1976, 94 pp.

An investigation was made into potential aggregate uses for the 3.5 billion tons of solid waste being generated annually. Types, sources, locations, quantities, and past and present uses of wastes having potential as a highway aggregate are listed. Maps of areas in the United States with aggregate shortage and maps of available waste materials are included. An economic evaluation including plant equipment, production costs, and environmental aspects is made for several of the promising aggregate systems.

32. Park, B. F., and B. C. Herod. Buildex Doubles Expanded Shale Production. Pit and Quarry, v. 54, No. 8, Feb. 1962, pp. 108-111, 114, 122.

Buildex, Inc., produces lightweight aggregate from shale. Shale is mined, crushed to a desired particle size, and fed to a rotary kiln where it is fired at 2,100° F. The fired material is transferred to a cooling pile, crushed, and screened. Plant layout, flowsheets, and equipment types are included in the article.

33. Pearson, A. S., and F. Asce. Lightweight Aggregate From Fly Ash. Civil Engineering, v. 34, No. 9, Sept. 1964, pp. 50-53.

Consolidated Edison uses fly ash from several of its power plants to produce 1000 tpd of lightweight aggregate. The fly ash is pelletized at 22 pct moisture and sintered at 2,300° F in a sinter grate furnace. It is then processed to the desired particle size.

34. Pfeiffenberger, L. E. Problems of Manufacturing Lightweight Aggregate by the Moving Grate Process. Am. Ceram. Soc. Bull., v. 36, No. 7, July 1957, pp. 272-275.

Process and raw material variables associated with the use of the sinter grate furnace for lightweight aggregate production are discussed. Variable aggregate quality is traced back to the raw clay, fuel, recycled material, pellet fabrication, and the placement of pellets on the grate.

35. Pindzola, D., and R. C. Chou. Synthetic Aggregate From Incinerator Residue by a Continuous Fusion Process. The Franklin Inst. Research Labs (Philadelphia, PA), Rept. FHWA-RD-74-23, Apr. 1974, 58 pp.

Waste residue from garbage plants is processed into a highway road aggregate. The aggregate forming process reduces garbage particle size by hammermilling, burns out the combustiles at 1,600° F, fires the residue at 2,000° F, and cools it at a controlled rate.

An in-depth study of the process is made including flowsheets, equipment, operating parameters, and cost estimates for plant operation and startup. The finished product was evaluated as a highway road aggregate.

36. Pit and Quarry. Fly Ash Transformed to Lightweight Aggregate via Lytag Process. v. 71, No. 3, Sept. 1978, pp. 82-83.

The manufacture of lightweight aggregate from fly ash is briefly described. Fly ash is pelletized in a tilted disc nodulizer and fed to a sinter hearth furnace where it is sintered at 1,300° C. The material is then crushed, and ground to the desired particle size. A flowsheet of the 250,000 cu meter/year process is given.

37. Pit and Quarry. Garbage - A New Aggregate Source. v. 68, No. 12, June 1976, pp. 100-101.

The Franklin Institute Research Lab. developed a process for making a highway road aggregate from garbage. In the process, waste material is crushed, screened, and fed to a rotary kiln. The material is preheated in the kiln and fed to a second furnace where it is fused at 2,000° F. It is then processed to an aggregate by crushing and screening.

38. Trauffer, W. E. Nytralite Barged Down Hudson to New York City Area. Pit and Quarry, v. 55, No. 8, Feb. 1963, pp. 86-95.

Nytralite Aggregate Co. makes 1,500 cu yd per day of lightweight aggregate from shale. Shale is mined, crushed, screened, and fed to a rotary kiln. Crushing of the finished product is eliminated through close control of the feed material. A detailed explanation of controls, safeguards, electrical connections, flowsheets, and equipment of this plant is included. Techniques used to make production more efficient are discussed.

39. Roy, D. M., H. E. Shull, P. D. Cady, W. E. Meyer, H. D. Batha, R. Naum, and R. Willet. Advanced Technology Materials Applied to Guideways, Highways, and Airport Runways. Pennsylvania State University. (University Park, Pennsylvania). Report DOT-OS-40009, Apr. 1977, 204 pp.; available from National Technical Information Service, Springfield, VA.

An investigation was made into advanced technology ceramic materials for use in high traffic areas. The wear resistance of five types of dense firebrick was investigated with different surface textures cut in the brick. A discussion of currently available and potential aggregate materials, processing techniques, and finished products costs is included in the study.

40. Stearn, E. W. Open House Unveils Revitalized Shale Plant. Rock Products, v. 75, No. 12, Dec. 1972, pp. 74-75.

Masslite, Inc., redesigned its plant facilities to produce 1,000 tpd of aggregate. Sandstone and shale are mined, mixed with coal, and fed directly to a sinter grate furnace. The material is then crushed and screened to the desired particle size. Several equipment manufacturers for the process are given.

41. Stearn, E. W. Sintering Plant Thrives After 300-Mile Move. Rock Products, v. 76, No. 2, Feb. 1973, pp. 80-81, and 99.

Onondaga Lightweight Aggregate Corp. acquired Consolidated Edison's fly ash sintering plant and had it moved from Queens to Syracuse, NY. Modifications were made in the system to enable it to sinter shale instead of fly ash into lightweight aggregate. A mixture of coal and shale is pelletized and fed to the sinter hearth furnace. The sintered product is water cooled, crushed, and ground to the desired particle size. An equipment list and flowsheet are included in the discussion.

42. University of Kentucky Research Foundation. An Implementation Plan for Industrial Development Related to Coal Refuse Utilization in Estill County, Kentucky. Contract No. 76-143/NY-4567-76, Dec. 1977, IV (various pagings).

Sixty-five tons of bituminous coal refuse from a coal plant in Kentucky was fired in a sinter grate furnace forming lightweight aggregate. Process conditions and product quality were evaluated to optimize process parameters and find potential product uses. Flowsheets and material balances for each process are included. The level of pollution emmissions from the process was also discussed. An in-depth economic evaluation of several sintering systems for the manufacture of 1000 tpd of aggregate is included.

43. University of Kentucky Research Foundation. Feasibility Study of Utilization of Coal Mine Refuse, Estill County, Kentucky. Prepared for the Appalachian Regional Commision (Washington, D.C.). Report No. ARC 74-217-KY-3685, Aug. 1976, IV. (various pagings); available from National Technical Information Service, Springfield, VA, PB-273 470.

Coal refuse utilization from Estill County, KY is discussed. The chemical and physical properties of refuse are characterized and potential uses examined. Sintering and air pollution tests in a sinter hearth furnace and a rotary kiln were conducted on 65 tons of sample. Test results and an estimate on the selling price of the finished aggregates are included. Flowsheets for a 1,000 tpd operation, details on the manufacturing process, and a market analysis of the aggregate are included.

44. Utley, H. F. Crestlite's New Expanded Shale Aggregate Plant. Pit and Quarry, v. 55, No. 3, Sept. 1962, pp. 94-97, and 102.

Crestlite produces 1,000 cu yd per day of lightweight aggregate from shale. Shale is mined, air-dried, crushed, screened and fired at 2,000° F in a rotary kiln. Techniques to improve kiln efficiency are mentioned. The fired product is screened and sold.

45. Utley, H. F. Utelite's New Plant Makes Expanded Shale Available to Intermountain Region. Pit and Quarry, v. 56, No. 3, Sept. 1963, pp. 125-127.

Utelite Corporation produces 300 cu yd per day of lightweight aggregate. Shale deposits are mined, air-dried, crushed, and screened. The material is fired in a rotary kiln at 2,000° F, then screened, and stored in piles for shipment.

Coal refuse utilization from Estill County, KY is discussed. The chemical and physical properties of refuse are characterized and potential uses examined. Sintering and air pollution tests in a sinter hearth furnace and a rotary kiln were conducted on 65 tons of sample. Test results and an estimate on the selling price of the finished aggregates are included. Flowsheets for a 1,000 tpd operation, details on the manufacturing process, and a market analysis of the aggregate are included.

44. Utley, H. F. Crestlite's New Expanded Shale Aggregate Plant. Pit and Quarry, v. 55, No. 3, Sept. 1962, pp. 94-97, and 102.

Crestlite produces 1,000 cu yd per day of lightweight aggregate from shale. Shale is mined, air-dried, crushed, screened and fired at 2,000° F in a rotary kiln. Techniques to improve kiln efficiency are mentioned. The fired product is screened and sold.

45. Utley, H. F. Utelite's New Plant Makes Expanded Shale Available to Intermountain Region. Pit and Quarry, v. 56, No. 3, Sept. 1963, pp. 125-127.

Utelite Corporation produces 300 cu yd per day of lightweight aggregate. Shale deposits are mined, air-dried, crushed, and screened. The material is fired in a rotary kiln at 2,000° F, then screened, and stored in piles for shipment.

APPENDIX II

DESCRIPTION AND INITIAL CHARACTERIZATION OF SYNTHETIC AGGREGATES

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
1	Tab Al_2O_3 (minus 48-, plus 100-mesh) and plastic kaolin	Pressed	1450	43	1
2	Tab Al_2O_3 (minus 28-, plus 48-mesh) and plastic kaolin	...do..	.do.	44	1
3	Tab Al_2O_3 (minus 14-, plus 28-mesh) and plastic kaolin	...do..	.do.	43	1
4	Tab Al_2O_3 (minus 8-, plus 14-mesh) and plastic kaolin	...do..	.do.	—	1,2
5	Tab Al_2O_3 (minus 6-, plus 8-mesh) and plastic kaolin	...do..	.do.	—	1,2
6	SiC (minus 48-, plus 100-mesh) and plastic kaolin	...do..	.do.	45	1
7	SiC (minus 28-, plus 48-mesh) and plastic kaolin	...do..	.do.	48	1
8	SiC (minus 14-, plus 28-mesh) and plastic kaolin	...do..	.do.	46	1
9	SiC (minus 8-, plus 14-mesh) and plastic kaolin	...do..	.do.	—	1,2
10	SiC (minus 6-, plus 8-mesh) and plastic kaolin	...do..	.do.	—	1,2
11	MgO (brine) and plastic kaolin	...do..	.do.	45	1
12	MgO (seawater) and plastic kaolin	...do..	.do.	47	1
13	MgO (magnesite) and plastic kaolin	...do..	.do.	45	1
14	Brucite and plastic kaolin	...do..	.do.	43	3
15	Fire clay grog and plastic kaolin	...do..	.do.	--	2
16	Calcined bauxite and plastic kaolin	...do..	.do.	--	2
17	Calcined bauxite (Alabama) and plastic kaolin	...do..	.do.	—	2
18	Fly ash (Gorgas) and plastic kaolin	...do..	1200	42	
19	Fly ash (Wilsonville) and and plastic kaolin	...do..	1100	44	
20	Bubbled Al_2O_3 and plastic kaolin	...do..	.do.	44	
21	Tab Al_2O_3 (minus 48-, plus 100-mesh) and low PCE shale	...do..	.do.	48	1

[1] High raw material cost
[2] No bond, highly friable
[3] Limited raw material availability
[4] High processing cost
[5] Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
22	Tab Al_2O_3 (minus 28-, plus 48-mesh) and low PCE shale	Pressed	1100	50	1,2
23	Tab Al_2O_3 (minus 14-, plus 28-mesh) and low PCE shale	...do..	.do.	41	1
24	Tab Al_2O_3 (minus 8-, plus 14-mesh) and low PCE shale	...do..	.do.	—	1,2
25	Tab Al_2O_3 (minus 6-, plus 8-mesh) and low PCE shale	...do..	.do.	—	1,2
26	SiC (minus 48-, plus 100-mesh) and low PCE shale	...do..	.do.	48	1
27	SiC (minus 28-,plus 48-mesh) and low PCE shale	...do..	.do.	49	1
28	SiC (minus 14-, plus 28-mesh) and low PCE shale	...do..	.do.	44	1
29	SiC (minus 8-, plus 14-mesh) and low PCE shale	...do..	.do.	--	1,2
30	SiC (minus 6-, plus 8-mesh) and low PCE shale	...do..	.do.	—	1,2
31	Bubbled Al_2O_3 and low PCE shale	...do..	.do.	51	1
32	MgO (brine) and low PCE shale	...do..	.do.	44	1
33	MgO (seawater) and low PCE shale	...do..	.do.	51	1
34	MgO (magnesite) and low PCE shale	...do..	.do.	46	1
35	Fire clay grog and low PCE shale	...do.	.do.	40	
36	Brucite and low PCE shale	...do..	.do.	55	3
37	Calcined bauxite and low PCE shale	...do..	.do.	—	2
38	Calcined bauxite (Alabama) and low PCE shale	...do..	.do.	—	2
39	Tab Al_2O_3 (minus 48-, plus 100-mesh) and fly ash	...do..	1260	54	1
40	Tab Al_2O_3 (minus 28-, plus 48-mesh) and fly ash	...do..	.do.	53	1
41	Tab Al_2O_3 (minus 14-, plus 28-mesh) and fly ash	...do..	.do.	54	1,2
42	Tab Al_2O_3 (minus 8-, plus 14-mesh) and fly ash	...do..	.do.	--	1,2
43	Tab Al_2O_3 (minus 6-, plus 8-mesh) and fly ash	...do..	.do.	—	1,2

1 High raw material cost
2 No bond, highly friable
3 Limited raw material availability
4 High processing cost
5 Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
44	SiC (minus 48-, plus 100-mesh) and fly ash	Pressed	1260	52	1
45	SiC (minus 28-, plus 48-mesh) and fly ash	...do..	.do.	51	1
46	SiC (minus 14-, plus 28-mesh) and fly ash	...do..	.do.	48	1
47	SiC (minus 8-, plus 14-mesh) and fly ash	...do..	.do.	--	1,2
48	SiC (minus 6-, plus 8-mesh) and fly ash	...do..	.do.	--	1,2
49	Tab Al_2O_3 (minus 48-, plus 100-mesh) and waste glass	...do..	940	50	1
50	Tab Al_2O_3 (minus 28-, plus 48-mesh) and waste glass	...do..	.do.	48	1
51	Tab Al_2O_3 (minus 14-. plus 28-mesh) and waste glass	...do..	.do.	48	1
52	Tab Al_2O_3 (minus 8-, plus 14-mesh) and waste glass	...do..	.do.	43	1
53	Tab Al_2O_3 (minus 6-, plus 8-mesh) and waste glass	...do..	.do.	41	1
54	SiC (minus 48-, plus 100-mesh) and waste glass	...do..	.do.	50	1
55	SiC (minus 28-, plus 48-mesh) and waste glass	...do..	.do.	53	1
56	SiC (minus 14-, plus 28-mesh) and waste glass	...do..	.do.	48	1
57	SiC (minus 8-, plus 14-mesh) and waste glass	...do..	.do.	--	1,2
58	SiC (minus 6-, plus 8-mesh) and waste glass	...do..	.do.	--	1,2
59	Al_2O_3 (minus 8-, plus 200-mesh) and waste glass	...do..	.do.	40	1
60	Al_2O_3 (minus 8-, plus 200-mesh) and plastic kaolin	...do..	1100	40	1
61	Tab Al_2O_3 (minus 8-, plus 200-mesh) and low PCE shale	...do..	.do.	40	1
62	Tab Al_2O_3 (minus 8-, plus 200-mesh) and fly ash	...do..	1540	47	1
63	Tab Al_2O_3 (minus 8-, plus 200) and high PCE clay	...do..	.do.	--	1,2

[1] High raw material cost
[2] No bond, highly frialbe
[3] Limited raw material availability
[4] High processing cost
[5] Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
64	SiC (minus 8-, plus 200-mesh) and waste glass	Pressed	900	—	1,2
65	SiC (minus 8-, plus 200-mesh) and plastic kaolin	...do..	1540	43	1
66	SiC (minus 8-, plus 200-mesh) and low PCE shale	...do..	.do.	48	1,5
67	SiC (minus 8-, plus 200-mesh) and fly ash	...do..	.do.	48	1,5
68	SiC (minus 8-, plus 200-mesh) and high PCE clay	...do..	.do.	44	1
69	Tab Al_2O_3 (plus 4-mesh)	...do..	NA	—	1
70	Calcined Alabama high Al_2O_3 clay	Extruded	1540	42	
71	Refractory grade calcined bauxite (Guyana)	...do..	.do.	54	
72	Calcined clay (47 pct. Al_2O_3)	...do..	.do.	38	
73	Calcined clay (60 pct. Al_2O_3)	...do..	.do.	24	
74	Calcined clay (70 pct. Al_2O_3)	...do..	.do.	28	
75	Calcined fire clay (California)	...do..	.do.	28	
76	Calcined clay/sand mix (California)	...do..	.do.	37	
77	Calcined fire clay (Missouri)	...do..	.do.	30	
78	Calcined fire clay (Pennsylvania)	...do..	.do.	48	
79	Sintered coal refuse (USSC)	Pelletized	1100	54	
80	Sintered coal refuse (EOB)	...do..	.do.	54	
81	Sintered coal refuse (ICP)	...do..	.do.	53	
82	Sintered coal refuse (SEI)	...do..	.do.	53	
83	Sintered coal refuse (BEP)	...do..	.do.	54	
84	Sintered coal refuse (blue clay)	...do..	.do.	54	
85	30 pct. plastic kaolin, 10 pct. limestone, 60 pct. sand	...do..	.do.	—	2
86	20 pct. plastic kaolin, 20 pct. limestone, 60 pct. sand	...do..	.do.	—	2
87	Crushed commercial refractory brick	Crushed and sized	NA	51	3

[1] High raw material cost
[2] No bond, highly friable
[3] Limited raw material availability
[4] High processing cost
[5] Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., °C	PV	COMMENTS (SEE FOOTNOTES)
88	Crushed commercial refractory brick (94 pct. Al_2O_3)	crushed and sized	NA	49	3
89	Crushed commercial refractory brick (90 pct. Al_2O_3)	...do..	NA	44	3
90	Crushed commercial refractory brick (heavy duty fire clay)	...do..	NA	56	3
91	Crushed commercial refractory brick (99 pct. Al_2O_3)	...do..	NA	51	3
92	Crushed commercial refractory brick (99 pct. Al_2O_3)	...do..	NA	28	3
93	Crushed commercial refractory brick	...do..	NA	44	3
94	Boiler slag	...do..	NA	44	2
95	Slate waste and marble waste (sintered)	Pelletized	1200	37	4
96	Slate waste and marble waste (melted)	Melted, cooled, crushed	1500	33	4
97	Commercial calcined clay (43 pct. Al_2O_3)	Crushed and sized	NA	26	
98	Commercial calcined clay (43 pct. Al_2O_3)	...do..	NA	36	
99	Calcined bauxite (Guyana)	...do..	NA	43	
100	Foamed glass/ceramic (slate/marble waste)	Pelletized	Melted-1500 Heat-treated 920	33	
101	Alumina smelter waste (82 pct. Al_2O_3)	Pressed	1500	48	
102	Bottom ash	Crushed and sized	NA	--	2
103	Fly ash (Florence)	Pressed	1225	--	2
104	Crushed commercial refractory (89 pct. Al_2O_3, 11 pct. SiO_2)	Crushed and sized	NA	46	3
105	Crushed commercial refractory (65 pct. Al_2O_3, 22 pct. ZrO_2, 13 pct. SiO_2)	...do..	NA	47	3
106	Crushed commercial refractory (35 pct. Al_2O_3, 60 pct. SiC, 5 pct. SiO_2)	...do..	NA	43	3

1 High raw material cost
2 No bond, highly friable
3 Limited raw material availability
4 High processing cost
5 Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
107	Calcined fire clay and waste glass	Pressed	900	41	
108	Calcined fire clay and waste glass	...do..	.do.	50	
109	90 pct. sand (minus 10-, plus 20-mesh) and 10 pct. waste glass	...do..	.do.	—	2
110	80 pct. sand (minus 10-, plus 20-mesh) and 20 pct. waste glass	...do..	.do.	51	2
111	70 pct. sand (minus 10-, plus 20-mesh) and 30 pct. waste glass	...do..	.do.	44	
112	60 pct. sand (minus 10-, plus 20-mesh) and 40 pct. waste glass	...do..	.do.	45	
113	50 pct. sand (minus 10-, plus 20-mesh) and 50 pct. waste glass	...do..	.do.	44	
114	40 pct. sand (minus 10-, plus 20-mesh) and 60 pct. waste glass	...do..	.do.	48	2
115	90 pct. sand (minus 20-, plus 35-mesh) and 10 pct. waste glass	...do..	.do.	—	2
116	80 pct. sand (minus 20-, plus 35-mesh) and 20 pct. waste glass	...do..	.do.	50	2
117	70 pct. sand (minus 20-, plus 35-mesh) and 30 pct. waste glass	...do..	.do.	49	
118	60 pct. sand (minus 20-, plus 35-mesh) and 40 pct. waste glass	...do..	.do.	47	
119	50 pct. sand (minus 20-, plus 35-mesh) and 50 pct. waste glass	...do..	.do.	47	
120	40 pct. sand (minus 20-, plus 35-mesh) and 60 pct. waste glass	...do..	.do.	48	
121	Tab Al_2O_3 (minus 14-, plus 28-mesh) amd waste slate/marble glass	...do..	1150	41	1
122	Expanded slate waste (Maine)	Crushed and sized	1200	49	
122A	Expanded waste slate overburden	Extruded and chopped	1150	45	
123	Coke	Crushed and sized	NA	60	
124	Lightweight aggregate (Texas)	...do..	NA	45	
125	Foamed glass/ceramic (slate/marble waste)	Pelletized	Melted-1500 heat-treated-920	44	4

1 High raw material cost
2 No bond, highly friable
3 Limited raw material availability
4 High processing cost
5 Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
126	Glass/ceramic (blast furnace slag)	Crushed and sized	920	30	
127	Bauxite with 20 volume pct. rice hulls	Pressed	1530	—	2
128	Coal refuse with 20 volume pct. rice hulls	...do..	1200	—	2
129	Clay (47 pct. Al_2O_3) with 20 volume pct. rice hulls	...do..	1530	39	
130	Fire clay (California) with 20 volume pct. rice hulls	...do..	.do.	43	
131	Fire clay (Alabama) with 20 volume pct. rice hulls	...do..	.do.	42	
132	Aluminum smelter waste with 20 volume pct. rice hulls	...do..	.do.	—	2
133	Slate/marble glass with 20 volume pct. rice hulls	...do..	1050	—	2,4
134	Slate/marble glass with 35 volume pct. rice hulls	...do..	.do.	—	2,4
135	Clay (70 pct. Al_2O_3) with 20 volume pct. rice hulls	...do..	1530	45	
136	Clay (70 pct. Al_2O_3) with 35 volume pct. rice hulls	...do..	.do.	49	
137	Clay (70 pct. Al_2O_3) with 50 volume pct. rice hulls	...do..	.do.	—	2
138	Clay/sand mix with 20 volume pct. rice hulls	...do..	.do.	50	2
139	Clay/sand mix with 35 volume pct. rice hulls	...do..	.do.	—	2
140	Clay/sand mix with 50 volume pct. rice hulls	...do..	.do.	—	2
141	45 pct. sand (minus 10-, plus 20-mesh) and 55 pct. waste glass	...do..	940	43	
142	55 pct. sand (minus 10-, plus 20-mesh) and 45 pct. waste glass	...do..	.do.	44	
143	65 pct. sand (minus 10-, plus 20-mesh) and 35 pct. waste glass	...do..	.do.	43	
144	75 pct. sand (minus 10-, plus 20-mesh) and 25 pct. waste glass	...do..	.do.	46	

1 High raw material cost
2 No bond, highly friable
3 Limited raw material availability
4 High processing cost
5 Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
145	45 pct. sand (minus 20-, plus 35-mesh) and 55 pct. waste glass	Pressed	940	42	
146	55 pct. sand (minus 20-, plus 35-mesh) and 45 pct. waste glass	...do..	.do.	42	
147	65 pct. sand (minus 20-, plus 35-mesh) and 35 pct. waste glass	...do..	.do.	41	
148	75 pct. sand (minus 20-, plus 35-mesh) and 25 pct. waste glass	...do..	.do.	43	
149	Foames slate/marble glass/ceramic	...do..	1150	29	
150	High Al_2O_3 clay (Alabama)	Extruded	1350	57	2
151	Guyana bauxite	...do..	.do.	—	2
152	Clay(47 pct. Al_2O_3)	...do..	.do.	41	
153	Clay (60 Pct. Al_2O_3)	...do..	.do.	46	
154	Clay (70 pct. Al_2O_3)	...do..	.do.	—	2
155	Fire clay (California)	...do..	.do.	36	
156	Clay/sand mix (California)	...do..	.do.	—	2
157	High Al_2O_3 clay (Missouri)	...do..	.do.	—	2
158	High Al_2O_3 clay (Pennsylvania)	...do..	.do.	—	2
159	High Al_2O_3 clay (Alabama)	...do..	1450	48	
160	Guyana bauxite	...do..	.do.	—	2
161	Clay (47 pct. Al_2O_3)	...do..	.do.	38	
162	Clay (60 pct. Al_2O_3)	...do..	.do.	40	
163	Clay (70 pct. Al_2O_3)	...do..	.do.	43	
164	Fire clay (California)	...do..	.do.	—	2
165	Clay/sand mix (California)	...do..	.do.	—	2
166	Fire clay (Missouri)	...do..	.do.	—	2
167	Fire clay (Pennsylvania)	...do..	.do.	48	
168	50 pct. periclase (minus 8-, plus 28-mesh) and 50 pct. waste glass	Pressed	900	43	1,2
169	60 pct. periclase (minus 8-, plus 28-mesh) and 40 pct. waste glass	...do..	.do.	45	1
170	70 pct. periclase (minus 8-, plus 28-mesh) and 30 pct. waste glass	...do..	.do.	43	1

[1] High raw material cost
[2] No bond, highly friable
[3] Limited raw material availability
[4] High processing cost
[5] Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
171	50 pct. calcined clay (minus 8-, plus 28-mesh) and 50 pct. waste glass	Pressed	900	42	1,2
172	60 pct. calcined clay (minus 8-, plus 28-mesh) and 40 pct. waste glass	...do..	.do.	42	2
173	70 pct. calcined clay (minus 8-, plus 28-mesh) and 30 pct. waste glass	...do..	.do.	39	
174	50 pct. periclase (minus 8-, plus 28-mesh) and 50 pct. fly ash	...do..	1260	43	1
175	60 pct. periclase (minus 8-, plus 28-mesh) and 40 pct. fly ash	...do..	.do.	44	1,2
176	70 pct. periclase (minus 8-, plus 28-mesh) and 30 pct. fly ash	...do..	.do.	43	1
177	50 pct. calcined clay (minus 8-, plus 28-mesh) and 50 pct. fly ash	...do..	.do.	41	
178	60 pct. calcined clay (minus 8-, plus 28-mesh) and 40 pct. fly ash	...do..	.do.	41	
179	70 pct. calcined clay (minus 8-, plus 28-mesh) and 30 pct. fly ash	...do..	.do.	43	
180	50 pct. sand (minus 8-, plus 28-mesh) and 50 pct. fly ash	...do..	.do.	44	2
181	60 pct. sand (minus 8-, plus 28-mesh) and 40 pct. fly ash	...do..	.do.	47	2
182	70 pct. sand (minus 8-, plus 28-mesh) and 30 pct. fly ash	...do..	.do.	47	2
183	50 pct. periclase (minus 8-, plus 28-mesh) and 50 pct. low PCE clay	...do..	1200	40	1
184	60 pct. periclase (minus 8-, plus 28-mesh) and 40 pct. low PCE clay	...do..	.do.	40	1
185	70 pct. periclase (minus 8-, plus 28-mesh) and 30 pct. low PCE clay	...do..	.do.	46	1
186	50 pct. calcined clay (minus 8-, plus 28-mesh) and 50 pct. low PCE clay	...do..	.do.	38	
187	60 pct. calcined clay (minus 8-, plus 28-mesh) and 40 pct. low PCE clay	...do..	.do.	41	
188	70 pct. calcined clay (minus 8-, plus 28-mesh) and 30 pct. low PCE clay	...do..	.do.	41	2
189	50 pct. sand (minus 8-, plus 28-mesh) and 50 pct. low PCE clay	...do..	.do.	42	

1 High raw material cost
2 No bond, highly friable
3 Limited raw material availability
4 High processing cost
5 Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
190	60 pct. sand (minus 8-, plus 28-mesh) and 40 pct. low PCE clay	Pressed	1200	44	
191	70 pct. sand (minus 8-, plus 28-mesh) and 30 pct. low PCE clay	...do..	.do.	45	
192	50 pct. sand (minus 8-, plus 28-mesh) and 50 pct. waste glass	...do..	900	42	2
193	60 pct. sand (minus 8-, plus 28-mesh) and 40 pct. waste glass	...do..	.do.	42	2
194	70 pct. sand (minus 8-, plus 28-mesh) and 30 pct. waste glass	...do..	.do.	46	2
195	20 pct. aluminum smelter waste and 80 pct. high Al_2O_3 clay	...do..	1500	38	
196	30 pct. aluminum smelter waste and 70 pct. high Al_2O_3 clay	...do..	.do.	43	
197	10 pct. aluminum smelter waste and 90 pct. high Al_2O_3 clay	...do..	.do.	43	
198	20 pct. aluminum smelter waste and 80 pct. fire clay	...do..	.do.	37	
199	30 pct. aluminum smelter waste and 70 pct. fire clay	...do..	.do.	38	
200	10 pct. aluminum smelter waste and 90 pct. fire clay	...do..	.do.	34	
201	40 pct. aluminum smelter waste and 60 pct. high Al_2O_3 clay	...do..	.do.	44	
202	50 pct. aluminum smelter waste and 50 pct. high Al_2O_3 clay	...do..	.do.	45	
203	60 pct. aluminum smelter waste and 40 pct. high Al_2O_3 clay	...do..	.do.	50	
204	40 pct. aluminum smelter waste and 60 pct. fire clay	...do..	.do.	46	
205	50 pct. aluminum smelter waste and 50 pct. fire clay	...do..	.do.	42	
206	60 pct. aluminum smelter waste and 40 pct. fire clay	...do..	.do.	40	
207	50 pct. sand (minus 10-, plus 35-mesh) and 50 pct. low PCE shale	...do..	1370	39	5
208	60 pct. sand (minus 10-, plus 35-mesh) and 40 pct. low PCE shale	...do..	.do.	41	5
209	70 pct. sand (minus 10- plus 35-mesh) and 30 pct. low PCE shale	...do..	.do.	44	5

[1] High raw material cost
[2] No bond, highly friable
[3] Limited raw material availability
[4] High processing cost
[5] Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
210	50 pct. calcined clay (minus 8-, plus 28-mesh) and 50 pct. phosphate slime	Pressed	1370	30	5
211	60 pct. calcined clay (minus 8-, plus 28-mesh) and 40 pct. phosphate slime	...do..	.do.	32	5
212	70 pct. calcined clay (minus 8-, plus 28-mesh) and 30 pct. phosphate slime	...do..	.do	35	5
213	50 pct. periclase (minus 8-, plus 28-mesh) and 50 pct. phosphate slime	...do..	.do.	41	1,5
214	60 pct. periclase (minus 8-, plus 28-mesh) and 40 pct. phosphate slime	...do..	.do.	44	1,5
315	70 pct. periclase (minus 8-, plus 28-mesh) and 30 pct. phosphate slime	...do..	.do.	49	1,5
216	50 pct. sand (minus 8-, plus 28-mesh) and 50 pct. phosphate slime	...do..	.do.	43	5
217	60 pct. sand (minus 8-, plus 28-mesh) and 40 pct. phosphate slime	...do..	.do.	45	5
218	70 pct. sand (minus 8-, plus 28-mesh) and 30 pct. phosphate slime	...do..	.do.	48	5
219	50 pct. calcined clay (minus 8-, plus 28-mesh) and 50 pct. phosphate slime	...do..	1200	39	
220	60 pct. calcined clay (minus 8-, plus 28-mesh) and 40 pct. phosphate slime	...do..	.do.	38	
221	70 pct. calcined clay (minus 8-, plus 28-mesh) and 30 pct. phosphate slime	...do..	.do.	42	
222	50 pct. periclase (minus 8-, plus 28-mesh) and 50 pct. phosphate slime	...do..	.do.	45	1
223	60 pct. periclase (minus 8-, plus 28-mesh) and 40 pct. phosphate slime	...do..	.do.	44	1
224	70 pct. periclase (minus 8-, plus 28-mesh) and 30 pct. phosphate slime	...do..	.do.	47	1
225	50 pct. sand (minus 8-, plus 28-mesh) and 50 pct. phosphate slime	...do..	.do.	--	2
226	60 pct. sand (minus 8-, plus 28-mesh) and 40 pct. phosphate slime	...do..	.do.	--	2
227	70 pct. sand (minus 8-, plus 28-mesh) and 30 pct. phosphate slime	...do..	.do.	--	2
228	50 pct. fused Al_2O_3 (B) and 50 pct. low PCE shale	...do..	1100	42	1

[1] High material cost
[2] No bond, highly friable
[3] Limited raw material availability
[4] High processing cost
[5] Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
229	40 pct. fused Al_2O_3 (B) and 60 pct. low PCE shale	Pressed	1100	42	1
230	50 pct. fused Al_2O_3 (B) and 50 pct. fly ash	...do..	1260	41	1
231	40 pct. fused Al_2O_3 (B) and 60 pct. fly ash	...do..	.do.	41	1
232	50 pct. fused Al_2O_3 (A) and 50 pct. low PCE shale	...so..	1100	42	1
233	40 pct. fused Al_2O_3 (A) and 60 pct. low PCE shale	...do..	.do.	45	1
234	50 pct. fused Al_2O_3 (A) and 50 pct. fly ash	...do..	1260	38	1
235	40 pct. fused Al_2O_3 (A) and 60 pct. fly ash	...so..	.do.	37	1
236	Expanded shale (Missouri)	Extruded	1150	47	
237	Low PCE shale	...do..	1100	—	2
238	5 pct. brucite and 95 pct. low PCE shale	...do..	.do.	—	2,3
239	10 pct. brucite and 90 pct. low PCE shale	...do..	.do.	—	2,3
240	20 pct. brucite and 80 pct low PCE shale	...do..	.do.	—	2,3
241	30 pct. brucite and 70 pct. low PCE shale	...do..	.do.	—	2,3
242	40 pct. brucite and 60 pct. low PCE shale	...do..	.do.	—	2,3
243	50 pct. brucite and 50 pct. low PCE shale	...do..	.do.	—	2,3
244	50 pct. copper mill tailings (CT 2388) and 50 pct. calcined clay	Pressed	1150	33	
245	50 pct. copper mill tailings (CT 2401) and 50 pct. calcined clay	...do..	1250	39	
246	50 pct. copper mill tailings (CT 2403) and 50 pct. calcined clay	...do..	1150	34	
247	50 pct. copper mill tailings (CT 2388) and 50 pct. periclase	...do..	1200	51	1
248	50 pct. copper mill tailings (CT 2401) and 50 pct. periclase	...do..	1250	45	1

[1] High material cost
[2] No bond, highly frialbe
[3] Limited raw material availability
[4] High processing cost
[5] Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
249	50 pct. copper mill tailings (CT 2403) and 50 pct. periclase	Pressed	1150	52	1
250	50 pct. copper mill tailings (CT 2388) and 50 pct. sand	...do..	1200	38	
251	50 pct. copper mill tailings (CT 2401) and 50 pct. sand	...do..	1250	43	
252	50 pct. copper mill tailings (CT 2403) and 50 pct. sand	...do..	1150	41	
253	40 pct. copper mill tailings (CT 2403) and 60 pct. calcined clay	...do..	1200	39	
254	40 pct. copper mill tailings (CT 2401) and 60 pct. calcined clay	...do..	1250	39	
255	40 pct. copper mill tailings (CT 2403) and 60 pct. calcined clay	...do..	1150	39	
256	40 pct. copper mill tailings (CT 2388) and 60 pct. periclase	...do..	1200	52	1
257	40 pct. copper mill tailings (CT 2401) and 60 pct. periclase	...do..	1250	40	1
258	40 pct. copper mill tailings (CT 2403) and 60 pct. periclase	...do..	1150	47	1
259	40 pct. copper mill tailings (CT 2388) and 60 pct. sand	...do..	1200	43	
260	40 pct. copper mill tailings (CT 2401) and 60 pct. sand	...do..	1250	44	
261	40 pct. copper mill tailings (CT 2403) and 60 pct. sand	...do..	1150	46	
262	Copper mill tailings (CT 2388)	Extruded	.do.	46	
263	Copper mill tailings (CT 2401)	...do..	.do.	43	
264	Copper mill tailings (CT 2403)	...do..	1100	49	2
265	Copper mill tailings (CT 2403)	...do..	1250	41	
266	60 pct. sand (minus 48-mesh) and 40 pct. low PCE shale	Pressed	1280	43	2
267	60 pct. periclase (minus 48-mesh) and 40 pct. low PCE shale	...do..	1200	45	1,2
268	60 pct. calcined clay (minus 48-mesh) and 40 pct. low PCE shale	...do..	.do.	—	2

1 High raw material cost
2 No bond, highly friable
3 Limited raw material availability
4 High processing cost
5 Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., °C	PV	COMMENTS (SEE FOOTNOTES)
269	60 pct. sand (minus 48-mesh) and 40 pct. fly ash	Pressed	1260	40	
270	60 pct. periclase (minus 48-mesh) and 40 pct. fly ash	...do..	.do.	41	1,2
271	60 pct. calcined clay (minus 48-mesh) and 40 pct. fly ash	...do..	.do.	43	
272	60 pct. sand (minus 48-mesh) and 40 pct. waste glass	...do..	900	35	
273	60 pct. periclase (minus 48-mesh) and 40 pct. waste glass	...do..	.do.	38	1
274	60 pct. calcined clay (minus 48-mesh) and 40 pct. waste glass	...do..	.do.	44	
275	60 pct. sand (minus 48-mesh) and 40 pct. copper mill tailings	...do..	1200	41	2
276	60 pct. periclase (minus 48-mesh) and 40 pct. copper mill tailings	...do..	1280	--	1,2
277	60 pct. calcined clay (minus 48-mesh) and 40 pct. copper mill tailings	...do..	1200	36	
278	60 pct. sand (minus 48-mesh) and 40 pct. phosphate slime	...do..	1280	44	2
279	60 pct. periclase (minus 48-mesh) and 40 pct. phosphate slime	...do..	1200	49	1,2
280	60 pct. calcined clay (minus 48-mesh) and 40 pct. phosphate slime	...do..	.do.	--	2
281	Porous waste slate/marble glass	Crushed	.do.	30	4
282	Slate overburden	Hand formed	1100	45	
283	Slate overburden	Extruded and chopped	1150	45	
284	Ground slate (Vermont)	...do..	1100	--	5
285	Ground slate (Georgia)	...do..	1200	45	
286	Dense waste slate/marble glass	Crushed and sized	NA	28	4
287	Porous waste slate/marble glass	...do..	NA	34	4
288	Lightweight clay aggregate (Louisiana)	Extruded and chopped	900	42	

[1] High raw material cost
[2] No bond, highly friable
[3] Limited raw material availability
[4] High processing cost
[5] Overfired and/or melted

SAMPLE NO.	AGGREGATE DESCRIPTION	AGGREGATE FABRICATION	SINTERING TEMP., ° C	PV	COMMENTS (SEE FOOTNOTES)
289	60 pct. calcined clay (minus 48-mesh) and 40 pct. low PCE shale	Pressed	1320	30	
290	Calcined serpentine waste	—	1350	34	
291	60 pct. periclase ans 40 pct. waste glass (minus 325-mesh)	Pressed	900	59	1
292	60 pct. periclase and 40 pct. waste glass (minus 12-, plus 325-mesh)	...do..	.do.	45	1
293	60 pct. periclase and 40 pct. waste glass (minus 16-, plus 325-mesh)	...do..	.do.	42	1
294	60 pct. periclase and 40 pct. waste glass (minus 20-, plus 325-mesh)	...do..	.do.	42	1
295	60 pct. periclase and 40 pct. waste glass (minus 40-, plus 325-mesh)	...do..	.do.	41	1

[1] High raw material cost
[2] No bond, highly friable
[3] Limited raw material availability
[4] High processing cost
[5] Overfired and/or melted

APPENDIX III

PROCESS EVALUATION

COMPARISON OF PROCESSES FOR PRODUCING
WEAR-RESISTANT ROADWAY AGGREGATE

November 1979

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

Process Evaluation Office

Avondale, Maryland

COMPARISON OF PROCESSES FOR PRODUCING
WEAR-RESISTANT ROADWAY AGGREGATE

November 1979

By
Lorraine H. Lawson

TABLE OF CONTENTS

SUMMARY

Presented in this report is an economic comparison of eleven proposed processes for producing wear-resistant roadway aggregate from various materials including mining, metallurgical, and municipal waste products. The evaluations are based on data supplied by researchers at the Tuscaloosa Research Center. This study shows that the major cost in producing each of the aggregates is the cost of raw materials. Processes using low cost waste products as their raw materials have significantly lower operating costs than the other proposed processes. If similar but less expensive materials can be substituted for the high-cost raw materials, operating costs for those processes can be reduced significantly.

Actual operating costs will vary depending on plant location, availability of raw materials, transportation costs, and the local market for aggregates. These factors are not considered in the cost estimates because of the many possible plant locations. A company considering the production of aggregate by one of these processes should obtain the local cost of each of the raw materials and substitute these costs in the estimates to determine which process would be the least expensive.

INTRODUCTION

An investigation of the production of wear-resistant and polish-resistant roadway aggregates is being conducted at the Tuscaloosa Research Center under an agreement with the Federal Highway Administration. Results of abrasion testing and a literature survey convering production of aggregates and availability of raw materials have led to the selection of eleven aggregate compositions for evaluation. This report has been prepared to compare the costs to produce 1,000 tons per day of each of these aggregates.

PROCESS DESCRIPTIONS

A common scheme for the production of roadway aggregates involves agglomeration and calcination of the feed material, followed by crushing to the desired product size. The eleven processes follow this plan with modifications to suit each aggregate composition. For the agglomeration step, seven of the proposed processes use a pug-mill extruder, three use a disc pelletizer, and one does not require agglomeration.

A brief description of each of the processes follows.

Processes Using Extrusion

Calcined Clay and Fly Ash Aggregate

In this process, calcined clay and fly ash are the major raw materials with bentonite added as a binder. Calcined clay is delivered by truck or rail, conveyed to a hammer mill for crushing to minus 12 mesh, then transferred to covered storage. Fly ash is also delivered by truck or rail and conveyed directly to covered storage. The storage facilities hold up to a 3-day supply of clay and fly ash. Bentonite, which represents only 1.5 percent by weight of the feed, is delivered periodically and stored in a silo holding up to a 14-day supply.

The raw materials are conveyed from storage to a dry feed mixer forming a feed composition of 59 percent calcined clay, 38.5 percent fly ash, and 1.5 percent bentonite. This mixture is conveyed to a pug-mill extruder, water is added to achieve 16 percent moisture, and the material is extruded in 1-inch long by 1-inch diameter slugs. The slugs are fired in a rotary kiln, cooled, and conveyed to a hammer mill for crushing to minus 1/2 inch. The crushed aggregate is conveyed to a stock pile awaiting shipment.

Off gases from the rotary kiln are passed through multiple cyclone and continuous bag dust collectors for particulate removal. The gas stream is then wet-scrubbed with a limestone slurry for sulfur dioxide removal. Residue from the scrubbing operation is pumped to a tailings pond.

High Alumina Clay Aggregate

This process has a single raw material, high alumina clay, which does not require crushing or mixing prior to extrusion. The extrusion, calcination, crushing, and pollution control steps are the same as described for the first process.

Fourty Percent Aluminum Dross and 60 Percent Refractory Clay Aggregate

The feed for this process consists of 40 percent aluminum dross and 60 percent high PCE (pyrometric cone equivalent) clay. Neither raw material requires crushing prior to mixing, and the extruded material contains 22 percent moisture. The extrusion, calcination, crushing, and pollution control steps are the same as described for the first process.

Sixty Percent Aluminum Dross and 40 Percent Refractory Clay Aggregate

The feed for this process consists of 60 percent aluminum dross and 40 percent high PCE clay. The raw materials do not require crushing prior to mixing, and the extruded material contains 18 percent moisture. The extrusion, calcination, crushing, and pollution control steps are the same as described for the first process.

Slate Waste Aggregate

This process uses a single raw material, slate overburden, which must pass a minus 30-mesh screen, with the oversize material being discarded. The minus 30-mesh feed is mixed and extruded at 20 percent moisture. The extrusion, calcination, crushing, and pollution control steps are the same as described for the first process.

Calcined Clay and Low PCE Clay Aggregate

The feed for this process is 60 percent calcined clay and 40 percent low PCE clay. The calcined clay is ground to minus 12-mesh and the low PCE clay is shredded before mixing and extrusion at 14 percent moisture. The extrusion, calcination, crushing, and pollution control steps are the same as described for the first process.

Copper Mill Tailings Aggregate

This process produces aggregate from copper mill tailings, which contain 20 percent moisture as received. These tailings are dried to 14.5 percent moisture before being mixed with bentonite (1.5 percent by weight), extruded, calcined, and crushed as described in the first process. Treatment of off gases from the rotary kiln is the same as described for the first process.

Processes Using Disc Pelletization

Calcined Clay and Waste Glass Aggregate

In this process, raw materials are received and handled as in the first process. Feed to the dry mixer is 58.5 percent calcined clay, crushed to minus 12-mesh, 39.5 percent waste glass, and 2 percent bentonite. From the mixer the aggregate feed material is fed to disc pelletizers where the moisture is adjusted to 12 percent and plus 1/2 inch diameter pellets are formed. These pellets are then fired in a rotary kiln, cooled, and crushed to minus 1/2 inch. Due to the excessive fines being generated during crushing, 15 percent of the product is recycled to the mixer for repelletization and firing with the raw materials. Treatment of off gases from the rotary kiln is the same as described for the first process.

Periclase and Waste Glass Aggregate

The aggregate feed for this process is composed of 58.5 percent periclase, 39.5 percent waste glass, and 2 percent bentonite. The feed stream is treated as in the preceding process including the 15 percent product recycle and the pollution control step.

Coal Refuse Aggregate

Coal refuse containing 8 percent moisture is the raw material used in this process. This material is fed to a rotary dryer to reduce the moisture to 4 percent, crushed to minus 3/8 inch, and mixed with a product recycle stream. This mixture is pelletized and fed to a sintering machine. In the sintering machine the wet pellets are discharged onto a traveling grate where they are fired by drawing combustion air from coal fired burners up through the bed of pellets. The sintered pellets then pass over cooling rails and are conveyed to a hammer mill for crushing to minus 1/2 inch. After crushing, 40 percent of the product stream is recycled to the disc pelletizer to be processed with the raw materials. Pollution control equipment for treatment of sintering emissions is similar to that used for rotary kiln emissions in the first process.

Process Not Requiring Agglomeration

Serpentine Waste Aggregate

Serpentine waste, the raw material for this process, is delivered and stored as in the other processes. No moisture adjustment or agglomeration is required before calcination of the aggregate. The raw material is fed directly from storage to the rotary kiln. Treatment of off gases from the rotary kiln is the same as described for the first process. The product is crushed and stored as in the other processes.

ECONOMIC EVALUATION

This economic evaluation compares the costs for producing roadway aggregate from various raw materials, including mining, metallurgical, and municipal waste products. The capital and operating costs for producing 1,000 tons per day of aggregate by each of the proposed processes are summarized in table 1. More detailed cost tables for each process are included in the appendix.

The capital cost estimates are of the type generally referred to as a study estimate, and are expected to be within 30 percent of the actual costs. Equipment costs are based on informal cost quotations from equipment manufacturers and from capacity-cost data, using third-quarter 1979 costs (Marshall and Swift index of 606.4). The estimated operating costs are based on 350 days per year of plant operation, 3 shifts per day, 7 days per week, excluding certain raw material and product handling facilities, which operate 1 shift per day, 5 days per week. These cost estimates are made from available data on the proposed processes and may vary significantly when plant location and raw material availability are determined. Raw material costs used in this evaluation have been supplied by the researchers through quotations from various suppliers.

Raw material cost makes up a significant portion of the operating cost in seven of the proposed processes. The other four processes produce aggregate from waste products with no present value. The operating costs per ton, excluding the charge for raw materials, for each of the proposed processes are very similar, so local availability and cost of raw materials is a major factor in choosing the most economical process. None of the proposed processes should be excluded based on the raw material costs used for this evaluation. These costs may vary greatly when transportation costs are included. Transportation costs are not included in this cost estimate since a definite plant site is not considered. To minimize transportation costs, the plant should be located at or near the source of its raw material and near a market area for roadway aggregate.

Energy requirements used in the evaluation are based on data supplied by the Fuller Company and are shown in table 1. The coal refuse aggregate has a significantly lower fuel requirement than the other processes due to the fuel value in the feed itself. This aggregate process also requires more pollution control equipment than the remaining processes due to the ash content of the material. The fuel requirements of the other processes depend on the moisture content of the agglomerated feed material. Although energy costs vary among the processes, these differences are outweighed by the strong dependence of operating costs on raw material and transportation costs.

TABLE 1. - Fixed capital costs, operating costs and thermal requirements for 11 processes for producing roadway aggregate

	Fixed capital cost	Operating cost per ton aggregate	Daily thermal requirements, MMBtu coal
Calcined clay and fly ash aggregate.......	$16,152,800	$ 44.63	2,470.0
High alumina clay aggregate...............	15,697,500	71.08	3,410.0
Fourty percent aluminum dross and 60 percent refractory clay aggregate...............................	16,556,400	34.25	4,290.0
Sixty percent aluminum dross and 40 percent refractory clay aggregate.......	16,017,000	35.98	3,250.0
Slate waste aggregate.....................	15,665,900	13.05	3,050.0
Calcined clay and low PCE clay aggregate..	15,844,800	53.01	2,750.0
Copper mill tailings aggregate............	16,005,000	13.58	2,654.2
Calcined clay and waste glass aggregate...	16,608,300	43.51	2,310.0
Periclase and waste glass aggregate.......	15,457,400	120.09	1,870.0
Coal refuse aggregate.....................	32,694,600	18.56	604.9
Serpentine waste aggregate................	14,365,100	10.62	2,050.0

The processes using slate waste, copper mill tailings, coal refuse, and serpentine waste have significantly lower operating costs than the other proposed processes because no charge has been included for raw materials. These processes appear to be the most economical but the final decision depends on plant location, raw material availability and transportation costs. Any of the proposed processes may be favorable in a given location when these costs are included. A comparison of the estimated operating costs of the eleven processes with the current cost of roadway aggregate is not included because the current costs also depend heavily on location, raw material availability, and local demand for the aggregates.

RECOMMENDATIONS

- Consideration should be given to substituting similar but less expensive materials in those processes with prohibitively high raw material costs.

- Local availability and cost of raw materials should be investigated before identification of the most economical process for a particular plant location can be made.

Table A-1.—Estimated capital cost(1), roadway aggregate from calcined clay and fly ash

Fixed capital:	
Calcined clay / fly ash aggregate	$ 12289300.
Subtotal	12289300.
Plant facilities, 10 percent of above subtotal	1228900.
Plant utilities, 12 percent of above subtotal	1474700.
Total plant cost	14992900.
Land cost	0.
Subtotal	14992900.
Interest during construction period	1159900.
Fixed capital cost	16152800.
Working capital:	
Raw material and supplies	942200.
Product and in-process inventory	1284000.
Accounts receivable	1284000.
Available cash	1156500.
Working capital cost	4666700.
Total capital cost	20819500.

(1) Basis: M and S equipment cost index= 606.4.

Table A-2.—Estimated annual operating cost, roadway aggregate from calcined clay and fly ash

	Annual Cost	Cost per ton Roadway aggregate
Direct cost:		
Raw materials:		
Calcined clay at $52.00 per ton.....	$ 11138400.	$ 31.82
Fly ash at $ .00 per ton............	0.	.00
Bentonite at $28.00 per ton.........	152900.	.44
Limestone at $7.00 per ton..........	31400.	.09
Total........................	11322700.	32.35
Utilities:		
Electric power at $ .025 per Kwhr...	258200.	.74
Process water at $ .50 per Mgal.....	8600.	.02
Coal at $30.00 per ton..............	960600.	2.74
Total........................	1227400.	3.50
Direct labor:		
Labor at $8.00 per hour.............	316200.	.90
Supervision, 27 percent of labor....	87400.	.25
Total........................	403600.	1.15
Plant maintenance:		
Labor...............................	339700.	.97
Supervision, 8 percent of maintenance labor.................	27200.	.08
Materials...........................	339600.	.97
Total........................	706500.	2.02
Payroll overhead, 35 percent of above payroll......................	269700.	.77
Operating supplies, 20 percent of plant maintenance..................	141300.	.40
Total direct cost.............	14071200.	40.19
Indirect cost, 40 percent of direct labor and maintenance...........	444000.	1.27
Fixed cost:		
Taxes, 1.0 percent of total plant cost	149900.	.43
Insurance, 1.0 percent of total plant cost.........................	149900.	.43
Depreciation, 20 year life............	807600.	2.31
Total operating cost...........	15622600.	44.63

Table A-3.—Estimated capital cost(1), roadway aggregate from high alumina clay

Fixed capital:	
High alumina clay aggregate	$ 11942600.
Subtotal	11942600.
Plant facilities, 10 percent of above subtotal	1194300.
Plant utilities, 12 percent of above subtotal	1433100.
Total plant cost	14570000.
Land cost	0.
Subtotal	14570000.
Interest during construction period	1127500.
Fixed capital cost	15697500.
Working capital:	
Raw material and supplies	1673700.
Product and in-process inventory	2043900.
Accounts receivable	2043900.
Available cash	1919800.
Working capital cost	7681300.
Total capital cost	23378800.

(1) Basis: M and S equipment cost index= 606.4.

Table A-4.—Estimated annual operating cost, roadway aggregate from high alumina clay

	Annual Cost	Cost per ton Roadway aggregate
Direct cost:		
Raw materials:		
High alumina clay at $50.00 per ton.	$ 20184500.	$ 57.67
Limestone at $7.00 per ton..........	39400.	.11
Total........................	20223900.	57.78
Utilities:		
Electric power at $ .025 per Kwhr...	315200.	.90
Process water at $ .50 per Mgal.....	9700.	.03
Coal at $30.00 per ton..............	1326100.	3.79
Total........................	1651000.	4.72
Direct labor:		
Labor at $8.00 per hour.............	299500.	.86
Supervision, 29 percent of labor....	87400.	.25
Total........................	386900.	1.11
Plant maintenance:		
Labor...............................	334300.	.96
Supervision, 8 percent of maintenance labor................	26700.	.08
Materials...........................	334300.	.96
Total........................	695300.	2.00
Payroll overhead, 35 percent of above payroll.......................	261800.	.75
Operating supplies, 20 percent of plant maintenance..................	139100.	.40
Total direct cost.............	23358000.	66.76
Indirect cost, 40 percent of direct labor and maintenance..........	432900.	1.24
Fixed cost:		
Taxes, 1.0 percent of total plant cost	145700.	.42
Insurance, 1.0 percent of total plant cost........................	145700.	.42
Depreciation, 20 year life............	784900.	2.24
Total operating cost...........	24867200.	71.08

Table A-5.—Estimated capital cost(1), roadway aggregate from 40$ aluminum dross, 60% refractory clay

Fixed capital:	
40% aluminum dross / 60% refractory clay aggregate..	$ 12596200.
Subtotal....................................	12596200.
Plant facilities, 10 percent of above subtotal......	1259600.
Plant utilities, 12 percent of above subtotal.......	1511500.
Total plant cost...........................	15367300.
Land cost..	0.
Subtotal....................................	15367300.
Interest during construction period...............	1189100.
Fixed capital cost.........................	16556400.
Working capital:	
Raw material and supplies........................	572000.
Product and in-process inventory.................	984900.
Accounts receivable..............................	984900.
Available cash...................................	854800.
Working capital cost.......................	3396600.
Total capital cost.........................	19953000.

(1) Basis: M and S equipment cost index= 606.4.

Table A-6.—Estimated annual operating cost, roadway aggregate from 40$ aluminum dross, 60% refractory clay

	Annual Cost	Cost per ton Roadway aggregate
Direct cost:		
Raw materials:		
High pce clay at $28.00 per ton.....	$ 6765900.	$ 19.33
Aluminum dross at $ .00 per ton.....	0.	.00
Limestone at $7.00 per ton..........	47000.	.13
Total........................	6812900.	19.46
Utilities:		
Electric power at $ .025 per Kwhr...	371600.	1.06
Process water at $ .50 per Mgal.....	10800.	.03
Coal at $30.00 per ton..............	1668300.	4.77
Total........................	2050700.	5.86
Direct labor:		
Labor at $8.00 per hour.............	299500.	.86
Supervision, 29 percent of labor....	87400.	.25
Total........................	386900.	1.11
Plant maintenance:		
Labor...............................	352800.	1.01
Supervision, 8 percent of maintenance labor.................	28200.	.08
Materials...........................	352700.	1.01
Total........................	733700.	2.10
Payroll overhead, 35 percent of above payroll......................	268800.	.77
Operating supplies, 20 percent of plant maintenance..................	146700.	.42
Total direct cost.............	10399700.	29.72
Indirect cost, 40 percent of direct labor and maintenance...........	448200.	1.28
Fixed cost:		
Taxes, 1.0 percent of total plant cost	153700.	.44
Insurance, 1.0 percent of total plant cost..........................	153700.	.44
Depreciation, 20 year life............	827800.	2.37
Total operating cost...........	11983100.	34.25

Table A-7 .-Estimated capital cost(1), roadway aggregate from 60% aluminum dross, 40% refractory clay

Fixed capital:	
60% aluminum dross / 40% refractory clay aggregate..	$ 12185900.
Subtotal....................................	12185900.
Plant facilities, 10 percent of above subtotal......	1218600.
Plant utilities, 12 percent of above subtotal.......	1462300.
Total plant cost............................	14866800.
Land cost.......................................	0.
Subtotal....................................	14866800.
Interest during construction period.................	1150200.
Fixed capital cost..........................	16017000.
Working capital:	
Raw material and supplies...........................	669700.
Product and in-process inventory....................	1035300.
Accounts receivable.................................	1035300.
Available cash......................................	909000.
Working capital cost........................	3649300.
Total capital cost..........................	19666300.

(1) Basis: M and S equipment cost index= 606.4.

Table A-8 .—Estimated annual operating cost, roadway aggregate from 60% aluminum dross, 40% refractory clay

	Annual Cost	Cost per ton Roadway aggregate
Direct cost:		
Raw materials:		
High pce clay at $50.00 per ton.....	$ 7973000.	$ 22.78
Aluminum dross at $ .00 per ton.....	0.	.00
Limestone at $7.00 per ton..........	33300.	.10
Total........................	8006300.	22.88
Utilities:		
Electric power at $ .025 per Kwhr...	283000.	.81
Process water at $ .50 per Mgal.....	6100.	.02
Coal at $30.00 per ton..............	1263900.	3.61
Total........................	1553000.	4.44
Direct labor:		
Labor at $8.00 per hour.............	299500.	.86
Supervision, 29 percent of labor....	87400.	.25
Total........................	386900.	1.11
Plant maintenance:		
Labor...............................	340400.	.97
Supervision, 8 percent of maintenance labor.................	27200.	.08
Materials...........................	340400.	.97
Total........................	708000.	2.02
Payroll overhead, 35 percent of above payroll......................	264100.	.75
Operating supplies, 20 percent of plant maintenance.................	141600.	.40
Total direct cost.............	11059900.	31.60
Indirect cost, 40 percent of direct labor and maintenance...........	438000.	1.25
Fixed cost:		
Taxes, 1.0 percent of total plant cost	148700.	.42
Insurance, 1.0 percent of total plant cost........................	148700.	.42
Depreciation, 20 year life............	800900.	2.29
Total operating cost...........	12596200.	35.98

Table A-9 .-Estimated capital cost(1), roadway aggregate from slate waste

Fixed capital:	
Slate waste aggregate	$ 11918800.
Subtotal	11918800.
Plant facilities, 10 percent of above subtotal	1191900.
Plant utilities, 12 percent of above subtotal	1430300.
Total plant cost	14541000.
Land cost	0.
Subtotal	14541000.
Interest during construction period	1124900.
Fixed capital cost	15665900.
Working capital:	
Raw material and supplies	15000.
Product and in-process inventory	374700.
Accounts receivable	374700.
Available cash	250500.
Working capital cost	1014900.
Total capital cost	16680800.

(1) Basis: M and S equipment cost index= 606.4.

Table A-10.—Estimated annual operating cost, roadway aggregate from slate waste

	Annual Cost	Cost per ton Roadway aggregate
Direct cost:		
Raw materials:		
Slate waste at $ .00 per ton........	$ 0.	$ .00
Limestone at $7.00 per ton..........	41700.	.12
Total........................	41700.	.12
Utilities:		
Electric power at $ .025 per Kwhr...	323000.	.92
Process water at $ .50 per Mgal.....	500.	.01
Coal at $30.00 per ton.............	1186100.	3.39
Total........................	1509600.	4.32
Direct labor:		
Labor at $8.00 per hour.............	299500.	.86
Supervision, 29 percent of labor....	87400.	.25
Total........................	386900.	1.11
Plant maintenance:		
Labor..............................	339100.	.97
Supervision, 8 percent of maintenance labor.................	27100.	.08
Materials..........................	339000.	.97
Total........................	705200.	2.02
Payroll overhead, 35 percent of above payroll......................	263600.	.75
Operating supplies, 20 percent of plant maintenance..................	141000.	.40
Total direct cost..............	3048000.	8.72
Indirect cost, 40 percent of direct labor and maintenance...........	436800.	1.25
Fixed cost:		
Taxes, 1.0 percent of total plant cost	145400.	.42
Insurance, 1.0 percent of total plant cost..........................	145400.	.42
Depreciation, 20 year life..........	783300.	2.24
Total operating cost...........	4558900.	13.05

Table A-11.—Estimated capital cost(1), roadway aggregate from calcined clay and low pce clay

Fixed capital:	
Calcined clay / low pce clay aggregate	$ 12054900.
Subtotal	12054900.
Plant facilities, 10 percent of above subtotal	1205500.
Plant utilities, 12 percent of above subtotal	1446600.
Total plant cost	14707000.
Land cost	0.
Subtotal	14707000.
Interest during construction period	1137800.
Fixed capital cost	15844800.
Working capital:	
Raw material and supplies	1156700.
Product and in-process inventory	1524700.
Accounts receivable	1524700.
Available cash	1394800.
Working capital cost	5600900.
Total capital cost	21445700.

(1) Basis: M and S equipment cost index= 606.4.

Table A-12.-Estimated annual operating cost, roadway aggregate from calcined clay and low pce clay

	Annual Cost	Cost per ton Roadway aggregate
Direct cost:		
Raw materials:		
Calcined clay at $52.00 per ton.....	$ 13064000.	$ 37.33
Low pce clay at $5.00 per ton.......	837400.	2.39
Limestone at $7.00 per ton..........	32300.	.09
Total.........................	13933700.	39.81
Utilities:		
Electric power at $ .025 per Kwhr...	272400.	.78
Process water at $ .50 per Mgal.....	6000.	.02
Coal at $30.00 per ton..............	1069400.	3.06
Total.........................	1347800.	3.86
Direct labor:		
Labor at $8.00 per hour.............	449300.	1.28
Supervision, 19 percent of labor....	87400.	.25
Total.........................	536700.	1.53
Plant maintenance:		
Labor...............................	335600.	.96
Supervision, 8 percent of maintenance labor.................	26800.	.08
Materials...........................	335600.	.96
Total.........................	698000.	2.00
Payroll overhead, 35 percent of above payroll......................	314700.	.90
Operating supplies, 20 percent of plant maintenance.................	139600.	.40
Total direct cost.............	16970500.	48.50
Indirect cost, 40 percent of direct labor and maintenance...........	493900.	1.41
Fixed cost:		
Taxes, 1.0 percent of total plant cost	147100.	.42
Insurance, 1.0 percent of total plant cost.........................	147100.	.42
Depreciation, 20 year life............	792200.	2.26
Total operating cost...........	18550800.	53.01

Table A-13.—Estimated capital cost(1), roadway aggregate from copper mill tailings

Fixed capital:	
Copper mill tailings aggregate	$ 12176600.
Subtotal	12176600.
Plant facilities, 10 percent of above subtotal	1217700.
Plant utilities, 12 percent of above subtotal	1461200.
Total plant cost	14855500.
Land cost	0.
Subtotal	14855500.
Interest during construction period	1149500.
Fixed capital cost	16005000.
Working capital:	
Raw material and supplies	30500.
Product and in-process inventory	390600.
Accounts receivable	390600.
Available cash	262000.
Working capital cost	1073700.
Total capital cost	17078700.

(1) Basis: M and S equipment cost index= 606.4.

Table A-14.-Estimated annual operating cost, roadway aggregate from copper mill tailings

	Annual Cost	Cost per ton Roadway aggregate
Direct cost:		
Raw materials:		
Bentonite at $28.00 per ton.........	$ 192100.	$ .55
Copper mine tailings at $ .00 per ton.................	0.	.00
Limestone at $7.00 per ton..........	35800.	.10
Total........................	227900.	.65
Utilities:		
Electric power at $ .025 per Kwhr...	329800.	.94
Process water at $ .50 per Mgal.....	400.	.01
Coal at $30.00 per ton..............	1032200.	2.95
Total........................	1362400.	3.90
Direct labor:		
Labor at $8.00 per hour.............	366100.	1.05
Supervision, 23 percent of labor....	87400.	.25
Total........................	453500.	1.30
Plant maintenance:		
Labor...............................	342800.	.98
Supervision, 8 percent of maintenance labor.................	27400.	.08
Materials...........................	342700.	.98
Total........................	712900.	2.04
Payroll overhead, 35 percent of above payroll......................	288300.	.82
Operating supplies, 20 percent of plant maintenance.................	142600.	.41
Total direct cost.............	3187600.	9.12
Indirect cost, 40 percent of direct labor and maintenance...........	466600.	1.33
Fixed cost:		
Taxes, 1.0 percent of total plant cost	148600.	.42
Insurance, 1.0 percent of total plant cost..........................	148600.	.42
Depreciation, 20 year life............	800300.	2.29
Total operating cost...........	4751700.	13.58

Table A-15.—Estimated capital cost(1), roadway aggregate from calcined clay and waste glass

Fixed capital:	
Calcined clay / waste glass aggregate	$ 12635700.
Subtotal	12635700.
Plant facilities, 10 percent of above subtotal	1263600.
Plant utilities, 12 percent of above subtotal	1516300.
Total plant cost	15415600.
Land cost	0.
Subtotal	15415600.
Interest during construction period	1192700.
Fixed capital cost	16608300.
Working capital:	
Raw material and supplies	906200.
Product and in-process inventory	1252000.
Accounts receivable	1252000.
Available cash	1121300.
Working capital cost	4531500.
Total capital cost	21139800.

(1) Basis: M and S equipment cost index= 606.4.

Table A-16.—Estimated annual operating cost, roadway aggregate from calcined clay and waste glass

	Annual Cost	Cost per ton Roadway aggregate
Direct cost:		
Raw materials:		
Calcined clay at $52.00 per ton.....	$ 10647000.	$ 30.42
Bentonite at $28.00 per ton.........	196000.	.56
Waste glass at $ .00 per ton........	0.	.00
Limestone at $7.00 per ton..........	38200.	.11
Total........................	10881200.	31.09
Utilities:		
Electric power at $ .025 per Kwhr...	312000.	.89
Process water at $ .50 per Mgal.....	7100.	.02
Coal at $30.00 per ton..............	898300.	2.57
Total........................	1217400.	3.48
Direct labor:		
Labor at $8.00 per hour.............	316200.	.90
Supervision, 27 percent of labor....	87400.	.25
Total........................	403600.	1.15
Plant maintenance:		
Labor...............................	347700.	.99
Supervision, 8 percent of maintenance labor.................	27800.	.08
Materials...........................	347700.	.99
Total........................	723200.	2.06
Payroll overhead, 35 percent of above payroll......................	272700.	.78
Operating supplies, 20 percent of plant maintenance.................	144600.	.41
Total direct cost.............	13642700.	38.97
Indirect cost, 40 percent of direct labor and maintenance...........	450700.	1.29
Fixed cost:		
Taxes, 1.0 percent of total plant cost	154200.	.44
Insurance, 1.0 percent of total plant cost........................	154200.	.44
Depreciation, 20 year life............	830400.	2.37
Total operating cost...........	15232200.	43.51

Table A-17.—Estimated capital cost(1), roadway aggregate from periclase and waste glass

Fixed capital:	
Periclase / waste glass aggregate....................	$ 11760300.
Subtotal....................................	11760300.
Plant facilities, 10 percent of above subtotal......	1176000.
Plant utilities, 12 percent of above subtotal.......	1411200.
Total plant cost............................	14347500.
Land cost...	0.
Subtotal....................................	14347500.
Interest during construction period................	1109900.
Fixed capital cost..........................	15457400.
Working capital:	
Raw material and supplies..........................	3143100.
Product and in-process inventory...................	3454300.
Accounts receivable................................	3454300.
Available cash.....................................	3332300.
Working capital cost........................	13384000.
Total capital cost..........................	28841400.

(1) Basis: M and S equipment cost index= 606.4.

Table A-18.-Estimated annual operating cost, roadway aggregate from periclase and waste glass

	Annual Cost	Cost per ton Roadway aggregate
Direct cost:		
Raw materials:		
Periclase at $185.00 per ton.........	$ 37878700.	$ 108.22
Bentonite at $28.00 per ton..........	196000.	.56
Waste glass at $ .00 per ton.........	0.	.00
Limestone at $7.00 per ton...........	30900.	.09
Total.........................	38105600.	108.87
Utilities:		
Electric power at $ .025 per Kwhr...	247100.	.71
Process water at $ .50 per Mgal.....	7100.	.02
Coal at $30.00 per ton..............	727200.	2.08
Total.........................	981400.	2.81
Direct labor:		
Labor at $8.00 per hour.............	299500.	.86
Supervision, 29 percent of labor....	87400.	.25
Total.........................	386900.	1.11
Plant maintenance:		
Labor...............................	324700.	.93
Supervision, 8 percent of maintenance labor................	26000.	.07
Materials...........................	324700.	.93
Total.........................	675400.	1.93
Payroll overhead, 35 percent of above payroll......................	258200.	.74
Operating supplies, 20 percent of plant maintenance..................	135100.	.39
Total direct cost.............	40542600.	115.85
Indirect cost, 40 percent of direct labor and maintenance...........	424900.	1.21
Fixed cost:		
Taxes, 1.0 percent of total plant cost	143500.	.41
Insurance, 1.0 percent of total plant cost.........................	143500.	.41
Depreciation, 20 year life............	772900.	2.21
Total operating cost...........	42027400.	120.09

Table A-19.-Estimated capital cost(1), roadway aggregate from coal refuse

Fixed capital:	
Coal refuse aggregate	$ 24294700.
Subtotal	24294700.
Plant facilities, 10 percent of above subtotal	2429500.
Plant utilities, 12 percent of above subtotal	2915400.
Total plant cost	29639600.
Land cost	0.
Subtotal	29639600.
Interest during construction period	3055000.
Fixed capital cost	32694600.
Working capital:	
Raw material and supplies	37600.
Product and in-process inventory	533800.
Accounts receivable	533800.
Available cash	288300.
Working capital cost	1393500.
Total capital cost	34088100.

(1) Basis: M and S equipment cost index= 606.4.

Table A-20.-Estimated annual operating cost, roadway aggregate from coal refuse

	Annual Cost	Cost per ton Roadway aggregate
Direct cost:		
Raw materials:		
Coal refuse at $ .00 per ton.........	$ 0.	$ .00
Limestone at $7.00 per ton..........	168800.	.48
Total........................	168800.	.48
Utilities:		
Electric power at $ .025 per Kwhr...	492900.	1.41
Process water at $ .50 per Mgal.....	5500.	.02
Coal at $30.00 per ton............	235200.	.67
Total........................	733600.	2.10
Direct labor:		
Labor at $8.00 per hour.............	366100.	1.05
Supervision, 23 percent of labor....	87400.	.25
Total........................	453500.	1.30
Plant maintenance:		
Labor............................	693700.	1.98
Supervision, 8 percent of maintenance labor................	55500.	.16
Materials........................	693600.	1.98
Total........................	1442800.	4.12
Payroll overhead, 35 percent of above payroll......................	420900.	1.20
Operating supplies, 20 percent of plant maintenance..................	288600.	.82
Total direct cost..............	3508200.	10.02
Indirect cost, 40 percent of direct labor and maintenance...........	758500.	2.17
Fixed cost:		
Taxes, 1.0 percent of total plant cost	296400.	.85
Insurance, 1.0 percent of total plant cost........................	296400.	.85
Depreciation, 20 year life............	1634700.	4.67
Total operating cost...........	6494200.	18.56

Table A-21.—Estimated capital cost(1), roadway aggregate from serpentine waste

Fixed capital:	
Serpentine waste aggregate	$ 10929200.
Subtotal	10929200.
Plant facilities, 10 percent of above subtotal	1092900.
Plant utilities, 12 percent of above subtotal	1311500.
Total plant cost	13333600.
Land cost	0.
Subtotal	13333600.
Interest during construction period	1031500.
Fixed capital cost	14365100.
Working capital:	
Raw material and supplies	11800.
Product and in-process inventory	304900.
Accounts receivable	304900.
Available cash	192400.
Working capital cost	814000.
Total capital cost	15179100.

(1) Basis: M and S equipment cost index= 606.4.

Table A-22.—Estimated annual operating cost, roadway aggregate from serpentine waste

	Annual Cost	Cost per ton Roadway aggregate
Direct cost:		
Raw materials:		
Serpentine waste at $ .00 per ton...	$ 0.	$ .00
Limestone at $7.00 per ton..........	15900.	.05
Total........................	15900.	.05
Utilities:		
Electric power at $ .025 per Kwhr...	213700.	.61
Process water at $ .50 per Mgal.....	300.	.01
Coal at $30.00 per ton.............	797200.	2.28
Total........................	1011200.	2.90
Direct labor:		
Labor at $8.00 per hour.............	233000.	.67
Supervision, 37 percent of labor....	87400.	.25
Total........................	320400.	.92
Plant maintenance:		
Labor...............................	306800.	.88
Supervision, 8 percent of maintenance labor.................	24500.	.07
Materials...........................	306800.	.88
Total........................	638100.	1.83
Payroll overhead, 35 percent of above payroll......................	228100.	.65
Operating supplies, 20 percent of plant maintenance.................	127600.	.36
Total direct cost..............	2341300.	6.71
Indirect cost, 40 percent of direct labor and maintenance...........	383400.	1.10
Fixed cost:		
Taxes, 1.0 percent of total plant cost	133300.	.38
Insurance, 1.0 percent of total plant cost........................	133300.	.38
Depreciation, 20 year life............	718300.	2.05
Total operating cost...........	3709600.	10.62

APPENDIX IV

MARYLAND STATE HIGHWAY ADMINISTRATION
DIVISION OF MATERIALS AND RESEARCH
2323 WEST JOPPA ROAD
BROOKLANDVILLE, MARYLAND 21022

TEST RESULTS

The following test results on aggregate supplied by U.S. Bureau of Mines, Tuscaloosa Metallurgy Research Center under Purchase Order P3290292 dated April 3, 1979, are in accordance with MSMT Designation 411, "Laboratory Method of Predicting Frictional Resistance of Polished Aggregates and Pavement Surfaces."

	Polish Value	
Aggregate Description	Strain	B.P.N.
1. Sintered Coal Refuse	22	78
2. Aluminum Waste	19	70
3. Copper Tailings	19	63
4. Calcined Clay Waste Glass	18	57
5. Calcined Serpentine	14	50
6. Calcined Low P.C.E. Clay	14	46
7. Slate Overburden	11	45

ANALYSIS OF RESULTS

This method of test is based on results of Report FHWA-MD-R-77-1, "Development of Laboratory Method of Predicting Wear Resistance of Aggregates". The empirical strain polish value is based on the Maryland control sample which is a dolomitic marble whose strain polish value is established as (6) six.

The Maryland control specimen was used in determining the reports results. The polish value is also reported in terms of B.P.N. as described in ASTM E 303. Regression analysis of B.P.N. and strain polish values has a correlation coefficient of 0.94.

Reported polish values when compared to aggregate data from FHWA-MD-R-77-1, Appendix D, indicate higher frictional resistance than all previously tested carbonate and serpentinite rock types. Also four (4) reported polish values are higher than any natural aggregate this laboratory has tested.

Reported by: ______________________
Eugene J. Morawski
Materials Engineer

LABORATORY METHOD OF PREDICTING FRICTIONAL RESISTANCE OF POLISHED AGGREGATES AND PAVEMENT SURFACES

MSMT Designation 411

SCOPE:

This procedure provides a method of evaluating the degree to which an aggregate or dense grade bituminous concrete mix used as pavement surface may be expected to polish from pneumatic tired vehicle traffic. Two procedures (Method A) Exposed Aggregate and (Method B) Dense Graded Bituminous Concrete are tested using a test series consisting of two control specimens and seven duplicate candidate test specimens.

MATERIAL AND EQUIPMENT:

1. Two G 78-15 size automobile tires.

2. Circular test track with a 3 ft (1 m) radius, capable of maintaining a tire rotation speed range from creep speed to peripheral speed of 30 mph (48 kph).

3. Strain gages.

4. Sixteen steel specimen molds to contain sample with 90 in.^{2} (570 cm^2) of exposed surface area.

5. Ten 100 ob (45 kg) test load weights.

6. Hydraulic cement retarding agent.

TEST PROCEDURES:

Method A Exposed Aggregate

1. Prepare the specimens by inverting the mold on a smooth flat plywood board brushed with a coating of hydraulic cement retarding agent.

2. Hand position aggregate particles as close to each other as possible in the mold.

3. Prepare a 2 part sand to 1 part cement mortar and pour into mold. After initial set, the surface cement paste is removed and the specimen is moist cured until time of testing.

4. The samples are placed on the test track and are polished by the two G 78-15 tires loaded with a 1,000 lb (450 kg) each. Rotate the wheels at the rate of approximately 20 rpm for 1,000,000 revolutions. During this period mechanical adjustments will be made to ensure uniform polishing across the surface of the specimen.
5. Ten stops for measurements of polish will be taken from 2,000, 25,000, 50,000 and 100,000 revolutions. The 6 remaining measurements will be taken at intervals which increase with the number of revolutions attained.

6. At each stop the track is flooded and the specimens covered by approximately 1/2 in. of water. The test wheel is put into place and allowed to make two complete revolutions around the track at creep speed while the spinning wheel slips over the track at a peripheral speed of 30 mph (48 kph). The strains induced in the arm holding the mechanism in place are recorded by a trace on paper tape. An average strain level is taken from the trace made as the spinning wheel passes over each sample. This is recorded on a work sheet, Figure 1, and the mean of the two values so determine is taken as an expression of the degree of polish for that specimen at that number of revolutions as shown in CALCULATIONS.

Method B Dense Graded Bituminous Concrete

1. Prepare a sample to conform to the desired job mix. Test track specimens are compacted under static load to a density of at least 95 percent of that obtained in standard Marshall design specimens.

2. Room temperature during polishing will be maintained at 55° F (13° C) to prevent shoving of the sample and the test load weight will be 500 lb (22.5 kg) on each tire.

3. Follow the procedures as outlined in Steps 4 though 6 of Method A.

CALCULATIONS:

1. The control specimen data is reduced to an appropriate hyperbolic curve by an interation procedure using cycle vis-a-vis measurement data as follows:

$$P = \frac{A+BT}{1+CT}$$

where:

P = polish measurement,
T = tire coverage, number of cycles, and
A, B, C = constants selected by iteration

2. As the numbered traffic coverage approaches infinity, the polish measurements asymtote is defined as the terminal value for the control material as follows:

$$U = \frac{B}{C}$$

where:

U = terminal value for the control material, and
B and C = constant selected by iteration.

3. Linear relationships between the polish value for the control specimen and each candidate material using the measurement stops are developed by regressions analysis for each candidate as follows:

$$Y = MX + D$$

where:

Y = candidate polish value,
X = control polish value, and
M and D = constants established by regression.

4. The terminal value for each candidate is determined as follows:

$$Z = MU + D$$

where:

Z = terminal value for each candidate material,
U = terminal value for the control material, and
M and D = constants established by regression.

REPORT:

The difference between the terminal values of the candidates and the control in each series is calculated. This difference is applied to a standard terminal value previously assigned the control to establish a polish value for the candidate.

REFERENCE:

FHWA-MD-R-77-1

APPENDIX V

Report of
Polishing Tests on Aggregate Samples
From
U. S. Bureau of Mines, University, Alabama
Prepared by

W. G. Mullen[1] and Durwood Barbour[2]

Scope:

To perform wear and polishing tests on aggregate samples following ASTM Method E660 utilizing a small wheel circular track. Friction measurements to be taken at 0, 1, 2, 4, 6 and 8 hours of polishing exposure using the British Pendulum Tester, ASTM E303, and the Variable Speed Friction Tester, ASTM E707.

Procedure:

Six inch diameter test specimens were made in sets of three from each of the Bureau of Mines aggregates. For each nine test specimens, three control specimens were made using a local aggregate that is used for control with the ASTM E660 Circular Track. Each track or "ring" holds 12 specimens, nine test and three control in this case.

Control:

Control specimen friction values are averaged with others from past tests to produce a running average that is used as the "master" curve for adjustments to friction values from each ring. For example, the three control specimens from a current ring are averaged for each time exposure point. The average is averaged with other averages to

[1]Coordinator, Highway Research Program, North Carolina State University.

[2]Bituminous Design Engineer, North Carolina Department of Transportation Materials Laboratory.

produce the "master" curve average. Control average from a given ring is compared to master curve and adjustment is determined at each data point to make the two curves agree. These adjustments are then applied to the raw data from test and control specimen sets in the ring and recorded as the adjusted test results.

Data:

Raw and adjusted data are tabulated for each aggregate variable as the average of three test specimens. Data are plotted for each aggregate showing BPN and VSN_{40} values compared to the laboratory control aggregate. Speed gradients are plotted for the VSN values using 8, 30, 40 and 50 mph.

Interpretation of Data:

It would have been desirable to have run each variable for three replications to provide an average of nine specimens per aggregate instead of three. There was limited aggregate and one set of three for each variable was all that was possible. It may be observed from the curves that are plotted, however, that reasonable comparisons may be made for each aggregate against the control aggregate and against each other.

BPN values are measures of microtexture and are approximately ten numbers higher than VSN values. VSN values are more nearly comparable to SN values, almost one on one and they represent measure of both microtexture and macrotexture.

Conversion equation for 40 mph tests is

$$y = 1.15x - 4.722$$

where $y = VSN_{40}$

and $x = SN_{40}$

The control aggregate is a medium to low skid resistant aggregate when polished. Field experience has shown that field polish seldom exceeds circular track polish of three to four hours exposure.

Based upon the plotted curves at VSN_{40} the aggregates could be ranked for four hour polish as follows:

Aluminum waste and refractory clay
Calcined clay and low PCE clay
Aluminum waste and high Al_2O_3 clay
Calcined serpentine waste
Copper mill tailings
Sintered coal refuse
Calcined clay and waste glass
Calcined clay and fly ash
Waste slate

Four of the aggregates ranked equal to or higher than the control aggregate while five ranked lower.

Speed gradients for all aggregates are much the same as they are a property of the mixture rather than the aggregates. All mixes were made to the grading requirements ASTM E660, paragraph 8.1.2.

It is noted that BPN values when compared to control show opposite results from those obtained by the VSN in some cases. It must be noted that BPN represents microtexture only and velocity of test is 8 miles per hour.

BUREAU OF MINES
SYNTHETIC AGGREGATES

On 8-9-79 the Materials and Tests Unit of NCDOT received 9 different synthetic aggregates from the US Bureau of Mines for polishing in the NC State U-Circular Track and utilizing the Variable Speed Tester and the British Pendulum Tester to determine skid resistance values. The aggregates were identified numerically and by name as follows:

No.	Name	Loose Volume Wt. (lbs.)/Ft^3	%AC
122A	Waste Slate Overburden	39	13.0
262	Copper Mill Tailings	75	10.0
1363	Sintered Coal Refuse	38	13.0
274	Calcined Clay & Waste Glass	54	10.5
204	Aluminum Waste & high Al_2 O_3 Clay	59	10.0
271	Calcined Clay & Fly Ash	55	12.5
290	Calcined Serpentine Waste	76	6.0
203	Aluminum Waste & Refractory Clay	51	10.5
289	Calcined Clay & low PC_2 E_3 Clay	59	10.5
Control	Crabtree Quarry	81	6.0

We determined the loose volume unit weight of each in order to gain a better judgment as to optimum asphalt content and the weight required to mold the proper thickness of bituminous specimens for the circular track. The samples were separated on the 3/8", #4, #8, P8 Ret. #200, and Pass. No. 200 sieves and recombined to a sieve analysis of % pass. 1/2" -100, 3/8-95, #4-43, #8-10, #200-2.

Considering the unit weight and the porous nature of these aggregates we made a trial sample of each using a volume of AC 20 asphalt which we felt would give an adequate bond and coating. These trial samples did not coat well, and the asphalt content had to be increased. Also we treated the asphalt with 1/2% by weight no strip additive to improve the adherence of asphalt to the minerals. The cooper mill tailings were especially difficult to coat relative to unit weight.

Three specimens with each of 3 aggregates plus 3 samples made with the control aggregate were included in each circular track of 12 specimens. The surface of the specimens exhibited little or no distress except for the control aggregate which did experience a moderate amount of ravelling during the latter part of track time.