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Survey of Uses of Waste Materials in Construction in the United States

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Materials and Composites Section
Center for Building Technology
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Survey of Uses of Waste Materials in Construction in the United States

James Roger Clifton, Paul Wencil Brown and Geoffrey Frohnsdorff

ABSTRACT

A survey has been made of the sources, amounts and methods of disposal of major mining, industrial and municipal wastes available in the 48 conterminous states of the United States. This includes the present and potential uses of these wastes as construction materials.

While over 3 x 10^9 tons of waste materials are generated annually in the United States, only small amounts are being used by the construction industry. The low level of use does not yet reflect the advances being made in converting wastes into viable construction materials. In several cases, construction materials produced from wastes have been at least the technological equivalent of materials produced from virgin resources. Factors which are impeding the increased utilization of wastes are discussed and emerging incentives which could facilitate their increased use are covered.

1. INTRODUCTION

1.1 Solid Wastes in the United States

The United States is both a major consumer of natural resources and a major producer of mining, industrial, agricultural and municipal waste materials. For example, it has been predicted that, within the next 100 years, the United States will consume over 6.8 x 10^9 tons[1/] of iron ore, 1 x 10^9 tons of phosphate rock and 1.5 x 10^9 tons of aluminum ore, resulting in a massive generation of mining waste [1]. Present U.S. production of mining waste and coal refuse exceeds 360,000 tons daily which is being added to some 23 x 10^9 tons already accumulated. The generation of large amounts of municipal refuse, building rubble, sulfate wastes, fly ashes, industrial processing and other wastes are also contributing to massive disposal problems. Disposal of wastes is posing increasingly difficult problems because of rapidly growing concern for the quality of the environment and enactment of legislation to ensure its protection.

Many waste materials can be used directly as, or be converted into, viable construction materials, thereby conserving natural resources and energy, and mitigating the harmful effects of the wastes on the environment. Because of the large quantities of materials used in construction, such applications could consume significant amounts of the wastes.

1.2 Developments in the Use of Wastes in Construction

With the exception of the program established some 60 years ago by the Bureau of Mines [2], the United States government gave little emphasis to research and development on the use of waste materials in construction until the late 1960's. Consequently, only a small fraction of the construction materials used in the United States is derived from waste materials. During the past decade, however, significant programs which should facilitate the increased use of waste materials in construction have been established by federal and state governmental agencies. For example, the feasibility of using waste materials as sources of aggregate is being explored in projects sponsored by the Federal Highway Administration; the Federal Energy Administration and the Energy Research and Development Administration are supporting work relating to the conservation of energy by substituting waste materials for more energy-intensive materials; the Environmental Protection Agency is supporting demonstrations of uses of waste materials as an approach to improve the nation's environment; and the Bureau of Mines is continuing its program on developing uses for mineral wastes. In addition, the recently passed Resource Conservation Act of 1976 [3] is intended to stimulate the increased use of waste materials.

1/ Amounts are given in metric tons throughout this report.

The business sector of the United States is also promoting the recycling of solid waste. For example, the National Center for Resource Recovery is a nonprofit organization founded by leaders of major United States industry and labor organizations to advance the technology of resource recovery from solid wastes. Its present emphasis is on resource recovery from municipal refuse.

Other important activities in the United States which are stimulating interest in the use of waste materials include the Mineral Waste Utilization Symposia,[2/] the Ash Utilization Symposia,[3/] and the work of Committee E-38 on Resource Recovery of the American Society for Testing and Materials (ASTM). Within the committee, subcommittee E38.06 was specifically established to cover "Materials of Construction from Other Recovered Materials."

1.3 Survey of Waste Materials

This survey covers the sources, amounts and disposal of major mining, industrial and municipal wastes available in the 48 conterminous states of the United States along with their present and potential uses as construction materials. Agricultural wastes are not included because only in a few cases has their use as viable construction materials been seriously considered. One of the few examples is research with the conversion of certain types of agricultural waste into construction materials. It has recently been shown [4] that hydraulic acid-resisting cements can be produced using the ash of rice hulls. Similar cements probably could be produced using residues from the straw from wheat, barley, oats and rye.) Furthermore, much of the agricultural waste rapidly re-enters the biological cycle which facilitates its disposal.

In this report wastes from mining, industrial and municipal sources are treated separately and in that order. This is the order of decreasing amount of usable wastes available from each major classification (table 1). Wastes from mineral, metallic ore and coal mining operations are covered in Section 2. Industrial wastes are treated in Sections 3 to 5, with Section 3 describing a variety of important wastes which have found few markets; by-products from coal combustion, which are examples of wastes for which there are growing markets, are discussed in Section 4; and Section 5 covers slags, by-products which are already extensively used as aggregates in construction but for which there may be higher value uses. Municipal wastes, including municipal refuse, incinerator residue, glass, demolition waste and sewage sludge, are the subject of Section 6. Then Section 7 is directed towards some potential wastes which may be generated in substantial amounts by emerging technologies related to energy production and environmental protection. Obstacles to and incentives for the increased use of waste materials in construction are discussed in Section 8.

1/ Biannual Symposia held since 1968, co-sponsored by the U.S. Bureau of Mines and the Illinois Institute of Technology Research Institute (IITRI).
2/ Triannual Symposia held since 1967, sponsored jointly by the National Coal Association, Edison Electric Institute, American Public Power Association, National Ash Association and the U.S. Bureau of Mines.

Table 1. Amounts of Mining, Industrial and Municipal Wastes

Type of Waste	Annual Amounts[1/] (10^6 tons)	Section of Survey
Mining	2,270	2
Industrial	180	3-5
Municipal	180[2/]	6

1/ Estimates based on amounts given in this survey.
2/ Includes some 135 x 10^6 tons of municipal refuse of which about 36 x 10^6 tons might be suitable for use in construction.

2. MINING WASTES

Mining wastes, considered collectively, form the greatest part of the solid waste material generated in the United States with over 2.2×10^9 tons being generated annually. A distinction is usually made between mineral mining wastes and coal refuse. Mineral mining wastes are usually described as being either waste rock or mill tailings. Waste rock is the coarse material that is excavated to expose the ore during mine development. Mill tailings are the residues obtained from the separation of minerals from their ores. Wastes from the sizing and cleaning of coal, from either underground mining or from strip mining operations, are defined as coal refuse. Coal refuse may contain mine rock, carbonaceous shale, pyrites, and other debris from mining operations. Dredge spoils are also covered in this section because their mineralogical compositions and physical states are like those of mining wastes.

This section is concerned with the sources, amounts, disposal, and present and potential uses of wastes resulting from mining operations. Much of this information has been provided by the members of ASTM Subcommittee E38.06.

2.1 Inventory and Sources of Mining Wastes

Estimates of the amounts of waste rock, mill tailings, and coal refuse produced annually by major mining industries in the United States are listed in table 2. This table includes estimates of the amounts of the mill tailings and phosphate processing wastes which have accumulated over the years. The copper industry accounts for nearly one half of the mining waste generated annually. Other operations which produce large amounts of waste include the mining of iron ore and taconite, coal, uranium, phosphate, gold, gypsum, lead, and zinc.

Areas of the United States in which large quantities of waste rock and mill tailings are located are shown in figure 1. These include the large copper producing states (Arizona, Utah, Montana, Michigan, and Tennessee); the Mesabi Range taconite mines (northeastern Minnesota); the major iron ore mining areas (Minnesota, Michigan, Missouri, Pennsylvania, California, and Wyoming); and several lead-zinc regions (Idaho, Tennessee, and Wisconsin). There are also large accumulations of dredge tailings from past gold mining in the Mother Lode district (northern California) and of chat (coarse tailings) from past mining of lead-zinc ores in the Tri-State mining district (Missouri, Kansas, and Oklahoma) [5].

The largest accumulations of coal refuse are located (figure 2) in the eastern states of Pennsylvania, West Virginia, Tennessee, and Kentucky. Other significant accumulations are in Illinois, Ohio, and Wyoming. There are more than 3×10^9 tons of coal refuse in Pennsylvania and Kentucky alone. The amount of coal refuse produced annually will certainly increase because of the greater emphasis being placed in the United States on coal

Table 2. Amounts and Possible Uses of Major Mining Wastes

Mining Industry	Waste Rock Annual Quantity[1/] (10^6 tons)	Mill Tailings Annual Quantity (10^6 tons)	Estimated Accumulated Mill Tailings (10^6 tons)	Possible Uses of Tailings in Construction	References
Copper	624	234	7700	Brick, embankments, mineral filler in bituminous mixtures.	5, 19
Dredge spoil	270-360	-	Uncertain	Landfill.	
Taconite	100	109	3600	Concrete aggregate, skid-resistant aggregate, building block.	5, 19
Coal	Included in tailings	>100[2/]	2700[2/]	Highway construction, land and minefill.	5, 6, 20, 28
Phosphate	230	54[3/]	907[4/]	Landfill, dikes for phosphate slimes.	5
Iron ore	27	27	730	Concrete aggregate.	5, 7, 9
Gold	15	5	450	Brick, sand and gravel, mineral filler.	5, 12
Uranium	156	5.8	110	None because of concern with low level radioactivity.	33
Lead	0.5	8	180	Mineral filler in bituminous mixtures; refractory brick.	5, 8
Zinc	0.9	7.2	180	Mineral filler in bituminous mixtures; refractory brick.	5, 8
Quarry	68	-	Uncertain	Aggregate.	5, 19
Gypsum	14.2	2.7	Uncertain	Brick.	13
Asbestos	0.6	2	14	Ceramic tile, refractory brick, mineral filler in bituminous mixtures.	5, 13

Table 2. Amounts and Possible Uses of Major Mining Wastes (cont.)

Mining Industry	Waste Rock Annual Quantity 1/ (10^6 tons)	Mill Tailings Annual Quantity (10^6 tons)	Estimated Accumulated Mill Tailings (10^6 tons)	Possible Use of Tailings in Construction	References
Barite	1.9	3.1	24	Road surfacing material.	5
Fluorspar	0.1	0.4	Uncertain	Aggregate.	5
Feldspar	0.2	0.8	Uncertain	Manufacture of brick and lightweight building materials.	13, 14, 15

1/ Includes overburden in some cases.
2/ Coal refuse, which includes mine rock, shale, pyrite and other mining debris.
3/ Includes both phosphate slimes and phosphogypsum.
4/ Includes estimated 136 x 10^6 tons of phosphogypsum.

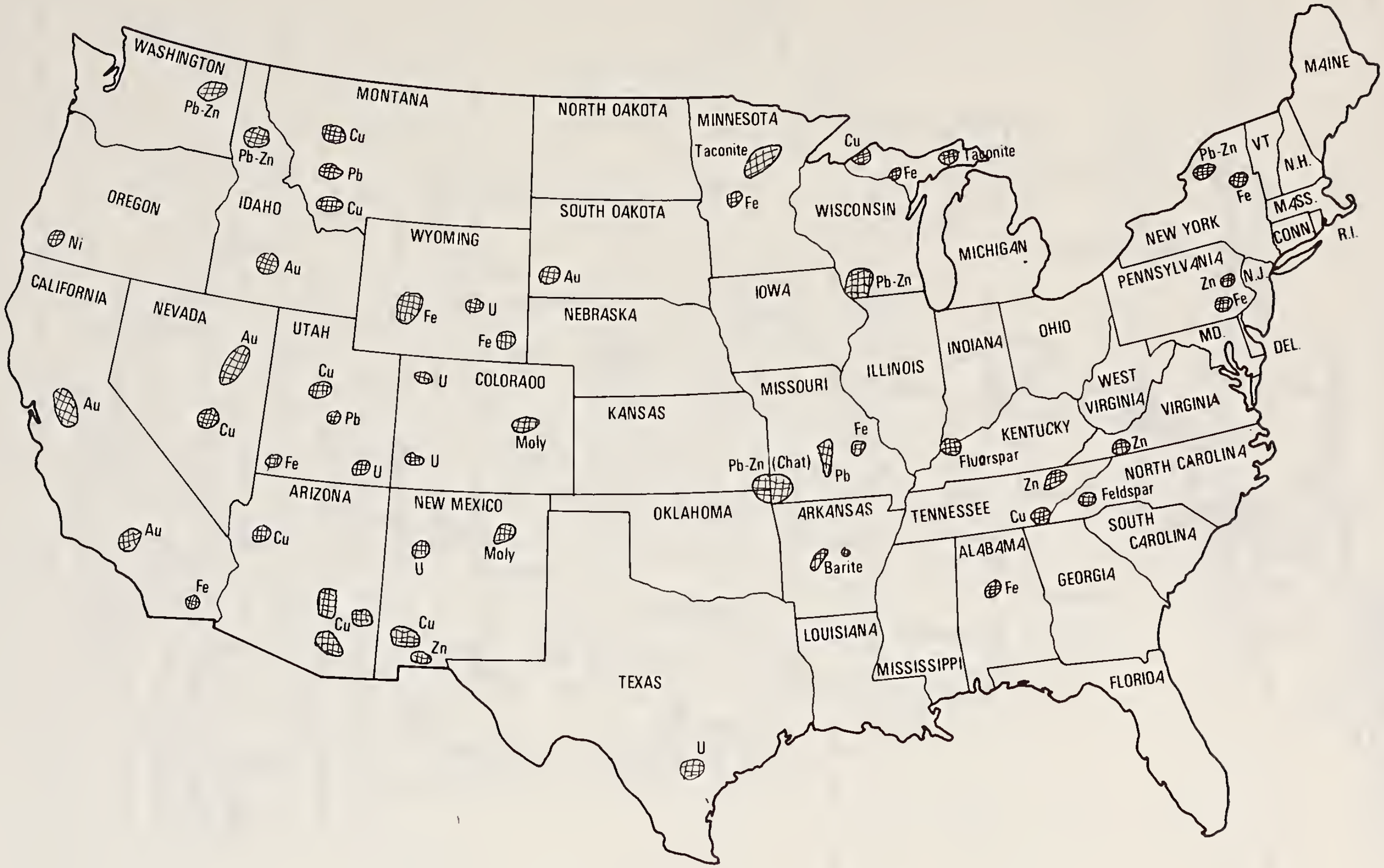

Figure 1. Locations of Large Accumulations of Waste Rock and Mill Tailings.

Figure 2. Locations of Large Accumulations of Coal Refuse.

utilization. It is estimated that while 560 x 10^6 tons of coal will be produced in 1975, approximately 900 x 10^6 tons will be produced in the year 2000 [6]. Much of the increased coal production will be in western states. Most of this western coal will probably be burned in the uncleaned state directly from the mine resulting in a smaller ratio of coal refuse to coal production than is currently obtained [6]. Nevertheless, there is no doubt that stockpiles of coal refuse will continue to grow for many years.

Dredge spoil is available along the major navigable waterways in the United States, such as the Mississippi and Columbia rivers and from coastal sites.

2.2 Description, Disposal, and Uses of Mining Wastes

2.2.1 Waste Rock

Over 1.1 x 10^9 tons (table 2) of waste rock are removed each year during mineral mining operations. Most of this waste rock comes from open-pit mines. The composition of waste rock can vary from one mining operation to another. Depending on the geological formation from which the ore is removed, the waste rock may be igneous, metamorphic, or sedimentary. Generally, igneous and metamorphic rocks are harder than sedimentary rocks and are more suitable for uses requiring hard rock, such as aggregate for concrete. However, some well consolidated sedimentary rocks, such as some limestones, are also good aggregate materials [5]. The particle size of waste rock can vary because of variations in geological formations and differences in mining methods. While individual pieces might be larger than 1 m in diameter, waste rock is usually less than 0.3 m. Waste rock from any source can generally be reduced to a desired size range by normal crushing and sizing methods.

Waste rock along with overburden is often disposed of in large dumps. For example, over 5580 hectares in Minnesota are covered with a waste rock overburden from the mining of iron ore [7]. Waste rock is sometimes used as backfill in open pit mining operations and in highway construction. The total use of waste rock in construction appears, however, to be only a small fraction of the amount generated each year. The largest use of waste rock has been in highway construction using rock from iron ore mines [5]. Traprock from an underground mine in Pennsylvania was used to resurface a section of the Pennsylvania Turnpike and in Missouri a similar waste rock is being crushed and marketed as a skid-resistant aggregate. Waste rock from ore mining in Michigan, New York, Wisconsin, and Wyoming has also been used successfully in highway construction as aggregates, subbase material, and for embankments. Waste rock from copper mining has occasionally been crushed and used as a base or subbase material in Arizona and Michigan. Waste rock from gold mining has been used as an aggregate in Colorado and as a highway resurfacing material in South Dakota. Waste rock from lead-zinc mines has been used as an aggregate for bituminous paving in Washington, Wisconsin, and Missouri.

2.2.2 Mill Tailings

The physical and chemical characteristics of mill tailings depend on their source and the method of ore processing. For example, the tailings from lead-zinc mining are often dolomitic [8], while those from taconite, gold, and copper ore mines have high silica contents [9, 10] (table 3).

In operations where the tailings are not a residue produced by size separation, they are usually finely divided having particle sizes in the silt-clay particle size range. The processing of copper, taconite, gold, uranium, lead, and zinc ores all require about the same degree of crushing and fine grinding. Between fifty and ninety percent of the particles from these tailings are smaller than 75 μm. Where size separation is practiced, the coarse fraction of the tailings approximate a well-graded sand, predominantly in the fine to medium sand range. Iron ore tailings are often separated into a fine fraction which is in the silt to coarse particle size range and a coarse fraction which is graded from a fine sand to a gravel [5].

Tailings are usually separated from ore minerals by wet processing and are transported as a slurry by pipelines for disposal in tailing ponds. Coarse tailings and waste rock are used for construction of the containment dikes. Much of the slurry water is recirculated or allowed to evaporate resulting in the formation of slimes in the case of lead-zinc tailings [9] and sometimes in the case of iron [7] and copper tailings [9]. Tailings are also disposed of through use as mine backfill materials [11]. Coarse tailings are often stockpiled [7, 8].

As with waste rock, the amount of mill tailings used annually in construction appears to be only a small fraction of the amount produced. However, there are many examples of the use of mill tailings in highway construction [5]. Coarse taconite tailings have been used successfully as skid-resistant aggregate for bituminous overlays of highways in Minnesota. Chat, the coarse by-product from the milling of lead-zinc ores, has been an approved highway construction material for many years in Kansas, Missouri, and Oklahoma. In Utah, millions of tons of copper tailings have been used in highway embankments and as mineral filler in bituminous mixtures. Gold dredge tailings are routinely used as sand and gravel in northern California and have been used for similar purposes in Colorado. These and other mill tailings have performed well in many highway applications. Other possible uses of mill tailings include the manufacture of ceramic products such as brick [10, 12-17] lightweight building block [9, 14, 18], and mineral wool [19]. Many mill tailings have excellent engineering properties [11, 20] and are suitable for the construction of small earth dams and as backfill materials [11].

Table 3. Oxide Analyses of Some Taconite, Copper, Gold and Lead-Zinc Tailings

Constituent	Taconite Tailings [9] Percent	Copper Ore Tailings [9] Percent	Gold Tailings [5] Percent	Lead-Zinc Tailings [9] Percent
SiO_2	59	71.1	93	9.8
Fe_2O_3	21	4.9	1.9	1.1
Al_2O_3	2.7	13.2	3.5	0.3
MgO	3.7	2.1	0.41	17.8
CaO	2.7	1.1	1	29.4
Na_2O	--	0.3	0.07	--
K_2O	--	3.3	0.33	--
Loss on Ignition	7.4	2.6	0.22	42

2.2.3 Coal Refuse

Coal refuse from anthracite and bituminous coal mine operations consists of a variety of minerals (table 4) and is usually rich in SiO_2, Al_2O_3, and Fe_2O_3 [21, 22]. Anthracite refuse has a high proportion of coarse particles with over 65 percent being 13 mm or larger in size [21]. The refuse from bituminous coal mines in Kentucky is usually separated into coarse and fine fractions through separation by sedimentation [22].

In the past, coal refuse has been placed in refuse piles or banks. Coal refuse often contains carbon which can be ignited by spontaneous, accidental, or intentional ignition. If it is ignited, and if sufficient oxygen is available, a bank becomes a self-sustaining source of air pollution. State and federal programs have been established to extinguish existing burning banks of coal refuse. Furthermore, atmospheric or other ozidation of pyrite creates a sulfuric acid effluent which may pollute water resources. Presently, most states require that coal refuse be placed in cleaned sites free of underground or surface drainage and laid down in layers followed by compaction, contouring, and vegetation. The effectiveness of the legislation and of these disposal methods is still a controversial subject [23-25]. Coal refuse has also been disposed of by being flushed into underground mines. Over 1.8×10^8 m^3 of coal refuse had been flushed into mines by 1968 [21].

A small amount of coal refuse has been used in the past for construction purposes, primarily for highway applications such as base and subbase material [6], and aggregates for pavement [26, 27], including anti-skid material [28]. Anthracite coal refuse has been used, on a relatively small scale, to make concrete block, lightweight aggregate, and brick [21]. Other small scale uses of coal refuse have been in the manufacture of mineral wool and cement [21]. These applications represent only a small tonnage and seem to have only a small potential for growth. Another possible use of coal refuse is as landfill material [6]. Coal refuse has been used successfully in England as landfill for a variety of construction purposes [29-30]. In general, coal refuse appears to have many of the engineering properties, handling characteristics, and availability desired for a landfill material [21].

2.2.4 Dredge Spoil

Dredge spoil, the waste from dredging operations, is usually divided into three types of materials for engineering purposes: coarse grained, fine grained, and organic. Fine grained materials are defined as those smaller than 75 μm. It is the fine grained and organic spoils that normally cause dredging problems [5]. Over two thirds of dredge spoil is disposed of in open water and the remainder is disposed of in landfill.

Table 4. Oxide and Mineralogical Analyses of Coal Refuse

Anthracite Refuse[1]				Bituminous Refuse[2]			
Oxide	Percent	Mineral	Percent	Oxide	Percent	Mineral	Percent
SiO_2	50-57	Kaolinite	70	SiO_2	43-61	Kaolinite	16-72
Al_2O_3	30-37	Illite	1-10	Al_2O_3	14-20	Illite	16-50
Fe_2O_3	3-10	Gypsum	1-10	Fe_2O_3	2-31	Quartz	7-32
TiO_2	1-2	Quartz	1-20	TiO_2	0.8-2.2	Calcite	0-17
CaO	1-2	Calcite	1-10	CaO	0.1-10	Pyrite	0.4-12
MgO	0-1	Pyrite	1-10	MgO	0.5-3	Magnesite	0-4
$K_2O + Na_2O$	1-3	Rutile	1-10	$K_2O + N_2O$	2-5.5	Apatite	0.1-4
SO_3	0-1			SO_3	0-2		

1/ Anthracite refuse from Pennsylvania, reference 21.
2/ Bituminous refuse from Kentucky, reference 22.

2.3 Prospects for the Increased Use of Mining Wastes

Enormous amounts of mining wastes are produced annually in the United States and it is anticipated that most types of mining wastes will be generated even more rapidly in the next several decades. Only a small fraction of these wastes is currently being used in any application. Probably their largest use is for self-containment purposes. The most promising prospective use of mining wastes appears to be in large engineering projects such as the construction of highways and earth dams, and in land and minefills. Their application as highway materials, especially as aggregates, continues to receive significant attention [5, 31-33].

Waste rock, coal refuse, and gold and taconite tailings have often performed better as aggregates and fillers than conventionally used materials. Furthermore, a significant portion of these waste materials is located in regions of the United States which have shortages of high quality aggregates [34-37]. There appear to be no significant institutional obstacles to the use of these mining wastes as aggregates and current ASTM specifications for aggregates do not preclude the use of mining wastes, with beneficiation if required, provided they meet essential physical requirements. The main factor which determines the use of specific waste materials as aggregates is the economics [36]. As shortages of high quality natural aggregates from traditional sources develop regionally and transportation costs increase, the use of locally available waste materials may become economically attractive [35]. Therefore, it is expected that waste rock and coal refuse generated near large construction activities will find increasingly wide use as aggregates in many types of construction.

The prospects for large scale use of mill tailings (with the exception of gold and taconite tailings and coarse tailings) as aggregates and highway construction materials are not encouraging based on present technology and economics [31]. A more promising application is their use in the production of ceramic building materials such as brick and lightweight building blocks, and in autoclaved calcium silicate insulation materials. However, even these applications would consume only a small portion of the available mill tailings.

3. WASTES FROM THE PHOSPHATE, ALUMINUM AND CEMENT INDUSTRIES, AND SULFATE WASTES

Major processing waste materials generated in the phosphate fertilizer, aluminum extraction, and cement manufacturing industries, and those which can be classified as waste sulfates are considered in this section. The amounts of these waste materials generated annually in the United States are given in table 5. Presently, only small quantities of these waste materials are used for construction or any other purpose. However, as discussed in this section, many of these materials could be used to produce construction materials.

Table 5. Amounts and Possible Uses of Some Major Industrial Wastes

Waste Material	Accumulated Quantity (10^6 tons)	Annual Production (10^6 tons)	Possible Uses for Construction Purposes	References
Phosphate Processing Waste				
Sand	N.A.[1/]	9-13	Landfill, pond dikes, concrete.	37
Phosphate slime	1800[2/]	9-13	Lightweight aggregate.	37-40
Sulfate Wastes				
Phosphogypsum	136	5	Plasterboard, floor and roof filler, admixture in concrete.	15
Fluorogypsum	N.A.	0.1	Plasterboard.	42
Gas scrubber waste	>5[3/]	5[3/]	Combined with fly ash and lime to form highway construction and landfill materials.	44, 47-48
Mud Residues from Aluminum Extraction	90	5	Ceramic foam, cement, lightweight aggregate.	49-53
Cement Kiln Dust	N.A.	5[4/]	Incorporation in blended cements, substitute for lime and limestone.	54, 57-59

1/ Not available.
2/ Contains about 75 percent water.
3/ Contains calcium sulfite.
4/ Altogether about 17 x 10^6 tons are collected, with 12 x 10^6 tons being fed back into the process and the remainder discarded.

3.1 Phosphate Ore Processing Wastes

3.1.1 Production and Sources of Phosphate Ore

The primary ore for phosphorus fertilizers is phosphate rock, in which the phosphate occurs as apatite, i.e. calcium fluophosphate, $Ca_5F(PO_4)_3$. Phosphate ore is generally composed of roughly equal quantities of sand, clay, and phosphate [37].

Phosphate mining operations consist of stripping off the overburden and transferring the phosphate ore to large sumps or wells where it is converted into a slurry by high pressure jets of water. The slurry is then pumped to the ore processing plants. In the processing operation, the clay particles are removed from the sand and phosphate and pumped to large settling ponds. The sand tailings, which are mostly silica, are used for building dikes around the waste settling ponds and for filling mined areas being reclaimed. The phosphate concentrate is dried and shipped to chemical manufacturing plants.

Phosphate rock is mined in Florida, North Carolina, Tennessee, Idaho, and Montana. Florida produces about 70 percent (about 23×10^6 tons annually) of all the phosphate rock produced in the United States, with most of it coming from a 32 x 48 kilometer area in the Bone Valley District of central Florida [37].

3.1.2 Characteristics and Disposal of Phosphate Processing Wastes

The major waste materials from the processing of phosphate ores are silica sand and phosphate slimes. Few problems are encountered in the disposal or use of the sand as it can be used without further treatment in concrete and landfill operations, and for the construction of dikes. The most significant problem of the phosphate mining industry is the handling, disposal and reclamation of the slimes. Phosphate slimes constitute over one half of the plant wastes. Between 9×10^6 and 13×10^6 tons of phosphate slimes are produced each year and their production is increasing at about 4 percent per year.

Phosphate slimes consist of colloidal clay particles with 75 percent of the particles being under 3 microns and 50 percent under 0.3 microns. The slimes are rich in SiO_2, Al_2O_3, CaO, and P_2O_5 (table 6).

Phosphate slimes are pumped to large ponds where the clay gradually settles. As much of the supernatant water is reused as possible. Many of the slime ponds are enormous, being up to 3 kilometers long and 3 kilometers wide, and surrounded by walls and dikes up to 13 m in height. It has been estimated that nearly 2×10^9 tons of phosphate slime, containing about 1.4×10^9 tons of water, are stored in these ponds. The colloidal clay particles settle very slowly and after about 25 years the slimes have a solids content of between 20 and 30 percent and the consistency of grease [38].

Table 6. Oxide and Mineralogical Compositions of Phosphate Slimes [37]

Oxide Composition		Mineralogical Composition	
Oxide	Percent	Mineral	Percent
P_2O_5	9-17	Calcium fluophosphate	20-25
SiO_2	31-46	Quartz	30-35
Fe_2O_3	3-7	Montmorillonite	20-25
Al_2O_3	6-18	Attapulgite	5-10
CaO	14-23	Wavellite	4-6
MgO	1-2	Feldspar	2-3
Loss on ignition	9-16	Heavy minerals	2-3
		Dolomite	1-2

3.1.3 Prospective Uses of Phosphate Slimes

Major problems encountered in the use of phosphate slimes are their slow settling rates, their low percentages of solids, and the extreme fineness of the mineral constituents.

Slimes have been stabilized and used as landfill materials by being mixed with sand tailings from phosphate rock processing plants. The sand tailings capture the slimes and a paste with about 90 percent solids content is produced when the mixture is passed through a narrow channel at high velocity. This paste is then allowed to settle in long, narrow, mined-out channels which are subsequently backfilled in land reclamation projects [39]. This method can consume only about 35 percent of the slimes generated at a processing plant because of the resultant ratio of slime to tailing in the landfill material [37].

Other uses of phosphate slimes depend on thermally drying the slimes to high solid levels. Cross-flow fluid dryers have been found to be efficient in drying slimes to a 95-99 percent solids content [40].

The most promising application of dried slimes to date has been in the production of lightweight aggregates. Dried phosphate slime is pelletized and heated to between 1050 to 1100°C in a rotary kiln, producing an aggregate with a bulk density between 320 and 480 kg/m^3. These aggregates meet the requirements of ASTM Specification C330, Lightweight Aggregates for Structural Concrete [41]. Furthermore, they appear to have better load-bearing characteristics than some conventional lightweight aggregates such as perlite and vermiculite [40].

Brick and sewer pipe have been manufactured from phosphate slime but neither product was of high quality [40].

3.2 Sulfate Wastes

Calcium sulfate is generated as a by-product or waste material in a variety of processes, the major one being the manufacture of phosphoric acid. In the near future, scrubbing of combustion gases from coal burning power plants is also expected to produce large quantities.

3.2.1 Phosphogypsum

During the conversion of phosphate rock to chemical fertilizers and other products, the rock is treated with sulfuric acid to form phosphoric acid and gypsum:

$$Ca_5F(PO_4)_3 + 5\ H_2SO_4 + 10\ H_2O = 3\ H_3PO_4 + 5\ CaSO_4 \cdot 2\ H_2O + HF.$$

The phosphoric acid is then often used to produce fertilizers such as triple superphosphates and mono- and diammonium phosphates [37]. The by-product gypsum is pumped into diked areas where it settles out and the supernatant water is reused. The dike walls are often constructed with dewatered gypsum. Because the gypsum contains a significant amount of phosphoric acid it is called phosphogypsum. Phosphogypsum is also disposed of by being placed in exhausted phosphate mined areas. Approximately 5 x 10^6 tons of phosphogypsum are produced annually in the United States [5], primarily in areas where phosphate ore is mined. Accumulated amounts have been estimated to be 136 x 10^6 tons [5].

At present, gypsum recovered from phosphogypsum has little commercial value because of its impurity [42] and also because adequate alternative sources of gypsum are generally available [43]. Nevertheless, the feasibility of producing plasterboard and filler materials for floor and roof systems from the recovered gypsum is being investigated [15, 42]. The recovered gypsum could possibly be used as a set-regulating admixture for portland cement.

3.2.2 Fluorogypsum

Approximately 90 x 10^3 tons of anhydrite ($CaSO_4$) are produced annually in the production of hydrofluoric acid from fluorspar and sulfuric acid. The anhydrite by-product is a dry material containing 4 to 6 percent calcium fluoride and smaller amounts of various other salts. The anhydrite by-products are disposed of by dumping on dry land or use as landfill material. They have little commercial value at present. A possible use is production of an impure plasterboard.

3.2.3 Gas Scrubber Waste

Gas scrubber waste is the material obtained using the lime or limestone slurry process for removing sulfur dioxide from the stack gases of coal burning power plants. The sulfur dioxide is converted to calcium sulfite and calcium sulfate in the processes used in the United States. The resulting gas scrubber waste is a sludge having solid contents in the range of 19 to 50 percent [44, 45].

At present about 5 x 10^6 tons per year of gas scrubber waste are generated in the United States [45]. Because of the increasing use of high sulfur coals, the amounts of waste generated will increase rapidly; it has been estimated that 64 x 10^6 tons of solid scrubber waste will be generated in 1980 [45]. Approximately 17 power plants which incorporate scrubber systems are either being planned or are in operation [44, 46].

Proposed methods for disposing of most of the scrubber wastes include placing it in ponds and using it in landfill operations [45].

3.2.4 Prospective Uses of Sulfate Wastes

Recent studies have indicated that sulfate wastes from a variety of sources can be mixed with lime and fly ash to form structurally stable construction materials [44, 47]. Potential applications of the waste sulfate-lime-fly ash material include use as a structural landfill material [47], and as highway construction material for embankments, subbases and bases for pavements [44, 48]. These materials appear to have acceptable mechanical properties but their durability, especially to freezing and thawing appear to be marginal in the present state of their development [44]. The proximity of fly ash and waste sulfate sources to each other and to large metropolitan areas [44] could result in sulfate-lime-fly ash material becoming an economically viable construction material if additional development work indicates it has acceptable long-term performance.

3.3 Muds from the Processing of Aluminum Ores

The feedstock for the reduction of alumina to aluminum metal is obtained from the processing of bauxite. Bauxite ores are mined in Arkansas or imported from Caribbean area deposits and are processed in domestic plants located in the southern states of Arkansas, Alabama, Louisiana, and Texas.

The major waste materials from the processing of bauxite are "red muds" and, to a lesser amount, "brown muds." Over 5×10^6 tons of solid waste are produced annually from the processing of bauxite and approximately 90×10^6 tons have been accumulated in settling ponds [49]. Red muds comprise about 90 percent of this tonnage. During the processing of bauxite from Arkansas, a "black sand," comprising 8 to 18 percent by weight of the total waste, is separated from the mud [49].

The red muds are pumped from alumina extracting plants as slurries containing about 20 percent solids. The slurries are stored in ponds where the solids settle and the supernatant water is reused. The solid contents of slurries gradually approach 50 percent after years of settling [49].

3.3.1 Properties of Muds

The properties of a red mud depend on the source of the bauxite. The oxide and mineralogical compositions of typical red muds are given in table 7. The chemical compositions of muds derived from the same source of bauxite may vary by 10 percent. Their mineralogical compositions depend on the ore as well as processing conditions, and they have been described as being clay-like materials similar to noselite in composition [49]. The oxide analysis of a typical brown mud shown in table 7 suggests that it is composed largely of dicalcium silicate. The particle size distribution of dried muds also depends on the source of the ore and processing conditions. Red muds consist of fine particles with almost 90 percent being smaller than 45 μm [50].

3.3.2 Prospective Uses of Muds

Considerable effort has been devoted to finding uses for muds from the processing of bauxite including the recovery of valuable minerals and by-products. Possible direct uses include use as an additive to concrete, as a thermal insulation material and as a highway road bed stabilizer; other possible uses are incorporation in building materials such as portland cement, binders (e.g. for taconite pellets), and bricks [42, 49]. Some of these uses have reached the commercial stage but no consistent use has been maintained on a sufficient scale to even consume current output.

The Bureau of Mines has sponsored work to develop new uses for red muds [42, 51]. Recently, it has been demonstrated that lightweight structural building materials can be produced from red muds [50]. These materials have densities ranging from 480 to 1120 kg/m^3 with excellent thermal and acoustical insulation properties [49-50]. Another prospective use for red muds is the manufacture of synthetic aggregates. Red mud has been molded into balls and heated in a muffle furnace at 1260 to 1316°C to produce a dense synthetic aggregate [52]. However, the performance of these aggregates either in concrete or in asphalt has not yet been investigated. Granular lightweight aggregates of bulk density 704 kg/m^3 have been prepared in West Germany by firing a 1:1 mixture of red mud and fly ash [53].

3.4 Cement Kiln Dust

In the manufacture of portland cement clinker in rotary kilns, between 10 to 20 percent of the weight of the raw material leaves the kiln as dust. Approximately 17×10^6 tons of kiln dust were collected in 1972, of which about 12×10^6 tons were fed back into the process and the remaining 5×10^6 tons were discarded [54]. The most common method of discarding the collected dust is to dump it on surface piles or in abandoned quarries.

Table 7. Oxide and Mineralogical Analyses of Some Red Muds and a Brown Mud [49, 50]

Oxide	Oxide Analysis (Percent)			
	Domestic Ore	Imported Ores Source 1	Imported Ores Source 2	Brown Mud
Al_2O_3	26.5	19.1	20.0	6.4
Fe_2O_3	10.7	38.3	49.0	6.1
SiO_2	22.9	9.3	3.4	23.3
CaO	8.1	5.3	6.8	46.6
Na_2O	11.8	6.4	0.5 to 5.0	4.1
TiO_2	3.3	6.7	4.5	3.0
P_2O_5	--	1.0	0.8	--
SO_3	2.8	--	Trace	0.5
Loss on ignition	12.9	11.0	13.1	7.3

Mineralogical Analysis of Red Mud from Jamaican Bauxite

Mineral	Percent
Hematite	75-80
Goethite	5-10
Calcite	5-10
Boehmite	3-5

Cement kiln dust consists primarily of fine particles with more than 90 percent being smaller than 12 μm [55]. The chemical analysis of a kiln dust is given in table 8, which indicates that it has a high content of alkali, particularly potassium. Dust fractions which have low alkali contents, usually the coarser fractions, are usually returned to the kiln. However, dusts with high alkali contents often cannot be returned to the kiln because of limitations on the alkali contents of the clinker. For example, according to ASTM C150 [56], cements with 0.6 percent or less total alkali expressed as Na_2O are classified as low-alkali cements. Low-alkali cements may be necessary when certain alkali-reactive aggregates are incorporated in the concrete. Low-alkali cements are often specified even where higher alkali cements would be adequate. This results in the producers disposing of more kiln dust than would be necessary if the cement users did not overspecify. Problems associated with disposal of high-alkali kiln dust also could be reduced by only using raw materials, especially clays, which have small amounts of alkalis. However, low-alkali materials are usually more expensive than those commonly used.

The substitution of kiln dust for lime and limestone in a variety of applications has been investigated. Possible applications include agricultural uses [57], reclamation of acidic bays and lakes [58], and the treatment of municipal or process waters [59]. Kiln dust has been used as a soil stabilizer and as a subbase for secondary roads and parking lots. Bituminous paving materials and asphalt roofing materials have been filled with cement kiln dust in a few applications. However, kiln dust has found little use in construction. Current research may result in its increased use. For example, the feasibilities of incorporating kiln dust in blended cements and of using it in the manufacture of lightweight aggregates are being investigated [54].

4. BY-PRODUCTS FROM COAL COMBUSTION

By-products from coal combustion for steam generation are classified as fly ash and, depending on the design of the boiler, as bottom ash or boiler slag. Fly ashes are the small particles carried in combustion gases up the stacks of coal burning units. Their emergence from stacks is largely prevented by electrostatic precipitators or by other collection methods. In open-grate boilers, the ashes with the largest sizes fall through the grates and are collected in water-filled ash hoppers. This material is called bottom ash. In slag-tap boilers, molten ash is allowed to run down into a water-filled hopper. This material is called boiler slag [60].

Fly ash, bottom ash, and boiler slag from bituminous coals have a wide range of compositions, but in general they consist primarily of SiO_2, Al_2O_3, and Fe_2O_3, with smaller amounts of CaO, MgO, unburned carbon, and alkali sulfate. Ashes and slags from lignite or subbituminous coal also tend to consist largely of SiO_2, Al_2O_3, and Fe_2O_3; however, CaO and

Table 8. Oxide Composition of a Cement Kiln Dust [54]

Oxide	Percent
SiO_2	11.1
Al_2O_3	5.5
Fe_2O_3	2.9
CaO	44.0
MgO	2.5
Na_2O	0.9
K_2O	6.0
SO_2	5.6
Loss on ignition	21.5

MgO are present in greater amounts than in the corresponding products from bituminous coal. These higher CaO contents generally will result in higher free lime contents. Table 9 lists typical ranges of fly ash composition along with a few actual compositions.

Fly ash occurs as small spherical particles whose diameters range from a few micrometers to about 100 micrometers. Bottom ash particles range in size from about 0.08 to about 20 mm, have angular shapes, and are very porous. Boiler slags have particle size distributions similar to bottom ashes. They also have angular shapes but are glassy and the larger particles often have porous surfaces [64].

4.1 Amounts and Disposal of Combustion Products

The accumulated amounts of fly ash, bottom ash, and boiler slag and the amounts collected in 1975 by the U.S. electric power generating industry are listed in table 10 along with the amounts utilized. Over a two-fold increase in the amount of fly ash collected occurred between 1965 and 1975 and an even greater rate of growth is anticipated in the next decade because of the increased dependence on coal as an energy source. The largest amounts of coal are, of course, burned in high population density areas and this concentration has caused serious disposal problems. However, this also means that ash is available in areas where the largest amount of construction occurs. Figure 3 shows, by state, the approximate coal consumption in millions of tons in the U.S. in 1972.

The weights of ash produced vary between 12 and 20 percent of the weight of coal burned. Approximately 50 percent of unused ash is sluiced to disposal ponds. The remaining 50 percent is trucked to disposal areas, mixed with about 20 percent water, compacted, and used as fill. However, between 65 and 80 percent of the power plants have facilities for dry collection and loading of ash which could be used if markets were available [65].

4.2 Use of By-Products

In 1975, less than 10 percent of the coal by-products were used in construction (table 10). However, it appears that promising markets are being developed in the construction industry as discussed in the following.

4.2.1 Cement Manufacture and Concrete Products

While only a relatively small amount of ash and boiler slag have been used in cement manufacture and in concrete products, much larger amounts could potentially be used. Ash can be introduced into the cement manufacturing process either as a raw material for portland cement clinker manufacture or as a pozzolanic ingredient of a blended cement [66]. Bottom ash and boiler slag have also been used as raw materials for cement manufacture. Many fly ashes are also used as mineral admixtures in concrete. When used in blended cements or as an admixture in concretes, fly ash is usually required to comply with ASTM Specifications

Table 9. Percentage Compositions of U.S. Coal Ashes

Coal Type	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Alkalis (as Na_2O)	Unburned Carbon	Reference
Bituminous (Range)	34-52	13-31	6-25	1-12	0.5-3	0-2	0.2	1-12	61
Bituminous[1/] (Actual)	50	22	15	5.2	1.1	0.7	1.8	4.5	65
Bituminous[1/] (Actual)	58.6	30.6	6.3	0.9	1.0	N.A.[2/]	0.6	2.7	65
Lignite (Range)	15-52	8-25	2-19	11-36	2-11	0.7-27	0-7	1-12	62
Lignite (Range) (Montana)	37.7	24.7	3.9	24.4	5.8	1.2	0.1	N.A.	63
Lignite (Actual) (North Dakota)	36.9	11.9	14.2	27.4	5.5	2.9	0.6	N.A.	63
Lignite (Actual) (Minnesota)	20.4	17.5	9.0	22.9	6.5	125	7.0	N.A.	63

1/ Used in production of ASTM Type IP cement.
2/ N.A. denotes no data available.

Table 10. Amounts and Uses of By-Products from Coal Combustion [65]

	Fly Ash (10^6 tons)	Bottom Ash (10^6 tons)	Boiler Slag (10^6 tons)
Ash Collected (1975):	42.3	13.1	4.6
Amounts Accumulated:	200-300	50-100	25-30
Ash Utilized (1975):			
1. Use in ASTM Type IP cement or as raw material in cement manufacture.	0.23	0.07	0.04
2. Use as a mineral admixture for concrete or concrete products.	0.95	--	--
3. Lightweight aggregate manufacture.	0.09	0.04	--
4. Soil stabilization subbase.	0.45	0.53	0.07
5. Filler in asphalt.	0.14	--	--
6. Blast grit and roofing.	--	0.42	0.41
Total Used:	1.86	1.06	0.52
Percent Used:	4.4	8.1	11.3

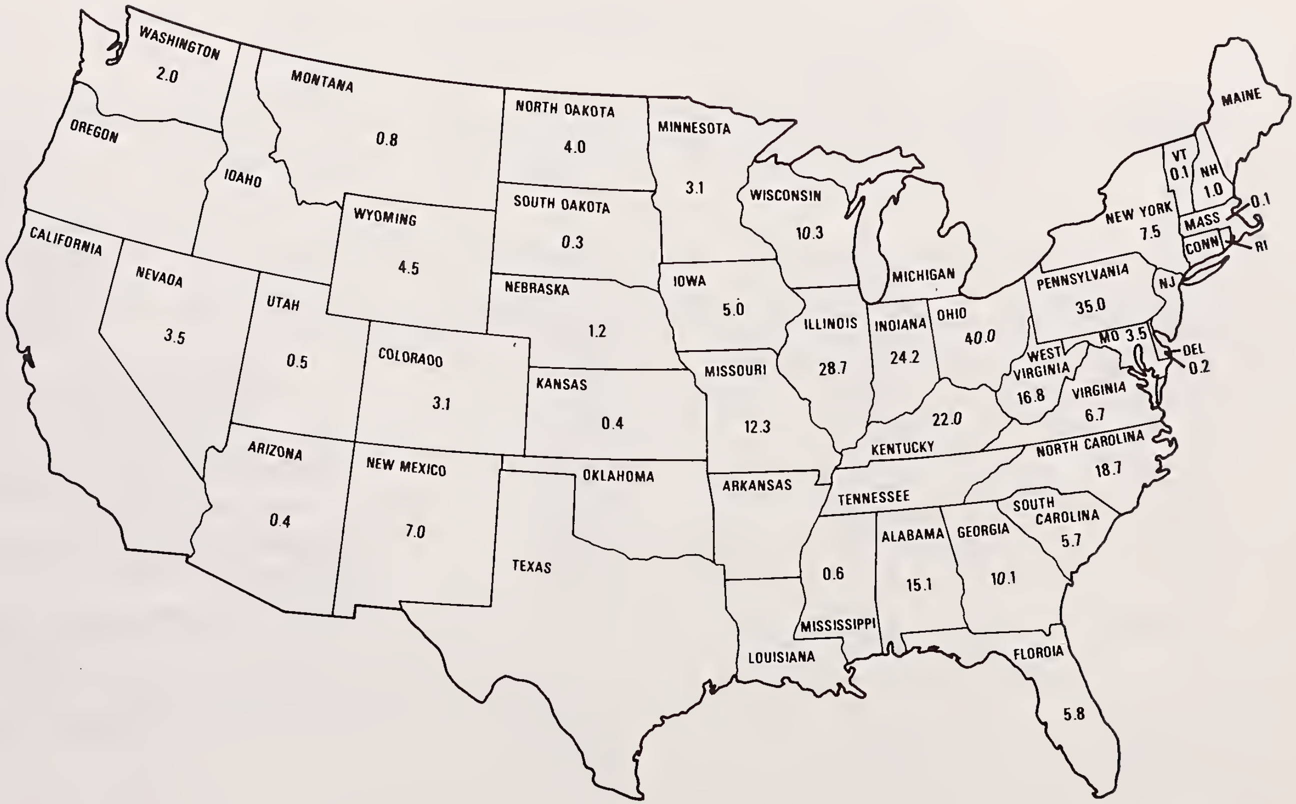

Figure 3. Coal Consumption by State in 1972 (10^6 tons).

C595 [67] or C618 [68]. Blended cements produced by intergrinding fly ash with portland cement clinker to comply with the ASTM requirements for Type IP cement [67] must contain between 15 and 40 percent fly ash by weight. The anticipated increased use of fly ashes by intergrinding will result in several benefits to the cement industry including decreased energy consumption in cement manufacture and increased capacity for a relatively low capital expenditure. At present, incentives for the use of fly ash in cement are low because of the reduced demand for cement coupled with lack of experience in manufacture and the use of blended cement [69]. The limitations on the minimum amount of fly ash permitted in a blended cement under ASTM C595 may also hinder experimentation with different levels of fly ash addition.

The use of fly ash as a mineral admixture by the ready mixed concrete industry, which uses over 60 percent of the cement manufactured in the U.S., is rapidly increasing. Fly ash is also finding commercial use in the manufacture of steam-cured concrete products.

4.2.2 Conventional and Lightweight Aggregates

Fly ash may be used in the manufacture of lightweight aggregates. The U.S. lightweight aggregate production in 1970 was 13.3×10^6 tons, of which about 10×10^6 tons were manufactured [70] and the remainder was natural lightweight aggregates. Lightweight aggregates include expanded clay, shale and slate, along with some slag and sintered fly ash. Sintered fly ash aggregates have good strength to weight ratios and they facilitate the mixing of concretes [70]. The extent to which sintered fly ash will supplant expanded clay, slate, and shale is uncertain. The use of bottom ash as a lightweight aggregate may be preferred because it is available in larger sizes than sintered fly ash and it does not require sintering. The use of bottom ash and boiler slag as conventional aggregate should also increase significantly in view of the aggregate shortages developing in some of the larger metropolitan areas. These products have been used as aggregate base course as well as base course with portland cement for highway construction [71].

4.2.3 Lime-Fly Ash-Aggregate Mixtures

Lime-fly ash-aggregate (LFA) mixtures and lime-fly ash-portland cement-aggregate mixtures have been used successfully in the construction of highway bases and subbases. In 1971, for example, 2×10^6 tons of LFA were placed in the U.S. [72]. The compressive strengths of LFA range from about 5.2 to 14 MN/m^2 after about 1 year, depending on the mix design, and these materials exhibit adequate durability [73] and good dimensional stability [72]. As mentioned in Section 3.2.4, lime and fly ash are also being mixed with sulfate wastes to form construction materials.

4.2.4 Miscellaneous Uses

Fly ash has been used in small quantities in a variety of other materials of construction including asphalt, roofing shingles and brick. However, one midwestern utility has sold over 1.2×10^6 tons of fly ash for use as an asphalt filler since 1939 [74]. Fly ash is also used in granules for roofing shingles. Several studies [75-77] have indicated that bricks meeting or exceeding the current ASTM requirements [78] for strength, saturation coefficient, and water absorption can be successfully produced from fly ash. In addition, bricks from fly ash can in some cases be produced more rapidly while requiring less energy than conventional bricks. Although bricks manufactured from fly ash have not been marketed commercially in the U.S., brick manufacture could become a large tonnage market for fly ash [13].

5. METALLURGICAL AND MINERAL SLAGS

The term slag is generally used to describe the nonmetallic melt which forms during the thermal reduction of metallic ores. This term is also applied to similar materials produced in other processes such as coal combustion or phosphorus production. Slags are usually composed of the same major constituents although their relative proportions vary widely. Generally, slags contain oxides of calcium, silicon, aluminum, iron, and smaller amounts of magnesium. The compositions of slags from a variety of processes are listed in table 11 and the annual amounts produced are listed in table 12.

5.1 Slag Production

The bulk of the slag generated in the U.S. comes from the production of iron and steel and, therefore, largely consists of blast furnace, converter, and foundry slags. Annual productions of blast furance and converter[4/] slags are about about 27.5×10^6 tons and 9.7×10^6 tons, respectively [83]. Foundry slag is produced in smaller amounts. Other types of slag are also produced in small amounts, however, because their production tends to be concentrated within small geographic areas, their use might be attractive in such areas. For example, about 2×10^6 tons of slag from phosphorus production are produced annually at two sites in Idaho [80].

5.2 Uses of Slags

While slags are used in a variety of construction materials (table 13), their primary use is as aggregate. In 1973, 21 of the 27.5×10^6 tons of blast furnace slag produced were used as some form of aggregate. Similarly, 7.8 of the 9.7×10^6 tons of converter slag produced were used as aggregate [83]. If unsoundness is anticipated because of a high free CaO content, converter slag is stockpiled to allow CaO to hydrate prior to utilization

4/ Converter slag is the molten residue of the conversion of pig iron into steel.

Table 11. Oxide Compositions of Some Slags

Slag	Oxide Composition, weight percent						Reference
	SiO_2	Al_2O_3	FeO	CaO	MgO	Other	
Copper reverberatory slag	36	8	46	6	--	--	79
Ferromolybdenum slag	37	36	21	1.9	1.0	--	79
Tin slag	23	15	12	5	11	heavy metal oxides, 27	79
Phosphate slag	44.8	6.2	1.4	41.7	0.8	alkalis as Na_2O, 1.1; fluorides, 2.8	80
Typical blast furnace slag	34-38	11-15	1.3-4.5	45-47	1.3	--	81
Converter slag 1/:							
Open hearth (avg. of 3 slags)	25.6	6.7	16	25.1	10.6	MnO, 3.3	66
BOF 2/ (avg. of 6 slags)	21.7	3.8	14.7	40.3	4.4	MnO, 3.5	66
Foundry slag (avg. of 4 slags)	33.3	18.2	9.8	40.9	3.8	--	82

1/ Slag produced when pig iron is converted into steel.
2/ Basic oxygen furnace.

Table 12. Annual Production of Slags

Type of Slag[1/]	Annual Production (10^6 tons)	Year	Reference
Blast furnace slag	27.5	1973	83
Converter slag	9.7	1973	83
Phosphate slag	4.0	1976	5
Copper smelting slag	5.2	1965	84
Foundry wastes[2/]	20.0	1976	5

1/ Data not available for all types of slags listed in table 11.
2/ Includes both dust and slag of which approximately 2 x 10^6 tons are slag.

Table 13. Uses of Slags

Type of Slag	Uses in Construction	Amount Used or Produced (10^3 tons) Per Year	Reference
Blast furnace (all types)	(total produced)	27,543	83
Converter	(total produced)	9,739	83
Blast furnace (all types)	Aggregate.	20,973	83
Blast furnace (air cooled)	Railroad ballast, mineral wool, roofing slag.	4,436	83
Blast furnace (granulated)	Cement manufacture.	232	83
Blast furnace (expanded)	Cement manufacture.	450	83
Converter	Aggregate, railroad ballast.	9,204	83
Phosphate slag	Aggregate, ceramic tile.	N.A.[1/]	80
Zinc smelter slag	Fine aggregate.	N.A.	5
Foundry waste	Fine aggregate, pigments.	N.A.	5

1/ N.A. indicates data not available.

of the slag as aggregate. Other uses for slags produced by the iron and steel industry include railroad ballast, mineral wool production, use in roofing, and raw materials for manufacture of portland and blended cements.

Unlike many other industrial by-products, the quantity of slags produced by the iron and steel industry is relatively constant. In addition, virtually all of these materials, with the exception of foundry slags, are used. However, the extensive use of slags as aggregate may not represent their highest value use. Because most slags, if properly quenched, exhibit hydraulic properties, slags could be extensively used as cementitious materials as is currently done in many other industrialized countries. Use in this way should offer advantages in terms of energy conservation, raw materials conservation, cost savings, and possibly in the durability of the concrete produced [85]. In addition, air-cooled slags which are low in MgO may be suitable as raw materials for the manufacture of cement. It has been recently demonstrated that portland cements can be produced by the pyroprocessing of blast furnace and converter slags along with limestone and a small amount of sand [86].

6. MUNICIPAL WASTES

A wide variety of municipal wastes, which include domestic wastes, are being generated in the United States. Collectively, they amount to more than 172×10^6 tons annually. The types, amounts, and possible uses of these wastes are given in table 14. Refuse constitutes the most abundant municipal waste and its rate of generation is increasing at an annual rate of 4.5 percent [87]. However, at present, little refuse is used in construction other than as a landfill material. The National Center for Resource Recovery is investigating other prospective uses of refuse. Incineration of the refuse produces a residue which can be converted into aggregate. Extraction of the glass fraction from the refuse yields another material which has a potential market either as aggregate or as a raw material for the manufacture of building materials. Demolition wastes and sewage sludge also are being considered for use in construction.

6.1 Incinerator Refuse

Incineration is becoming an increasingly important method for disposing of municipal refuse in the United States. It facilitates disposal of the refuse because the volume of the residue is usually between 3 to 20 percent of the initial refuse volume. Furthermore, power plants are being developed which can utilize the combustible portion of the municipal waste as a supplementary fuel source [87].

Table 14. Amounts of Major Municipal Wastes Generated Annually [5, 87]

Municipal Waste	Estimated Annual Production (10^6 tons)	Prospective Uses in Construction
Municipal refuse	135	Landfill.
Incineratory residue	5.0	Aggregate for concrete and asphalt.
Glass	11	Glasphalt, ceramic brick, lightweight aggregate.
Demolition waste	25	Aggregate for concrete and asphalt.
Sewage sludge	7-11	Landfill, embankments.
Rubber tires	3-5	Landfill.

During 1975, there were 141 incinerators and 1 pyrolysis plant operating in the United States, treating an estimated 15 x 10^6 tons of refuse and producing approximately 5 x 10^6 tons of residue [87]. Most of these plants are located in metropolitan areas of the northwestern states. Little information about the future availability of incinerator residue has been published; however, current programs should result in its increased availability. Landfill is currently the major disposal method for incinerator residues.

With the exception of unburned combustibles, the compositions of incinerator residues from different sources throughout the United States are relatively uniform regardless of the size of plant and method of incineration. Based on a moisture and combustible free basis, incinerator residues consist of approximately 43 to 55 percent glass; 23 to 37 percent ferrous metals; 13 to 16 percent ash; 1 to 3 percent ceramics and stone; and 1 to 4 percent nonferrous metals [87].

A promising application of incinerator residue is as aggregate for both portland cement concrete and asphaltic concrete [88]. Pilot plant tests carried out at the Franklin Institute Research Laboratories (Philadelphia, Pennsylvania) indicated that aggregate could be produced at a cost of $4 to $5 per ton (including capital cost) based on the production of 109 tons of aggregate per day [89]. Aggregate from this pilot plant is being incorporated in a bituminous wearing surface of a test highway pavement [90]. The residual aluminum in this type of aggregate may preclude its use in portland cement concrete [89]. The feasibility of using incinerator residue as aggregate in asphaltic concrete is also being investigated in Houston, Texas [91] and Baltimore, Maryland [89]. The feasibility of using aggregate from incinerator residue in the manufacture of concrete block has recently been demonstrated [88].

6.2 Glass

Glass comprises some 6 to 11 percent by weight of municipal and commercial refuse or at least 11 x 10^6 tons annually [92]. At present, only a small amount of the waste glass in municipal refuse is used as cullet in the manufacture of new glass. Cullet for glass manufacture must be essentially free of nonglass constituents and be color sorted. This requires an advanced separation technology which is being developed [93, 94]. Normally, waste glass is not extracted from municipal refuse and the refuse is disposed of in dumps and landfills.

One approach being developed to utilize waste glass is its incorporation as an aggregate in asphaltic mixtures for pavements [92, 95-96]. The composite material is commonly referred to as "glasphalt." Glasphalt appears to give adequate performance in numerous test strips laid in the United States and Canada [93]. However, the substitution of glass for conventional aggregates may produce a slightly more abrasive asphaltic pavement surface [92]. The prospective use of waste glass as aggregate in portland cement concrete is not encouraging because of the potential for the occurrence of expansive reactions between the cement matrix and the glass [97]. Possibly, replacing part of the portland cement with reactive fly ash could mitigate the expansive effects of these reactions [98]. Other uses for waste glass for construction purposes include the manufacture of mineral wool [99-100]; a raw material in the manufacture of ceramic brick [101]; and a raw material for the production of lightweight aggregate [102-103].

A wide range of potential markets exist for waste glass. However, waste glass is relatively thinly distributed throughout the United States and is abundant only in large metropolitan areas. These are areas of high levels of construction, and in such areas construction materials produced from waste glass could possibly become economically and technologically competitive with materials produced from virgin resources. Advances are being made in the technology of collection and separation of municipal waste which could facilitate the increased use of waste glass in the production of construction materials. This has led to the establishment of a section in ASTM Committee E-38 on Resource Recovery for the purpose of developing standard test methods and specifications covering the use of waste glass in the manufacture of brick.

6.3 Building and Highway Demolition Waste

The demolition of buildings and highways results in the generation of large amounts of potentially usable materials. Only recently have significant studies been carried out to determine the types, amounts, and potential uses of demolition materials being produced in the United States. In many cases only crude estimates of the amounts being generated are available and little is known about the extent of their reuse.

6.3.1 Amounts of Demolition Waste

The annual amount of waste material resulting from the demolition of buildings and highways has been estimated to be of the order of 27×10^6 tons [104]. This figure is a gross estimate extrapolated from demolition rate data and the combination of population and building densities. Estimated amounts of the major demolition materials generated annually and their levels of reuse are given in table 15. The amount and type of demolition material available depends on the age of demolished structures. For example, the mean age of demolished buildings in Boston, Massachusetts, is approximately 65 years; in Atlanta, Georgia, 35 years; and in Los Angeles, California, and 45 years. These ages are reflected by the

Table 15. Estimated Amounts of Materials in New Construction and in Demolition Waste

Material	Amount Used as Construction Material in 1971 [105] (10^6 tons)	Annual Amount 1/ of Demolition Waste (10^6 tons)	Demolition Reuse of Waste [106] (percent)
Concrete	315	18	Negligible
Wood products	42	1.3	5
Iron and steel	22	1.7	50
Gypsum products	11	N.A. 2/	N.A.
Clay products	18	1.4	Negligible
Plastics	1.2	Negligible	Negligible
Aluminum	0.9	0.01	13
Copper	0.34	0.07	50
Asphalt	2.3 3/	N.A.	N.A.

1/ Based on 25 x 10^6 tons of demolition waste produced annually [104].
2/ Information not available.
3/ Amount used in highway construction during 1973 [107].

compositions and relative amounts of the various types of demolition wastes available in these cities [104].

6.3.2 Uses and Disposal of Demolition Waste

The level of use of recovered material depends on the specific material and the geographic region. Metals are recycled to a significant extent and, as deposits of rich ore are consumed, metal scrap will become more valuable. The market for used bricks varies substantially across the country, with most of the recovered brick in the New England region being reused, whereas used brick has little value in the midwest region [106]. At present, only an insignificant portion of the available concrete, wood, gypsum, asphalt, and plastics from demolished buildings and highways are recycled. Large quantities of these materials are disposed of in landfills.

Concrete clearly constitutes the major fraction of demolition material currently generated in the United States and, based on current levels of use (table 15) [105], it will be the predominant demolition material for at least the next 100 years. This fact, coupled with prospects of future regional aggregate shortages, has stimulated investigations of the feasibility of using crushed concrete rubble as aggregate for new concrete. Buck [108] has concluded that concrete of adequate quality for many applications can be produced using crushed concrete rubble as both the fine and coarse aggregate. This is consistent with the experience gained in Europe after World War II when concrete rubble was used as aggregate in the reconstruction of devastated cities [109]. Recently, the American Concrete Paving Association reported [110] the first full scale use, in the United States, of crushed old concrete as the aggregate in new concrete.

As with the recycling of concrete, the technological and economic feasibility of recycling of asphalt pavements has been demonstrated [107, 111]. Over 2.3×10^6 tons of asphalt are used in highway construction annually in the United States [107] and the materials from old asphalt pavements are being recycled in demonstration projects. It is estimated that about 500,000 tons of asphalt pavement will be recycled during 1977.

The low level of recycling of demolition materials is attributable to several factors [104-106] including higher processing cost of the demolition materials compared to virgin materials; low cost of dumping demolition materials; and institutional restrictions. The technology of separating the materials present in rubble needs to be improved. For example, large amounts of sulfate from gypsum plaster and board could contaminate concrete rubble. If such concrete were used as aggregate for new concrete, the concentration of sulfate ions could be sufficient to produce disruptive reactions with the cement matrix. Another factor which appears to be limiting the recycling of demolition materials is lack of data on amounts and availability of specific types of demolition materials.

6.4 Sewage Sludge

Between 7 and 11 x 10^6 tons [5] of sewage sludge are generated annually by the chemical treatment of municipal sewage. The sludge is usually deposited in settling basins and allowed to thicken. This thickened sludge is usually either dumped into waterways or incinerated. The incinerator residue is an ash somewhat similar to fly ash. The ash is disposed of in the dry form or as a slurry by being mixed with plant effluent [5].

Sewage sludge ash can be compacted to a high strength mass which gradually gains additional strength [112]; therefore, it could be used in landfills. Sewage sludge, itself, has been combined with a mixture of soil, lime, fly ash, and waste calcium sulfate to produce a material which could be used in highway embankments [113]. However, its freeze-thaw resistance was found to be marginal.

7. WASTE MATERIALS FROM EMERGING TECHNOLOGIES

Increasing demands for energy, coupled with depletion of petroleum reserves are stimulating the development of new technologies for energy production and for protection of the environment. The commercialization of these technologies will probably result in the generation of substantial amounts of processing and mineral wastes. The types and prospective uses of some of these potential waste materials are discussed in this section.

7.1 Oil Shale Residues

Massive deposits of oil-rich sedimentary marlstone are located in Colorado, Utah and Wyoming, which may contain over 288 x $10^9 m^3$ (1800 x 10^9 barrels) of extractable oil [114]. The average yield per ton of processed shale is 0.13 m^3 (0.74 barrels) of oil [114]; therefore, over 2180 x 10^9 tons of oil shale residue could be produced if the deposits were fully developed. Although progress has been slow in developing these resources, generation of significant amounts of oil and of residue may commence within the next 20 years. The amount of residue requiring disposal will depend on the oil extraction method; if the rock is processed above ground, then essentially all the residue will require disposal; on the other hand, if the oil is extracted in situ only a small amount of residue will require disposal [115-116].

Raw oil shale generally consists of dolomite, quartz, clay, calcite, and a number of minor inorganic constituents, and the organic substance kerogen [117]. Kerogen is readily vaporized and converted to shale oil when the shale is heated to about 450°C which results in the generation of an expanded porous residue. This residue when mixed with limestone and calcined produces a hydraulic cement, which may merit further investigation [118]. Other potential uses of the residue are as lightweight aggregate, fines in asphaltic concrete, and as a surface course layer for secondary roads [117].

7.2 Slags and Ashes from Coal Gasification and Liquefaction Processes

Substantial amounts of fly ash and coal slag having pozzolanic value may become available in the next two decades if coal gasification proves economically feasible. By 1985 as much as 180 x 10^6 tons of coal may be converted into gas annually [119] resulting in an annual production of approximately 18 x 10^6 tons of ash and slag.

Coal gasification fly ashes should have compositions similar to the fly ashes currently generated by burning coal from the same source, except that the former should be virtually free of sulfates and unburned carbon. Coal gasification slags should also be similar in composition to the fly ashes except that limestone may be added to the coal to improve the rheological properties of the slags, thereby producing slags which may have intrinsic hydraulic properties [66].

The coal liquefaction process will probably produce slags having pozzolanic or hydraulic properties similar to the slags produced by coal gasification. Although coal liquefaction technology is lagging behind that for coal gasification, it may result in the annual production of as much as 14 x $10^6 m^3$ (90 x 10^6 barrels) of oil by 1985 [119]. This could require the processing of approximately 30 x 10^6 tons of coal per year with the generation of about 3 x 10^6 tons of slag.

The slags and fly ashes with pozzolanic properties from the coal conversion processes could be used in the manufacture of cement and concrete products in the same way as fly ash is currently being utilized (Section 4.3). The slags may have sufficient cementitious value to be used as hydraulic cements by themselves or with suitable activators.

7.3 Elemental Sulfur

The slight oversupply of sulfur which currently exists in the United States is anticipated to grow rapidly because of the necessity for the removal of sulfur from solid, liquid, and gaseous effluents, and wastes for the protection of the environment. The recovery of sulfur from coal gasification and liquefaction processes could greatly aggravate the oversupply problem [120]. The amount of recovered sulfur is already rapidly increasing, e.g., it has increased by over 50 percent between 1969 and 1973, with approximately 2.1 x 10^6 tons being recovered in 1973 [43].

Elemental sulfur has many potential applications for construction purposes, including sulfur-impregnated concrete [121-122], sulfur concrete [123-124], and sulfur-asphaltic mixes for pavements [125]. Recently, experimental houses have been constructed using sulfur-concrete blocks [126] and also by surface bonding cinder blocks with a sulfur-fiberglass formulation [127].

8. OBSTACLES TO AND INCENTIVES FOR THE INCREASED USE OF WASTE MATERIALS IN CONSTRUCTION

The direct use, processing or conversion of waste materials into construction materials has the potential of consuming significant amounts of the over 3×10^9 tons of wastes generated annually in the United States. This is because over 1.5×10^9 tons of nonmetallic materials (sand, gravel, crushed stone, gypsum, slag, and cement) and over 140×10^6 tons of steel are consumed annually in construction [33]. No reliable estimates of the total amount of wastes used in construction are available, but it appears that only a small amount of the total wastes are used.

Several major barriers must be overcome before any material is widely accepted for use in construction. These include those posed by economic, institutional and technical considerations. An example of an economic barrier to the use of waste materials is the higher costs sometimes charged for their transportation as compared to virgin materials. Apparently, few obvious institutional restrictions have been placed on the use of waste materials; only in the case of recycling demolition wastes have such restrictions been mentioned [104-106]. Technical requirements for construction materials are usually defined by standards and specifications. The lack of such technical requirements, as well as overly restrictive requirements, can discourage experimentation with the use of waste materials in construction. Building materials standards which are based on performance tests and criteria do not appear to pose any severe restrictions on the use of waste materials. However, specifications based on compositional requirements can be more restrictive. For example, the ASTM specification for blended cements, C595, [67] appears to place unnecessarily narrow restrictions on the amounts of fly ashes and slag materials which can be added to portland cement to form Types IP and IS blended cements, respectively. Recent developments suggest that this specification may be broadened.

Many technical programs have been carried out in the past to develop viable construction materials from wastes. While some of these endeavors have been technical successes, few have resulted in products reaching the commercial stage. Often the building materials from wastes have not been economically competitive with those from virgin materials, or the necessary markets have not existed near the wastes disposal areas.

Forces are emerging in the United States because of changing patterns of supply and demand of materials and energy, economic factors, and heightened concern for the quality of the environment, which are providing new incentives for the increased use of waste materials. Overall the United States has abundant resources, except for petroleum, but material shortages may exist in some areas. For example, Witczak [34] has identified areas in the United States which lack good quality aggregates. Many of these areas have large amounts of waste rock and coarse mill tailings which could be used directly as aggregates. Increasing energy costs coupled with energy conservation policies should increase the recycling of energy-intensive materials such as steel, aluminum, asphalt, and ceramic building materials.

These pressures will also facilitate the substitution of waste materials for energy-intensive materials as, for example, in the addition of fly ashes to portland cement to form Type IP blended cements [81, 85]. Regulations established to protect the environment will provide incentives for using wastes in construction because both the complexities and costs of disposing of wastes will be increased. Land reclamation policies coupled with environmental concerns will provide incentives for using accumulated wastes, especially the wastes stored near highly populated areas or on land containing important minerals.

The various pressures for direct use of wastes as, or for converting them into construction materials will be effective only if the wastes are technically and economically competitive with conventional materials. As indicated throughout this survey, some of the construction materials produced from waste are at least the technical equivalent of materials produced from virgin resources, and the technology of converting other wastes into usable materials is rapidly advancing. Growth in the use of waste materials in construction, therefore, appears to depend on the development of economic incentives, either formed in the market place or created by governmental policies.

9. SUMMARY AND CONCLUSIONS

Over 3×10^9 tons of mining, industrial, agricultural, and municipal wastes are generated annually in the United States. More than 70 percent of this amount comes from mining operations in the form of waste rock, mill tailings, and coal refuse, which are being added to some 23×10^9 tons of mining waste already accumulated. Production of many of the wastes is expected to grow steadily, while production of others may grow at alarming rates. For example, because of the new emphasis on coal utilization, the stockpiles of coal refuse, fly ashes and sulfate sludges could grow rapidly. The commercialization of developing technologies for energy production and for protection of the environment could also result in the generation of substantial amounts of processing and mineral wastes.

Most of the wastes are disposed of by being stockpiled or by being placed in settling ponds and containment dikes, or by being used as landfill materials. Only small amounts of most wastes are being used for construction purposes. An exception is slags, which are being used extensively as aggregate. In several other cases, construction materials which are at least the technical equivalent of materials produced from virgin resources have been produced from wastes.

Several factors have impeded the large scale use of wastes in construction including the abundant supply of natural resources; abundant supply of and low cost of energy for processing natural resources; low cost of disposing of wastes; lack of adequate technical information on the performance of materials produced from wastes; and lack of appropriate standards and specifications for materials produced from wastes. However, during the past decade significant programs which should facilitate the increased use of waste materials in construction have been established in the United States. Regional material and energy shortages, and heightened concern for the quality of the environments are also providing growing incentives for the increased use of waste materials. Ultimately, the amount of waste materials used in construction will depend on the development of economic incentives, either formed in the market place or created by governmental policies.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A survey has been made of the sources, amounts and methods of disposal of major mining, industrial and municipal wastes available in the 48 counterminous states of the United States. This includes the present and potential uses of these wastes as construction materials.

While over 3 x 10^9 tons of waste materials are generated annually in the United States, only small amounts are being used by the construction industry. The low level of use does not yet reflect the advances being made in converting wastes into viable construction materials. In several cases, construction materials produced from wastes have been at least the technological equivalent of materials produced from virgin resources. Factors which are impeding the increased utilization of wastes are discussed and emerging incentives which could facilitate their increased use are covered.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Coal by-products; construction materials; industrial wastes; mining wastes; municipal waste; slags; waste materials.

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