Commercial Use of Coal Utilization By-products and Technology Trends

Summary

The availability of affordable energy will continue to be essential to our Nation's economic strength. At present over half of the electrical energy demand in the United States is met by the combustion of coal and the reliability of low cost coal-fired power has been a significant factor in our Nation's economic growth and development. Demand for electricity is expected to increase steadily throughout the future, and coal will continue to play a significant role in meeting this demand. However, the contribution of coal to the Nation's energy mix, and the overall cost of electricity, will increasingly depend on our ability to find economical ways to reduce or eliminate any potential adverse environmental impacts associated with the disposal and utilization of coal combustion by-products.

Despite the demonstrated capability of newer, Clean Coal technologies to meet future power and environmental demands, the electric power industry's response to the 1990 Clean Air Act has been to increase the levels of environmental control at existing plants that produce "conventional" coal utilization by-products (CUB) such as fly ash, bottom ash, and wet FGD sludge. For example, the industry's response to the Act's mandate to reduce emissions of nitrogen oxides has been to install low-NO_X burners; the fly ash produced from these burners can have unburned carbon contents which render the ash unsuitable for use in cement manufacture. This has eliminated a source of revenue for power producers and increased the total cost of their by-product management operations. Also, the response of many major utilities to SO_2 emissions requirements has been to accelerate the use of wet FGD devices rather than switch to "clean" coal combustion technologies. The result has been an excessive growth in the production of wet FGD material that is outpacing the utilities' capacity to utilize the material. The American Coal Ash Association (1997) has estimated that less than 7% of the FGD by-product is currently being utilized. Concurrently, the implementations of increasingly stringent solid waste disposal regulations at the state and local level have increased the cost of developing new landfill capacity for all CUB's. Therefore, the environmentally beneficial utilization of wet FGD by-products, high-LOI ashes, and other utility by-products for which commercial markets have not been well-developed.

The Coal Combustion Products Partnership (C^2P^2) program is a cooperative effort between the U.S. Environmental Protection Agency, American Coal Ash Association, Utility Solid Waste Activities Group, US Department of Energy, and US Federal Highway Administration to help promote the beneficial use of coal utilization by-products and the environmental benefits that result from their use.

Introduction

The recycling of coal combustion by-products , or coal utilization by products (CUB) which includes the solid residue from coal and gasification, is a practice that can play a significant role in maintaining both the cost advantage and environmental acceptability of coal-fired power plants. Coal burning electric utilities produce over 100 million tons of CUB materials annually in the United States, but only about one-third are recycled for productive purposes. The remainder is disposed of in landfills or ponds, representing both a significant cost to electric utilities and the waste of raw materials that could potentially be of greater value if they were utilized. In many cases, the use of CUBs provides the end-user with a product that is superior to the one that would have been obtained by using conventional materials. The purpose of this paper is to describe the most important applications that have been developed for CUBs and discuss the issues and problems associated with CUB recycling.

The terms Coal Utilization By-Products (CUB) are further defined by the National Energy Technology Laboratory. CUBs are defined as “fly ash, bottom ash, boiler slag, fluidized-bed combustion (FBC) ash, or flue gas desulphurization (FGD) material produced primarily from the combustion of coal or the cleaning of stack gases.

Definitions of Coal Utilization By-Products

Coal Utilization By-Products: (CUBs) (i.e. fly ash, bottom ash, flue gas desulfuratization (FGD) material, and fluidized bed combustion (FBC) material)

Coal ash: a collective term referring to any solid materials or residues (such as fly ash, bottom ash, or boiler slag) produced primarily from the combustion of coal. Current usage of the coal ash collective term is synonymous with the term coal combustion ash and coal combustion residue. Also, coal ash is a component of the term coal utilization by-product (CUB) covering only the materials or residues associated with the combustion of coal.

Fly Ash: coal ash that exits a combustion chamber in the flue gas and is captured by air pollution control equipment such as electrostatic precipitators, bag houses, and wet scrubbers.

Class C fly ash: fly ash that meets criteria defined in ASTM C618 for use in concrete**.** Sub bituminous and lignite coal -- low ash coal
Class F fly ash: fly ash that meets criteria defined in ASTM C618 for use in concrete. Bituminous and sub bituminous coal -- medium to high-ash coals
Conditioned ash: ash that has been moistened with water during the load out process at the temporary storage silo at the power plant to allow for its handling, transport, and placement without causing fugitive dusting.

Dry fly ash: fly ash that has been collected by particulate removal equipment such as electrostatic precipitators, bag houses, mechanical collectors, or fabric filters.

Ponded ash: ash that is in an ash pond or that has been excavated from an ash pond.

Bottom ash: agglomerated ash particles formed in pulverized coal boilers that are too large to be carried in the flue gases and impinge on the boiler walls or fall through open grates to an ash hopper at the bottom of the boiler. Bottom ash is typically grey to black in color, is quite angular, and has a porous surface structure.

Boiler slag: a molten ash collected at the base of slag tap and cyclone boilers that is quenched with water and shatters into black, angular particles having a smooth, glassy appearance.

Fluidized-bed combustion (FBC) ash: the fly ash and bed ash produced by an FBC boiler.

Fluidized-bed combustion (FBC) bed ash: the spent bed material that is produced by an FBC boiler. The bed ash is usually collected separately and can be considered as being equivalent to bottom ash in dry bottom or wet-bottom wall-fired furnace.

Fluidized-bed combustion (FBC) products: the unburned coal, ash, spent bed material, and unreacted sorbent produced by an FBC boiler.

Flue gas desulphurization (FGD): removal of gaseous sulfur dioxide from boiler exhausts gas. Primary types of FGD processes are wet scrubbers, dry scrubbers, and sorbent injection. Sorbents include lime, limestone, sodium based compounds, and high-calcium coal fly ash.

Ammoniated ash: ash that contains ammonia and/or ammonium salts as a result of the addition of ammonia or ammonium salts to the flue gas at the power plant.

History of CUB's in Industry

In a pulverized coal boiler the incombustible solid material either falls to the bottom of the boiler or exits via the flue gas stream. Fly ash, the fine particulate material exiting the boiler via the flue gas stream is subsequently collected by electrostatic precipitation (ESP) devices or fabric filters (bag houses) to prevent its release into the atmosphere. Coarser grained material that falls to the bottom of the boiler is typically referred to as bottom ash if it is removed in a dry state or as boiler slag if it is removed in a molten state. The ratio of fly ash to bottom ash in a typical dry-bottom pulverized coal boiler is about 80:20; in wet-bottom boilers, the ratio of fly ash to boiler slag is somewhat smaller (50:50) because some of the finer particles stick to the molten ash on the boiler walls. Most often the composition of the fly ash, bottom ash, and boiler slag are determined by the composition of the incombustible portion of the source coal and the combustion conditions within the boiler. The characteristics of these materials and their suitability for utilization are also affected by operating conditions such as time-temperature regime they experience within the boiler system, and whether the plant utilizes a wet (slurry) or dry materials handling system. The elemental compositions of the slag produced in gasification systems are similar to the bottom ash from conventional coal combustion systems.

Removal of sulfur dioxide (SO_2) from the flue gas stream via scrubbing technologies result in the production of a class of CUBs called flue gas desulphurization (FGD) byproducts; these byproducts are quite different than fly ash and bottom ash. In a typical scrubber, some type of alkaline reagent such as lime, limestone, or a sodium-based reagent, is applied to the flue gas stream, causing the to react chemically to form a solid sulfate (SO_4) or sulfite (SO_3) compound. Unlike fly ashes, SO_2 bottom ashes, and boiler slag, neither the parent coal nor the boiler conditions have a significant effect on the physical or chemical properties of the FGD byproducts. Instead, the characteristics of the FGD byproducts are strongly controlled by the type of reagent used, the operating temperature, pressure, and degree of oxidation within the scrubbing unit and the amount of water used to distribute the reagent through the flue gas. For example, wet scrubbers produce a slurry byproduct that must be dewatered prior to utilization or disposal, while dry scrubbers produce FGD byproducts in the form of a dry powder. These and other FGD process variables have a significant effect on the properties of the materials and affect their use and or disposal.

It is also quite common for coal burning operations to generate CUBs that are mixtures of fly ash, bottom ash, and FGD byproducts. A common CUB mixture, called "fixated" FGD material, is produced by plants that employ wet scrubbing with lime or limestone under low-oxidizing conditions resulting in a FGD byproduct that is rich in calcium sulfite. This by product after dewatering tends to be sticky and difficult to handle even in a simple waste disposal operation. This problem is corrected by fixating the sulfite-rich FGD byproduct by adding fly ash, and usually some additional lime. The chemical reactions within the resulting mixture tend to make it drier, easier to handle for trucking to a disposal site, or for various beneficial uses. A few wet scrubbers have also been designed to remove fly ash as well as sulfur dioxide within the same process unit.

Another process that produces mixtures of CUBs is fluidized bed combustion (FBC). FBC processes blend a ground limestone (or lime) sorbent with the finely pulverized coal directly in the combustion chamber, such that the calcium in the sorbent reacts with gaseous SO_2 to remove it before it enters the flue gas stream. Both the fly ash and bottom ash from FBC boilers typically contain assorted mixtures of ash, spent sorbent usually calcium sulfate and unreacted sorbent such as limestone or free lime that has been created by the in-situ calcining of limestone within the boiler. The relative proportions of each component and the properties of the resulting mixture can vary widely, depending on the type of coal burned, the type of sorbent used, the temperature, pressure, and residence time within the combustor, and the process (if any) by which the materials are recycled back through the combustion zone.

CUB Utilization, Options, and Benefits

Production and utilization data for the four highest volume CUBs from conventional pulverized coal boilers, fly ash, bottom ash, boiler slag, and FGD byproducts are collected annually by the American Coal Ash Association. The production and use figures for these four types of CUBs are shown in Tables 1 and 2. The overall utilization rate for these materials is just under 30%, with the highest rate (over 80%) for boiler slag and the lowest (10%) for FGD byproducts. Both fly ash and bottom ash have utilization rates of just over 30%. In the following sections, each type of CUB is considered separately in terms of the physical and chemical properties that make them suitable for various applications.

Table 1.Coal Combustion Byproduct Production and Utilization,
(in short tons)
Data courtesy of the American Coal Ash Association

CCB Type	Production	Utilization	Percent Utilized
Fly ash	62,956,000	21,106,000	33.5%
Bottom ash	16,760,000	5,239,000	31.3
Boiler slag	2,981,000	2,388,000	80.1
FGD byproducts	25,003,000	2,494,000	10.0
TOTAL	107,740,000	31,227,000	29.0

Table 2. Utilization of Coal Combustion Byproducts,
(short tons)
Data courtesy of the American Coal Ash Association

Application	Fly Ash	Bottom Ash	Boiler Slag	FGD Byproducts	Total Use
Cement/concrete/grout	10,350,987	648,222	10,857	205,245	11,215,311
Structural fill	2,792,948	1,172,589	56,026	20,809	4,042,372
Waste stabilization/solidification	3,481,522	144,290		15,609	3,641,421
Road base/sub base	1,447,146	1,603,224	500	20,809	3,134,635
Blasting grit/roofing granules		220,914	2,138,958		2,359,872
Mining applications	1,917,898	139,167		106,300	2,163,365
Wallboard				1,814,944	1,814,944
Snow and ice control	3,276	707,424	56,620		767,320
Mineral filler	336,264	78,578	12,424		427,266
Flowable fill	382,367	16,664			399,031

Agriculture	36,928	8,591		57,293	102,812
Miscellaneous/Other	356,132	499,521	112,352	190,297	1,158,302

Fly Ash Utilization Applications

Cement and concrete

Table 2 shows that over 10 million tons of fly ash was used in cement and concrete applications, accounting for almost half of the fly ash use. The physical and chemical characteristics of fly ash make it well-suited for use in cement and concrete. First, the size distribution of fly ash particles is similar to that of Portland cement, but many fly ash particles are spherical in shape because they become slightly molten while passing through the boiler and solidify upon cooling in the flue gas. When fly ash is used as a partial replacement for Portland cement in a concrete mixture, the fly ash spheres act as ball bearings within the concrete mix that can significantly lower the water requirements and improve the flowability and workability of the concrete.

Most importantly, the chemical composition of many fly ashes is similar to that of Portland cement consisting mainly of silica, alumina, and calcium oxides. Fly ashes usually have much lower amounts of calcium oxides than cement mixtures. Such fly ashes tend to be pozzolanic in nature; pozzolans are substances that do not form cementatious compounds on their own when exposed to water, but will react in the presence of water and calcium hydroxide to create cementatious compounds. When Portland cement hydrates, calcium hydroxide is liberated. This compound contributes nothing to the strength of concrete and may cause long-term problems because it is soluble in water and may be removed from concrete by leaching or chemical action. When fly ash is employed with a Portland cement the pozzolanic reactions consume the lime to form additional stable cementatious compounds that increases the ultimate strength of the concrete and renders the calcium hydroxide unavailable for leaching or chemical attack. Another advantage of using fly ash as a pozzolanic additive to concrete is that it slows the rate of heat release that occurs as the result of Portland cement hydration. This can be especially advantageous in mass pours such as for dams or bridge abutments where heat buildup within the interior of the concrete mass can cause cracking to occur and weaken the structure.

Many different types of fly ashes can be used successfully in concrete, at rates ranging from 5 to 30 percent of the cement portion of the concrete mixture. However, the exact proportion of fly ash that will yield the most desirable concrete properties will vary depending on the composition of the fly ash. Eastern bituminous coals generally produce fly ashes that are relatively low in calcium oxides and contain significant amounts of iron. Such ashes, termed Class F have been used most extensively over the past several decades as pozzolans to improve the properties of concrete as described above. Fly ashes from western sub-bituminous coals tend to have significantly higher amounts of calcium oxides and lower iron levels than Eastern bituminous ashes. These Class C ashes can be self-cementatious as well as pozzolanic because of their inherently high calcium oxide contents. In recent years Class C ashes have also been used successfully to replace Portland cement in concrete, but the proportions generally differ from those used for Class F ashes. ASTM specifications (ASTM C618) have been developed to provide guidance for the use of both Class F and Class C fly ashes as a concrete admixture. Professionals in the ash marketing and cement/concrete business have also gained extensive experience with both classes of fly ashes over the years, and can provide accurate information as to how any particular ash will behave in a concrete mixture.

Probably the greatest concern with the use of fly ash to replace cement in concrete is the detrimental effects brought on by the presence of unburned carbon in the ash. This issue is discussed later in this paper as one of the primary technical barriers toward increased utilization of CUBs overall.

In addition to its advantage in poured structural concrete, fly ash is frequently used in the manufacture of concrete masonry units (blocks) to add plasticity to the concrete mixture and to produce blocks with better texture and better corners. Fly ash also increases the service life of the molds used to form the concrete blocks. Depending on the type of curing used, fly ash can be added to replace from 20 percent to as much as 50 percent of the cement in the block manufacturing process.

Fly ash can also be used successfully in the cement/concrete industry is as a raw material in the manufacture of Portland cement. In this application, the pozzolanic properties of the fly ash are not important. Its usefulness stems from the fact that its bulk chemical composition is very similar to shale or clays that are commonly used as feed materials to cement kilns. The use of fly ash as a cement kiln feed is not nearly as common as its use as a cement replacement, however, this application has some potential for growth because it can accommodate a wide variety of fly ashes including those that do not meet ASTM specifications for use as a cement replacement. The cement manufacturer must be willing to experiment with changes in his current kiln feed formula to accommodate the slightly different properties of fly ash compared to the feed material it replaces. Fly ash can also be used in the manufacture of blended Portland cement by mixing it with the cement clinker during the grinding and mixing process that converts the clinker into cement. Use of fly ash in blended cement production is covered by ASTM Standard C595.

Structural fills, road bases/sub bases, and flowable fill

The size distribution and compaction characteristics of many fly ashes are similar to those of silty clay soils. Fly ashes have been used extensively for many of the same civil engineering purposes as the equivalent soils. The use of fly ash in highway fills and embankments is especially prevalent in Europe and in urban road projects in the United States, where large quantities of suitable soils may not be available. Fly ashes will have a lower unit weight than the equivalent natural soil, which is an advantage in earth fills that are placed behind retaining structures or above buried pipes because it reduces the load that is placed on the structures. As with any soil-like material fly ashes must be tested individually to determine the level of moisture and compaction that will yield the desired engineering properties. The use of fly ash and other CUBs in structural fill applications is expected to increase in the future because of the recent development of ASTM Standard E1861, that provides a standard guide for the use of fly ash and other CUBs in structural fill applications.

Fly ashes have frequently been blended with hydrated lime and aggregate materials to form road base materials that are stronger and more durable than conventional crushed stone or gravel base courses. Class F fly ashes that have been blended with lime or cement, and self-cementatious Class C fly ashes have been used extensively to stabilize the soils beneath the road base. The compressive strength of the ash-stabilized soil is usually greater than the equivalent natural soil, and the ash addition tends to take up excess moisture that would otherwise cause problems during the compaction process.

Flowable fill or controlled low-strength material (CLSM) generally consists of water slurry with a solids makeup of 90-95% fly ash, some sand, and 5-10% Portland cement. Such flowable backfill is ideally suited to fill hard-to-reach areas such as spaces under floors, trenches around buried pipes and utility lines, excavations around underground storage tanks, and abandoned tunnels and underground mine workings. Flowable fill usually achieves a compressive strength similar to that of compacted soil within 24 hours after its emplacement; the actual strength can be adjusted as desired by changing the fly ash: Portland cement ratio of the mix. The relatively low strength of flowable fill compared to normal Portland cement mixes allows the fill material to be re-excavated easily at a later date if necessary, as is often the case with buried pipes and tanks. Another advantage of using flowable fill rather than compacted earth to fill trenches is that laborers are not exposed to the physical hazards associated with working in trenches.

Waste stabilization

Pozzolanic fly ashes, used in combination with Portland cement or other cementatious agents, have been used successfully for stabilizing biological and industrial sludge's and liquid wastes from wastewater treatment. The chemical stabilization provided by the cementatious and pozzolanic reactions serves to reduce the leachability of the toxic substances within the waste sledges, and results in the drying and thickening of the wastes to improve their handling and compaction characteristics. Metal-bearing wastes are particularly amenable to this type of stabilization.

Mineral fillers

Asphalt pavement normally consists of a blend of a bituminous asphalt binder, coarse aggregate, and a fine-grained additive, commonly referred to as mineral filler. Fly ash has been used since the early 1930's as mineral filler in bituminous asphalt mixes. The low plasticity and fine, relatively uniform grain size of fly ash make it particularly suitable for this application. Since the advantage of using fly ash does not relate to its pozzolanic behavior, fly ashes that do not meet ASTM specifications for use in concrete pavements can often be used successfully as mineral fillers in asphalt pavements.

Mining applications

The most beneficial mining applications of fly ash is to place it as a flowable fill in abandoned underground mine voids to prevent or control subsidence above the mine workings. Many mine subsidence prevention/abatement projects in the Appalachian coal region specify the use of high-fly ash flowable fill for this purpose. The soil-like quality of fly ashes can also be advantageous in surface mine reclamation applications in areas where good-quality top soils are scarce. The use of fly ash as a bulk backfill for active or abandoned strip mine pits can also be advantageous, especially if the ash is somewhat alkaline in character. This alkalinity and can offset some of the acidity that would otherwise be produced by the mine spoil. However, fly ashes from conventional coal boilers do not usually contain sufficient levels of alkalinity to provide complete neutralization of highly acidic mine spoils, so the role of these fly ashes in acid mine drainage abatement is somewhat limited. Because of this, there is some question as to whether the backfilling of some fly ashes into surface mine spoils constitutes a beneficial use or an alternative method of disposal.

Agriculture

Mixing fly ash with poor-quality soils can improve their drainage and water-retention properties and improve the ability of the soil mixture to sustain vegetative growth. Fly ash can also contain "micronutrients" such as iron, manganese, molybdenum, and boron, copper and zinc that growing plants require. Traditionally, native soils and impurities in commercial fertilizers were relied on to supply sufficient amounts of these nutrients to crops. Today, with more intensive cropping systems and purer, higher analysis fertilizers, the need for fertilization with these micronutrients is being recognized, and the presence of these nutrients in fly ash can be beneficial.

Other commercial products and applications

The spherical nature of fly ash, and, in particular, the cenosphere (hollow, gas-filled sphere) component of the fly ash, makes it particularly well-suited for blending into plastics or paint materials to enhance the properties of these mixtures and reduce their overall cost. When used as a filler, the very light unit weight of cenospheres (specific gravity of 0.6 to 0.8) can reduce the weight of the manufactured products, and can lower manufacturing costs by reducing the amount of more expensive materials required. Fly ash has also been used successfully in other high-value commercial products such as specialty ceramic pipes and conduits, heat shields for racing automobiles, refractory furnace linings, decorative flooring and paving materials, paints and fillers in cast aluminum products. Because of their unique properties and cost advantages, fly ash and cenospheres can command fairly high prices when sold for such applications; however, the size of these specialty markets is usually not large, and many fly ashes do not possess the properties required by these markets.

Perhaps the fly ash product with the greatest potential for increased utilization in the U. S. is a building material known alternatively as autoclaved aerated concrete (AAC) or autoclaved cellular concrete (ACC). This material consists of a mixture of roughly 70 percent fly ash (or sand), water, cement, lime, and aluminum powder that is cured under high-pressure steam in an autoclave. The resulting concrete is a lightweight, porous material with an excellent combination of strength and insulating properties. At a density of roughly one-fifth that of conventional concrete and a compressive strength of about one-tenth, AAC is used in load-bearing walls only in low-rise buildings. In high-rises, AAC is used in partition and curtain walls. The material is also fairly friable and must be protected from weather with stucco or siding. It can be drilled, sawed, screwed, and nailed with ordinary carpentry tools, and is more resistant to fire, sound, mildew, and insects than wood. It is currently being produced at over 200 plants worldwide, but its use in the U.S. has lagged far behind the rest of the world because of the relative abundance and low price of wood in this country.

Bottom Ash Utilization Technology

Bottom ash has a bulk chemical composition that is generally similar to fly ash, because they both consist primarily of the incombustible materials that were present in the parent coal. The physical characteristics of bottom ash are distinctly different from those of fly ash because the two materials go through different formation and cooling regimes. Whereas fly ash spends very little time within the combustion zone of the boiler and undergoes a relatively long, gradual cooling process as it passes out with the flue gas; bottom ash generally spends a greater amount of time within the boiler and undergoes more rapid cooling. As a result, bottom ash tends to have a larger median particle size than fly ash; has a more glassy and granular texture, and contains a preponderance of angular rather than spherical particles. It is also more common for utilities to use wet methods to transport and store bottom ash, that further affects its suitability for re-use. The practical applications of bottom ash are therefore significantly different than those of fly ash, although both materials have been used extensively in some of the same general market sectors.

Structural fills road bases and flowable fills

Table 2 shows that structural fills and road bases accounted for over half of the bottom ash utilization. Bottom ash is often physically and chemically similar to the natural soils and fine aggregate sands that are normally used for these purposes and the applicability of any bottom ash source for these applications can be determined via standard soil engineering tests. In many cases the decision whether to use bottom ash, sand, or soils for these purposes rests solely on the relative local availability of the competing materials and their associated transportation costs. In cement-stabilized road bases and flowable fills, bottom ash acts as a fine aggregate that can add to the compressive strength of the emplaced material after curing.

Snow and ice control

The coarse texture and angular shape of many bottom ashes make them ideally suited for use as anti-skid materials that are applied to roadways. During the winter months, several Northeastern power stations sell 100% of their bottom ash production to State and local transportation departments for use as an anti-skid material. Both fresh and ponded bottom ash can be used for this purpose, and it can be stored in outdoor stockpiles for indefinite periods prior to use.

Cement, concrete and other products

Since bottom ash does not possess pozzolanic properties and does not possess spherical particles like fly ash, bottom ash cannot be used as a cement replacement and does not impart the same beneficial characteristics to the concrete mixture that fly ash does. However, bottom ash has been used extensively as a substitute for sand in Portland cement concrete mixtures, asphalt concrete, and concrete block manufacturing. Like fly ash, bottom ash has also been used as a raw kiln feed material in the manufacture of Portland cement, as mineral filler in various types of commercial products, and as a substitute for sand in a wide variety of miscellaneous applications.

Boiler Slag Utilization Technology

Boiler slag is produced by wet bottom" or slag tap pulverized coal fired boilers, which are designed to burn coals whose ashes are known to have relatively low fusion temperatures. Ash collects on the walls of the boiler, melts, and falls into a tank of water at the base of the boiler where it is quenched rapidly. Cyclone boilers, which use a comparatively large coal feed size compared to pulverized coal boilers and retain the coal and ash for a longer time period within the combustion zone, also produce boiler slag. Most boiler slags tend to be hard, black, glassy, and comparatively inert materials that may require crushing to attain a size consistency suitable for utilization.

Table 1 shows that a relatively high percentage of boiler slag was utilized compared to the other types of CUB materials. Table 2 shows that about 90% of the re-used boiler slag was used as either blasting grit or in roofing shingles. The hard and abrasive nature of boiler slag particles make them well-suited for the process of "sand blasting" to remove paint and rust from industrial equipment surfaces. The low free silica content of boiler slag compared to sand makes it more attractive than sand as a sand-blasting agent from a worker health standpoint. The glassy appearance of boiler slag and its inherent physical characteristics make it an attractive candidate for incorporation into the surface of roofing shingles. Table 2 also shows that boiler slag has been used in minor amounts in various other applications.

Although the high rate of boiler slag utilization has been a very positive development, its effect on the overall CUB re-use rate in the U.S. has been and will continue to be limited because of the lower production volumes of boiler slag compared to the other common CUB materials. For various reasons primarily economics of operation, dry-bottom pulverized coal boilers have been and will continue to be preferred by coal-burning utilities for sustained base-load power generation.

Wet FGD Byproduct Utilization Technology

The FGD byproduct utilization figures contained in Tables 1 and 2 reflect primarily the byproducts from wet FGD scrubbers. Wet scrubbers have been by far the most prevalent type of SO_2 emission control device used in the U.S. thus far because they remove SO_2 more efficiently than dry scrubbers. Limestone has become the most popular reagent for use in wet scrubbers because of its lower costs, although lime scrubbing systems are also fairly common. Only a few sodium-based FGD systems are used on utility coal boilers in the U. S. Both lime and limestone wet scrubbers produce a calcium sulfate or calcium sulfite slurry which, after dewatering, can be utilized for a variety of applications. Tables 1 and 2 do not separate the production and utilization data for "FGD gypsum from that of fixated FGD sludge. These two materials have very different physical and chemical characteristics and different re-use markets; therefore, it is important to clarify these differences.

The primary factor affecting the type of FGD byproduct produced by lime or limestone-based wet scrubbers is the degree to which oxidation has taken place within the FGD system. In the scrubber, the kinetics of the reaction between the SO_2 gas and the calcium-based sorbent favors the initial formation of calcium sulfite ($CaSO_3$) solids. If additional oxidation is subsequently promoted by the FGD system design, the byproduct will be mainly in the form of calcium sulfate dihydrate ($CaSO_4$•$2H_2O$), or FGD gypsum. If oxidation is not promoted much of the byproduct will remain in the calcium sulfite form. In general, FGD gypsum is the more desirable byproduct because it is relatively easy to dewater and can be sold in a variety of re-use markets.

FGD byproducts dominated by calcium sulfite form a sticky, hard-to-dewater sludge that is not suitable, on its own, for any re-use market. Sulfite-based sludge cannot even be sent to a disposal site without first being fixated by adding fly ash (usually at a fly ash:FGD ratio of slightly less than 1:1) and additional lime (about 2% to 4% by weight). Cementatious reactions that occur within the fixated FGD sludge make it drier and easier to transport to a disposal site. More importantly, producers of fixated FGD sludge have also found that the additions of fly ash and lime can be manipulated to produce materials that are useful in a variety of engineering applications.

Many of the earliest scrubbers installed in the U. S. were not designed to promote oxidation because this added to the cost of the FGD system. The overall economics of FGD system operation at the time appeared to favor sludge fixation and disposal over oxidation and production of FGD gypsum. In recent years the economics of new scrubber installations have favored the incorporation of in-situ oxidation into the FGD system design and the production of FGD gypsum.

Wallboard

As shown in Table 2, the wallboard market accounted for almost three fourths of the FGD byproduct utilization in the U. S.. Wallboard is essentially a layer of gypsum sandwiched between two sheets of paper; however, the wallboard manufacturing process is actually quite complex, and requires fairly precise specifications on the quality of gypsum used. Considerable effort has been directed in recent years toward the development of technology to make the processes of FGD gypsum production and wallboard manufacture more compatible with each other. One of the major reasons for the slow but steady increase in the utilization rate of FGD byproducts has been the increasing recognition by the wallboard industry that FGD gypsum generally is of a higher purity than natural mined gypsum, and, provided that the proper quality controls can be achieved, constitutes a preferred feedstock for wallboard manufacture. Recent opportunities associated with the sale of FGD gypsum for wallboard in the U. S. have encouraged utilities to retrofit external forced oxidation systems to wet scrubbers that were originally designed to produce sulfite sludges. The wallboard market in some regions of the U.S. is nearing saturation, so the future rate of increase in the use of FGD gypsum for wallboard is unclear.

Cement and Concrete

A common application of FGD gypsum in the cement and concrete industry is its use as a raw material in the manufacture of Portland cement. Gypsum is an essential component of Portland cement; it is inter-ground with cement clinker in small amounts (up to 5%) to serve as a set retardant in the cement mixture. Unlike fly ash and bottom ash which are added to the cement kiln as a substitute for shale and clays in the manufacture of clinker, FGD gypsum is used to replace natural gypsum as one of the final steps in the cement manufacturing process. As with wallboard, the FGD gypsum must be of fairly high purity, free from contamination, and of a consistent composition to be used for cement manufacture. FGD gypsum can also be processed to produce specialty products such as gypsum-based plasters, mortars, and blocks.

Structural fills, road bases and flowable fills

Fixated FGD sludge has been used successfully as an engineering material in structural fills and road bases in a manner similar to cement-stabilized fly ash and self-cementing fly ashes. The cementatious reactions that occur within the fixated FGD material create a monolithic layer that is well-suited for these purposes. Although Table 2 does not contain a tonnage figure for the use of

FGD byproducts as flowable fills, fixated FGD sludge has been used successfully for this purpose also. As with flowable fills made from fly ash, the cementitious reactions within the fixated FGD material add to the strength of the mixture after the material has flowed into the desired space. Since the term “flowable fill” has traditionally been associated with fly ash based materials but not with materials made from fixated FGD byproducts, it is possible that its use was reported in Table 2 under the category of “grout” rather than under the category of flowable fill. Also, since one of the more common uses of FGD-based flowable fill has been to prevent subsidence over abandoned mine shafts and tunnels, it is possible that such FGD byproduct use was reported as a “mining application” in Table 2.

Agriculture

Gypsum is commonly used as an agricultural amendment for soils that are deficient in calcium, especially when the desired crops are known to be intolerant of the elevated pH that accompanies the application of agricultural limestone. Gypsum also adds sulfur, an essential nutrient for many plants, to soils that are sulfur deficient, and can improve the drainage and texture characteristics of some soils. Saline and acidic soils are particularly benefited by the addition of gypsum provided that the additional sulfate can be tolerated. The use of FGD gypsum as a substitute for natural gypsum in agricultural applications is somewhat more flexible than in wallboard and cement manufacture because less stringent specifications on sulfite content, ash content, and chloride content can be tolerated in agriculture than in manufacturing applications.

In recent years, fixated FGD sludge has seen an increased level of use on farms to construct cattle feed lots and hay storage pads. The FGD-based pads supply a firm surface that prevents the loss of the feed into the mud, and allows cattle to walk and feed during winter months without excessive effort (and resulting weight loss). Although the cured FGD material surface is not as hard and smooth as concrete, it serves the equivalent purpose at less than half the cost. Also, when manure from the pad is scraped and spread on the farm fields at the end of the winter season, a thin layer of the pad surface (approx. 1 inch) becomes incorporated with the manure and acts as a beneficial soil amendment.

Commercial products and other applications

Except for the applications described above, the production of commercially-salable “specialty” items from FGD byproducts is not as common as for products made from fly ash. Because of the persistent low rate of utilization for FGD byproducts, there is much ongoing research into the development of new applications for these materials. Investigations include some of the same high-value, small-volume applications for which fly ash is now used along with processes for converting FGD-fly ash mixtures into aggregates suitable for construction purposes, and higher value specialty products.

Fluidized Bed Combustion (FBC) Ash Utilization Technologies

Table 3 shows production and use data for FBC ashes that were collected by the Council of Industrial Boiler Operators. Over this period, the overall percentage utilization of FBC ashes was significantly higher (almost 70 %) than the historical utilization rate for CUBs from conventional boilers (less than 30%). It would be incorrect to assume from these numbers that FBC ashes are more desirable from a re-use standpoint than conventional CUBs, because a single use category — mining applications — accounted for almost 60 percent of all the FBC ash generated, and 84 percent of all uses. Mining utilization accounts for less than 2 percent of conventional CUB production and only about 6 percent of total use. Less than 12 percent of the FBC ashes produced were used for anything other than mining applications or disposal.

Table 3. FBC Ash Utilization, (data from Council of Industrial Boiler Operators)

Total Production: 24,517,000 Tons

Application	Tons Used	% of Total Production	% of Total Use
Mining Applications	14,347,452	58.5%	84.0%
Waste Stabilization	952,504	3.9%	5.6%
Structural Fill	905,470	3.7%	5.3%
Agriculture	565,952	2.3%	3.3%
Other	270,835	1.1%	1.6%
Flowable Fill	30,531	0.1%	0.2%
Cement	16,722	0.1%	0.1%
Total	17,089,467	69.7%	100%

Mining Applications

The relatively high utilization rate of FBC ashes in mining compared to conventional CUBs has resulted from several interrelated factors. Many FBC boilers are located near abandoned coal mining or preparation facilities that are already causing environmental or safety problems (acid mine drainage, erosion, unstable slopes, etc.). Furthermore, the source of fuel to many FBC boilers is coal refuse from the abandoned site itself, or coal from a mine very close to the problematic site. Since the FBC ash usually contains significant amounts of free lime, which helps neutralize acid-forming materials that are commonly found on the mine site, the haul back of the entire ash output of the FBC boiler to the site is often looked upon very favorably by environmental regulatory agencies. Regarding of unstable slopes and high walls, filling of abandoned shafts, and establishment of vegetation and erosion controls at the abandoned site also occurs as a positive side effect of the ash haul back operation. The FBC operation is thus viewed as a means of achieving environmental remediation at no cost to the taxpayer, and the placement of the ash at the mine site is truly a beneficial re-use rather than a disposal method.

Haul back of highly alkaline FBC ash to active surface coal mining operations is also fairly common in historically acid-producing areas. A regulatory condition for obtaining a mining permit in such areas is often a requirement to place alkaline materials in the mine backfill in quantities that exceed the potential amount of acidity that could be generated by the mine spoil. The availability of alkaline FBC ash in a haul back operation allows the mine operator to meet this requirement much more economically than if another alkaline source (e.g., limestone) were used. In fact, the economic viability of some mining operations depends entirely on the availability of alkaline FBC ash for backfilling purposes.

Waste Stabilization

The unreacted lime (CaO) and anhydrite ($CaSO_4$) in FBC ashes are effective for alkaline stabilization of sanitary sewage treatment plant sludge. The hydration of the lime and anyhdrite to form slaked lime and gypsum release heat that, in connection with the alkaline conditions, provides the pasteurization for elimination of pathogens and odor causing bacteria. The final soil-like material has good physical handling characteristics, low odor potential, has a pleasing, acceptable appearance and can readily be spread using conventional equipment. This material is suitable for subsequent use in agriculture and land reclamation.

The lime in FBC ash can also be used to neutralize acidic liquid wastes from a wide variety of processing operations. Although liquid acid wastes generally need to be neutralized to a pH of around 7 prior to disposal, it may be necessary in some cases to raise the pH to around 10 or 11 to precipitate the metal hydroxides out of the solution. The free lime in FBC ashes is often sufficient to raise the pH to these levels, whereas this is not possible with most conventional CUBs. Like conventional fly ash, FBC ash can also be used to solidify a variety of liquid wastes.

Because of the self-cementitious properties of many FBC ashes, addition of Portland cement may not be needed to achieve a sufficient strength in the final product.

Structural fills, road bases and flowable fills

FBC ashes have been used successfully in the same types of structural fill, road base and flowable fill applications as other CUBs. Like conventional fly ashes, FBC ashes generally have the advantage of lower unit weights than the natural soils they would replace in structural fill applications. The self-cementitious properties of FBC ashes can be an advantage in road base and flowable fill applications because lesser amounts of cement admixtures would be needed to achieve the final strength required by the material.

One important consideration when using FBC ashes for construction applications, especially structural fills, is the documented tendency of some FBC ashes to gradually expand over time. There are two potential reasons for this tendency. First, conditions within the FBC boiler often favor the formation of anhydrite over gypsum. When fresh FBC ash is placed into a structural fill, the ash becomes exposed gradually to increasing amounts of moisture at ambient temperatures. These conditions promote the growth of gypsum crystals, and the accompanying expansion of the in-place material can continue to occur for many months after the material is emplaced. It is also possible that the presence of high levels of sulfur and free lime in combination with common cementitious compounds can result in the gradual formation of the mineral ettringite, a complex calcium aluminosulfate hydrate. Ettringite, while cementitious, is also highly expansive; it also tends to decompose gradually over time when exposed to ambient temperature, pH, and moisture conditions. The expansion and subsequent decomposition of ettringite can cause FBC ashes to perform poorly in some structural applications.

When considering the use of FBC ash for construction purposes, it is essential that the material be tested to determine the potential for long-term swelling and expansion. In some cases, it may be possible to counteract the negative effects of expansion by first conditioning the FBC ash with just enough water to initiate the gypsum and ettringite formation reactions, then delaying utilization of the material until all expansive reactions have proceeded to completion.

Agriculture

Historically, agriculture has used ground limestone and commercial fertilizers to provide lime and essential plant nutrients such as magnesium, potassium and phosphorus that are required by many crops. Because of its inherent lime content, FBC ash has been demonstrated to be an effective replacement for lime and provides at least a portion of essential plant nutrients. The fly ash portion of FBC ash also serves as a source of plant micronutrients. The U. S. Department of Agriculture (USDA) has developed guidelines for the application of FBC ash as a substitute for commercial agricultural lime and fertilizers.

Cement and concrete

FBC ash has limited applications in concrete production because the materials are usually too low in silica, alumina and ferric oxide, and too high in sulfur trioxide (SO_3) to meet the ASTM C618 standard for fly ash use as a Portland cement replacement in concrete. However, like fly ash, FBC ash can be incorporated into the cement manufacturing process as a raw material for clinker production. The gypsum component of FBC ash allows for its use as a substitute for gypsum that is added to blended cements for set retardation.

Commercial products and other applications

Because of the widespread acceptance of FBC ashes for use in mining applications and the relatively small supplies of FBC ashes available from any given source. Relatively little work has been performed to develop markets for using FBC ashes in commercial products. Research into the production of specialty aggregate materials from FBC ashes has shown some promise.

Dry FGD Byproduct Utilization Technology

Any FGD process that involves the injection of a sulfur-collecting sorbent downstream of the boiler exit, and results in the formation of a byproduct that does not require dewatering, can be categorized as a dry scrubber. Spray dryers, the most common type of dry scrubber, use small amounts of water to help distribute the alkaline sorbent (lime is the most common) throughout the flue gas stream, but this water evaporates quickly, leaving behind a dry byproduct material. Spray dryers and other "dry scrubbing" processes are not nearly as prevalent as wet scrubbers, especially for large power generating facilities in the U. S. However, these processes are used somewhat more frequently on industrial boilers and on utility installations in Europe. No reliable nationwide production and utilization data are available for byproducts from dry scrubbers.

If the dry scrubbing unit is located upstream of the primary particulate control device, then the resulting byproduct will be somewhat similar to FBC fly ash because it will consist of a mixture of fly ash, spent sorbent (calcium sulfite or sulfate) and unreacted sorbent (calcium hydroxide). The characteristics and utilization options associated with dry scrubber ashes will therefore be similar to those of FBC ashes, described above. If the dry scrubbing unit is located downstream of the primary particulate collection device, then the resulting byproduct will contain reacted and unreacted sorbent, but no fly ash. Because of the lack of water, however, the byproduct will not be similar to either FGD gypsum or calcium sulfite sludge. In most utilization applications involving dry scrubber ashes (artificial aggregates, cement and concrete admixtures, and specialty brick or wallboard-type products) additional quantities of fly ash are mixed with the dry scrubber by-products prior to or during utilization.

Avoided Cost of Disposal

Multiple factors go in to determining the cost of disposal of coal ash that cannot otherwise be used. The specific type of ash, location, transportation methods, climate and terrain, regulatory requirements and potential for future use all enter into determining disposal costs. The physical location of the power plant also has a great impact on disposal. Plants located in urban areas may have no space for on-site disposal necessitating transport to other locations for disposal. Today many communities have permitted locations within their communities specifically for the disposal of ash. However, as these locations are filled, new land must be found for disposal. New permits often require extensive environmental reviews and regulatory hurdles. In western states or parts of the country where the plant is located farther from population centers, there is often more land available for disposal. Therefore the distance to the disposal site or the cost of land can influence disposal costs. Transportation of fly ash that is collected from silos is often mixed with modest amounts of water during loading into a truck to prevent dusting and make handling easier. In some situations, the fly ash is not mixed with water, but instead loaded directly into covered trucks or pneumatic tank trucks for transport. If this material is disposed, then handling at the disposal site is normally more challenging due to potential dusting issues. Bottom ash and other heavy ash material may be conveyed hydraulically using water in pipes to deliver the material to ponds. In some cases these ponds are only temporary holding locations, from which the material is later excavated and transported to a final disposal site. At some power plants, the material is transported to its final disposal location in these water filled pipes. At still other plants, the wet material may be stacked and after it dries, be transported to a final disposal site.

The type of climate has a significant impact on methods of disposal. In areas where water tables are high and where rain or snowfall is significant, precautions may be required to ensure that disposed material is contained. To prevent leachates from leaving a disposal site, liners may be installed or other types of barriers implemented. In arid climates, where water tables are far beneath a disposal site and annual rainfall is low, few barriers, if any, may be required. The need for barriers and liners, therefore impact the construction of disposal locations and affects the cost of disposal.

Each of the requirements imposes different design requirements on a disposal facility and will impact cost commensurately. Some sites actually serve as stockpiles for material that can be used in future construction, such as in structural fills, highway projects or industrial developments. Since construction is seasonal, these sites are not disposal areas but instead temporary storage facilities. Many utilities can also provide numerous examples of old disposal sites being “mined” to recover coal ash for uses not envisioned when originally placed.

Utilization Trends

The spherical nature of fly ash, and, in particular, the cenosphere (hollow, gas-filled sphere) component of the fly ash, makes it particularly well-suited for blending into plastics or paint materials to enhance the properties of these mixtures and reduce their overall cost. When used as a filler, the very light unit weight of cenospheres (specific gravity of 0.6 to 0.8) can reduce the weight of the manufactured products, and can lower manufacturing costs by reducing the amount of more expensive materials (e.g., resins in plastics) required. Fly ash has also been used successfully in other high-value commercial products such as specialty ceramic pipes and conduits, heat shields for racing automobiles, refractory furnace linings, decorative flooring and paving materials, and fillers in cast aluminum products. Because of their unique properties and cost advantages, fly ash and cenospheres can command fairly high prices when sold for such applications; however, the size of these specialty markets is usually not large, and many fly ashes do not possess the properties required by these markets.

Perhaps the fly ash product with the greatest potential for increased utilization in the U. S. is a building material known alternatively as autoclaved aerated concrete (AAC) or autoclaved cellular concrete (ACC). This material consists of a mixture of roughly 70 percent fly ash (or sand), water, cement, lime, and aluminum powder that is cured under high-pressure steam in an autoclave. The resulting concrete is a lightweight, porous material with an excellent combination of strength and insulating properties. At a density of roughly one-fifth that of conventional concrete and a compressive strength of about one-tenth, AAC is used in load-bearing walls only in low-rise buildings. In high-rises, AAC is used in partition and curtain walls. The material is also fairly friable and must be protected from weather with stucco or siding. It can be drilled, sawed, screwed, and nailed with ordinary carpentry tools, and is more resistant to fire, sound, mildew, and insects than wood. Its use in the U.S. has lagged far behind the rest of the world because of the relative abundance and low price of wood in this country.

Conclusions

There are many technical, economic, regulatory and institutional barriers to increased use of CUBs. A lack of standards and guidelines for certain applications and new applications heads the list of technical barriers. Anytime CUBs are used in lieu of another natural material, like soil, sand or gypsum, a portion of the fossil energy required to mine, transport, place or process is reduced. Using coal ash instead of natural soil in the construction of highway fills or embankments eliminates the need to remove soil from undisturbed areas, saving energy. The use of FGD synthetic gypsum provides a very efficient process to manufacture wallboard. This also avoids the energy intensive mining and processing activities when natural gypsum is used.

The monetary value of CUBs is dependent on a number of factors. The type of CUBs, its market location and seasonal aspects all contribute to determining the value of CUBs. Some such as fly ash that meets concrete quality as defined by engineering standards, can not only lower the costs of construction, but actually improves the quality of the finished product. The substitution of fly ash for Portland cement allows a contactor to replace some portion of the cement in concrete with fly ash, reducing the cost of the resulting concrete. Fly ash that cannot otherwise be used in concrete due to its lower quality is often used to stabilize soils or wastes which makes this process less expensive. Other CUBs, such as synthetic gypsum, have value because they can meet technical requirements for use in wallboard, which avoids the processing required of natural gypsum. These examples also pertain to bottom ash, boiler slag and CUBs used instead of other manufactured or mined materials. The market place in which the CUBs are produced or going to be used has great impact on value. If there are many sources of CUBs of similar type and quality are available in a market, then the value will be somewhat lower. Like any other product, supply and demand determines the value of CUBs. Transportation costs lead the economic barriers, which limit the shipment of CUBs to within about a 50-mile (80 kilometer) radius of the power plants. Transportation is also a major factor in the cost of using CUBs. The method of transportation rail, truck, pneumatic trailer, open trailer, accompanied by the loading and unloading methods all contribute to the cost of handling, which is reflected in the price of the CUBs. The time of year may also contribute to pricing. In many parts of the country, the production of coal ash is very high during both the coldest and hottest months of the year. These same periods of the year are often the slowest times for construction and other applications that beneficially use the ash. This sort of imbalance in the production and demand for CUBs can contribute to highs and lows in pricing. Many utilities and CUBs marketing firms work to overcome this by using storage silos and sometimes large distribution networks. Recognizing that the factors above will vary greatly across the US , some of the typical price ranges one will find for various CUBs are as follows:

- Concrete quality fly ash - $20 to $45 a ton
- Self-cementing fly ash for soil stabilization - $10 to $20 a ton
- Bottom ash for snow and ice control - $3 to $6 a ton
- Fly ash for flowable fill - $1 a ton and up
- Bottom ash and/or fly ash for road base - $4 to $8 a ton
- Self-cementing fly ash for oilfield grouting or waste stabilization - $15 to $25 a ton

Industry's ability to recycle CUBs may be limited by more restrictive environmental controls. In April 2000, the U.S. EPA stated that the use of CUBs does not warrant regulatory oversight but left the door open to stricter regulation of CUBs in the future. Later, the EPA nearly issued a ruling that would have classified CUBs as hazardous wastes under the Resource Conservation and Recovery Act (RCRA). However, in May 2000, the EPA reaffirmed its position that CUBs are non-hazardous.

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