# Center for By-Products Utilization

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**ABSTRACT.** Over 5 billion tonnes of non-hazardous by-product materials are produced annually in the United States. Large quantities of by-products generated from industrial and domestic sources are generally landfilled due a lack of other economically viable options. Landfilling is undesirable because it causes not only huge financial burdens to producers of by-products, but also future unknown environmental liabilities. To overcome these problems, it has become essential to find cost-effective solutions to these waste disposal problems. By-product materials generated from various sources must provide innovative solutions to environmental challenges leading to recycling options. This paper briefly describes various combustion products produced from industrial operations and post-consumer wastes, as well as current best recycling use options for these materials. Materials, productions, properties, potential applications in manufacture of emerging materials for sustainable construction, as well as environmental impact are briefly discussed. Additionally, future recycling and research needs are also presented.

**Keywords:** Combustion by-products, Fly ash, Boiler slag, Bottom ash, Environmental impact assessment.

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## INTRODUCTION

Over 5 billion tonnes of non-hazardous by-product materials are produced annually in the United States. The amounts of by-product materials generated are 2,100 million tonnes from agricultural sources, 200 million tonnes from municipal sources, 400 million tonnes from industrial sources, and 1,800 million tonnes from mineral sources [1]. Federal lawmakers have passed legislation to encourage beneficial use of these by-product materials. The Federal Resource Recovery Act of 1970 was the first law, which encouraged recycling, resource recovery, and energy recovery of by-product materials. Later on, this law was replaced by the Federal Resource Conservation and Recovery Act of 1976 (RCRA). This law requires selection of appropriate disposal of solid residue in order to avoid any injury to human health as well as the environment. Subsequent amendments to the RCRA were made in 1980 and 1984, with more emphasis on suitable disposal of by-product materials and resource recovery. The law further encourages recycling of such materials. The Federal government has continued its efforts for recycling of materials in sustainable construction [2].

Large quantities of by-products generated from industrial and domestic sources are generally landfilled due to absence of some other economically viable options. Landfilling is undesirable because it causes not only huge financial burdens to producers of by-products, but also future unknown environmental liabilities. Moreover, due to shortage of landfill space and stringent environmental guidelines, cost of landfilling is escalating. To address these issues, it has become essential to find cost-effective solutions to these waste disposal problems. Recycling of by-product materials generated from various sources must provide innovative solutions to environmental challenges leading to recycling options.

Various by-product materials widely produced in USA are coal combustion by-products, wood ash, pulp and paper industry by-products, municipal solid waste materials, agriculture by-products ash, foundry by-products, metallurgical by-products, scraped tires, plastics, glass, recycled concrete for aggregates, recycled asphalt pavement for asphalt, demolition debris, Ilmenite fines and titanium fumes, etc.

This paper briefly describes various combustion products produced from industrial operations, agriculture by-products, and post-consumer wastes, as well as current best recycling use options for these materials. Material, productions, properties, potential applications in manufacture of emerging materials for sustainable construction, as well as environmental impact are briefly discussed. Additionally, future recycling and research needs are also presented.

## COAL-COMBUSTION BY-PRODUCTS

Coal-fired power plants derive energy by burning coal in their furnaces. These power plants generally use either pulverized coal-fired furnaces or cyclone furnaces [3]. The ash collected from pulverized coal-fired furnaces are fly ash and bottom ash. Fly ash constitutes a major component (75 to 90%), and bottom ash component being in the range of 10 to 25%. The combustion of coal in cyclone furnaces occurs by continuous swirling of the coal in a high-intensity heat zone [3]. This causes fusing of fly ash particles into a glassy slag, called boiler slag and/or bottom ash, which drops to the bottom of the furnace. The boiler slag constitutes the major component of the cyclone boiler by-product (70 to 85%). The remaining combustion by-products exit along with the flue gases. Clean-coal ash is defined as the ash derived from plants involving the use of $SO_x$ and $NO_x$ control technologies. Clean-coal ash is dry-collected FGD materials such as spray drier ash.

According to ACAA [4], the estimated production of fly ash was approximately 63 million tones in 1999. Fly ash is a heterogeneous mixture of particles, varying in shape, size, and chemical composition. Fly ash is predominantly composed of spherical glassy particles, which can be less than 1 µm to more than 1 mm in size. Major mineralogical component of fly ash is silica-aluminate glass containing $Fe_2O_3$, CaO, and MgO. According to ASTM C 618, CaO content in Class F fly ashes is typically less than 10%, whereas it is more than 10% in Class C fly ashes. The surface area of fly ash ranges between 300 to 500 $m^2/kg$. Generally, density of fly ash varies between 1.6 and 2.8 $kg/m^3$. The chemical and physical properties of fly ash from different coal burning power plants are given in Table 1.

According to ACAA [4], approximately 17 million and 3 million tonnes of bottom ash and boiler slag were produced, respectively. Bottom ash and slag are generally non-spherical and are typically composed of particles ranging from 2 ìm to 20 mm in size. Bottom ash particles could be rounded in shape but can also be angular. They generally have porous structures. Boiler slag is composed of angular particles with a glassy appearance. Specific gravity for bottom ash and slag varies between 2.2 and 2.8, respectively. Their bulk densities range from 737 to 1586 $kg/m^3$ [3].

Approximately 25 million tonnes of FGD (wet scrubbers or flue gas desulfurization) materials were generated in 1999 [4]. The residue from such systems consists of a mixture of calcium sulfite and sulphate, $CaCO_3$, fly ash, and water. The fly ash amount in FGD material varies from less than 10% to as much as 50%. Concern over $SO_2$ emissions from power plants has resulted in development of several advanced $SO_2$ control systems that produce dry by-products [5]. These new processes avoid the complexity and operating problems in handling large volumes of liquid or semi-liquid wastes produced in the case of wet FGD systems. In addition, dewatering is not needed prior to utilization or landfilling. However, costly sorbent materials are needed for theses process. The advanced systems include Atmospheric Fluidized Bed Combustion (AFBC), Lime-Spray Drying, Sorbent Furnace Addition, Sodium Injection, and other clean coal technologies such as integrated coal classification combined cycle process.

The AFBC process produces clean-coal ash, sulfur-reaction products, and calcined limestone reaction products. The sulfur reaction products are primarily composed of calcium sulfate and sulfite, and calcium oxide. Calcined limestone reaction in AFBC process primarily forms calcium sulfate. Chemical composition of the AFBC residues is given in Table 2a. The by-products, also known as clean coal ash (Table 2b) primarily consists of spherical fly ash particles coated with calcium sulfite/sulphate, fine crystals of calcium sulfite/sulphate, unreacted sorbent composed of mainly $Ca(OH)_2$, and a minor fraction of calcium carbonate. The clean coal by-products are higher in concentrations of calcium, sulfur, and hydroxide, and lower in concentrations of silicon, aluminum, and iron compared to the conventional Class C fly ash.

Table 1 Chemical and physical properties of fly ash from different coal sources [6]

| | Bituminous | Sub-bituminous | Northern Lignite | Southern Lignite |
|---|---|---|---|---|
| $SiO_2$, % by mass | 45.9 | 31.3 | 44.6 | 52.9 |
| $Al_2O_3$, % by mass | 24.2 | 22.5 | 15.5 | 17.9 |
| $Fe_2O_3$,% by mass | 4.7 | 5.0 | 7.7 | 9.0 |
| CaO, % by mass | 3.7 | 28.0 | 20.9 | 9.6 |
| $SO_3$, % by mass | 0.4 | 2.3 | 1.5 | 0.9 |
| MgO,% by mass | 0.0 | 4.3 | 6.1 | 1.7 |
| Alkalis*,% by mass | 0.2 | 1.6 | 0.9 | 0.6 |
| LOI, | 3 | 0.3 | 0.4 | 0.4 |
| Fineness, Air permeability, $m^2/kg$ | 403 | 393 | 329 | 256 |
| 45 µm (No. 325) sieve retention, percent | 18.2 | 17.0 | 21.6 | 23.8 |
| Density, $kg/m^3$ | 2.28 | 2.70 | 2.54 | 2.43 |

* Available alkalis expressed as $Na_2O$ equivalent.

The Lime Furnace Injection (LFI) by-products, as shown in Table 2a, also known as clean-coal ash, consists of coal ash, calcium sulfite and sulfate, and unreacted lime. By-products generated by LFI contain 40 to 70% fly ash, 15 to 30% free lime, and 10 to 35% calcium sulfate by weight.

The calcium injection process produces by-products as shown in Table 2a similar to that of LFI and calcium spray dryer because of similarities in sorbents and injection methods used. The sodium injection process differs from the calcium injection in regards to type of sorbent used. This process uses a sodium-based sorbent such as sodium bicarbonate, soda ash, trona, or nahcalite [7]. By-products generated by this process include fly ash particles coated and intermixed with sodium sulfite/sulfate, and unreacted sorbent.

Table 2a Clean coal by-products chemical composition in percent by weight [7]

| SAMPLE NO. | $A1_2O_3$ | CaO | $Fe_2O_3$ | MgO | $K_2O$ | $SiO_2$ | $Na_2O$ | $SO_3$ |
|---|---|---|---|---|---|---|---|---|
| AFBC: | | | | | | | | |
| TVO3 (bed) | 2.72 | 45.07 | 4.77 | 0.62 | 0.31 | 3.17 | 0.27 | 6.50(b) |
| TVO4 (char) | 7.29 | 30.79 | 13.20 | 0.48 | 0.78 | 7.97 | 0.05 | 20.00 |
| TVO5 (ash) | 15.04 | 22.64 | 18.88 | 0.51 | 1.93 | 15.26 | 0.34 | 17.25 |
| SFO6 (comp.) | 6.12 | 39.13 | 17.11 | 0.54 | 0.72 | 6.04 | 0.29 | 12.00 |
| Spray Dryer: | | | | | | | | |
| ARO7 | 25.20 | 21.73 | 3.26 | 0.84 | 1.69 | 21.17 | 3.29 | 17.50 |
| STO7 | 12. 60 | 31.22 | 10.92 | 2.93 | 1.45 | 15.60 | 1.76 | 12.00 |
| LRO7 | 21.20 | 26.88 | 6.11 | 2.33 | 0.74 | 17.72 | 2.08 | 12.25 |
| HSO5 | 24.90 | 20.02 | 6.51 | 2.62 | 0.75 | 21.30 | 1.81 | 10.25 |
| APO7 | 24.90 | 17.67 | 3.11 | 0.65 | 1.35 | 25.72 | 2.05 | 18.25 |
| NVO4 | 15.00 | 21.32 | 4.83 | 1.53 | 0.60 | 20.42 | 6.58 | 14.00 |
| RSO5 | 19.00 | 28.50 | 15.34 | 2.85 | 0.42 | 15.96 | 2.12 | 13.75 |
| AVO6 | 18.00 | 19.03 | 9.23 | 4.62 | 1.46 | 24.52 | 9.17 | 11.50 |
| Lime Furnace Injection: | | | | | | | | |
| SRO7 (lime) | 16.40 | 28.83 | 14.20 | 2.50 | 2.84 | 17.72 | 1.77 | 12.50 |
| SRO9 (limestone) | 17.20 | 29.15 | 16.48 | 0.82 | 2.96 | 19.33 | 1.64 | 11.25 |
| OLO3 (limestone) | 17.80 | 36.13 | 13.17 | 0.63 | 1.11 | 15.75 | 0.48 | 6.25 |
| OLO4 (limestone) | 17.10 | 40.00 | 11.91 | 0.70 | 1.08 | 16.18 | 0.51 | 5.50 |
| OLO8 (limestone) | 29.80 | 16.80 | 16.86 | 0.67 | 2.12 | 27.86 | 1.02 | 3.50 |
| Calcium Injection: | | | | | | | | |
| AHO6 | 9.07 | 40.57 | 2.17 | 0.56 | 0.82 | 10.27 | 0.59 | NA |
| AA1O-01 | 31.37 | 15.39 | 8.86 | 1.13 | 3.37 | 29.95 | 1.24 | NA |
| AA1O-02 | 31.37 | 13.99 | 8.86 | 1.13 | 3.37 | 27.81 | 1.27 | NA |
| Sodium Injection: | | | | | | | | |
| NXO4 | 28.90 | 4.54 | 2.50 | 1.16 | 0.77 | 25.18 | 24.7 | 12.00 |
| NBO4 | 30.50 | 4.40 | 6.60 | 0.70 | 1.45 | 33.94 | 8 | 7.75 |
| | | | | | | | 12.8 | |
| | | | | | | | 9 | |

(a) All elements expressed as their oxides, but may occur in other forms.
(b) $SO_3$ content of the uncrushed sample; the crushed sample had a $SO_3$ content of 23.9%.

The IGCC process produces by-products similar to the $SO_2$ control processes. These by-products are also under the broader classification of clean coal ash.

From the above description, it is clear that most $SO_2$ control processes generate a by-product (clean coal ash) similar to that of conventional fly ash. Addition of sorbent modifies fly ash to a significant extent.

Table 2b. Chemical properties of clean coal ash samples in percent by weight [5]

| Source No. | $SiO_2$ | $Al2O_3$ | $Fe_2O_3$ | CaO | MgO | $TiO_2$ | $K_2O$ | $Na_2O$ | $SO_3$ | Moisture Content | LOI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 51.4 | 20.6 | 18.8 | 1.6 | 1.0 | 1.0 | 2.4 | 0.8 | 0.60 | 0.3 | 1.9 |
| | 52.2 | 20.4 | 17.8 | 1.6 | 1.0 | 1.0 | 2.4 | 0.8 | 0.6 | 0.3 | 2.1 |
| 2 | 21.1 | 8.0 | 41.6 | 6.6 | 0.4 | 0.4 | 0.8 | 0.3 | 2.4 | 0.4 | 18.8 |
| | 21.6 | 8.2 | 42.7 | 6.7 | 0.4 | 0.4 | 0.9 | 0.3 | 2.2 | 0.2 | 16.8 |
| 3 | 47.1 | 23.6 | 14.6 | 2.2 | 1.0 | 1.7 | 2.5 | 1.4 | 1.1 | 10.9 | 4.9 |
| | 45.9 | 20.8 | 16.6 | 3.6 | 1.0 | 1.0 | 2.2 | 1.0 | 1.5 | 6.5 | 6.1 |
| 4 | 54.8 | 24.1 | 9.1 | 2.7 | 1.0 | 1.0 | 1.6 | 2.0 | 0.6 | 0.1 | 2.3 |
| 5 | 57.5 | 13.3 | 17.8 | 5.5 | 1.0 | 1.0 | 1.6 | 2.0 | 1.2 | 0.1 | 0.2 |
| | 57.3 | 13.5 | 17.6 | 5.4 | 1.0 | 1.0 | 1.6 | 2.0 | 1.3 | 0.1 | 0.4 |
| 6 | 46.0 | 17.1 | 14.6 | 3.7 | 1.0 | 1.0 | 1.8 | 1.0 | 2.5 | 0.3 | 11.8 |
| | 45.0 | 17.0 | 14.0 | 4.7 | 1.0 | 1.0 | 1.8 | 1.0 | 2.6 | 0.2 | 12.3 |
| 7 | 48.3 | 19.5 | 14.8 | 3.0 | 1.0 | 1.0 | 2.5 | 1.0 | 2.2 | 0.2 | 7.1 |
| | 47.6 | 19.2 | 14.1 | 2.8 | 1.0 | 1.0 | 2.4 | 1.0 | 2.3 | 0.1 | 8.9 |
| 8 | 6.3 | 2.6 | 1.9 | 41 | 1.7 | 0.1 | 0.3 | 0.7 | 2.0 | 0 | 25.7 |
| | 13.3 | 5.7 | 4.1 | 34 | 1.0 | 0.3 | 0.6 | 0.7 | 6.8 | 0 | 32.3 |

The modified fly ash contains fly ash particles coated with sorbent and sorbent-reaction products, and smaller non-fly ash particles composed of reacted and unreacted sorbents. The by-products generated by these processes exhibit physical and chemical properties different than those for conventional coal ashes [5,7, 8].

## Applications of Coal-combustion By-products

The most common use of fly ash is in cement-based materials. However, in keeping with the primary emphasis of this paper, only emerging materials using fly ash are emphasized.

### Fly ash

Fly ash can be used either as a raw material in the production of the cement clinker, interground with the clinker, or blended with the finished cement. Fly ash can be utilized as a major component of blended cements, exceeding 50% of total blended cement mixture [9]. It can be used as a replacement of sand up to 100% in manufacturing Controlled Low Strength Materials (CLSM) [10-12], suitable for foundation support and backfilling of excavations, bridge abutments, buildings, retaining walls, utility trenches, etc.; for filling abandoned tunnels, sewers, and other underground facilities; and as embankments, grouts, etc.

Fly ash can be used in manufacturing of light-weight aggregates by using sintered (fired) and unfired (cold bonded) processing methods [13-15]. Naik, et al. [16] have reported that high volumes of Class C and Class F fly ashes can be used to produce high-quality concrete pavements with excellent performance.

Fly ash with and without silica fume can be used in manufacture of high-performance concrete [17]. High-performance concrete mixtures containing up to 30 to 40% fly ash can be proportioned to attain both high-strength and high-durability related properties. Studies [18, 19] have substantiated that concrete containing large amounts (more than 50%) of either Class C or Class F fly ash can be proportioned to meet strength and durability requirements for structural applications.

Naik and Ramme [20] have reported that superplasticized Class C fly ash concrete with low water-to-cementitious materials ratio can be proportioned to meet the very early-age strength as well as other requirements for precast/prestressed concrete products.

Fly ash as a fine filler material as well as a pozzolan can be used in roller-compacted concrete [21]. Cao et al. [22] examined the strength of roller-compacted concrete with high volume fly ash (HFRCC) and concluded that: (i) the strength at early ages of HFRCC is poor, while the fly ash effect is low or negative, (ii) strength of HFRCC increases rapidly with age, and (iii) with increasing proportion of fly ash, its effect on HFRCC at long-curing age becomes even more remarkable. In manufacture of autoclaved cellular concrete, fly ash can be used as a replacement of 30 to 100% of silica sand [23]. Cenospheres derived from fly ash are an ideal filler material for manufacture of polymer matrix composites [24, 25]. Rohatgi, et al. [26] have reported the use of fly ash as a particulate filler in cast metal matrix composites. Inclusion of the fly ash in such compositions is reported to increase hardness, abrasion resistance, stiffness, and decrease density of aluminum matrix [27].

Naik, et al.[28] based on their investigations have concluded that blending of Class C fly ash with Class F fly ash showed either comparable or better results than either the reference mixture without fly ash or the unblended Class C fly ash. Langley and Leaman [29] reported some practical applications of high-volume fly ash concrete utilizing low-calcium fly ash for structural applications, machinery foundations, impermeable surface membranes, etc.

Swamy and Hung [30] have reported engineering properties of high-performance, high-volume fly ash concrete incorporating small quantity of silica fume, and partial replacement of both cement and sand with fly ash. The mixtures gave compressive strength of 30 to 40 MPa at 28 days.

Churchill and Amirkhanian [31] have examined the effect of coal ash (fly ash and bottom ash) when used as a partial replacement of fine aggregate in asphaltic concrete mixtures. The specimens were made using three aggregate sources, two ash sources, three ash percentages (0%, 6%, and 8%) , and hydrated lime. They concluded that partial substitution of fine aggregates by coal ash had a moderate detrimental effect on short-term tensile strength, but met the minimum tensile strength requirements set by the South Carolina Department of Transportation. Poon, et. al.[32] have shown that concrete with 28-day compressive strength of 80 MPa could be obtained with a water-binder ratio of 0.24, with a low-calcium fly ash content of 45%.

Bilodeau and Malhotra [33] have advocated the use of large amounts of fly ash and other supplementary cementing materials in construction. They believe that use of high-volume fly ash concrete should be made mandatory for the concrete industry in order to reduce $CO_2$ emissions and other environmental considerations.

### Bottom ash/boiler slag

Large size (greater than 6 mm) bottom ash can be used as coarse aggregate and small size bottom ash can be used as fine aggregate. Naik and his associates [34, 35] have reported that bottom ash can be used as lightweight aggregates. They also demonstrated the feasibility of using bottom ash in manufacture of masonry products as a partial replacement of coarse as well as fine aggregates. Bottom ash and boiler slag used in CLSM slurry can enhance insulating ability of the fill. The most popular use of coal boiler slag is in architectural concrete as aggregates [36].

Bakoshi, et al. [37] demonstrated that compressive and tensile strengths of bottom ash concrete increases with an increase in the replacement ratio of fine aggregate. Freezing and thawing resistance of concrete using bottom ash was lower than that of ordinary concrete, whereas abrasion resistance was higher.

### Clean coal ash

Limited work has been reported concerning the use of clean coal ash. Such ash can be used in construction of stabilized road base, as a raw material for manufacturing of cement, use in concrete and other cement-based materials, for manufacture of wallboards, etc. Naik et al. [5] have reported that significant amount of clean coal ash can be used in concrete as well as masonry products. Naik et al. [38] have also established mixture proportions and production technologies for clean coal ash in CLSM as a replacement of sand and/or conventional fly ash.

Ghafoori and Mora [39] studied the engineering characteristics and long-term durability of laboratory-made compacted non-cement composites made with fluidized bed combustion (FBC) and pulverized coal combustion (PCC) fly ash. Based on their experimentation, they concluded that higher strength and expansion properties, and an improved performance in long-term durability were attained with increases in PCC fly ash to FBC ratio of the matrix; and inclusion of natural fine aggregate improved paste quality and properties of PCC:FBC compacted concretes.

## ENVIRONMENTAL IMPACT ASSESSMENT OF MATERIALS MADE WITH BY-PRODUCTS

### Leachate Test Methods

Greer, et al. [39] reported on four leachate methods: EP-Toxicity method, TCLP method, American Foundrymen's Society (AFS) method, and ASTM method. A comparison of these methods is presented in Table 3.

To determine toxicity of a solid waste, the Extraction Procedure (EP) toxicity technique employs an acidic (pH = 5 ± 0.2) leaching medium and a liquid to solid ratio of 20:1. The leachate from this test is analyzed for arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. If these parameters exceed 100 times the drinking water standards criteria then the waste is categorized as an EP hazardous waste.

The TCLP test is carried out to evaluate mobility of both inorganic and organic contaminants in liquid, solid, and multi-phase waste system. A sample of the waste is extracted with an appropriate buffered acetic acid solution for 18 ± 2 hours. Then the extract obtained from the TCLP is tested to see whether or not it exceeds the thresholds established by the US-EPA.

The AFS test employs de-ionized water as a leaching medium. This method provides an indication of the release of certain chemical parameters over a period of time.

The ASTM test method employs one solution, which is agitated for 18-hour period. The sample is then allowed to settle for 5 minutes after which a vacuum or pressure filter is used to filter the liquid through a 0.45 µm filter. The resulting filtrate is analyzed for concentration of certain constituents.

Naik, et al. [40], Pfughoeft-Hassett, et al. [41], American Engineering Testing, Inc. [42] have compared ASTM leach data with both drinking water standards and/or local ground water standards to judge the quality of the leachate. The results reported by Naik et. al. [11] are shown in Table 4. Generally by-products from coal combustion are non-toxic. Pflughoeft-Hassett, et al. [41] reported that leachate tests on fly ash, bottom ash, and boiler slag exhibited all elements below the RCRA limits.

## FUTURE OF RECYCLING AND RESEARCH NEEDS

To reduce waste disposal problems, it is important to develop technologies for high-volume use of by-products from various sources. Use of high-volume fly ash in cement-based materials have already been developed. Research on long-term strength and durability of high-volume fly ash (HVFA) concrete is under progress [77]. More research is required to investigate the use of blended cement technology with more than 50% of conventional coal ash in the total blended cement mixture. High-volume use technologies in cement-based materials for clean coal ash is somewhat lacking. Therefore, further research is needed to develop effective and economical uses of clean coal ash in cement-based materials.

More investigations needs to be carried out towards establishing mixture proportions for cement-based materials to encapsulate heavy metals and other contaminants found in treated wood ash. Also there is a distinct lack of data available for leachates for concrete containing fly ash and/or other by-products

Table 3 Comparison of laboratory leaching tests [39]

| Item | EP-Toxicity | TCLP | AFS | ASTM |
|---|---|---|---|---|
| Leaching Medium | Deionized Water, 0.5 N Acetic Acid Added to adjust pH to 5.0 ± 0.2 | pH 4.93 ± 0.05 Acetate Buffer | Deionized Water | Deionized Water |
| Liquid to Solid Ratio | 20 to 1 | 20 to 1 | 5 to 1 | 20 to 1 |
| Contact Time | 24 hours | 18 hours | 24 hours<br>48 hours<br>72 hours | 18 hours |
| Method of Mixing | Continuous Rotation at 30 RPM | Continuous Rotation at 30 RPM | Invert 15 time in 24 hours | Continuous Rotation at 29 RPM |
| Filtering | Once 0.45 ìm | Once 0.7 ìm glass | Once 0.45 ìm | Once 0.45 ìm |
| Number of Elutions | 1 | 1 | 3 | 1 |

Table 4 Leachate characteristics of the class f fly ash mixtures with and without foundry sand [5]

| Parameter | S1-2(P) (mg/l) | S4-2(P) (mg/l) | S7-2(P) (mg/l) | S8-2(P) (mg/l) | S9-2(P) (mg/l) | Drinking Water Standards (mg/l) | GWQS* Enforcement Standard, (mg/l) | GWQS* Prevention Action Limit, (mg/l) |
|---|---|---|---|---|---|---|---|---|
| Foundry Sand, (%) | 0 | 70(FS1) | 50(FS2) | 70(FS2) | 85(FS2) | - | | |
| Aluminum | 8.2 | 7.6 | 6.8 | 5.3 | 5.3 | | | |
| Antimony | 0 | 0 | 0 | 0 | 0 | | | |
| Boron | 0.065 | 0.053 | 0.065 | 0.062 | 0.034 | | | |
| Cobalt | 0 | 0 | 0 | 0 | 0 | | | |
| Iron | 0 | 0 | 0 | 0 | 0 | | 0.30** | 0.15** |
| Nickel | 0 | 0 | 0 | 0 | 0 | | | |
| Potassium | 12 | 6.6 | 9.3 | 13 | 13 | | | |
| Barium | 0.79 | 0.43 | 0.88 | 0.62 | 0.48 | 1.0 | 2.0** | 0.4** |
| Calcium | 100 | 88 | 120 | 89 | 90 | | | |
| Magnesium | 0 | 0 | 0 | 0 | 0 | | 0.05** | 0.025** |
| Manganese | 0 | 0 | 0 | 0 | 0 | | | |
| Molybdenum | 0.13 | 0 | 0.09 | 0.13 | 0.06 | | | |
| Silica | 3 | 3.5 | 3.1 | 4.3 | 4 | | | |
| Sodium | 8.1 | 4 | 3.7 | 3.6 | 3.4 | | | |
| Zinc | 0 | 0 | 0 | 0 | 0 | | 5** | 2.5** |
| Arsenic | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.005 |
| Chromium | 0.036 | 0.036 | 0.018 | 0.023 | 0.021 | 0.05 | 0.10 | 0.01 |
| Lead | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.015 | 0.0015 |
| Selenium | 0.008 | 0.005 | 0.01 | 0.015 | 0.007 | 0.01 | 0.05 | 0.01 |
| Cadmium | 0 | 0 | 0 | 0 | 0 | 0.01 | 0.005 | 0.0005 |
| Mercury | 0 | 0 | 0 | 0 | 0 | | 0.002 | 0.0002 |
| pH at 25° C | 11.3 | 11.4 | 11.3 | 11.2 | 11.2 | | | |
| Chloride | 0 | 0 | 0 | 1 | 1 | | 250** | 125** |
| Conductivity at 25° C (ì Mho) | 1150 | 852 | 1154 | 886 | 887 | | | |
| Sulfate | 20 | 20 | 16 | 14 | 14 | | | |
| Alkalinity as $CaCO_3$ | 290 | 220 | 280 | 230 | 210 | | | |
| Total Dissolved Solids | 324 | 256 | 354 | 255 | 278 | | | |
| Total Hardness as $CaCO_3$ | 250 | 220 | 300 | 222 | 225 | | | |
| Total Phosphorus | 0.03 | 0.02 | 0 | 0 | 0.02 | | | |

Note: A zero indicates a value below detection limit (BDL)
* GWQS = Ground Water Quality Standard (Public Health-Related)
** GWQS related to public welfare

## SUMMARY AND CONCLUSIONS

Generally, large volumes of by-product materials generated from industrial and post-consumer sources are disposed in landfills. The quantity of waste generation is increasing every year. Due to stricter environment regulations, it is becoming very difficult to obtain approval for developing new disposal facilities/sites. This results in escalating disposal cost. Recycling not only helps reducing disposal costs, but is also help in conserve natural resources; and it provides technical and economic benefits.

Several options for using by-products generated from industrial and post-consumer sources have been developed. The by-products reported in this paper are coal combustion by-products

(1) Fly ash can be used
- (i) as a major component of blended cement, even exceeding 50% of total blended cement mixture.
- (ii) up to 100% as replacement of sand for making CLSM.
- (iii) in manufacturing of lightweight aggregates.
- (iv) in making high performance concrete(HPC).
- (v) in the making super-plasticized structural–grade concrete by replacing more than 50% of cement.
- (vi) as a filler in polymer matrix composite.
- (vii) as a replacement of 30 to 100% silica sand in making autoclaved cellular concrete.
- (viii) as a fine filler and as a pozzolan in roller-compacted concrete.
- (ix) in making precast/ prestressed concrete elements by replacing cement upto 30%.

(2) Bottom ash/boiler slag can be utilized as both fine and coarse lightweight aggregates.

(3) Clean-coal ash can be used as a raw material in production of cement. FGD can be used as gypsum for the manufacturing of wallboards. It can also be used in concrete as well as cement-based masonry products.

(4) Sewage sludge can be used
- (i) in manufacturing lightweight aggregates.
- (ii) in making clay bricks by replacing clay upto 40%.

(5) Sewage sludge ash upto 10% can be used as a filler in concrete.

(6) Incineration ash can be used in making of synthetic aggregate.

(7) Wheat-straw ash can be used as a pozzolanic materials.

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