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# Environmental Considerations Associated With Using Industrial By- Products Such as Fly Ash in Concrete

by John Woodyard and Martha VanGeem

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by John Woodyard,<sup>1</sup> and Martha VanGeem<sup>2</sup>

## **BACKGROUND**

Concrete is often made using industrial by-products as either aggregate, or as a partial replacement or supplement for portland cement as a binder. This allows owners potential saving in both construction costs and raw materials. These by-products are waste materials from industrial processes, but those that are suitable for use in concrete now have well established markets and are therefore diverted from landfills. The by-products have different physical and chemical properties than the raw materials commonly used in the cement or natural aggregate they are replacing. These properties need to be considered both in terms of their suitability for use in concrete, and their potential impact on human health and the environment in different concrete applications.

### **Types of Industrial By-Products Used in Concrete**

Concrete is a composite material made of aggregate and a binder. While the most common binder is portland cement, other materials can be used depending on their physical and chemical properties. The cementitious portion is typically 7 to 15% of the mass of the concrete; the rest typically being water and aggregate (sand and gravel or crushed stone). There is a substantial body of technical knowledge governing the proper use of industrial by-products in concrete.

Examples of industrial by-products used as replacements or supplements for portland cement in concrete include fly ash, ground granulated blast furnace slag (GGBFS or slag cement), and silica fume. Air-cooled blast furnace slag can be used as aggregate. Foundry sand can be used as partial replacement for ordinary sand in concrete. Other materials such as metal shavings can also be used for specialty products. Recycled concrete can be processed and used as aggregate or sub-base, a potentially significant cost saving on road reconstruction; the industry envisions routine recycling of demolition waste. Fly ash, slag and silica fume are also used to make portland cement and blended cement.

### **Industrial By-Product Formation**

The production of industrial by-products varies within the particular waste generating industry based on major or even subtle process differences, which in turn can affect the physical and chemical properties of the by-product and therefore its suitability in concrete.

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Fly ash is produced from the combustion of coal in electric power generating plants, and is by far the most widely used by-product in concrete. The ash fraction of coal varies (typically 5-15%) depending on coal type and source. The ash is collected as either bottom ash, fly ash or boiler slag depending on the type of coal combustion technology used; approximately 80% of the ash produced in pulverized coal boilers, for example, leaves the furnace as fly ash, while cyclone and stoker-fired boilers will release only 10 to 30% of the ash as fly ash. Fly ash that is available for use in concrete is collected dry usually through the use of electrostatic precipitators.

The amount of fly ash that can be added to concrete varies depending on application. While fly ash rates of 50% to 80% of the total cementitious materials have been reported, the typical range is 15% to 25%. Higher rates of addition depend on the type of fly ash and compatibility with other materials in the concrete, and therefore may not be widely applicable.

Blast furnace slag is a by-product of steel making, specifically the production of molten iron resulting in the fusion of limestone and other fluxes with the ash from coke and silica and aluminum from iron ore (see ACI 233, 1995). Processed granulated blast furnace slag is a glassy, granular material formed when the molten slag is immersed in water. This product is then ground and used as a mineral admixture (partial replacement for portland cement) in concrete. Slag cement is used in concrete at rates of 20 to 80% of the total cementitious material depending on the application.

Silica fume is a byproduct of the reduction of high-quality quartz with coke or coal and wood chips in an electric arc furnace, during the production of silicon metal or ferrosilicon alloys (ACI 234, 1996). The fume, condensed from the exhaust gases, contains superfine spherical silicon dioxide particles, typically 100 times smaller than average cement particles. Silica fume is used in concrete at rates of 5 to 10% of the total cementitious material, and is used in applications where a high degree of impermeability is needed and in high-strength concrete.

### **Industrial By-Product Production Statistics**

An estimated 31% of fly ash and bottom ash produced in the U.S. is recycled, or over 24 million tons per year. Approximately 43% of the recycled ash is used to produce cement, concrete and grout. Nearly all fly ash suitable for use in concrete is recycled. Fly ash is used in about 50% of ready mix concrete. The use of slag cement is a growing industry and has increased an average of 16% over the past five years to 2.26 million metric tons in 2001 (Slag Cement Association).

### **Other Uses for Industrial By-Products**

More than half of all fly ash and bottom ash is used for applications other than cement and concrete. These other applications (and % use) are:

- Flowable Fill (1.4)
- Structural Fill (32.5)
- Road Base/Subbase (5)
- Mineral Filler (0.2)
- Snow and Ice Control (4.8)
- Mining Applications (9.8)
- Waste Stabilization and solidification (9.1)
- Agriculture (0.4).

Other less common but promising applications include roofing and insulation material, artificial reefs, and road surface traction additive.

### **Benefits Associated With By-Product Use in Concrete.**

Fly ash has been used as a cementitious and pozzolanic ingredient in portland cement concrete since the 1930s. Fly ash can be used directly as a cementitious material in concrete or as a raw material in cement manufacture. The use of fly ash in concrete has steadily increased over the years because it improves some properties of concrete and often results in lower cost concrete.

Fly ash is mixed with portland cement, water and aggregate to produce mortar and concrete. Fly ash is a pozzolanic material; it exhibits cementitious properties in the presence of portland cement. Fly ash was initially used as a partial mass or volume replacement for portland cement, but was later shown to result in improved properties of concrete, including increasing resistance to alkali-silica reactivity, reduction in peak temperatures after placement (generally Class F only), and improvement in the workability of fresh concrete.

Fly ash physical and chemical properties vary depending on the coal source and type of combustion system, which in turn affects its value in concrete. Fly ash is primarily silicate glass containing silica, alumina, iron, and iron. Class C fly ash is a by-product of burning sub-bituminous coal and lignite and is often high in calcium. Class F fly ash is a product of burning bituminous (mostly eastern) coal low in calcium, and needs to be activated by cement or lime. Class C fly ash generally develops strength faster than Class F fly ash.

Since slag cement is a cementitious rather than a pozzolanic material, it can be used at higher replacement levels than fly ash. Unlike fly ash, however, slag cement production is largely limited to areas where steel making is common and is therefore not always available. Similar to fly ash, slag cement in concrete can provide increased resistance to alkali-silica reactivity, reduced permeability of concrete, and contribute to a reduction of peak temperatures after placement.

Silica fume is a pozzolanic material that can be used in concrete to improve strength, decrease permeability, and aid in resisting deterioration. Corrosion in concrete from deicing salts, particularly on bridge decks, can be reduced by using concrete with silica fume.

Concrete demolition debris from buildings and roads is used as a substitute for other sources of aggregate and as a sub-base during road construction in particular. Mobile “crushing trains” on road removal projects and other portable concrete pulverization equipment on building demolition projects can both allow the aggregate and sub-base to be produced on-site or nearby, thereby reducing or eliminating the cost of transportation.

## **ENVIRONMENTAL CONSIDERATIONS ASSOCIATED WITH INDUSTRIAL BY-PRODUCTS**

### **Chemical Properties of By-Products**

Fly ash is comprised largely of silica, alumina, iron oxide, and calcium, with the relative proportion dictated by the source of the coal burned to form the ash. Fly ash particles are mostly microscopic spheres (hollow or solid) formed when these compounds solidify in the power plant exhaust gas.

Like most naturally occurring materials, coal contains trace quantities of a variety of natural elements. Unlike these other materials, however, the combustion of coal concentrates these elements on or in the solid by-products. The ultimate fate, form, and concentration of these elements is dictated by their physical and chemical properties; most are oxidized during combustion, and those with the lower boiling point tend to condense with the fly ash in the exhaust as it cools (often on the outer surface of the spheres). The higher boiling point elements condense with the bottom ash or boiler slag in the furnace, as is the case with GGBF slag. There is little data on silica fume trace chemical composition. The ACI committee 234 report on silica fume states that there are no known health problems that have been attributed to the use of silica fume in concrete.

Recycled concrete has the chemical composition of its original constituents much like fresh concrete, and the lack of chemical or thermal processing for recycling (such as in road aggregate) would result in no further change. Because some concrete rubble from industrial demolition may contain trace quantities of road salt or other chemicals from process or storage spills that could affect its fitness for use and environmental impact, care should be taken to identify the source of any recycled concrete before use.

### **Environmental Significance of Naturally Occurring By-Product Contaminants**

More than 30 trace elements are commonly identified in coal. Of those, less than a third tend to concentrate on fly ash. These elements include arsenic, cadmium, copper, molybdenum, lead, antimony, sulfur and zinc. Others such as barium and vanadium often split between ash fractions.

With the onset of improved fly ash collection (using electrostatic precipitators) and sulfur oxide collection (using wet scrubbers) for power plants in the 1960-1970s, most fly ash was collected and disposed of in on-site landfills near power plants. Concern over the possible leaching of these elements from the ash and contamination of the underlying groundwater or nearby surface water was raised at the time, prompting extensive research into this issue by the U.S. EPA and the electric utility industry.

Studies have now shown that these elements are present only in trace quantities (measured in parts per million, or ppm) and their mobility through leaching by water is so low as to present only a miniscule health risk to human health. Research into the use of fly ash as a soil amendment has still shown that some fly ash is unsuitable because of high alkalinity and trace element absorption and accumulation in plants, therefore requiring that it be used prudently in agricultural applications.

### **Regulations and Policies Governing Industrial By-Products**

Because the actual health risk varies depending on the quality and availability of accumulated fly ash (and the corresponding trace elements) in sufficient quantities to be of concern to local water supplies, EPA and state regulation of fly ash management has tended to focus on large-scale disposal sites.

The U.S. EPA in 1993 determined that power plant coal ash is non-hazardous following over 15 years of detailed laboratory and field research into the environmental and health impacts of coal ash. Ash disposal in large quantities to land is still regulated by states and under the Resource Conservation and Recovery Act (RCRA) by U.S. EPA; disposal site engineering and operational requirements are similar to those for municipal refuse disposal sites rather than for hazardous waste facilities.

Several of the trace elements found in fly ash are frequently seen in the press and often regulated in high concentrations by EPA, OSHA, and states, such as mercury and lead. However, the presence of lead in paint, for example, is typically as much as 100,000 times higher than in fly ash, and therefore deserves special regulatory attention when deteriorating or being removed. None of these elements vaporize to any appreciable extent, even under higher environmental temperatures.

Coal and, as a result, ash also emit natural radioactivity like many other raw materials, but the emission levels are so low as to be insignificant to human health or the environment. EPA considers coal ash to be a diffuse naturally occurring radioactive material (NORM), its most benign classification, and notes that radionuclide releases even from coal ash piles are within the typical range of “background” concentrations associated with surface rocks and soils in the US.

Trade associations and technical organizations representing ash, such as EPRI ([www.epri.org](http://www.epri.org)), Edison Electric Institute ([www.eei.org](http://www.eei.org)), and the American Coal Ash Association ([www.aaaa.org](http://www.aaaa.org)) have funded much of the necessary research with U.S. EPA

to develop the appropriate engineering controls and permitting requirements for ash disposal on land.

ASTM C 618, “Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete,” categorizes fly ash according to its chemical composition, resulting in the C and F classes cited earlier and issued to determine the suitability of the ash for certain concrete additive applications, along with other ASTM methods for determining size distribution, loss on ignition, and other physical properties.

ASTM C989-99, “Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars,” categorizes slag cement in three strength grades for use in concrete and mortars, Grades 80, 100, and 120. Silica fume for use in concrete must meet [C1240-01, “Standard Specification for Use of Silica Fume for Use as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout.”](#)

## **ENVIRONMENTAL CONSIDERATIONS ASSOCIATED WITH BY-PRODUCT USE IN CONCRETE**

### **Other Factors Limiting By-Product Use in Concrete**

As noted earlier, only the by-product and the desired properties of the concrete limit the dosage rates of industrial by-products. Fly ash use at rates of up to 80% of the total cementitious materials in concrete have been reported in the literature, but much lower ranges (15-25%) are most common.

No environmental considerations have been identified that would otherwise limit the use of by-products in concrete.

### **Regulations and Policies Governing Use of Industrial By-Products in Concrete**

There are no US regulations limiting the use of industrial by-products in concrete for environmental reasons. Limits on by-product use are only associated with the effects on product performance and its fitness for specific applications.

In 1996, EPA declared slag cement to be a “recovered” product under the Resource Conservation and Recovery Act (RCRA), which governs solid and hazardous waste treatment, disposal and recycling. This declaration allows slag cement to be used in concrete without regulatory limitation.

Likewise, fly ash has been classified by EPA as a recovered product, allowing it to be used in concrete. EPA issued its first federal procurement guideline for fly ash in cement and concrete in 1983, and since that time has encouraged coal ash utilization over disposal. Their final Regulatory Determination (May 22, 2000) concluded that beneficial use poses no significant risk and no additional national regulations are needed. A

summary of state standards regarding the reuse of ash is available at [www.netl.doe.gov/coalpower/environment/ccb](http://www.netl.doe.gov/coalpower/environment/ccb).

On August 28, 2001, the EPA published notice in the Federal Register (66 FR 45256) of its intent to add silica fume as a recovered product under the RCRA. If approved as proposed, silica fume will join fly ash and slag cement in the category of concrete materials covered by RCRA.

The Department of Energy, the Federal Highway Administration (FHWA) and the Army Corps of Engineers have all openly endorsed the use of fly ash in concrete, and have issued utilization guidelines for federally funded projects. The FHWA is working to educate state transportation agencies and industry professionals on the benefits of silica-fume concrete.

ASTM has established standards for the use of supplementary cementing materials to create “Blended Hydraulic Cements” (see ASTM C 595, “Standard Specification for Standard Blended Hydraulic Cements”, ASTM C 1157, “Standard Performance Specification for Hydraulic Cements”).

### **Environmental Significance of By-Product Contaminants in Concrete**

In general, the trace elements found on fly ash are not in sufficient concentrations or sufficiently mobile to represent a significant risk to human health or the environment. Processing the fly ash as a cementitious material or concrete additive will further reduce the mobility of these contaminants by binding them into the concrete matrix; cement is in fact used as a stabilizing agent to immobilize trace elements such as metals before land disposal.

To further illustrate this point, portland cement concrete has long been used to make drinking water system components that transport and store drinking water. In response to concerns over possible leaching of trace contaminants into drinking water from these components, a voluntary consensus standard, ANSI / NSF 61, “Standard 61 Drinking Water System Components - Health Effects”, was developed in 1988 and revised in 1995 to simulate leaching from concrete. The NSF website ([www.nsf.org/Certified/PwsComponents/](http://www.nsf.org/Certified/PwsComponents/)) provides a list of portland cement manufacturers and their plants with portland cements that have been tested and found acceptable for use in drinking water systems components. Cement Types IP and I(SM) have also been tested and found acceptable for use in concrete for drinking water systems. According to ASTM C595-02a, “Standard Specification for Blended Hydraulic Cements,” Type IP cement is a portland cement with a pozzolan and Type I(SM) is a portland cement with slag cement. This demonstrates pozzolans and slag cements used as partial replacements for portland cement can be used in concrete that passes standards for drinking water.

One possible exception to the above observations is associated with mercury. Recent concern over the release of mercury to the atmosphere during coal combustion has prompted EPA to consider increased regulation that would limit mercury emissions. The technical changes resulting from mercury emission regulation could increase the concentration and mobility of mercury in fly ash.

The U.S. DOE, through its National Energy Technology Laboratory (NETL), has commissioned a research program designed to address this and associated issues, including (a) to what extent mercury is leachable from by-products, (b) to what extent mercury is volatile from by-products, and (c) the fate of mercury in the manufacture of portland cement. Periodic updates are available through [www.netl.doe.gov/coalpower/environment/cfb](http://www.netl.doe.gov/coalpower/environment/cfb).

**Value of By-Product Use in Specific Concrete Applications.** Other than the tangible benefits to using by-products in concrete noted earlier, recycling industrial by-products for use in building construction is becoming widely recognized as a desirable attribute by many companies buying or renting space. In an attempt to quantify this and other environmental benefits, Leadership in Energy and Environmental Design (LEED) was created as a point rating system to evaluate the environmental performance of a building. The ratings system includes credits for (a) use of recycled content in the building, (b) use of local / regional materials, and (c) proper construction waste management (through concrete recycling, for example). These 3 areas benefit from the use of by-products such as fly ash, slag cement, and silica fume in cement and concrete.

**Environmental Benefits of Using By-Products in Concrete.** First and foremost, recycling by-products reduces the need for landfill capacity, both on-site and off-site. Permitting landfills and expansions is often difficult and time consuming; preserving valuable landfill space for wastes that cannot be recycled or represent a significant risk to human health or the environment is prudent.

In addition, the production of 1 kilogram of portland cement produces approximately 0.9 kilograms of carbon dioxide released to the atmosphere. Carbon dioxide is considered a “greenhouse gas” and is associated with global warming. The use of combustion by-products like fly ash provide correspondent reductions in emissions. The American Coal Ash Association estimates that use of fly ash as a cement substitute in concrete has the potential to eliminate 10 to 14 million tons of carbon dioxide emissions annually.

## **SUMMARY AND CONCLUSIONS**

The use of industrial by-products to make concrete is common, due to both economic and technical advantages. Commonly used by-products used as a partial replacement or addition to portland cement include fly ash, slag cement, and silica fume. Foundry sand and air-cooled blast furnace slag can be used as aggregates in concrete. Recycled concrete is used as an aggregate in concrete or road base. Technical specifications for use of these by products are available, a market has emerged for most of these materials in

many parts of the U.S, and the federal government has encouraged their use through both procurement practices and favorable environmental research into their impact.

Some by-products such as fly ash and slag cement contain trace quantities of various natural elements and low levels of natural radioactivity. Research into the behavior of trace elements in concrete containing industrial by-products has shown there is no significant leaching of these elements, no expectation of off-gassing, and radiation levels that are considered benign by EPA standards. After almost 20 years of research, EPA and industry alike have concluded that there is no significant risk to human health or the environment from either disposal of these materials as a regular (non-hazardous) solid waste or reuse of these materials in concrete, in the manufacture of cement and for other public uses.

Energy and environmental policy developments in the U.S. have in fact further encouraged the use of industrial by-products in concrete. The advent of standards for measuring the environmental benefit of so-called “green buildings” has created a scoring system in which the use of by-products in the concrete actually adds environmental value.

Research into the environmental effects of by-product use in concrete will continue. Since the processes used to produce the by-products impact their quality and composition, changes in these processes need to be watched closely and their effects quantified. The reader is encouraged to monitor this research through the many technical conferences and research programs cited in this paper.

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