2.0 INDUSTRY OVERVIEW, MATERIALS EVALUATED, AND CURRENT RMC SUBSTITUTION LEVELS

This section provides a summary of the production and beneficial uses associated with the RMCs identified in the Introduction (Section 1). This includes RMCs specifically identified by Congress for further study, as well as the "other potential RMCs" identified by EPA. These topics are consistent with Part (A) of the Congressional mandate, which instructs EPA to analyze "…the extent to which recovered mineral components are being substituted for portland cement, particularly as a result of current procurement requirements…."

The four mineral components identified by Congress include GGBFS, coal fly ash, BFSA, and silica fume. The other materials identified by EPA for consideration as RMCs include foundry sand, cenospheres, flue gas desulfurization (FGD) gypsum, flue gas desulfurization (FGD) dry scrubber material, power plant bottom ash, power plant boiler slag, steel furnace slag, and cement kiln dust (CKD). Descriptions and definitions of the materials and terms discussed in this section, and throughout the report, are provided in a glossary at the end of this report.

All of the materials examined in this section are currently being reused as material substitutes in the cement manufacturing process or the concrete mixing process (or both).[34] The degree to which these materials are being used in cement and concrete production ranges from relatively low (i.e., approximately 10% to 15%) to 100%. When used appropriately, these materials enhance the performance, handling, and durability of finished concrete products; this section qualitatively describes these benefits. In addition, the use of these materials in cement and concrete production yields a number of environmental and economic benefits, which we analyze and quantify in Section 3. Furthermore, using RMCs helps limit the amount of virgin material that must be mined or imported to meet U.S. demand for cement.

In its simplest form, concrete is a mixture of cementitious material, water, and aggregates. The principal cementitious material in concrete is portland cement. When portland cement is combined with water, a chemical reaction called hydration occurs that causes the cement and hence the concrete to harden and strengthen over time into a rock-like mass.

The concrete manufacturing process involves the production of portland cement and the mixing of cement with water and aggregates. This process can be summarized in the following steps:

- **Clinker Production**: Cement making raw materials are proportioned, crushed, and ground into a raw material mix or meal that is used to make portland cement (e.g., limestone, shale, clay, sand, iron, etc.) and then fed into a large rotary kiln. As the raw mix moves through the kiln, the temperature of the mix is gradually raised to 1400-1450 degrees Celsius, which cause

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[34] RMCs often have other applications as substitutes for aggregate in various applications (including concrete and unencapsulated uses, such as flowable fill and granular or stabilized road base) and other applications, such as blasting grit and soil amendments. However, consistent with the focus of the Congressional mandate, this report focuses on uses associated with cement and concrete.

volatiles (especially CO_2) to be given off, while the remaining chemical oxides in the mix recombine into new compounds that exhibit hydraulically cementitious properties. These new compounds ("cement or clinker minerals") exist together as semifused nodules of clinker that are up to about 4 inches in diameter.

- **Grinding**: The clinker is combined with other materials, such as gypsum, or another RMC, and fed into a cement mill where it is very finely ground into a powder-like consistency to form portland cement or blended cement.

- **Concrete Mixing**: Portland cement (plus any RMC incorporated as a partial substitute), fine and course aggregate, and water are mixed together in large drums to produce concrete. Soon after the aggregates, water, and the cement are combined, the mixture starts to harden. The concrete must be mixed thoroughly to coat all of the aggregate particles with cement paste.

The principal cementitious material in concrete is portland cement, but other supplementary cementitious materials (SCMs) can be used to partially offset portland cement in concrete. Some SCMs are called pozzolans, which by themselves do not have any cementitious properties, but when used with portland cement, react to form cementitious material. Other materials, such as slag, do exhibit cementitious properties. When SCMs are combined with portland cement in dry form prior to mixing in concrete, the result is a blended cement. Appendix A provides further technical detail on cement and concrete manufacturing.

2.1 RMCs Identified by Congress

2.1.1 Blast-furnace Slag

Blast-furnace slag is a byproduct of the process for smelting iron from iron ore. Various types of slags are produced when slagging agents (primarily limestone or dolomite) or fluxing materials are added to iron ores in blast furnaces to remove impurities. The fluxing process lowers the boiling point and increases the ore's fluidity. In the process of reducing iron ore to iron, a molten slag forms as a non-metallic liquid (consisting primarily of silicates and aluminosilicates of calcium and other bases) that floats on top of the molten iron. The molten slag is then separated from the liquid metal and cooled. Depending on the cooling process used, either granulated blast-furnace slag (GBFS) or BFSA is produced.

GBFS is produced by quickly quenching (chilling) molten slag to produce a glassy, granular product. The most common process is quenching with water, but air or a combination of air and water can be used. This rapid cooling allows very little mineral crystallization to take place and produces sand-sized particles of glassy material. When the cooled material is ground very finely into GGBFS, also known as slag cement, the disordered structure of the material gives it moderate hydraulic cementitious properties, meaning it will hydrate and gain strength when mixed with water, though at a much slower rate than portland cement. When used in concrete mixes with portland cement, however, the GGBFS combines with the free lime generated by partial portland cement hydration processes and hardens at an accelerated rate. When used in this manner, GGBFS develops strong hydraulic cementitious properties and can be used with portland cement in concrete manufacture. GGBFS can represent 20% to 80% of the total cementitious material used in concrete mixes, depending upon the application and engineering requirements. GGBFS is discussed in more detail in section 2.1.1.1.

Unground or less finely ground slag (GBFS) can also be used as aggregate in concrete mixes. Due to the greater cost of the granulation process compared to air-cooling, however, it is unlikely that newly created or high quality GBFS would be used in low-value applications, such as aggregate. The growing price for GGBFS further limits the opportunities for its use as an aggregate. Previously stockpiled or low-quality GBFS is more likely to be used as an aggregate.

BFSA, also referred to as air-cooled blast-furnace slag (ACBFS), is produced by allowing the molten slag to cool and solidify slowly under ambient (atmospheric) conditions. This is typically done by pouring the molten blast-furnace slag into pits for slow cooling. Once cooled, it is crushed, screened, and used as aggregate in applications, such as road base, concrete, asphalt concrete, rail ballast, roofing, shingles, mineral wool, and glass making. ACBFS also can be used as a raw material in clinker manufacture. This material is discussed in greater detail in section 2.1.1.2.

The iron and steel industries do not collect data on the total quantity of blast-furnace slag produced in the United States. The USGS estimates, however, that the quantity of blast-furnace slag produced is equivalent to 25% to 30% of crude iron (i.e., pig iron) production (van Oss, 2004b). In addition, USGS collects data on sales of slag. In 2004, U.S. sales of blast-furnace slag were valued at approximately $289 million. Most of the slag produced is air-cooled slag (approximately 75% by tonnage), with a lesser amount of granulated slag (approximately 25%) and a small amount of pelletized slag. Some is also used as lightweight aggregate for concrete. A significant quantity of the GGBFS sold in the United States is produced by grinding imported material.

USGS estimates that approximately one million metric tons of blast-furnace slag were imported into the United States in 2005, including about 760,000 metric tons of granulated slag. Table 2-1 summarizes the estimated total blast-furnace slag production in the United States for 2000 through 2005 (van Oss, 2006, unless otherwise noted). Table 2-1 also includes U.S. sales of GBFS and BFSA. Sales of GGBFS in 2004 were approximately 3.6 million metric tons out of a total GBFS sales of 4.1 million metric tons.

Table 2-1: U.S. Iron Blast-furnace Slag Domestic Production and Sales (iron only)

Year	Estimated Slag Production	Sales of GBFS	Sales of GGBFS (subset of GBFS)	Sales of BFSA (ACBFS)
	--------------------------------*million metric tons*-------------------------------------			
2000	12.0–14.5	2.3*	2.0***	8.9
2001	10.5–12.5	2.3*	2.4***	8.1
2002	10.0–12.0	3.7	3.3 ** 2.9 ***	7.4
2003	10.0–12.0	3.6	3.5 ** 3.1 ***	7.3
2004	12.0–14.0	4.1	3.6 ** 3.5 ***	8.1
2005	9.0–11.0**	4.4**	3.7**	8.4**

* 2000 and 2001 sales were believed to be underreported
** van Oss, 2002, 2003, 2004, 2005, 2006.
*** National Slag Association Data, as reported by van Oss, 2002, 2003 and 2004b and Slag Cement Association, 2006.
Note: Sales of GGBFS includes imported material that is ground in the U.S.

As of December 31, 2005, 16 integrated steel mills located in nine different states were in operation in the United States (Wagaman, 2006).[35] According to USGS, 44 facilities were processing blast-furnace slag in the United States in 2004.[36] Five of these facilities produced GBFS (Wierton, West Virginia; South Chicago, Illinois; Gary, Indiana; Sparrows Point, Maryland; and Birmingham, Alabama). In addition, some grinding facilities only grind imported GBFS or are exploiting old slag piles from past years' production (van Oss, 2004b). Figure B-1 in Appendix B shows the geographic distribution of cement plants that use slag as a raw material in clinker production and blend slag into finished cement products. Also, a table containing additional information on these locations can be found in Appendix C.

2.1.1.1 Granulated Blast-furnace Slag (GBFS)[37]

According to the USGS, approximately 4.1 million metric tons of GBFS were sold in the United States in 2004 (see Table 2-2). The total value of these sales was approximately $236 million, the majority of which was represented by sales of GGBFS. Average sales prices for GBFS were $61.50 per metric ton, with a reported range of $22.05 per metric ton for unground GBFS to $71.65 per metric ton for GGBFS. This range does not include old, weathered GBFS from existing stockpiles that is sold as fine aggregate for a few dollars per metric ton. The prices for GBFS are rising, are much higher than for other slag types and GGBFS tends to sell for 75%-80% of the price of cement (von Oss, 2007). In 2004, approximately 91% of GBFS (3.73 million metric tons) was sold for cementitious uses. This included approximately 104,000 metric tons of GBFS used in the manufacture of clinker, and

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[35] An integrated steel mill is one that smelts iron ore into liquid iron in blast furnaces and uses basic oxygen furnaces to refine this iron into steel.
[36] Since slag producers can have contracts with multiple processors at the same location, some of these facilities might be doubled counted.
[37] Data presented in this section address GBFS, which includes ground and unground blast-furnace slag. Separate data are not available for GGBFS, but GGBFS is known to account for the majority of GBFS.

approximately 345,000 metric tons used in the manufacture of blended cement. The remaining GBFS sold for cementitious uses (3.28 million metric tons) was used directly in concrete as a substitute for portland cement. The majority of materials not sold for cementitious uses (i.e., the 9% of the 4.1 million metric tons sold in 2004) were old and poor quality material mined from existing slag piles; this material was sold for use as a fine aggregate (van Oss, 2004b). Although no data exist on the disposal or landfilling of blast-furnace slag, it is likely that the utilization of GBFS is nearly 100% of U.S. production, which reflects the high value of these materials as SCMs, aggregates, or components of blended cements. In fact, granulated slag is currently being imported into the U.S. in order to meet the needs of the U.S. construction industry.

Table 2-2 summarizes GBFS (both ground and unground) sales and usage in clinker and cement manufacture for 2000 through 2005 based on data from the USGS (van Oss, 2004, 2004b, 2003, 2003b, 2002, 2002b, 2001). GBFS usage in concrete is estimated by subtracting total usage in clinker and cement manufacture from total sales.

Table 2-2: Granulated Blast-furnace Slag (GBFS) Usage

Year	Estimated GBFS Sales	GBFS Usage in Clinker Manufacture	GBFS Usage in Cement Manufacture	GBFS Usage in Concrete
	---------------------------------*million metric tons*-----------------------------------			
2000	2.3*	--	0.303 0.105***	1.997**
2001	2.3*	--	0.300 0.154***	2.0**
2002	3.7	0.060	0.369 0.157***	3.271**
2003	3.6	0.017	0.333 0.157***	3.25**
2004	4.1	0.104	0.345 0.159***	3.651**
2005	4.4	0.144	0.521	3.735**

Source: USGS data
* 2000 and 2001 sales were believed to be underreported.
**Estimated by subtraction.
*** Slag Cement Association, 2006.

The primary benefit of using GGBFS as a SCM is that it allows the same amount of portland cement to yield more yards of concrete, increasing productivity and reducing the total quantity of portland cement required to meet demand for certain types of concrete. The beneficial properties of concrete mixes containing GGBFS include the following:

- **Strength Development:** Concrete containing GGBFS develops strength at a somewhat slower rate than concrete containing only portland cement, but ultimately can develop equivalent or even superior strength. The reduced early strength can be a concern where early strength development is important, such as for non-heat cured pre-cast concrete or where rapid repairs are sought on busy highway structures. Low temperatures generally have a more adverse impact on strength development with concrete containing GGBFS than concrete containing only portland cement. However, the higher ultimate strength development in concrete with GGBFS can allow for reductions in the portland cement component in a concrete mixture for a given ultimate (28-day) strength level.

- **Workability:** Concrete containing GGBFS as a partial cement replacement has longer-lasting workability and low slump loss during hot weather construction (though this can be a detriment during cold weather construction). Concrete containing GGBFS is also easier to finish.

- **Heat of Hydration:** Concrete with high replacement rates of GGBFS (i.e., approximately 70%) exhibits a lower heat of hydration than conventional portland cement concrete; this characteristic is an advantage for large mass concrete applications, but can be a disadvantage for some projects in colder climates.

- **Permeability**: Concrete containing GGBFS has significantly reduced permeability, which keeps moisture and harmful constituents out of the concrete

- **Corrosion Resistance**: The reduced permeability of concrete containing GGBFS can protect reinforcing steel in reinforced concrete from corrosion for much longer periods of time than concrete without GGBFS.

- **Alkali-Silica Reaction**: The use of GGBFS blended with portland cement in concrete reduces the alkali content of the cement paste and reduces permeability and water ingress, thus mitigating the potential of developing adverse reactions between alkalis in the cement paste and certain forms of silica present in some aggregates.[38]

- **Sulfate Resistance:** Use of GBFS with portland cement can give concrete moderate to high resistance to sulfate attack.

- **White Color**: GGBFS is a much lighter color than most other commonly used cementitious materials (i.e., grey portland cement, silica fume, coal fly ash). Thus, it measurably lightens the concrete and increases its solar reflectivity which provides benefits, such as greater safety at night, reduced lighting requirements, and preferred architectural finishes. It also can help reduce the urban heat island effect through higher albedo.

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[38] Holcim (US) Inc. commented that, in addition to the more common alkali-silica reaction, "alkali-aggregate reaction includes a particular, but little seen, reaction known as alkali-carbonate reaction," and it was its "understanding that slag [i.e., GGBFS containing] concrete shows some effectiveness in resisting this form of alkali-aggregate reaction, but there is no large volume of work on the topic."

According to the SCA, some laboratory testing has indicated that concrete containing GGBFS (and coal fly ash) might be more susceptible to salt scaling when deicer salts are applied and the concrete undergoes freeze-thaw cycling. On the other hand, other studies have not found this to be the case, or have even found improved performance. (Scaling is the loss of a thin layer, usually less than 1/4 inch of surface paste/mortar, sometimes exposing larger aggregates beneath.) To clarify this issue, FHWA and SCA, in conjunction with the Iowa State University's Center for Portland Cement Concrete Pavement Technology (PCC Center) are collaborating on a project to document the performance of GGBSF-containing concrete exposed to cyclical freeze-thaw cycles in the presence of deicing chemicals.[39]

2.1.1.2 Blast-furnace Slag Aggregate (Air-Cooled Blast-Furnace Slag)

BFSA, also known as air-cooled blast-furnace slag, emerges from iron furnaces in a molten state and is air-cooled. It is produced by pouring molten blast-furnace slag into outdoor pits and allowing it to cool and solidify slowly under atmospheric conditions. Small quantities of water are sprayed on top to induce fractures during the final cooling stages. Once cooled, BFSA is crushed and screened to produce a material similar to gravel that is used as a construction aggregate for road base, concrete, asphalt, rail ballast, roofing, granules for roofing shingles, and glass making.

Sales of BFSA for all uses for 2003 and 2004 are shown in Table 2-3. In 2004, BFSA sales were 8.1 million metric tons, with a total value of $49 million. Average sales prices of BFSA in 2004 were $6.50 per metric ton, with a range of $1.54 to $17.35 per metric ton. Total usage of BFSA in cement and concrete products (including clinker manufacture) for 2004 was approximately 2.08 million metric tons, which accounts for about 26% of annual U.S. sales.

Table 2-3: Sales of Blast-furnace Slag Aggregate (BFSA) by Use in 2003 and 2004

	2003		**2004*****	
BFSA Use	**Percent**	**Quantity** (million metric tons)	**Percent**	**Quantity** (million metric tons)
Ready-Mixed Concrete	9.3	0.68	20.4	1.65
Concrete Products	6.4	0.47	3.5	0.28
Clinker Raw Material	5.7	0.42	1.9	0.15
Other Uses*	78.6	5.73	74.2	6.00
Total**	**100**	**7.3**	**100**	**8.1**

Source: van Oss, 2004b

* Primarily as construction aggregate for granular and bound road base and asphalt road surfaces.

** Data may not add to total due to rounding. Data reporting on slag uses is biased towards major uses.

*** Recently received data show a total of 7.3 million metric tons of BFSA were sold in 2006, indicating declining usage.(Pulipaka, Aswani S., et.al.)

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[39] For more information, refer to: American Concrete Institute, "Proposed Changes to ACI 318-05" accessible at: http://www.concrete.org/Technical/FlashHelp/Proposed_Changes_to_318-05.htm.

As indicated in Table 2-3, 100% of BFSA is currently believed to be utilized[40], with its largest use as aggregate in road bases and surfaces, including use in asphaltic concrete. Its next largest use is primarily as an aggregate in concrete mixes and aggregate base (20.4% in 2004). When used in this capacity, it reduces the need to quarry, crush, sort, and transport virgin aggregate. Small amounts of BFSA also are used to replace raw feed in the clinker production process (less than 2% in 2004) and used as an aggregate in concrete products (3.5% in 2004).

2.1.2 Coal Fly Ash

Coal fly ash is the finely divided airborne mineral residue generated by the combustion of ground or powdered coal in coal-fired power plants. Four basic types of coal-fired boilers operate in the United States: 1) pulverized coal (PC) boilers, 2) stoker-fired or traveling grate boilers, 3) cyclone boilers, and 4) fluidized-bed combustion (FBC) boilers. The PC boiler is the most widely used, especially for large electric generating units. The other boilers are more common at industrial or cogeneration facilities. Typically, in a PC boiler, coal is pulverized and blown with air into the boiler's combustion chamber where it immediately ignites, generating heat and producing a molten mineral residue. Boiler tubes extract the heat from the boiler, cooling the flue gas and causing the molten mineral residue to harden and form ash. Coarse ash particles, referred to as bottom ash or boiler slag, fall to the bottom of the combustion chamber, and the lighter fine ash particles (coal fly ash) remain suspended in the flue gas. Prior to exhausting the flue gas to the atmosphere, coal fly ash is removed by particulate emission control devices, such as electrostatic precipitators or fabric filtration baghouses.

According to the ACAA survey data, of the 64.2 million metric tons of coal fly ash produced in the United States in 2004, approximately 40% (25.5 million metric tons) was beneficially used, while the remaining 60% (approximately 38.8 million metric tons) was disposed of in land disposal units. Utilization of coal fly ash has increased through 2006 to nearly 45%. Table 2-4 illustrates the major uses of coal fly ash for the years 2002 through 2006.

Table 2-4: Major Uses of Coal Fly Ash

	Year				
	2002	**2003**	**2004**	**2005**	**2006**
Production and Usage	--------------------*million metric tons*----------------------				
Total U.S. Production	*69.401*	*63.640*	*64.230*	*64.502*	*65.680*
Utilization:					
Concrete/Concrete Products/Grout	11.412	11.127	12.811	13.599	13.645
Cement/Raw Feed for Clinker	1.740	2.744	2.128	2.571	3.765
All Other Uses	11.006	10.388	10.525	10.246	12.004
Total Utilization	*24.158*	*24.259*	*25.464*	*26.416*	*29.414*
Percent Utilization	34.8%	38.1%	39.6%	41.0%	44.8%

Source: ACAA, 2002, 2003, 2004, 2005, and 2006.

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[40] Recently identified data indicate that BFSA may be utilized at less than 100% of generation. However, these data are from the year 2000 (Pulipaka, A. S., et. al., undated).

Typically, coal fly ash is used in construction applications. Both Class C and F coal fly ash can serve as substitutes for conventional materials in construction projects.[41] The most common beneficial use of coal fly ash is as a SCM in concrete. Coal fly ash is also used as a raw material in the production of cement clinker and as an additive to blended cements. The consistency and abundance of coal fly ash in many areas present unique opportunities for use in many construction applications, including pavements and highway and transportation structures, and can generate environmental benefits when used as a replacement for virgin materials (e.g., portland cement). Reported coal fly ash generation and use in cement manufacture and in concrete for the years 2000 through 2006 are summarized in Table 2-5.

Table 2-5: Coal Fly Ash Generation and Sales for Utilization in Cement, Clinker, and Concrete

	Coal Fly Ash Generation (ACAA)	**Coal Fly Ash Utilization in Cement and Clinker Manufacture**		**Coal Fly Ash Utilization in Concrete (ACAA)**
		USGS	**ACAA**	
Year	---------*million metric tons*---------			
2000	No Data	1.77	No Data	No Data
2001	61.8	1.67	0.94	11.2
2002	69.4	2.02	1.74	11.4
2003	63.6	2.29	2.74	11.1
2004	64.2	2.97	2.13	12.8
2005	64.5	3.10	2.57	13.6
2006	65.7	------	------	13.6

Sources: ACAA, USGS, and van Oss, 2001, 2002b, 2003b, 2004; ACAA, 2001, 2002, 2003, 2004, 2005, 2006.

Certain performance benefits can be attained through the use of coal fly ash in concrete, including greater workability, higher strength, and increased longevity in the finished concrete product. Specifically:

- Spherical particle shape allows the coal fly ash to flow and blend freely in mixtures improving mixing and handling.
- Ball bearing effect creates a lubricating action when concrete is in its plastic state; as a result, pumping is easier because less energy is required and longer pumping distances are possible.
- Strength increases as it continues to combine with free lime, increasing the structural strength over time.
- Reduced permeability and increased durability.
- Reduced shrinkage from the lubricating action of coal fly ash reduces water content and drying shrinkage.

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[41] The chemical composition of coal fly ash varies greatly depending on the type of coal used. Two types of coal fly ash, Class C fly ash and Class F fly ash, are included in the American Society for Testing and Materials' technical requirements for concrete. Information on these standards is available at <www.astm.org>. Additional information on coal fly ash is provided in Appendix B. Other coal fly ash classification standards are being considered to facilitate the best uses for coal fly ash. Examples include the CSA Canadian standards.

- Reduced heat of hydration reduces thermal cracking (e.g., for dams and other mass concrete placements).
- Improved workability makes concrete easier to place.
- Where sharp, clear architectural definition is easier to achieve, finishing is improved with less concern about in-place integrity.
- Reduced susceptibility to chemical attack (e.g., sulfate attack) (IEA, 2005).

There are a few potential issues with the use of coal fly ash in concrete, including:

- Lack of uniformity and consistency between coal fly ash sources, possibly requiring users to test each source.
- Slower setting and early-are strength gain in cool weather concreting.
- Loss of air entrainment caused by the fine structure of coal fly ash and/or residual unburned carbon content; this property requires additional air entrainment to maintain concrete strength and durability.
- Reduced freeze/thaw and scaling resistance is possible when a major part of the cementitious material is replaced with coal fly ash. However, if the strength and air-void properties of the concrete mixture are kept constant, no major effect on the freeze-thaw resistance has been observed.
- Reduced abrasion resistance in concrete mixtures where coal fly ash comprises greater than 50% of the cementitious material. Concrete mixtures with coal fly ash representing less than 40% of the cementitious material show no decrease in abrasion resistance.

2.1.3 Silica Fume

Silica fume, also referred to as microsilica or condensed silica fume, is a very fine, dust-like material generated during silicon metal and ferrosilicon and related ferroalloys production. Specifically, it is produced by the reduction of high purity quartz with coal or coke and wood chips in an electric arc furnace during silicon metal or ferrosilicon alloys production. The glassy, spherical particles are extremely small, measuring less than 1 micrometer (μm) in diameter, with an average diameter of about 0.1 μm. Silica fume particles are composed primarily of silicon dioxide (usually more than 85%). The silica fume is collected in electric arc furnace stack filters and recovered for reuse as a pozzolan in high performance concrete (HPC). Silica fume is sold in the United States in powder form and is often made denser by tumbling it in a silo, which leads to the build-up of surface charges and an agglomeration of particles.

ACI estimates that global silica fume production is approximately 900,000 metric tons per year and that at least 120,000 metric tons are used in concrete worldwide (ACI, 2006). The SFA estimates that silica fume production in the United States in 2004 was between 100,000 and 120,000 metric tons. Of that amount, an estimated 20,000 metric tons were used in clinker manufacturer, while less than 3,000 metric tons were used in blended cement production and approximately 60,000 metric tons were used in concrete manufacture. The SFA also estimates that about 25,000 metric tons of silica fume were landfilled in 2004 and that less than 16,000 metric tons will be landfilled in 2006 in the U.S. (Kojundic, 2006).

Table 2-6 summarizes silica fume production and usage in cement and concrete for the years 2000 through 2004.

Table 2-6: U.S. Silica Fume Production and Usage in Cement and Concrete

	Year				
	2000	**2001**	**2002**	**2003**	**2004**
	----------------------------------*metric tons*--				
Production	No Data	No Data	No Data	No Data	100,000 - 120,000
In Clinker	18,000	19,000	19,000	19,000	20,000
In Cement	No Data	No Data	No Data	No Data	<3,000
In Concrete	55,000	56,000	51,000	53,000	60,000

Source: The Silica Fume Association accessed at www.silicafume.org and Kojundic, 8/30/2006.

Silica fume's physical and chemical properties confer several benefits to finished concrete when used with portland cement in concrete mixes, including:

- **Increased compressive strength and abrasion resistance:** Significant improvements in compressive strength can be realized through the addition of silica fume to concrete, making silica-fume concrete particularly useful in applications, such as columns in high-rise buildings, girders in HPC bridges, and abrasion-resistant pavements or floors.

- **Reduced Bleeding**: Silica fume reduces the bleeding in concrete that leads to the formation of capillary channels, which can increase chloride intrusion in finished concrete. Eliminating bleeding also allows concrete to be finished earlier.

- **Permeability**: Reduced permeability of concrete containing silica fume limits intrusion of chloride ions from deicing chemicals and helps resist attack from chemicals, such as sulfates leading to increased durability.

- **Corrosion Resistance**: Reduced chlorine ion intrusion protects the reinforcing steel from corrosion and helps extend the life of structures.

- **Single-Pass (One-Pass) Finishing**: Silica fume concrete can utilize single-pass finishing whereby the finishing is condensed into a single operation that shortens finishing time.

Increased modulus of elasticity (with use of silica fume), however, makes the concrete more brittle and can result in additional cracking.

2.2 Other RMCs Evaluated

The discussion below reviews the generation and beneficial use of the "other potential RMCs" selected for this analysis. These RMCs were identified through the screening procedures described in Section 1.3.

2.2.1 Foundry Sand

Foundry sand is high-quality silica sand used in the production of both ferrous and nonferrous metal castings. The physical and chemical characteristics of foundry sand depend on the type of casting process and industry sector from which it originates. Industry sources estimate that approximately 90 million metric tons of foundry sand are used in production annually. Of that amount, approximately 8.5 million metric tons of foundry sand are discarded as "spent" in a year; the remainder is recycled and put back and reused in the foundry process. A survey by the American Foundry Society (AFS) estimates that 2.4 million metric tons of the spent foundry sand were beneficially used, suggesting that about six million metric tons may be available to be recycled into other products or used by other industries (U.S. EPA, 2007). A small percentage (approximately 2%) of the spent foundry sand are considered hazardous waste due to metal contaminants (U.S. EPA, 1998).

Some spent foundry sands that use organic binders also have been found to contain trace amounts of hazardous organic compounds, though most of these constituents have been found to be well below regulatory levels (U.S. EPA, 2002).

Spent foundry sand can be used in the manufacture of portland cement clinker. Most foundry sands are high in silica content and can serve as a potential alternative silica source in portland cement clinker production. In addition, portland cement clinker production requires certain minerals, such as iron and aluminum oxides, both of which are found in many spent foundry sands. Some foundry sands however, can have materials in it that are not appropriate for use in kilns and therefore may not be utilized.

Combined data for total quantities of sand and calcium silicate used in the production of cement clinker in the United States are available from the USGS for the years 2000 through 2004 and are provided in Table 2-7 (van Oss, 2004, 2003b, 2002b, 2001). These data may include the beneficial reuse of spent foundry sand, although the industry does not identify the quantity of spent foundry sand being used in cement kilns. The tonnages shown in Table 2-7 primarily consist of silica sand, as the amount of calcium silicates is generally insignificant (USGS, 2001-2004).

Table 2-7: Sand and Calcium Silicate Utilization in Cement Kilns

	Year				
	2000	**2001**	**2002**	**2003**	**2004**
	-------------*million metric tons*----------				
Sand and Calcium Silicate Used	3.142	3.500	2.960	2.860	3.150

Source: USGS, 2001 – 2004 (van Oss, 2004, 2003b, 2002b, 2001).

Spent foundry sand can be reused to replace virgin sand in both the cement clinker manufacturing process and in concrete mixing. The use of spent foundry sand eliminates the need to mine and mill virgin materials, saving energy and other resources. However, the amount of available foundry sand varies widely by region of the country. In many regions, foundry sand is not available in the quantities necessary for controlled production processes.

2.2.2 Cenospheres

Cenospheres are very small (10 to 350 μm in diameter), inert, lightweight, hollow, "glass" spheres composed of silica and alumina filled with air or other gases. They occur naturally in coal fly ash and are recovered from the ash for use as aggregate (filler) in many applications such as concrete and plastic products. Cenospheres are not usually intentionally manufactured. Their principal source is coal fly ash. The characteristics of and amount of cenospheres produced in coal fly ash varies depending upon the type of coal used, the plant type, and the firing conditions under which the spheres are formed.

The percentage of cenospheres used in concrete varies depending on the application and desired performance characteristics of the concrete. However, according to industry sources, the typical content of cenospheres in concrete ranges from 10% to 40% by volume. Concrete containing cenospheres also often contains coal fly ash.

ACAA began reporting cenosphere sales in its annual coal combustion product production and use survey in 2004. ACAA reports that approximately 5,200 metric tons of cenospheres were sold in the United States in 2004, 7,000[42] metric tons were sold in 2005, and 5,000 metric tons were sold in 2006. Actual annual cenosphere production is much greater than the volumes being sold, as not all cenospheres are separated from the coal fly ash for use. No current data are available on annual cenosphere production, and it is questionable whether sufficient data exist to allow a meaningful estimate of the cenosphere content of airborne particulates (i.e., percent of cenospheres to weight of coal fly ash). However, ACAA indicated that between 570,000 and 2,900,000 metric tons of cenospheres were generated in 1998 in the United States, of which 23,000 to 41,000 metric tons were separated from coal fly ash and recycled (EPA, 2004). Cenospheres that are not separated and reused are recycled or landfilled with the coal fly ash from which they are derived.

When incorporated into concrete mixes as fillers or extenders, cenospheres increase the strength of the concrete and decrease shrinkage and weight. However, cenospheres may also react in the concrete. Cenospheres are 75% lighter than other minerals currently used as fillers, which reduces the final concrete mix's weight and increases their thermal stability and overall durability. Cenospheres can be used in concrete with other recovered materials, such as coal fly ash and silica fume.[43]

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[42] This is an adjusted figure. The 2005 ACAA report: "2005 Coal Combustion Product (CCP) Production and Use Survey" erroneously reported this figure as 70,918 metric tons (78,174 U.S. tons).

[43] Cenospheres also are often used in other industrial filler applications replacing other filler materials, such as manufactured glass, calcium carbonate, clays, talc, and other silicas.

2.2.3 Flue Gas Desulfurization (FGD) Materials

Flue gas desulfurization (FGD) byproducts are generated by air pollution control devices used at any sulfur dioxide (SO_x) producing emissions source that has an appropriate scrubber, like some coal-fired electric power plants. Power plants and other types of facilities (e.g., some cement plants) use a number of FGD processes to control sulfur oxide (SO_x) emissions from the combustion of coal. FGD processes spray lime or limestone reagents into the exhaust gas, which removes and converts the SO_2 to sludge or a semi-sludge byproduct. In 2006, more than 27 million metric tons of FGD byproducts were produced in the United States (ACAA, 2006).

FGD processes are characterized as either wet or dry processes. Wet FGD scrubbers use aqueous solutions of either slaked lime (calcium hydroxide, $Ca(OH)_2$), or limestone (principally calcium carbonate, $CaCO_3$) to saturate the exhaust gas in a spray tower. These solutions react with and oxidize the SO_2 particles creating a byproduct known as scrubber sludge. Dry FGD systems use less water and generate a byproduct with different attributes.

Two types of wet FGD processes are used today—natural oxidation and forced oxidation. In natural oxidation, only the oxygen naturally occurring in the flue gas is used to remove SO_2. The resulting byproduct consists mostly of calcium sulfite ($CaSO_3$). In forced oxidation, additional air is supplied by blowers, which creates a byproduct consisting primarily of calcium sulfate dihydrate ($CaSO_4{\cdot}2H_2O$), or gypsum. While FGD sludge produced using natural oxidation has limited beneficial use options, gypsum from forced oxidation (also referred to as synthetic gypsum) is readily used as a direct replacement for natural gypsum in wallboard production and grinding with clinker to produce finished cement. The Portland Cement Association (PCA) reports that in 2005, 21 portland cement plants were using FGD sludge in the manufacture of cement (see Appendix B, Figure B-8) (PCA, 2005).

Table 2-8 summarizes FGD production for the years 2001 through 2006 (ACAA, 2001, 2002, 2003, 2004, 2005, and 2006). Additional discussion of the production and uses for FGD gypsum and dry scrubber material can be found in the sections that follow. FGD sludge from natural oxidation processes is not discussed further, as this material has seen little use in cement manufacture or in concrete.

Table 2-8: U.S. Flue Gas Desulfurization (FGD) Material Production

Year	Wet Scrubber Material: Forced Oxidation (FGD Gypsum)	Wet Scrubber Material: Natural Oxidation ($CaSO_3$)	FGD Dry Scrubber Material	Other FGD	Total FGD
	----------------------------------*million metric tons*-----------------------------				
2001*	No Data	No Data	No Data	No Data	**25.840**
2002	10.342	15.332	0.849	--	**26.522**
2003	10.796	15.740	1.310	0.152	**27.998**
2004	10.841	15.876	1.660	0.105	**28.482**
2005	10.864	16.057	1.295	--	**28.216**
2006	10.977	14.787	1.351	0.271	**27.386**

Source: American Coal Ash Association (ACAA), 2001, 2002, 2003, 2004, 2005, and 2006.
* No breakout of FGD materials by type was reported for 2001.

2.2.3.1 Flue Gas Desulfurization (FGD) Gypsum

According to ACAA, U.S. coal-fired power plants produced approximately 11.0 million metric tons of FGD gypsum in 2006, with approximately 8.7 million metric tons being reused—approximately 79%. Of this amount, approximately 81% is used in wallboard manufacturing, about 16% is used in concrete, concrete products and grout, and about 3% is interground with clinker to produce finished cement. This indicates that while there is FGD gypsum available for increased use, only a minimal amount may potentially be used in cement and concrete. Table 2-9 summarizes ACAA data on the production and utilization of FGD gypsum for the years 2002 through 2006 (ACAA, 2002, 2003, 2004, 2005, 2006).

Table 2-9: FGD Gypsum Production and Utilization

Production and Usage	Year: 2002	2003	2004	2005	2006
	---------------------*million metric tons*----------------------				
Total Production	*10.3421*	*10.7957*	*10.841*	*10.8637*	*10.9769*
Utilization					
Concrete/Concrete Products/Grout	0.0550	0.0595	0.2644	0.2982	1.3988
Cement/Raw Feed for Clinker*	0.2756	0.3811	0.4074	0.3608	.2400
All Other Uses (primarily wallboard)	6.7183	7.0883	7.5338	7.7493	7.0352
Total Utilization	*7.0489*	*7.5289*	*8.2056*	*8.4083*	*8.6740*
Percent Utilization	68.2%	69.7%	75.7%	77.4%	79.0%

* FGD Gypsum is primarily interground with clinker to produce finished cement, not as a raw feed in clinker production.
Source: ACAA, 2002, 2003, 2004, 2005, and 2006.

The availability of FGD gypsum is expected to grow as more scrubbers are installed nationally, potentially allowing for increased use. According to DOE, Energy Information Administration (DOE EIA-767), 32 facilities reported that they produced approximately 9.4 million metric tons of FGD gypsum in 2004 (DOE, 2004). Table B-5, found in Appendix B, indicates production and disposition of FGD gypsum by state for 2004. Also, a listing of FGD gypsum producers in 2004 is contained in Appendix C.

The handling of FGD gypsum can be problematic because it is abrasive, sticky, compressible, and much finer than natural gypsum. These difficulties are often offset by the resource's proximity to manufacturing facilities. While the majority of FGD gypsum produced is used in wallboard production, a small percentage is used in finished cement products. In the cement production process, FGD gypsum use has the benefit of replacing virgin gypsum that is ground with clinker to regulate the setting time of finished portland cement. Gypsum cement, a strong type of plaster, can also be made from FGD gypsum.

2.2.3.2 Flue Gas Desulfurization (FGD) Dry Scrubber Material

Dry FGD systems remove SO_2 emissions, such as from coal-fired power plant flue gas by contacting a lime or limestone sorbent slurry. The most common dry FGD design is the spray dryer system in which a slaked lime slurry is sprayed into the flue gas. The dry FGD process still uses water, although much less than wet processes, and it does not saturate the flue gas as the wet processes do. The resulting byproduct, formed by the reaction of the slurry and SO_2, is dried by the heat of the flue gas and collected with the coal fly ash in a particulate control device (either a fabric filter/baghouse or an electrostatic precipitator). Some dry FGD byproducts can contain high concentrations of sulfur materials that may form ettringite, a hydrophilic material, which expands when hydrated. As a result, these byproducts may not be suitable for use in concrete and are not suitable for foundation or paving use.

In 2006, about 1.35 million metric tons of dry FGD materials were produced in the United States (ACAA, 2006) and about 9,000 metric tons of dry FGD material was used in concrete products. The material not reused is primarily stored and/or disposed of in land disposal units. Table 2-10 summarizes dry FGD material production and usage for the years 2002 through 2006 (ACAA, 2002, 2003, 2004, 2005, 2006).

Table 2-10: Dry Flue Gas Desulfurization (FGD) Material Production and Usage

	Year				
	2002	**2003**	**2004**	**2005**	**2006**
Production and Usage	----------------------*thousand metric tons*------------------				
Total Production	*848.6*	*1,310.2*	*1,660.0*	*1,294.8*	*1,350.8*
Utilization					
Concrete/Concrete Products/Grout	32.1	31.1	33.9	12.7	8.7
Cement/Raw Feed for Clinker	2.7	2.2	--	--	--
All Other Uses	302.1	145.9	127.1	131.7	115.2
Total Utilization	*336.9*	*179.2*	*161.0*	*144.4*	*123.9*
Percent Utilization	39.7%	13.7%	9.7%	11.2%	9.2%

Source: ACAA, 2002, 2003, 2004, 2005, and 2006.

2.2.4 Power Plant Bottom Ash

Power plant bottom ash is the coarse, solid mineral residue that results from the burning of coal in utility boilers. The material is removed from the bottom of the boilers either in a wet or dry state and transported to handling areas by conveyor or pipe. Bottom ash has a similar chemical composition to coal fly ash, but is produced in size grades ranging from fine sand to medium gravel. Although larger in particle size, bottom ash has a smaller reactive surface area than coal fly ash. Because of its much larger particle sizes, bottom ash has a smaller total reactive surface area, for the same weight, as coal fly ash. With this and other characteristics, bottom ash does not have sufficient cementitious properties to be used as a replacement for cement, although it can be used in clinker manufacture as an alternative source for silica, alumina, iron and calcium.

Due to its salt content and, in some cases, its low pH, bottom ash also can exhibit corrosive properties (FHWA, 1998). As a result, the potential for corrosion of metal structures that come into contact with bottom ash should be evaluated when using this material in structural applications.

In 2006, nearly 17 million metric tons of bottom ash were produced in the United States, 7.6 million metric tons of which were beneficially used (ACAA, 2006). Table 2-11 summarizes bottom ash production and usage in clinker production and concrete for the years 2002 through 2006 (ACAA, 2002, 2003, 2004, 2005, 2006).

Table 2-11: Power Plant Bottom Ash Production and Utilization

Production and Utilization	Year				
	2002	**2003**	**2004**	**2005**	**2006**
	--------------------*million metric tons*----------------------				
Total Production	*17.963*	*16.420*	*15.604*	*15.967*	*16.874*
Utilization					
Concrete/Concrete Products/Grout	0.369	0.271	0.716	0.926	0.542
Cement/Raw Feed for Clinker*	0.531 0.990[a]	0.448 1.100[a]	0.558 1.050[a]	0.852 1.210[a]	0.840
All Other Uses	6.076	6.763	6.122	5.064	6.219
Total Utilization	*6.976*	*7.482*	*7.396*	*6.842*	*7.601*
Percent Utilization	38.8%	45.6%	47.4%	42.9%	45.0%

*Bottom ash used only in clinker production.

[a] USGS 2006.

Source (unless noted): ACAA, 2002, 2003, 2004, 2005, and 2006.

In contrast to the above data from ACAA, data from DOE EIA-767 indicate that approximately 20.4 million metric tons of bottom ash were produced at 410 facilities reported to produce bottom ash in 2004 (DOE 2004).

Bottom ash can be used as a replacement for aggregate in concrete and is usually sufficiently well graded in size to avoid the need for blending with other fine aggregates to meet gradation requirements. The porous surface structure of bottom ash particles make this material less durable than conventional aggregates and better suited for use in base course and shoulder mixtures or in cold mix applications, as opposed to wearing surface mixtures. The porous surface structure also makes this material lighter than conventional aggregate and useful in lightweight concrete applications. Bottom ash also can be used as a raw material in clinker production as an alternative source of silica, alumina, iron, and calcium.

2.2.5 Power Plant Boiler Slag

Boiler slag is a byproduct of the combustion of coal in power plants. It is produced in wet-bottom boilers, which have a solid base with an orifice that can be opened to allow the molten ash that has collected at the base to flow into an ash hopper below. There are two types of wet-bottom boilers—slag-tap boilers and cyclone boilers. Slag-tap boilers burn pulverized coal (coal ground to a fine powder so that at least 70% passes through a 200-mesh sieve), while cyclone boilers burn crushed coal (coal milled to 0.25 inch maximum size) (Bolumen). In each of these types of boilers, the bottom ash is kept in a molten state and tapped off as a liquid. This molten slag is quenched with water, which causes it to fracture instantly, crystallize, and form pellets. The resulting power plant boiler slag, often referred to as "black beauty," is a coarse, hard, black, angular, glassy material (FHWA, 1998). Owing to its abrasive properties, power plant boiler slag is used in the manufacture of blasting grit and roofing granules for asphalt shingles. However, smaller amounts of it also are used (or have been used) as an aggregate in concrete and as a raw feed for clinker production. In 2005, about 38,600 metric tons (approximately 2% of all power plant boiler slag used) were used as a raw feed in clinker production.

Utilization of power plant boiler slag, as a percentage of production, is the highest among all coal combustion products. In 2006, nearly 84% of all power plant boiler slag was beneficially used (ACAA, 2006); down from a high of nearly 97% in 2005 (ACAA, 2005). Though power plant boiler slag is in high demand for beneficial use, its supplies are expected to decrease in the future due to the removal from service of the aging power plants that produce it. Table 2-12 summarizes U.S. production and usage of power plant boiler slag for the years 2002 through 2006 (ACAA, 2002, 2003, 2004, 2005, 2006).

Table 2-12: Boiler Slag Production and Utilization

	Year				
	2002	**2003**	**2004**	**2005**	**2006**
Production and Utilization	------------------*million metric tons*----------------------				
Total Production	*1.741.4*	*1.6658*	*1.9979*	*1.7757*	*1.8380*
Utilization					
Concrete/Concrete Products/Grout	0.0082	0.0144	-	-	-
Cement/Raw Feed for Clinker*	-	0.0143	0.0304	0.0386	0.0161
All Other Uses	1.3979	1.5643	1.7599	1.6767	1.5179
Total Utilization	*1.4061*	*1.5930*	*1.7903*	*1.7153*	*1.5340*
Percent Utilization	80.7%	95.6%	89.6%	96.6%	83.46%

* Boiler slag is used only in clinker production.
Source: ACAA, 2002, 2003, 2004, 2005, and 2006.

PCA (2005b) reported that 21 portland cement plants utilized power plant bottom ash and power plant boiler slag in the production of clinker in 2005 (no further breakout by material type was provided). Figure B-9 in Appendix B shows the locations of these plants.

2.2.6 Steel Furnace Slag

Steel furnace slag, commonly referred to as steel slag, is a byproduct from either the conversion of iron to steel in a basic oxygen furnace (BOF) or the melting of scrap to make steel in an electric arc furnace (EAF). Similar to iron blast-furnace slag, steel slag is produced when slagging agents and/or fluxing materials are added to molten metals to remove impurities. Unlike iron blast furnaces, steel furnaces typically use lime as the slagging agent instead of limestone and /or dolomite. The liquid silicate slag floats on the molten metal and is separated and cooled. Steel slag is cooled in pools in a similar fashion as BFSA from iron blast furnaces.

No reliable data exist on the amounts of steel slag produced annually in the United States because not all of the slag produced during steel production is tapped, and the amount of steel slag tapped is not routinely measured. Hendrik G. van Oss (2005) estimates, however, that steel slag production is between 10% and 15% of crude steel output. This estimate translates to 11 million to 16 million metric tons produced in 2004, of which nine million metric tons were sold for reuse (van Oss, 2004b). Table 2-13 summarizes steel slag production and usage for the years 2000 through 2005, as well as steel slag usage in cement and clinker manufacture (Kalyoncu, 2001; van Oss 2002, 2002b, 2003, 2003b, 2004, 2004b). In 2004, total U.S. steel slag sales were valued at about $39 million. Sales prices for steel slag ranged from $0.22 to $7.89 per metric ton, with an average of $4.32 per metric ton (van Oss 2004b).

Table 2-13: U.S. Steel Slag Production and Usage

Year	Estimated Steel Slag Production	Estimated Steel Slag Sales	Steel Slag Usage in Cement and Clinker Manufacture
	-------------------------------*million metric tons*---------------------------------		
2000	No Data	5.2	0.805
2001	No Data	6.5	0.500
2002	9-14	8.0	0.481
2003	9-14	8.8	0.448
2004	11-16	9.0	0.401
2005	10-14	8.7	0.525

Source: Kalyoncu, 2001; van Oss, 2002, 2002b, 2003, 2003b, 2004, and, 2004b.

According to USGS, steel slag was processed at 99 locations in the United States in 2004. Some duplication in these locations exists, since steel slag producers can have contracts with multiple processors at the same location (van Oss, 2004b). Table 3 in Appendix C contains additional information on these locations.

Steel slag has been successfully used as a raw material substitute in clinker manufacturing. The economic and environmental benefits of the utilization of steel furnace slag in Portland cement manufacturing may include energy savings, decreased CO_2 and NO_X emissions, and increased production capacity.

Because of its expansive characteristics, steel slag is not typically used as an aggregate in concrete for fixed-volume applications. Steel slag is useful as an aggregate in granular base applications,[44] and can be processed into a coarse or fine aggregate material for use in hot mix asphalt concrete pavements and in cold mix or surface treatment applications.

2.2.7 Cement Kiln Dust (CKD)

CKD is the fine-grained, solid, highly alkaline material removed from the cement kiln exhaust gas by scrubbers (filtration baghouses and /or electrostatic precipitators). The composition of CKD varies among plants and over time at a single plant. Much of the material comprising CKD is actually incompletely reacted raw material, including a raw mix at various stages of burning, and particles of clinker.

Because of the high percentage of raw mix and clinker in CKD, large amounts are put back into the production process through closed loop processes. CKD not returned to the production process is either landfilled or sold for other beneficial uses (PCA, 2006).

Because of the high rate of direct reuse, CKD generation rates are not routinely measured, and limited data are available. One recent estimate, based upon informal conversations with U.S. cement kiln industry personnel, is that CKD generation (including material returned to the kiln) is equivalent to approximately 15% to 20% (by weight) of total annual clinker production. This amount translates into approximately 12 million to 15 million metric tons per year (van Oss, 2005).

USGS domestic survey data show that in 2003, at least 289,000 metric tons of CKD captured by air emission control devices were used in clinker manufacture, and another 149,000 metric tons were used in cement manufacture. In 2004, these amounts were at least 333,000 metric tons in clinker manufacture and 165,000 metric tons in cement manufacture (van Oss, 2004). As discussed by van Oss (2004), and based upon PCA data and discussions with industry personnel, these figures appear to grossly underreport the actual rate of reuse. As discussed previously, direct reuse of CKD in the manufacturing process is common, but largely unreported.

Table 2-14 presents a breakdown of the amount and percent of the beneficially used CKD (and not returned to the kiln) by use in 2006 (PCA, 2006). Nearly half of the CKD beneficially used in 2006 was used for soil or clay stabilization. Approximately 16% was used as a cement additive or for blending. CKD in concrete mixes generally increases the water demand, decreases workability, retards setting time, and decreases concrete strength. Research into this use for CKD has suggested, however, that limited substitution of CKD for portland cement can create undiminished concrete mixes. Studies suggest that effective substitution rates range from as low as 5% to as much as 50% for certain concrete applications (EPA, 1993). Other beneficial uses for CKD include waste stabilization, mine reclamation, agricultural soil amendment, and in pavement manufacturing.

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[44] This use must take into account volume expansion tendencies where the granular material is confined.

Table 2-14: Estimated Beneficial Uses of CKD Beneficially Reused, 2006

Beneficial Use	Quantity (Metric Tons)	Percent of CKD Total Beneficially Used (not returned to the kiln)
Soil/Clay Stabilization	533,365	46%
Waste Stabilization/Solidification	213,675	18%
Mine Reclamation	152,756	13%
Cement Additive/Blending	183,228	16%
All Other Uses	76,987	7%
Total	**1,160,011**	**100%**

Source: Portland Cement Association. Summary of 2006 Cement Kiln Dust and Clinker Production, CKD Beneficially Reused.
Note: CKD recycled into the kiln is under a closed loop process, not removed from the kiln system, and is not considered a beneficial reuse for purposes of this document.

2.3 Summary of RMC Generation and Beneficial Use

The RMCs examined in the study vary widely in terms of their generation and beneficial use rates. Table 2-15 summarizes total generation and beneficial use (all uses) of the RMCs in 2004. By quantity, the most significant materials beneficially used are coal fly ash, BFSA, and flue gas desulfurization (FGD) gypsum. Several materials – including GGBFS, BFSA, power plant boiler slag, and steel furnace slag from electric arc furnace facilities– have beneficial use rates at or near 100%. Table 2-15 provides summary information on the generation and beneficial use for the RMCs addressed in this Report.

Table 2-15: Summary of RMC Generation and Beneficial Use (2004)

Material	Estimated Annual Quantity Generated, 2004 *(million metric tons)*	Estimated Quantity Beneficially Used, 2004 *(million metric tons)*	Percent Beneficially Used (all uses)	Beneficial Use Rate in Cement or Concrete
RMCs Named by Congress				
Ground Granulated Blast-furnace Slag (excluding lead slag)	3.60	3.60	100%	High
Coal Combustion Fly Ash	64.20	25.50	40%	Moderate
Blast-furnace Slag Aggregate (excluding lead slag)	8.10	8.10*	100%	Moderate
Silica Fume	0.10 – 0.12	0.08	67%-80%	Moderate
Other RMCs Identified by EPA				
Foundry Sand	8.5	2.40	28%	Low
Cenospheres	N.A.	0.0052 (reported sales)	N.A.	Moderate
Flue Gas Desulfurization (FGD) Gypsum	10.80	8.20	76%	Low
Flue Gas Desulfurization (FGD) Dry Scrubber Material	1.70	0.16	9%	Low
Power Plant Bottom Ash	15.60	7.40	47%	Low
Power Plant Boiler Slag	2.00	1.80	90%	Low
Steel Furnace Slag **	9.00	9.00	100%	Low
Cement Kiln Dust (CKD)	12.00 – 15.00	1.20 (excludes reuse back into kiln	N.A.	Low

Note: Data sources and caveats discussed in detail in section 1, and earlier in this section.
* Recently received information indicates that BFSA may be used at around 85% (Kiggins, 2007). However, this is based on a single data point.
** Includes both EAF and BOF steel furnace slag. BOF steel furnace slag may be used at less than 100% (Lehman, Rich. October 3, 2007)