Presented at 2008 IEEE/PCA 50th Cement Industry Technical Conf., Miami, FL, May 19-22, 2008

BENEFICIAL USES OF CEMENT KILN DUST

By:
IEEE-IAS Cement Industry Committee
Wayne S. Adaska, P.E., Director, Public Works, Portland Cement Association
Donald H. Taubert, Director, Promotion & Technical Service, Capitol Cement

Abstract:

Cement manufacturing is a critically important industry in the United States and throughout the world. In 2006, U.S. cement plants produced 99.8 million metric tons of cement. Worldwide production accounted for about 2.5 billion metric tons. As with most large manufacturing industries, by-product materials are generated. These industrial by-product and waste materials must be managed responsibly to insure a clean and safe environment. Cement kiln dust (CKD) is a significant by-product material of the cement manufacturing process. Over the past several years dramatic advances have been achieved in the management and use of cement kiln dust, thus reducing its dependency on landfill disposal.

Sustainability is the cornerstone of the cement industry, not only in the products that use cement, but also in its manufacturing process. From 1990 to 2006, the U.S. cement industry has reduced the amount of landfilled CKD 47 percent. This reduction in landfilled CKD comes despite the fact that domestic clinker production, as reported by the participants in the PCA CKD study, increased 95 percent during this same period. Overall clinker capacity in the U.S. has increased 28 percent since 1990. Many of the older, inefficient plants are being replaced by more modern plants or being renovated with new technologies to be more efficient as well as more environmentally friendly.

The majority of CKD is recycled back into the cement kiln as raw feed. In addition, new technology has allowed the use of previously landfilled CKD to be used as raw feed stock. Recycling this by-product back into the kiln not only reduces the amount of CKD to be managed outside the kiln, it also reduces the need for limestone and other raw materials, which saves natural resources and helps conserve energy.

Another principal use of CKD is for various types of commercial applications. These applications depend primarily on the chemical and physical characteristics of the CKD. The major parameters that determine CKD characteristics are the raw feed material, type of kiln operation, dust collection systems, and fuel type. Since the properties of CKD can be significantly affected by the design, operation and materials used in a cement kiln, the chemical and physical characteristics of CKD must be evaluated on an individual plant basis.

This paper will discuss the basic characteristics of CKD including current production status and regulatory requirements. Beneficial commercial uses are then presented covering a wide variety of applications including agricultural soil enhancement, base stabilizing for pavements, wastewater treatment, waste remediation, low-strength backfill and municipal landfill cover.

Introduction

Cement kiln dust is created in the kiln during the production of cement clinker. The dust is a particulate mixture of partially calcined and unreacted raw feed, clinker dust and ash, enriched with alkali sulfates, halides and other volatiles. These particulates are captured by the exhaust gases and collected in particulate matter control devices such as cyclones, baghouses and electrostatic precipitators (Figure 1).

Several factors influence the chemical and physical properties of CKD. Because plant operations differ considerably with respect to raw feed, type of operation, dust collection facility, and type of fuel used, the use of the terms typical or average CKD when comparing different plants can be misleading. The dust

Figure 1- Dust control device (Courtesy of Capitol Cement)

from each plant can vary markedly in chemical, mineralogical and physical composition (Klemm, 1993). However, to provide a general reference point, a typical dust composition as reported by the Bureau of Mines is given in Table 1.

Table 1 – Typical Composition of Cement Kiln Dust (Haynes and Kramer, 1982)

Constituent	% by weight	Constituent	% by weight
$CaCO_3$	55.5	Fe_2O_3	2.1
SiO_2	13.6	KCl	1.4
CaO	8.1	MgO	1.3
K_2SO_4	5.9	Na_2SO_4	1.3
$CaSO_4$	5.2	KF	0.4
Al_2O_3	4.5	Others	0.7

At many facilities all or a major portion of the dust is recycled back into the kiln to supplement the raw feed. Other facilities market their CKD for beneficial commercial uses. For CKD not returned to the kiln system, the most common reasons are equipment limitations for handling the dust and chemical constituents in the dust that would be detrimental to the final cement product or would make the product non-compliant with applicable consensus quality standards. The fraction of the CKD that is not returned to the kiln or otherwise beneficially used is placed in landfills (Bhatty, 2004).

Cement Kiln Dust Characteristics

CKD consists primarily of calcium carbonate and silicon dioxide which is similar to the cement kiln raw feed, but the amount of alkalies, chloride and sulfate is usually considerably higher in the dust. CKD from three different types of operations: long-wet. long-dry, and alkali by-pass with precalciner were characterized for chemical and physical traits by Todres et al. (1992). CKD generated from long-wet and long-dry kilns is composed of partially calcined kiln feed fines enriched with alkali sulfates and chlorides. The dust collected from the alkali by-pass of precalciner kilns tend to be coarser, more calcined, and also concentrated with alkali volatiles. However, the alkali by-pass process contains the highest amount by weight of calcium oxide and lowest loss on ignition (LOI), both of which are key components in many beneficial applications of CKD. Table 2 provides the composition breakdown for the three different types of operation and includes a typical chemical composition for Type I portland cement for comparison.

Table 2 – Composition of CKD from Different Operation Sources (Adapted from Todres et al. 1992)

Constituent	Long-wet kiln (% by weight)	Long-dry kiln (% by weight)	Alkali by-pass from preheater/precalciner (% by weight)	Typical Type I portland cement (% by weight)
SiO_2	15.02	9.64	15.23	20.5
AL_2O_3	3.85	3.39	3.07	5.4
Fe_2O_3	1.88	1.10	2.00	2.6
CaO	41.01	44.91	61.28	63.9
MgO	1.47	1.29	2.13	2.1
SO_3	6.27	6.74	8.67	3.0
Na_2O	0.74	0.27	0.34	< 1
K_2O	2.57	2.40	2.51	< 1
Loss on Ignition (LOI)	25.78	30.24	4.48	0 – 3
Free lime (CaO)	0.85	0.52	27.18	< 2

Dust collected from gas- or oil-fired kilns contain higher proportions of soluble K_2O compared to coal-fired kilns. This is probably due to a more favorable K_2O:SO_3 molar ratio in the latter as compared to the former (Klemm, 1980).

CKD contains insignificant amounts of trace metals and therefore metal concentrations are not usually a concern for most applications. A comprehensive study evaluated the presence of trace metals in CKD from 79 plants in the United States and 10 plants in Canada using both conventional and waste derived fuels (PCA 1992). Each CKD was tested for the eight RCRA metals: arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. The samples were also analyzed for antimony, beryllium, thallium and nickel, which are regulated under the Boiler and Industrial Furnace rule for hazardous solid wastes. Results showed that the average level of trace metals found in the CKD were significantly below the regulation limits (PCA, 1992).

The particle size of CKD is dependent upon the type of kiln operation. Muller (1977) showed that the dusts collected from dry kilns were finer than those from wet and semi-wet/semi-dry kilns. This was true for both the returned dust and the discarded dusts. Studies conducted by Todres et.al. (1992) showed that for modern cement plants equipped with alkali by-pass, the dust is relatively coarse compared to the CKD from both the wet and dry kilns. Table 3 provides a particle size distribution for three CKDs.

Table 3 – Particulate Size Distribution of Dust Samples (Todres et al. 1992)

Particulate size	long-wet kiln (% by weight)	Long-dry kiln (% by weight)	Alkali by-pass from preheater/precalcinner (% by weight)
>100 μm	5.0	0.0	2.0
<45 μm	85.0	99.2	84.5
<30 μm	77.3	98.8	66.0
<7 μm	43.0	87.2	14.0
<1 μm	12.0	12.0	3.0
<0.6 μm	7.5	5.6	2.0
Median size	9.3 μm	3.0 μm	22.2 μm

According to Steuch (1992), the largest amount of dust is generated from long dry kilns in which the dust is stirred up by chains and the gas velocities are high. In contrast, in preheater kilns, feed loading is high and the resulting dust contact with kiln gases is short. Thus, the CKD generation is fairly low. Some wet kilns produce the lowest amounts of dust, mainly because these kilns contain pebble-size dust agglomerates that are difficult to sweep away by the moving gases. Yet, the range of dust generated from these kilns does vary.

Regulatory Background

In 1976 Congress passed the Resource Conservation and Recovery Act (RCRA) (Public Law 94-580) which required EPA to develop regulations governing the identification and management of hazardous wastes. As a result, in 1978 EPA published the first set of proposed hazardous waste management standards in the Federal Register (43 FR 58946). This Federal Register notice included a proposal to exempt six categories of "special wastes" from the RCRA Subtitle C regulations until further study could be completed. Cement kiln dust was identified as one of the six special wastes.

In 1980 Congress enacted the Solid Waste Disposal Act Amendments (SWDA) (Public Law 96-482) which amended RCRA. Among the amendments, Section 3001(b) (3) (A) (i-iii) – frequently referred to as the Bevill Amendment – temporarily exempted three special wastes including CKD from hazardous waste regulation until further study could be completed. At the same time, Section 8002 (o) required EPA to study CKD and submit a Report to Congress evaluating the status of its management and potential risk to human health and the environment. EPA was also required to make a regulatory determination as to whether CKD warranted regulation under RCRA Subtitle C or some other set of regulations.

In 1993 EPA issued the Report to Congress on CKD. The report concluded that CKD generally posed little, if any, risk to human health and the environment. In 1995 EPA issued its final regulatory determination for CKD in the Federal Register (60 FR 7366). EPA determined that, though CKD may pose some risk to human health and the environment if mismanaged, it should not be regulated using overly stringent standards of RCRA's Subtitle C. Instead, EPA recommended that a more tailored set of standards be developed for managing CKD.

In 1999 EPA published "Standards for the Management of Cement Kiln Dust; Proposed Rule" (64 FR 45632). EPA's proposed approach would allow CKD to remain a non-hazardous waste provided that the specific management standards are met. CKD not managed in compliance with the standards was proposed to be a "listed waste" and would need to comply with tailored RCRA Subtitle C management standards.

The American Portland Cement Alliance (APCA)* on behalf of the cement industry submitted formal comments on the EPA proposal, opposing the use of federal authorities for CKD management. In 2000 EPA issued a Regulatory Determination addressing Fossil Fuel Combustion Wastes (FFCW), where EPA elected to retain the Bevill exclusion. Based on the logic used in the FFCW Determination, APCA filed a petition in 2001 requesting EPA withdraw the CKD proposal and reinstate the Bevill status for CKD.

In 2002 EPA published a notice of data availability (NODA) in the Federal Register (67 FR 48648). In addition to announcing the availability of new data to the public, the NODA explained that EPA was considering a new approach to CKD management whereby it would finalize the proposed CKD management standards as RCRA Subtitle D (solid waste) rule and temporarily suspend the proposed RCRA Subtitle C (hazardous waste) portion rule for 3 to 5 years to assess how CKD management practices and state regulatory programs evolve. Based upon this assessment, EPA will either formally withdraw or promulgate that portion of the 1999 proposed rule.

As of this writing no formal action has been taken on the 1999 proposed rule regarding management standards for CKD. The cement industry continues to work with EPA to resolve this issue.

Note *- The American Portland Cement Alliance (APCA) merged with the Portland Cement Association (PCA) in August 2002.

CKD Production - Past, Present, Future

The cement industry has embraced the concept of sustainability in the materials and products that use cement as well as in the manufacturing process. As a result the industry has established the Cement Manufacturing Sustainability (CMS) Program. This program, developed by PCA, addresses the Industry's commitment to sustainable development into consistent, tangible actions. The goal of the program is to balance society's need for cement products with stewardship of air, land and water, conservation of energy and natural resources, and maintenance of safe work places and communities. The centerpiece of the CMS Program is a voluntary code of conduct, which is a set of principles, performance measures, and reporting protocol, designed to guide decision making, business practices, and operating performance in a sustainable fashion (PCA, 2007).

A major element of the CMS Program is the establishment of Environmental Performance Measures. Voluntary long-term targets have been identified for each key performance measure. In the case of CKD the U.S. cement industry has adopted a year 2020 voluntary target of a 60 percent reduction (from a 1990 baseline) in the amount of cement kiln dust disposed per ton of clinker produced (PCA, 2007). Through CKD reduction efforts by PCA member companies, this goal was accomplished in 2004 as shown in Figure 2. PCA is currently developing a new CKD reduction goal.

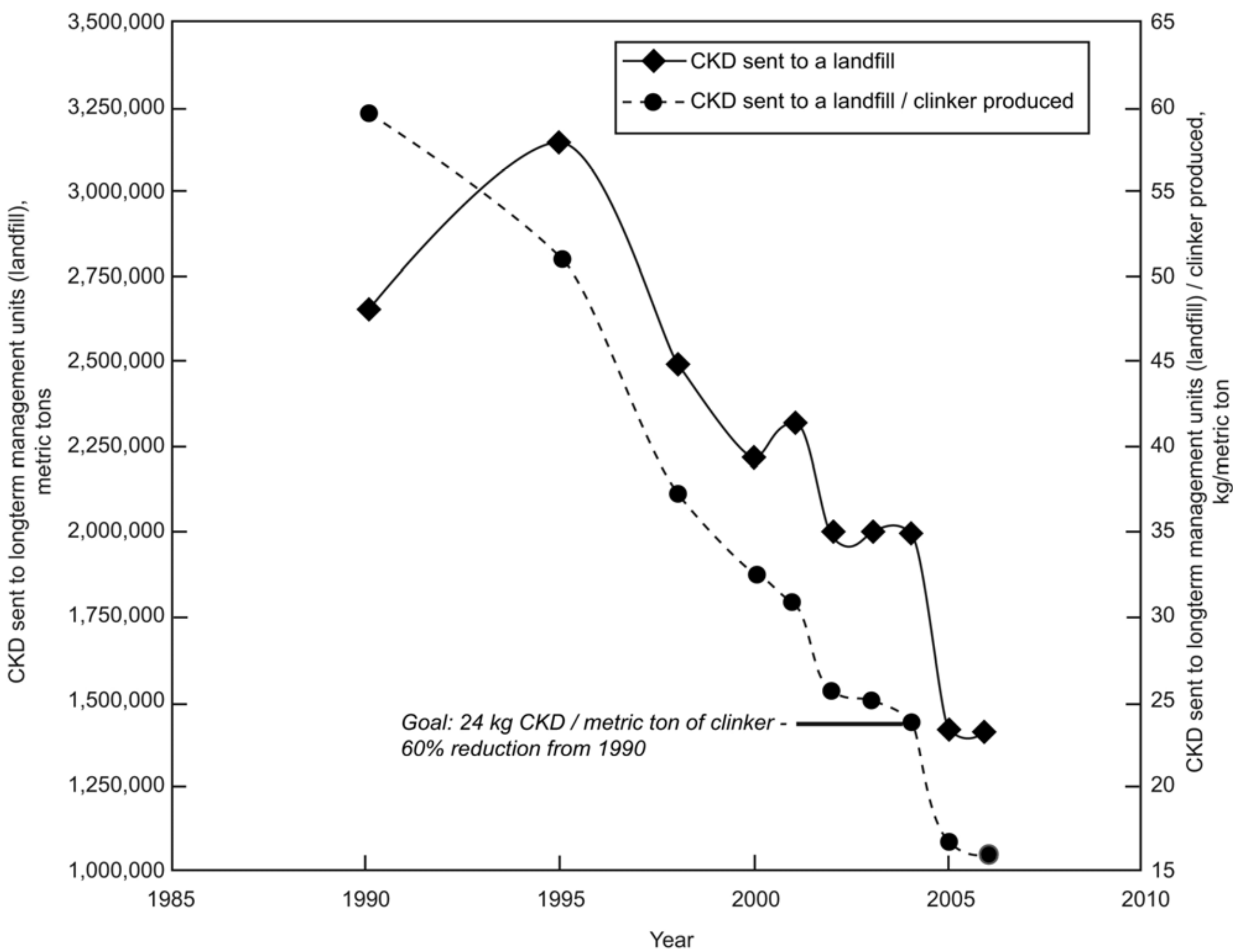

Figure 2 – Cement Kiln Dust (CKD) Disposal Rates with Reduction Goal (From PCA member company surveys)

Fewer than 20 of the 118 cement plants in the United States manage 90% of the CKD disposed on-site at cement plants. Virtually all of the disposal operations at these 20 plants are authorized – or soon will be authorized – through state solid waste programs. The plants employ management standards similar to those developed by the industry, which were largely endorsed by EPA in the 1999 proposal. Most importantly, the practice of CKD disposal continues to be phased out, as more plants are retrofitted to allow in-processing recycling. Table 4 provides a summary of management practices of CKD since 1990. The amount of CKD used for beneficial applications has increased dramatically over the 16 years the PCA members companies have been surveyed. Annual use of CKD for beneficial applications has ranged from a low of 574,800 metric tons to 1.16 million metric tons.

*Table 4 – Historical Cement Kiln Dust Production and Management**

Year	Plants responding to survey for given year	CKD beneficially reused on or off site, metric tons	CKD sent to landfill, metric tons	CKD reclaimed from landfilled, metric tons	Annual clinker production, metric tons	CKD sent to a landfill/clinker produced, kilograms / metric tons
1990	84	752,152	2,655,725	No data	44,360,364	60
1995	94	651,205	3,146,952	No data	61,729,315	51
1998	95	768,601	2,499,651	13,409	67,104,547	37
2000	92	574,803	2,223,190	79,171	68,263,086	33
2001	102	924,552	2,329,132	231,904	75,683,170	31
2002	101	664,848	1,989,680	103,223	77,636,598	26
2003	102	718,410	1,995,143	116,416	79,356,511	25
2004	102	917,968	1,993,421	69,099	83,945,430	24
2005	102	987,717	1,429,150	104,952	85,568,243	17
2006	101	1,160,011	1,403,062	261,351	86,686,834	16

Note* – From PCA member company surveys

A key performance indicator is the relationship between the amount of CKD disposed versus the quantity of clinker produced. Table 4 shows that the quantity of CKD landfilled decreased dramatically when compared to the quantity of clinker produced. It dropped from 60 kg/metric ton in 1990 to 16 kg/metric ton in 2006. This is notable given the amount of clinker produced over the same time period, increased by 95 percent. This comparison is shown graphically in Figure 3.

Cement Kiln Dust Management

Because CKD varies in physical-chemical composition between plants, the managing of dust is a plant-by-plant situation. As previously mentioned, the bulk of CKD is recycled back into the kiln system as kiln feed. The remainder of the CKD is used either for beneficial applications or landfilled. The trend in recent years indicates there has been an increase in the reuse of CKD for beneficial applications and a reduction in the amount of CKD being landfilled.

Table 5 shows the top 10 states in 2006 which beneficially reuse CKD. These ten states represent 76% of the beneficially reused CKD throughout the U.S. Of the 1.16 million metric tons of CKD removed from the cement manufacturing process in 2006, the majority of beneficial uses centered on four primary applications: stabilization/consolidation of soils, stabilization/solidification of waste materials, cement additive/blending, and mine reclamation (Table 6).

Reclaimed Previously Landfilled CKD

A recent trend at some cement manufacturing facilities is the removal or “mining” of CKD placed in landfills or other long-term management units. From the PCA CKD surveys of member companies, it was

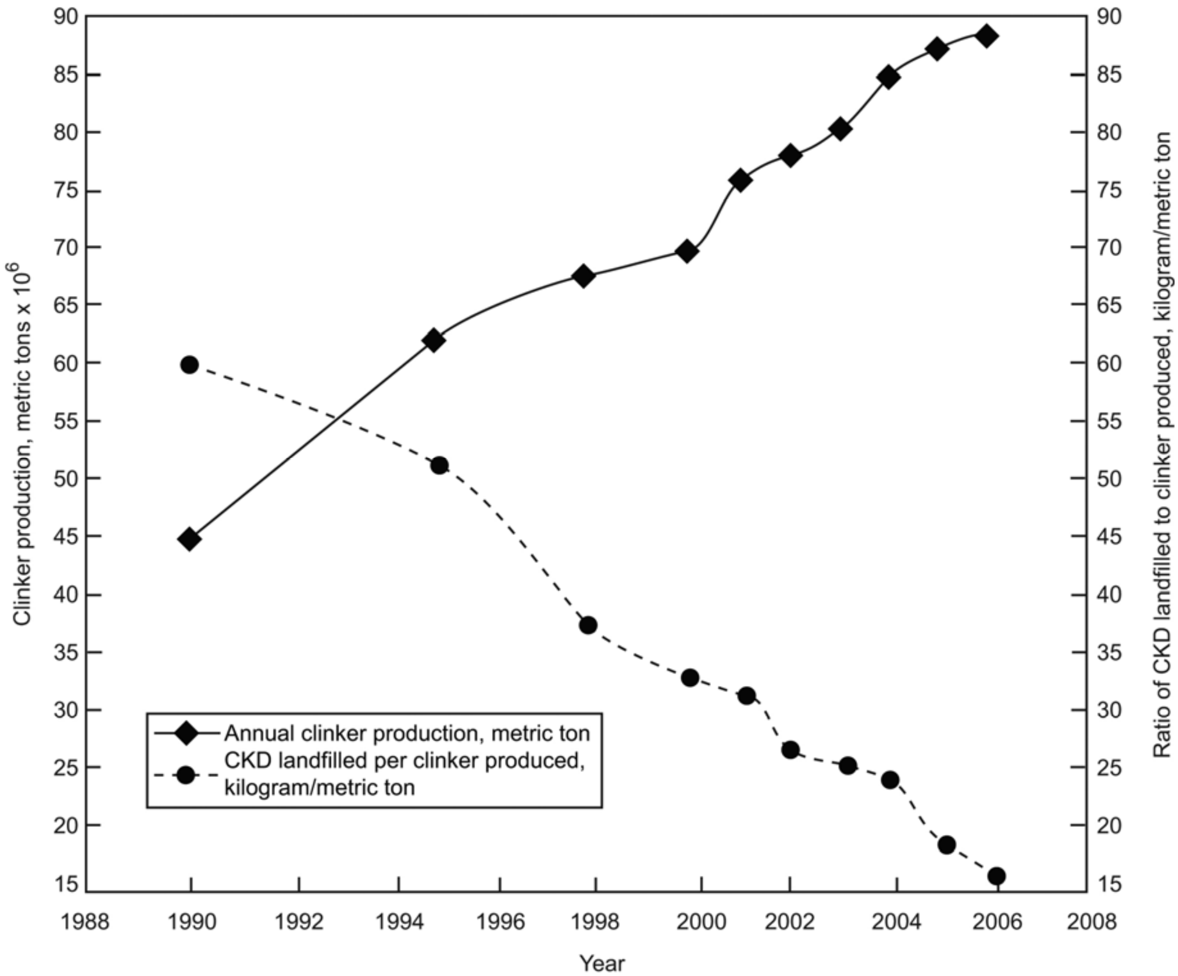

Figure 3 – Clinker Production and Ratio of CKD Landfilled/Clinker Produced (From PCA member company surveys)

learned that the amount of CKD removed from onsite landfills has grown from just over 13,400 metric tons in 1998 to more than 261,000 metric tons in 2006 (Table 4). Because CKD is very similar to the raw materials entering the kiln system and may contain partially processed feed or final product, the CKD becomes more valuable as energy and other manufacturing costs rise. Through the addition of equipment for the return of dust to the kiln (dust insufflation equipment or dust scoops), long kilns can return a portion or all of their dust.

*Table 5 – States with the Highest Amount of CKD Used for Beneficial Applications**

State	Quantity of CKD beneficially reused, metric tons	State	Quantity of CKD beneficially reused, metric tons
Oklahoma	154,477	Indiana	82,325
Texas	144,043	California	66,801
Pennsylvania	102,760	Arkansas	61,990
Ohio	86,453	Maryland	50,562
Illinois	85,330	Missouri	48,250

Note* – From PCA member company survey for 2006

*Table 6 – Beneficial Uses of Cement Kiln Removed from the Cement Manufacturing Process**

Uses of CKD	Quantity of CKD beneficially reused, metric tons
Soil / Clay Stabilization / Consolidation	533,365
Waste Stabilization / Solidification	213,675
Cement Additive / Blending	183,228
Mine Reclamation	152,756
Agricultural Soil Amendment	33,546
Sanitary Landfill Liner / Cover Material	15,042
Wastewater Neutralization / Stabilization	12,302
Pavement Manufacturing	12,066
Concrete Products	374
Beneficial Use Not Provided	3,657
Total	1,160,011

Note* – From PCA member company survey for 2006

Cement plants that convert an existing long kiln into a semi-dry, preheater, or preheater/precalciner process or add such a kiln system to their facility may choose to remove CKD from existing landfills to augment the raw materials and CKD internally recycled to the manufacturing process. To do such "mining" will be a site-specific decision dependent on the impact to final product, plant operations, energy use, and economic benefits.

A Thomaston, Maine cement producing plant utilizes recovery scrubber technology to manage its CKD, recycles not only all the CKD it generates, but also consumes CKD from its on-site stockpile of dust generated during 100 years of operation. Material from this pile is being mined and reintroduced to the kiln at a rate of approximately 90 to 270 metric tons per day.

In 2006, PCA member companies were asked to provide details on the use of CKD reclaimed from landfills or other long-term management units. The reported beneficial uses of the reclaimed CKD are summarized in Table 7. Nearly half of the CKD was returned to the kiln system for the manufacture of clinker. Other beneficial uses included the stabilization/solidification of waste materials, agricultural soil amendment, and stabilization/consolidation of soils. Because of the wide variation in the chemical and physical composition of the landfilled CKD, CKD removed from existing landfills for any beneficial use would be a site-specific decision.

*Table 7 – Beneficial Uses of CKD Reclaimed from Landfills**

Uses of CKD	Quantity of CKD beneficially reused, metric tons
Returned to Kiln	114,935
Waste Stabilization / Solidification	91,982
Agricultural Soil Amendment	27,745
Soil / Clay Stabilization / Consolidation	21,321
Wastewater Neutralization / Stabilization	2,901
Cement Additive / Blending	2,331
Pavement Manufacturing	137
Total Reclaimed from Landfills	261,352

Note* – From PCA member company survey for 2006

CKD for Blended Cements

The use of CKD as an addition to portland cement has been evaluated by a number of researchers. A summary of some examples can be found in Detweiler et al. (1996). M. S. Y. Bhatty (1983, 1984a-c, and 1986) published a series of reports on the use of CKD blended with portland cement as well as fly ash and ground granulated blast furnace slag. The studies found that cements containing only CKD had reduced workability, setting times, and strength. The loss of strength was attributed to alkalies in the dust. It is believed that the use of fly ash with CKD diluted the alkalies and thus improved the strength. Addition of slag to a cement-CKD blend generally decreased workability, but produced higher strengths than blends containing no slag. It was found that blended cement with high sulfate produced the greatest strength, and that the impact of the alkalies in the dust could be negated by the fly ash and/or slag. Overall, the ratios of alkali, chlorides, and sulfates in the dust are important in determining the properties of the blended cement.

Ravindrarajah (1982) reported that kiln dust could be used in masonry and concrete blocks without loss of strength or workability. His study showed that up to 15% of the portland cement could be replaced with CKD. If higher percentages of dust were used, the setting was retarded, workability was reduced, and water demand was increased.

Daugherty and Funnell (1983) reported that the use of up to ten percent interground CKD did not have any adverse effects on the setting time, soundness or shrinkage of the final portland cement concrete. However, the strength results varied, most likely attributed to the changing dust composition.

Abo-El-Enein et al. (1994) studied the mechanical properties of blended cements using by-pass dusts. The initial and final setting times of cement pastes were decreased due to the high free lime content in the CKD. Blended cements with up to 15% kiln dust had increased compressive strengths and accelerated hydration. Compressive strengths decreased when more than 15% of the portland cement was replaced with CKD.

Soil Stabilization

The value of CKD is not limited to its use as a raw material for return to the cement kiln or as an additive in a blended portland cement. CKD is also used in a variety of other applications as-is or in combination with other additives. Methods for determining and evaluating characteristics of CKD suitable for various applications are given in ASTM D5050 *Standard Guide for Commercial Use of Lime Kiln Dusts and Portland Cement Kiln Dusts.*

As indicated in Table 6, more than half million metric tons of CKD was used for soil stabilization. Because of the free lime content and ability to enhance the effectiveness of other stabilizers like fly ash, CKD has been used extensively as a binder in soil stabilized base and subbase pavement applications (Figure 4).

Sayah (1993) and Zaman et al. (1992) have demonstrated the effectiveness of CKD in stabilizing highly expansive clay soils. Their data showed similarities to those for portland cement, fly ash, and lime for stabilizing expansive soils. Miller et al. (1980) used CKD and fly ash in stabilized base courses in road construction in the form of a pozzolanic non-cement concrete with limestone as an aggregate. Such mixes were also found to have autogenous healing characteristics. McCoy and Kriner (1971) reported a wide range of tests conducted on kiln dust compositions for soil stabilization. The use of CKD in stabilization of clays has been shown to improve the unconfined compressive strength and reduce the plasticity index using dust with low LOI. On the other hand, adding CKD with high LOI resulted in relatively lower unconfined compressive strengths and higher plasticity indices (Bhatty et al., 1996).

Figure 4 – Constructing a pavement base using CKD (Courtesy of Lafarge North America)

Miller and Zaman (2000) indicated that CKD can be used as an alternative to quick lime for subgrade stabilization in highway construction. The laboratory and field test data showed that CKD was more effective than quicklime for stabilizing soil. Additional laboratory tests showed that the influence of CKD and lime on the plasticity index of soils was similar and that both additives imparted some resistance to freeze-thaw and wet-dry cycles. In addition, the tests showed that the LOI content was an important factor in the effectiveness of the CKD. High LOI implies a higher percentage of bound water within its chemical structure and less CaO available to react. Conclusions were that treatment with CKD can be cost-effective and that it requires less construction time than treatment with quicklime.

The Kansas Department of Transportation (KDOT) preformed cyclic wet-dry durability tests on CKD and determined that CKD preformed similar to other stabilizing additives in regard to the number of cycles survived (KDOT, 2004). The Oklahoma Department of Transportation (ODOT) conducted tests on CKD to determine swell potential. Results showed negligible swelling tendencies. The results also found that shale treated with both quick lime and CKD preformed similarly throughout the curing process. However after 14 days of curing the quick lime proved much less effective than CKD (ODOT, 2003). ODOT has incorporated approved procedures for using CKD (ODOT, 2004) as well as mix design procedures for soil stabilization and soil modification (ODOT, 2006a-b).

The U.S. Department of Transportation and the U.S. Department of Energy tested the effectiveness of substituting CKD for hydrated lime in lime-fly ash-aggregate road base systems. CKD was found to perform well in pozzolanic road base compositions involving some form of lime-fly ash stabilization. CKD generally yielded mixes with high resistance to freezing and thawing and some mixes developed early strength, possibly extending the normal cut-off dates for late season construction. The study found that, with few exceptions, fresh CKD worked with nearly any fly ash to produce strengths high or even higher than those observed with commercial hydrated lime and fly ash, although larger CKD quantities were required compared to normal hydrated lime to achieve the same strength. The study also found that aged CKD from stockpiles had a lower free lime content and resultant poor reactivity. In addition, CKD from dry process plants tended to produce the highest strength. Total dusts containing both fine and coarse CKD were better than separated CKD. The study concluded that, owing to its free lime content, CKD may be used in lieu of hydrated lime as a pozzolanic road base material (Valley Forge Laboratories, Inc., 1982).

Waste Stabilization/Solidification

CKD use has also been reported in a number of solidification/stabilization projects, primarily in remedial actions, and central hazardous waste management facilities. The absorptive quality of the dust, along with its high alkaline nature makes it very effective for waste treatment. Connor (1990) and others (1992) went into great detail on the chemistry and applicability of CKD in the stabilization of soils and sludges, including several case studies. A paper by MacKay and Emery (1992) describes the stabilization of contaminated soils and sludges in which CKD is used in conjunction with other cementitious products such as slag cement, lime kiln dust, fly ash, hydrated lime, and portland cement.

Several uses of CKD for the stabilization/solidification of specific wastes have been suggested over the last several decades. Cocozza (1977) and Holley (1992) patented processes in which flue gas desulfurization residues are treated to produce stable, leach-resistant solids. The CKD-fly ash process developed by Nicholson (1982), is applicable to sewage sludge solidification, but appears to be equally appropriate for other wastes. Ader et al. (1989) proposed a method for the stabilization of mercury-containing waste while Kigel et al. (1994) developed a chromium ore waste treatment utilizing CKD. Funderburk (1990) suggested a method of solidifying and immobilizing hazardous waste in an organic matrix using CKD as one of the components, and Weszely (1996) proposed a general solidification process of hazardous waste.

At the Port of Richmond on San Francisco Bay, CKD was used as part of a cost-effective sediment remediation program. The CKD was used to turn contaminated sediment dredged from a marsh and shoreline into an engineered fill. Approximately 5,100 cubic meters of treated material were reused as a structural subbase material for a paved parking lot (Bourne, 2007).

The final process in handling hazardous wastes is the responsibility of the treatment, storage and disposal facility (TSDF). The regulations pertaining to TSDFs are more stringent than those that apply to generators, transporters or municipal landfill operators. US Ecology Texas (USET), a division of American Ecology is a licensed TSDF permitted under Subtitle C of RCRA. The USET facility is located in Robstown, TX near Corpus Christi and includes a 97 hectare active waste site. The facility, which began operations in 1973, treats and disposes of RCRA, PCB remediation waste, and low-concentration NRC-exempt radioactive waste. USET is capable of treating a wide variety of organic and inorganic wastes, either liquid or solid. The use of CKD plays an integral part in the treatment. Table 8 provides a partial list of wastes that can be treated with CKD.

Table 8 – Partial list of Hazardous Wastes Treated with CKD (Source USET)

Aqueous wastes	Metal solids	Plating sludge	Organic & Inorganic liquids
Spent acids	Petroleum solids	Drilling mud	Organic paint/ink/lacquer
Spent caustics	Adhesives/epoxies	Catalyst wastes	Ethylene glycol antifreeze
Waste oils	Incinerator residues	Resins/tar sludge	Leachate contaminated wastes
Brine solutions	WWT sludge	Contaminated soil	Hazard sandblasting wastes

The process in determining the appropriate treatment begins by first evaluating the materials through an on-site laboratory using profile information and shipment samples to determine what compounds/toxins are present, and what would be the proper mix design to solidify or treat the material. Once this procedure is established; treatment starts. The material to be treated is placed into a 92 cubic meter treatment tank; CKD is added and homogenized with a backhoe type mixer (Figure 5). CKD has proved to be effective in reducing pH of acidic materials. It has also been shown to be effective in treating listed solid and liquid hazardous wastes, refinery and drilling industry wastes.

The Texas Commission on Environmental Quality requires a minimum unconfined compressive strength of 345 kPa be achieved prior to disposal. This criterion can be met with as little as 10% CKD, but may require up to 200% addition. The CKD comes from a San Antonio based cement plant and contains a relatively high CaO content (60.9% by weight) and low LOI (2.2% by weight) making it well suited for this

Figure 5 – Mixing wastes in treatment tank (Courtesy of USET)

type of application. After the material is processed, it is stored for verification of treatment and approved for disposal. Subsequently, it is placed into a landfill and covered.

According to Kenneth Knibbs, General Manager of USET facility, “CKD works better than other granular or dust type materials. It may take a little more, but it’s so much easier to use. The CKD can be handled with end-loaders, it’s not extremely dusty and it’s easy to mix.”

Sanitary Liner and Cover Material

Studies have been carried out to use CKD as a watertight barrier (liner) for sanitary landfill sites (Ballivy et al., 1992). The dust could be consolidated and stabilized when used in conjunction with varying amounts of Class C fly ash and silica fume. The mixes had a water to dry-solid ratio of 0.4 and were cured at 100% relative humidity for 10 days after demolding. After consolidation the mixes showed permeability lower than the standard 10^{-7} cm/sec. When tested as liners, these mixes exhibited a good capacity for absorbing heavy metals.

Cement kiln dust was used successfully as a cover material instead of clay at a sanitary landfill located at a California cement plant (Crosby et al., 2000). In the early 1900s, cement plant employees began disposing of household waste at the company’s on-site landfill. This practice continued until the mid-1980s when landfill disposal was limited to construction debris. In the 1990s, all waste disposal was stopped, and the regulatory closure process began. From detailed geotechnical testing, the State of California determined that compacted CKD would be an acceptable landfill cover material. CKD was also used as a fill material to protect the landfill from erosion from future storm events. Also, the cost of the CKD was calculated as only 20% of what was estimated for alternative cover and fill materials.

Hansen (1996) developed a synthetic waste pile cover material based on a mixture of fibers (paper, wood, and/or plastic) and a cementitious material such as CKD. A slurry of this material would be applied to a waste pile and allowed to harden to minimize water infiltration, fugitive dust releases, odor, and animal intrusion. An example of a spray-applied coating used for landfill daily cover is shown in Figure 6.

Figure 6 – Spray applied coating used for landfill daily cover (Courtesy of Landfill Services Corp)

Mine Reclamation

The U.S. Bureau of Mines study (Haynes and Kramer, 1982) documented the use of CKD as partial hydraulic filler for backfilling coal mine shafts and tunnels. Because of its fine particle size and high alkali contents, CKD is also being premixed to neutralize acidic media and effluent from mining and mineral processing industries. For instance, CKD was used to neutralize a chemical pond containing acidic sulfates. The attempts were only partially successful because the particular CKD used was very coarse (Klemm, 1980). Nehdi and Chan (2007) reported on the stabilization of sulfuric mine tailings to prevent metal release and acid drainage.

The dust also has the potential to replace fly ash for controlling the spread of fires in coal mines. CKD has also been used as a binder in pelletizing iron ore fines for recycling in steel making. It has also found applications as coagulant for dewatering of waste sludge from tin rolling mills (Klemm, 1980).

Agricultural Amendment

Because of the high lime and potassium concentrations, CKD is used as a soil amendment or fertilizer in many parts of the world. The acid neutralizing capacity of the lime in CKD counteracts the acidic soils that result from years of farming. Neutral soils are a better growing environment for crops and also enhance herbicide effectiveness. The dust may provide potassium and trace metals that are also depleted from agricultural soils due to plant withdrawal requirements. The following describe some of the work that has been completed on this subject within the U.S.

For agricultural uses of CKD in the U.S. before 1975, Davis and Hook (1975) completed a survey of dust applications in their report for the USEPA. They found that kiln dust was suited to replace liming agents and potassium fertilizers. Baker et al. (1975) developed nonputrescible soil-like products for general agricultural applications by combining CKD with sewage sludge before vacuum filtering. Risser et al. (1981) produced a lime-potash soil additive composed of 35% CaO, 6% MgO, 5% K_2O, and 4% SO_3 from CKD having a controlled composition. Taylor (1987) also reported the usefulness of CKD as a substitute for lime and fertilizer elements. Since the quality of CKD varies with each cement plant, however, the nutrient value may also change. In Australia, Dan et al. (1989) found that CKD increased the crop yield equally well as crushed limestone. Fraiman et al. (1991) recommended the use of bypass dust containing high levels of K_2O, SO_3, and Cl, in fertilizer applications. Because potassium is the most valuable fertilizer element contained in the dust and the least desirable element for recycling, CKD with high potassium contents could be adequately utilized as a fertilizer. It should be noted that nutrients such as nitrogen and phosphorus are still required from other sources regardless of whether limestone or CKD is used on agricultural soils.

Because the placement of a fine dust, such as CKD, on agricultural lands is difficult, it has been suggested that granules or agglomerates of dust should be made (Kachinski, 1983; Wommack et al., 2001). The larger particles help to limit fugitive releases of dust while transporting, handling, and placing the CKD. Conversely, care must be taken so that the granules are not so rigid that rain and other natural processes cannot dissolve or break down the particles to release the beneficial constituents of the dust.

One of the concerns with using CKD as a fertilizer or soil amendment is the level of trace metals it may contain. The effect of those metals on the food chain through possible extraction by soil and subsequent movement into vegetation should be determined before such applications are to be considered. However, in a specific study on the use of CKD as a fertilizer in Iowa, Preston (1993) demonstrated that trace metals in CKD were well below the permissible levels for land application.

The USEPA (1999b) studied metals and other constituents of fertilizers including CKD. Their findings showed that the metals content of various fertilizers ranged over several orders of magnitude but did not provide any specific recommendations on the use of CKD on agricultural lands.

Kanare (1999) completed a study comparing CKD to soils, agricultural limestones (aglime), and sewage sludges. He found that sludges generally have the highest levels of chromium, lead, mercury, nickel, and silver compared to CKD, aglime, and North American soils. The highest levels of thallium and selenium are found in CKD. Other elements of interest are present in these materials at non-detectable or comparable concentrations.

Controlled Low-Strength Material (CLSM)

Controlled low-strength material (CLSM) is a self-compacted, cementitious material used primarily as a replacement for compacted soil fill. The American Concrete Institute (ACI) further defines CLSM as a material having a maximum compressive strength of 8.3 MPa. Often the ability to excavate CLSM at a later date is an important factor. In these cases, In many cases compressive strengths in the range of 0.7 to 1.4 MPa are specified. Because of the low strength requirements, CKD maybe well suited as a replacement or supplementary material to portland cement and fly ash.

Ramchairitar et al. (2003) studied different replacement ratios to determine comparable properties with CLSM mixtures using cement only. His studies indicated that slump and bleeding decreased with increasing CKD content, while compressive strength increased with increasing CKD content. He concluded that replacing the 25 kg/m^3 of cement in the control mix with 50 kg/m^3 of CKD gave the most optimum results.

Katz and Kovler (2004) investigated the effects of various by-product materials including CKD in CLSM. Fly ash mixtures showed greater bleeding than mixtures containing CKD. Fly ash mixtures had bleeding in excess of 3%, while CKD mixture reached a maximum of around 1%. The setting time of CKD mixtures was longer than those mixtures containing fly ash. Compressive strengths of CKD mixtures were less than corresponding mixtures containing equal amounts of fly ash.

Williams (2005) studied the effects of four distinctly different CKDs on the properties of CLSM. The four CKDs covered the range of high and low calcium oxide (CaO) and high and low loss on ignition (LOI). Results indicated that mixtures produced with CKD but no fly ash always set and hardened more slowly. Without fly ash, the mixtures containing CKD with high LOI never hardened. Compressive strengths of the mixtures varied considerably. In general the compressive strengths decreased with increasing CKD content and decreasing fly ash content. Of the CKD properties considered (CaO content and LOI); the LOI had the most significant impact on the hardened properties of CLSM. Mixtures containing low LOI

(<10%), regardless of content, had compressive strengths from 1.0 MPa to 10.3 MPa at 56 days. CKD having high LOI (>20%) could only obtain strength if fly ash or cement was added. Mixtures containing high LOI CKD, regardless of content, had compressive strengths less than 1.4 MPa up to 90 days. However, a small amount of cement vastly increased the strength.

Miscellaneous Applications

CKD has been used as a substitute for lime in stabilizing wastewater streams. This is possible primarily because of the high neutralizing potential of the CKD (high $CaCO_3$, and CaO) and fine particle size distribution, having Blaine finenesses often greater than 800 m^2/kg. Up to a 35% addition of CKD has satisfactorily met the specified pathogen control level in sewage sludge. High pH, an exothermic reaction, and the resulting accelerated drying when CKD was added were the factors mainly responsible for the pasteurizing effects on municipal wastewater sludge (Nicholson, 1988a and 1988b; Burnham, 1987; Nicholson and Burnham, 1988). Canadian study found that CKD could be used instead of caustic soda in the treatment of wastewater from a pulp and paper factory (Smith and Campbell, 2000).

Hydrated CKD has also been successfully evaluated as an anti-stripping agent in hot-mix asphaltic concrete (Klemm, 1993). Preliminary tests on replacing up to 3% hydrated lime by the hydrated CKD have shown favorable results. CKD has been used as inorganic filler in bituminous paving and asphaltic roofing. Kiln dust has also been used as filler for asphaltic insulating board sound-deadening materials (Davis and Hooks, 1975).

Cement kiln dust has also been used as a partial replacement for soda in the production of glass where color and high chemical stability are not essential considerations. High alkalies in CKD increase the rate of sulfate decomposition that is the main cause of foaming in glass baths (Emer, 1969). A soda-kiln-dust glass has many similarities to the conventional soda-lime glass. Fraiman et al. (1991) have also recommended the use of bypass dust in glass making.

In some Eastern European countries, kiln dust has been successfully incorporated into cementing compositions for gas and oil wells. The kiln dust appears to improve slurry pumpability and also functions as a fluid-loss additive. CKD also sufficiently retarded oil well cement slurries for use at temperatures up to 100°C, without additional retarders.

Conclusions

Cement kiln dust (CKD) is a significant by-product material of the cement manufacturing process. Over the past several years dramatic advances have been achieved in the management and use of cement kiln dust, thus reducing its dependency on landfill disposal.

From 1990 to 2006, the U.S. cement industry has reduced by 47 percent the amount of CKD landfilled. This reduction in landfilled CKD comes despite the fact that domestic clinker production, as reported by the participants in the PCA CKD study, increased 95% during this same period. Overall clinker capacity in the U.S. has increased 28 percent since 1990.

The majority of CKD is recycled back into the cement kiln as raw feed. In addition, new technology has allowed the use of previously landfilled CKD to be use as raw feed stock. Recycling this by-product back into the kiln not only reduces the amount of CKD to be managed outside the kiln, it also reduces the need for limestone and other raw materials, which saves natural resources and helps conserve energy.

The value of CKD is not limited to its use as a raw material for return to a portland cement kiln. There are many other beneficial uses of CKD including base stabilizer for pavements, solidifier and stabilizer for contaminated wastes, agricultural soil enhancement, low-strength backfill material and municipal daily landfill cover.

Studies have shown that CKD can be used alone, but often is more effective when used in combination with other cementitious materials including portland cement, fly ash and slag. CKD containing high CaO content and low loss on ignition (LOI) performs best for most applications. High LOI dusts contain a higher percentage of bound water within its chemical structure and less CaO is available to react. The high LOI can also interfere with the hydration process.

Several processing factors influence the chemical and physical properties of CKD. Because plant operations differ considerably with respect to raw feed, type of operation, dust collection facility, and type of fuel used, CKD from each plant can vary markedly in chemical, mineralogical and physical composition. Therefore it is important to thoroughly test CKD for any proposed application prior to use.

References

Abo-El-Enein, S. A.; Hekal, E. E.; Gabr, N. A.; and El-Barbary, M. I., "Blended Cements Containing Cement Kiln Dust," *Silicates Industrials*, Vol. 59, No. 9-10, 1994.

Ader, M.; Glod, E. F.; and Fochtman, E. G., *Stabilization of Mercury-Containing Waste*, Patent and Trademark Office, United States Department of Commerce,Washington, DC, USA, Patent No.: 4,844,815, 1989.

ASTM D5050-96, Standard Guide for the Commercial Use of Lime Kiln Dusts and Portland Cement Kiln Dusts, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA, 1996.

Baker, D. E.;Welch, S.; Stout,W.; and Doty,W., "Kiln Dust from Cement Factories for Vacuum Filter Processing of Sewage Sludge," *Compost Science*, Emmaus, Pennsylvania, USA, Vol. 16, No. 4, July-August 1975.

Ballivy, G.; Rouis, J.; and Breton, D., "Use of Cement Residual Kiln Dust as Landfill Liner," *Cement Industry Solutions to Waste Management*, LT168, Canadian Portland Cement Association, Toronto, Ontario, Canada, 1992.

Bhatty, M. S. Y., *Use of Kiln Dust in Blended Cements*, SN1717, Portland Cement Association, Skokie, Illinois, USA, 1983.

Bhatty, M. S. Y., (1984a) "Use of Cement-Kiln Dust in Blended Cements," *World Cement Technology*, London, UK, Vol., 15, No. 4,May 1984.

Bhatty, M. S. Y., (1984b) "Kiln Dust Cement Blends, Evaluated," *Rock Products*, Chicago, Illinois, USA, Vol. 88, No. 10, October 1984.

Bhatty, M. S. Y., (1984c) "Use of Cement-Kiln Dust in Blended Cements: Alkali-Aggregate Reaction Expansion," *World Cement Technology*, London, UK, Vol. 16, No. 10, December 1984.

Bhatty, M. S. Y., "Properties of Blended Cement Made with Portland Cement, Cement Kiln Dust, Fly Ash, and Slag," *8th International Congress on Chemistry of Cement*, Rio de Janeiro, Brazil, Theme 3, Vol. IV, No. 4, September 1986.

Bhatty, J.I., Bhattacharja, S., and Tordes, H.A., 1996, *Use of Cement Kiln Dust in Stabilizing Clay Soils,* Portland Cement Association, Skokie, Illinois, USA,1996.

Bhatty, J. I.; Miller, F.M.; and Kosmatka, S. H., *Innovations in Portland Cement Manufacturing*, SP400, Portland Cement Association, Skokie, Illinois, USA, 2004.

Bourne, S.A. and Chan, N., "Cost-Effective Sediment Remediation at Port of Richmond on San Francisco Bay", *ASCE Ports 2007 Conference*, San Diego, California, USA, March 2007.

Burnham, J. C., “Progress Report on the Pasteurization of Municipal Sludges Utilizing Cement Kiln Dust,” *A National Conference on Alkaline Treatment and Utilization of Municipal Wastewater Sludges,* National Kiln Management Association, Toledo, Ohio, USA, Section II, August 26-27, 1987.
Cocozza, E. P., Chemical Fixation of Desulfurization Residues, Patent and Trademark Office, United States Department of Commerce, Washington, DC, USA, Patent No.: 4,049,462, 1977.

Conner, J. R., *Chemical Fixation and Solidification of Hazardous Wastes*, Van Nostrand Reinhold, New York, New York, USA, 1990.

Connor, J. R.; Cotton, S.; and Lear, P. R., “Chemical Stabilization of Contaminated Soils and Sludges Using Cement and Cement By-Products,” *Cement Industry Solutions to Waste Management*, LT168, Canadian Portland Cement Association, Toronto, Ontario, Canada, 1992.

Crosby, T.W.; Duffey, A. M.; Hullings, D. E.; and Kulesza, E. M., “Cement Kiln Dust: From Mining By-Product to Valuable Cover Material,” *Proceedings of the Air & Waste Management Association’s 93rd Annual Conference & Exhibition*, Salt Lake City, UT, AWMA, Philadelphia, Pennsylvania, USA, June 2000.

Dan, P. R.; Dear, B. S.; and Cunningham, R. B., “Comparison of Sewage Ash, Crushed Limestone and Cement Kiln Dust As Ameliorants for Acid Soils,” *Australian Journal of Experimental Agriculture*, Commonwealth Scientific and Industrial Research Organization, East Melbourne, Australia, Vol. 29, No. 4, 1989.

Daugherty, E. D., and Funnel, J. E., “The Incorporation of Low Levels of By-Products in Portland Cement and the Effects on Cement Quality,” *Cement, Concrete, and Aggregates*, American Society for Testing and Materials, Philadelphia, Pennsylvania, USA, Vol. 5, No. 1, 1983.

Davis, T. A., and Hooks, D. B., *Disposal and Utilization of Waste Kiln Dust from Cement Industry,* National Environmental Research Center, Office of Research and Development, United States Environmental Protection Agency, Cincinnati, Ohio, USA, EPA 670-2-75-043, 1975.

Emer, P., “Formation of Foam on the Surface of Molten Glass Bath,” *Glastechnische Berichte,* Frankfurt, Germany, 42:30, June 1969.

Fraiman, L. S.; Ioganson, A. K.; and Solovushkov, N. E., “Study of Properties of Bypass Dust,” *Tsement*, Leningrad, USSR, Vol. 9-12, 1991.

Funderburk, R. F., *Method and Mixture for Solidifying and Immobilizing Various Hazardous Waste Contaminants in an Organic Matrix*, Patent and Trademark Office, United States Department of Commerce, Washington, DC, USA, Patent No.: 4,909,849, 1990.

Hansen, D. L., *Synthetic Bulk Material Cover and Method of Using Same*, Patent and Trademark Office, United States Department of Commerce,Washington, DC, USA, Patent No.: 5,525,009, 1996.

Haynes, B.W., and Kramer, G.W., *Characterization of U.S. Cement Kiln Dust, Bureau of Mines*, United States Department of Interior, Washington, DC, USA, Information Circular #8885, 1982.

Holley, C. A., *Process for Agglomerating Stack Gas Desulfurization Residue*, Patent and Trademark Office, U.S. Department of Commerce, Washington, DC, USA, Patent No.: 5,173,232, 1992.
Kachinski, J. L., *Method of Processing Waste Cement Kiln Dust to Make a Soil Treatment Composition*, Patent and Trademark Office, United States Department of Commerce,Washington, DC, USA, Patent No.: 4,402,891, 1983.

Kanare, H. M., *Comparison of Trace Metal Concentrations in Cement Kiln Dust, Agricultural Limestone, Sewage Sludge, and Soi*l, SN2080, Portland Cement Association, Skokie, Illinois, USA, 1999.

Katz, A., and Kovler, K., "Utilization of Industrial By-Products for the Production of Controlled Low-Strength Materials (CLSM)," *Waste Management*, Vol.24, No. 5, 2004.
KDOT, *Use of Cement Kiln Dust for Subgrade Stabilization*, KS-04-3, Kansas Department of Transportation, Topeka, Kansas, USA, October 2004.

Kigel, M. Y.; Shultis, J. F.; Goldman, E. S.; and Demytrk, M. K., *Method of Detoxification and Stabilization of Soils Contaminated with Chromium Ore Waste*, Patent and Trademark Office, United States Department of Commerce,Washington, DC, USA, Patent No.: 5,304,710, 1994.

Klemm,W. A., *Kiln Dust Utilization*, Martin Marietta Laboratories Report, Baltimore, Maryland, USA, Report MML TR 80-12, March 1980.

Klemm,W. A., "Cement Kiln Dust: A Look at its Uses and Characteristics," *Proceedings of the 1993 International Cement Seminar*, Primedia Publishing, Chicago, Illinois, USA, 1993.

MacKay, M., and Emery, J., "Stabilization/Solidification of Contaminated Soils and Sludges using Cementitious Systems," *Cement Industry Solutions to Waste Management*, LT168, Canadian Portland Cement Association, Toronto, Ontario, Canada, 1992.

McCoy, W. J., and Kriner, R.W., "Use of Waste Kiln Dust for Soil Consolidation," *Mill Session Papers*, Portland Cement Association, Skokie, Illinois, USA, June 21,197l.

Miller, G.A., and Zaman, M., "Field and Laboratory Evaluation of Cement Kiln Dust as a Soil Stabilizer", *Transportation Research Board*, Vol. 1714, Washington D.C., USA, 2000.

Müller, H.-P., "What is Dust? Characterization and Classification of Kiln Dust", *24th Technical Meeting, Holderbank Management and Consulting, Ltd. Technical Center,Material Division*, Aargau, Switzerland, Report No. MA 77/2505/E,1977.

Nehdi, M. and Tariq, A., "Stabilization of Sulphidic Mine Tailings for Prevention of Metal Release and Acid Drainage Using Cementitious Materials: A Review", *Journal of Environmental Engineering and Science*, Vol. 6, No.1, National Research Council of Canada, Ottawa, Ontario, Canada, July, 2007.

Nicholson, J. P., (1988a) "What are We Doing With Sludge?" *Pollution Engineering*, Northbrook, Illinois, USA,March 1988.

Nicholson, J. P., (1988b) *Method of Treating Wastewater Sludge*, Patent and Trademark Office, United States Department of Commerce,Washington, DC, USA, Patent No.: 4,781,842, 1988.

Nicholson, J. P., and Burnham J.C., *Treating Wastewater Sludge with Alkaline Materials for Decontamination and Conversion into Fertilizer*, European Patent Application #EP Z83153, September 1988.

ODOT, *Laboratory and Field Evaluation of Soil Stabilization Using Cement Kiln Dust*, Item 2144, ORA 125-5693, Oklahoma Department of Transportation, Norman, Oklahoma, USA, February 2003.

ODOT, *Approval Procedure for Cement Kiln Dust, Specification Reference: 702.03*, Oklahoma Department of Transportation, Norman, Oklahoma, USA, April 28, 2004.

ODOT, (2006a), *Soil Stabilization Mix Design Procedure OHD L-50*, Oklahoma Department of Transportation, Norman, Oklahoma, USA, October 20, 2006.

ODOT, (2006b), *Soil Modification Mix Design Procedure OHD L-51*, Oklahoma Department of Transportation, Norman, Oklahoma, USA, September 12, 2006.

PCA, *An Analysis of Selected Trace Metals in Cement and Kiln Dust,* SP109, Portland Cement Association, Skokie, Illinois, USA, 1992.

PCA, *Report on Sustainable Manufacturing*, Portland Cement Association, Skokie, Illinois, USA, 2007.

Preston,M. L., "Use of Cement Kiln Dust as an Agricultural Lime and Fertilizer," *Emerging Technologies Symposium on Cement and Concrete in the Global Environment*, SP114T, Portland Cement Association, Skokie, Illinois, USA, 1993.

Ramcharitar, M., Hossain, K.M.A., and Lachemi, M., "Development of Flowable Fill Products Using Cement Kiln Dust," *Proceedings of the Annual Conference of the Canadian Society of Civil Engineers,* Moncton, New Brunswick, Canada, 2003.

Ravindrarajah, R. S., "Usage of Cement Kiln Dust in Concrete," *International Journal of Cement Composites and Lightweight Concrete*, Harlow, U.K, Vol. 4, No. 2,May 1982.

Risser, J. A.; Doty,W. T.; and Baker, D. E., "Cement Kiln Dust Useful as Lime-Potash Fertilizer," *Science in Agriculture*, The Pennsylvania State University, College of Agriculture, Agricultural Experiment Station, University Park, Pennsylvania, USA, Vol. 28, No.2, 1981.

Sayah, A. I., *Stabilization of a Highly Expansive Clay Using Cement Kiln Dust*, M.Sc. Thesis, University of Oklahoma, Graduate College, Norman, Oklahoma, USA, 1993.

Smith, M. L., and Campbell, C. E., "Effects of Cement Kiln Dust on pH and Phosphorus Concentrations in an Activated Sludge Wastewater Treatment System," *Water Quality Research Journal of Canada,* Canadian Association on Water Quality, Toronto, Ontario, Canada, Vol. 35, No. 2, 2000.

Taylor, O., "Flue Dust: A Concrete Idea?" *Soybean Digest*, St. Louis, Missouri, USA, May 1987.

Todres, H. A.; Mishulovich, A.; and Ahmed, J., *Cement Kiln Dust Management: Permeability*, RD103, Portland Cement Association, Skokie, Illinois, USA, 1992.

USEPA, (1999b) *Background Report on Fertilizer Use, Contaminants and Regulations*, National Program Chemicals Division, Office of Pollution Prevention and Toxics, United States Environmental Protection Agency,Washington, DC, USA, EPA 747-R-003, January 1999.

Valley Forge Laboratories, Inc*., Kiln Dust-Fly Ash Systems for Highway Bases and Subbases*. U.S. Department of Transportation and U.S. Department of Energy. USA, September 1982.

Williams, R.J., "Effects of Cement Kiln Dust (CKD) Chemistry and Content of Properties of Controlled Low-Strength Materials (CLSM)," PCA R&D Serial No. 2816, Portand Cement Association, Skokie, Illinois, USA, 2005.

Wommack, G.; Holley, C.; and Greskovich, E., *Soil Conditioning Agglomerates Containing Calcium*, Patent and Trademark Office, United States Department of Commerce,Washington, DC, USA, Patent No.: 6,325,826, 2001

Zaman, M.; Laguros, J. G.; and Sayah, A. I., "Soil Stabilization Using Cement Kiln Dust," *Proceedings of the 7th International Conference on Expansive Soils*, Dallas, Texas, USA, August 1992.