Kiln Dust for Stabilization of Pavement Base and Subgrade Materials

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INTRODUCTION

The purpose of this synthesis of available information was to provide the Texas Department of Transportation (TxDOT) with a concise document on the state of the practice regarding the use of kiln dusts for stabilization of subgrade soils or granular base materials in highway pavements. This document should assist TxDOT in making decisions related to allowing the use of kiln dusts and the development of associated specifications, design procedures, construction practices, and evaluation processes. This review of current information should also help TxDOT develop relevant research programs.

According to Chesner et al. (1998), both cement kiln dust (CKD) and lime kiln dust (LKD) can be used as activators in pozzolanic stabilized base mixtures. Depending on its reactivity, CKD may have potential for use as the sole cementitious material in stabilized base mixtures. Most research and construction with kiln dusts, however, has involved combinations of kiln dusts and coal fly ash as the cementitious component of the mixture. The strength of kiln dust-fly ash-aggregate base and subbase materials is dependent on three factors: the kiln dust, the fly ash, and the aggregate. Either pozzolanic or self-cementing fly ash can be used as part of stabilized base mixtures, although precautions may be necessary when using a self-cementing fly ash, because, with self-cementing fly ashes, no activators are needed.

Mr. J. J. Emery (2003), who has done significant work in this area, stated that the use of kiln dusts to stabilize bases and soils is a mature technology. However, according to Collins and Ciesielski (1994) kiln dust was not included in any state highway agency (SHA) specifications in 1994.

Although CKD is not without potential usefulness for purposes other than paving, the quantities of CKD that are generated are sufficient to present the cement industry with serious disposal or storage problems (Miller et al., 1980). Kiln dusts have been used for slope stabilization, erosion control (Petry, 2001), solid waste (e.g., sewerage sludge) stabilization, neutralizing acidic drainage from mines, among other things (Miller et al., 1997). This synthesis will only deal with pavement subgrade stabilization and modification and base stabilization

ORIGINS OF KILN DUSTS

Production of lime and portland cement results in the annual generation of more than 20 million tons of kiln dust in north America, mostly cement kiln dust (Collins and Emery, 1983). As the name implies, kiln dusts are fine powder-like by-products of portland cement and lime production. They are collected from the stacks of high-temperature rotary kilns by the federally mandated dust collection systems (e.g., cyclones, electrostatic precipitators, and/or bag houses). In appearance, they typically resemble portland cement.

Figure 1 shows the locations of cement and lime plants in the United States (Collins and Ciesielski, 1994). Seven lime plants and thirteen cement plants are located within the state of Texas and at least five to ten plants in neighboring states would likely consider Texas to be in their market area. This shows that Texas could be a leading state for utilizing CKD and LKD.

Figure 1. Locations of Operating Cement and Lime Plants in the United States. (after Collins and Ciesielski, 1994)

There is generally no value in returning the dust to the kiln, as it is very fine and tends to pass directly through the kiln to the precipitators (dust collectors). Up to about 15 percent of the raw materials processed during lime manufacture may be collected as dust, which must be disposed of unless applications are available within economic transportation distance. (Emery, 1981)

Cement Kiln Dust

The US Environmental Protection Agency (EPA) (1993) reported that approximately 14.2 million tons of CKD are produced annually in the USA. Fresh CKDs can be classified as belonging to one of four categories, depending on the kiln process employed and the degree of separation in the dust collection system (Collins and Emery, 1983). According to Chesner et al. (1998), there are two types of cement kiln processes: wet-process kilns, which accept feed materials in a slurry form; and dry-process kilns, which accept feed materials in a dry, ground form. In each type of process, the dust can be collected in two ways: (1) a portion of the dust can be separated and returned to the kiln, or (2) the total quantity of dust can be utilized or discarded.

Chesner et al. (1998) further state that the chemical and physical characteristics of CKD that is collected for use outside of the cement production facility will depend in great part on the method of dust collection employed at the facility. Free lime can be found in CKD, and its concentration is typically highest in the coarser particles captured closest to the kiln. Finer particles tend to exhibit higher concentrations of sulfates and alkalis. If the coarser particles are not separated out and returned to the kiln, the total dust will be higher in free lime. CKD from wet-process kilns tends to be lower in calcium content than dust from dry-process kilns.

Lime Kiln Dust

Approximately two to four million tons of LKD are generated each year in the US (Collins and Ciesielski, 1994). Although LKD is physically similar to CKD, it is chemically quite different. LKD varies chemically depending on whether high-calcium lime (hydrated lime, quicklime) or dolomitic ($CaMg(CO_3)_2$) lime is being manufactured. (Chesner et al., 1998)

Fresh LKD can be divided into two categories based on relative reactivity, which is directly related to free lime and free magnesia content. Free lime and magnesia content are most dependent on whether the feedstock employed is calcitic or dolomitic limestone. LKD with a high free-lime

content is highly reactive, producing an exothermic reaction upon addition of water. This "quick" LKD is of greatest commercial interest as a direct replacement or substitute for hydrated lime for stabilization purposes. (Chesner et al., 1998)

In addition to routine CKD and LKD production, it is estimated that the total amount of kiln dust currently stockpiled throughout the US exceeds 100 million tons. These stockpiles are usually located near the cement/lime manufacturing plants, and vary in age and composition, with exposure to the elements (moisture and carbon dioxide, in particular), which reduces their chemical reactivity. (Chesner et al., 1998)

KILN DUST COMPOSITION AND ENVIRONMENTAL ISSUES

Analyses of Selected Kiln Dusts

Bhatty et al. (1996) stated that any potential application of kiln dust, including soil stabilization, is governed by the physical and chemical composition of the dust. In practical terms, CKDs vary markedly from plant to plant in chemical, mineralogical, and physical composition, depending upon the feed raw material, type of kiln operation, dust collection facility, and the fuel used (Klemm, 1980). In general, CKDs are particulate mixtures of partially calcined and unreacted raw feed, clinker dust, and fuel ash, enriched with alkali sulfates, halides, and other volatiles (Bhatty et al., 1996). Thus, because kiln dust is a by-product, it is by nature somewhat variable in its chemical composition and, thus, the engineering properties it imparts to stabilized soils.

Table 1 shows data developed by Miller et al. (1980) from analyses of CKDs representing nine different sources. Table 2 shows approximate composition of a CKD reported by Haynes and Kramer (1982). Table 3 shows typical ranges in compositions of CKD and LKD, which Emery (1981) summarized from Nicholson (1977). Emery (1981) indicated that LKD generally exhibits less variability in composition than CKD.

Table 1. Analyses of CKDs from Nine Different Sources. (after Miller et al., 1980)

Constituent or Property	Percentage		
	Low	**Mean**	**High**
SiO_2	6.0	16.5	28.5
Al_2O_3	3.2	4.4	9.6
Fe_2O_3	0.8	2.7	5.9
CaO			
From 9 sources	16.0	47.6	65.0
From 13 sources	8.3	12.6	20.2
MgO	0.8	2.3	4.8
SO_3	0.7	7.1	26.3
Na_2O	0.08	0.8	3.2
K_2O	1.08	5.5	26.2
Loss on Ignition	2.5	16.0	32.0

Table 2. Analyses of a CKDs from One Sources. (after Haynes and Kramer, 1982)

Constituent	Percent by Weight	Constituent	Percent 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

Table 3. Typical Ranges of Compositions of Kiln Dusts. (after Emery, 1981)

Constituent	Cement Kiln Dusts			Lime Kiln Dusts		
	Low	High	Average	Low	High	Average
SiO_2	6.0	28.5	16.5	--	--	--
Al_2O_3	3.2	9.6	4.4	--	--	--
Fe_2O_3	0.80	5.9	2.7	--	--	--
CaO	16.0	65.0	47.6	35.6	43.4	38.6
MgO	0.8	4.8	2.3	25.4	32.2	28.6
SO_3	0.7	26.3	7.1	--	--	--
Na_2O	0.08	3.2	0.8	--	--	--
K_2O	1.08	26.2	5.5	--	--	--
LOI	2.5	32.0	16.0	22.9	36.4	29.1
S	--	--	--	0.2	1.0	0.7
CO_2	--	--	--	11.0	22.3	18.0
Available Lime	--	--	--	8.3	20.2	12.6

According to Bhatty et al. (1996), the CKDs generated from long-wet and long-dry kilns are generally composed of partially calcined kiln feed fines enriched with alkali sulfates and chlorides. The dusts collected from the alkali bypass of precalciner kilns tend to be coarser, more calcined, and concentrated with alkali volatiles. Dusts from gas-fired or oil-fired kilns contain higher proportions of soluble alkalis (in the form of K_2SO_4) as compared to coal-fired kilns. However, such a generalization is not valid in many cases. Sample oxide compositions of CKDs from the three kiln types are shown in Table 4 (Todres et al., 1992).

Chemically, CKD has a composition similar to that of conventional portland cement. The principal constituents are compounds of lime, iron, silica and alumina. Table 5 lists Atypical@ compositions for fresh and stockpiled CKD and LKD (Collins and Emery, 1983). The free lime content of LKD can be significantly higher than that of CKD (up to about 40 percent), with calcium and magnesium carbonates as the principal mineral constituents. As with lime or cement, the pH of water solutions of CKD or LKD is typically about 12.

Table 4. CKD Oxide Composition from Three Different Operations.
(after Todres et al. 1992)

Constituent or Property	Long-Wet Kiln, %	Long-Dry Kiln, %	Alkali By-Pass, %
SiO_2	15.0	906	15.2
Al_2O_3	3.8	304	3.1
Fe_2O_3	1.9	1.1	2.0
CaO	41.0	44.9	61.3
MgO	1.5	1.3	2.1
SO_3	6.3	6.7	8.7
Na_2O_3	.074	0.27	0.34
K2O	2.6	2.4	2.5
L.O.I.	25.8	32.2	4.5
Free CaO	0.85	0.52	27.2
Mean Particle Size	9 µm	3 µm	22 µm

Table 5. Typical Chemical Compositions of Cement Kiln Dust and Lime Kiln Dust.
(after Collins and Emery, 1983)

Parameter	Cement Kiln Dust			Lime Kiln Dust		
	Fresh	Stockpiled		Fresh		Stockpiled
		Sample 1	Sample 2	High*	Low*	
CaO	40.5	31.4	44.2	54.5	31.2	31.2
Free Lime	4.4	0.0	0.0	26.4	5.1	0.0
SiO_2	14.5	11.7	11.9	9.94	2.46	1.74
Al_2O_3	4.10	3.18	3.24	4.16	0.74	0.71
MgO	1.55	0.97	1.73	0.49	23.5	23.3
Na_2O	0.44	0.13	0.27	0.03	0.00	0.05
K_2O	4.66	1.65	2.92	0.22	0.09	0.03
Fe_2O_3	2.00	2.16	1.45	1.98	0.94	1.3
SO_3	6.50	8.24	2.40	7.97	2.80	3.5
Loss on Ignition, 105°C	22.9	40.4	30.2	14.2	37.4	27.9

* Two types of LKD were classified in the reported data (high reactivity and low reactivity) on the basis of the release of heat and rise in temperature when placed in solution.

Trace constituents in CKD (including certain trace metals such as cadmium, lead, and

selenium, and radionuclides) are generally found in concentrations less than 0.05 percent by weight. Because some of these constituents are potentially toxic even at low concentrations, it is particularly important to assess their levels (as well as mobility or leachability) in CKD before considering its use (EPA, 1995).

Bhatty et al. (1996) indicated that the source of calcium in CKD could be present in the form of CaO_3 and free CaO. It may also be present as $Ca(OH)_2$ resulting from partial hydration with spray-water applied to control dust or from atmospheric moisture during open stockpiling.

Bhatty et al. (1996) stated that high loss on ignition (LOI) in the kiln dust may imply that it contains a large amount of $CaCO_3$ and/or that it has been exposed to moisture. When kiln dust is exposed to moisture, alkali sulfates rapidly go into solution and free lime and some cementitious phases, if present, undergo hydration. As a result, the availability of calcium ions is dictated by the equilibrium achieved through the solubility limit of $Ca(OH)_2$ and gypsum ($CaSO4 \cdot 2H2O$), if present. Evaporation of moisture from an open stockpile will result in the formation of gypsum and alkali hydroxides. Each of these compounds will contribute to higher LOI. However, LOI of kiln dust that has not been exposed to moisture may be related to the $CaCO_3$ content that undergoes decarbonation when ignited.

Bhatty et al. (1996) pointed out that the availability of calcium ions from CaO, $CaCO_3$, or $Ca(OH)_2$ differs because of their different molecular structures and solubilities in water. Table 6 lists the solubilities of these forms of lime (Boynton, 1980). This demonstrates that those kiln dusts containing relatively high amounts of $CaCO_3$ will provide less calcium ions and take longer to stabilize clay soils as compared to those containing CaO, $Ca(OH)_2$. Additionally, fine particles provide large specific surface areas, which can promote more rapid chemical reactions.

Table 6. Calcium Ion Availability from Different Calcium Sources in CKD.
(after Boynton, 1980)

Ca Source	Ca Present	Solubility	Ca Availability @ 25°C
CaO	71%	0.125^{20}, 0.116^{30}, (**0.120^{25})	High (***8.5)
$Ca(OH)_2$	54%	0.165^{20}, 0.153^{30}, (**0.159^{25})	High (***8.6)
$CaCO_3$	40%	0.0014^{25}	Very Low (***0.056)

*Superscripts indicate solubility temperature in °C
** Interpolated value of solubility at 25°C
*** Multiple of Ca present (Column 2) and solubility at 25°C (Column 3); example 71x0.12=8.5 for CaO

Some cement plants burn hazardous waste as the primary or alternate kiln fuel for the production of cement clinker. In these cases, some hazardous materials can end up in the CKD. Chesner et al. (1998) suggest that prospective users of CKD inquire from the potential supplier whether that plant is using hazardous waste as a kiln fuel. Kiln dusts from plants burning sulfur-bearing coal may contain sulfates or sulfites, which can react with alkali and cause swelling of a stabilized pavement layer (Little, 2003).

According to Dougherty and Funnell (1977), kiln dusts collected during normal kiln operations have been found to be reasonably consistent, while the dusts collected during upset periods (e.g., startup, shut down, change in kiln feed or fuel) are usually much more variable.

Chemically, LKDs may be very different from one plant to another, depending largely on whether the plant is producing lime from high calcium or dolomitic (high magnesium) limestone (Chesner et al., 1998). CKDs may also vary chemically depending on the type of fuel used to heat the kiln. Therefore, kiln dusts should be tested by the user or certified by the supplier so that the user knows the chemical make-up of the particular product being used.

Findings Related Specifically to CKD

In a Portland Cement Association (PCA)-sponsored study, Abeln et al. (1993) deduced that CKD has been studied often from a technical and regulatory perspective and, consequently, that CKD has been identified as a large-volume, low-hazard material. Using an EPA-approved landfill model,

they concluded that, in areas or situations where migration of leachate is predicted (primarily from cement plants or landfills), the model demonstrated that CKD can be managed using a single liner and leachate collection system. The requirements for each specific site will be unique, depending on the characteristics of the plant location or hydrology at the site of the landfill.

In 1982, a Bureau of Mines study (Haynes and Kramer, 1982) concluded that any environmental considerations related to CKD are minor, as the results of their extensive survey showed that U.S. CKD is not a hazardous waste as defined by regulations established under the Resource Conservation and Recovery Act (RCRA).

A decade later, a PCA (1992) study discussed the effects of changes in the cement manufacturing process, raw materials, fuels, and testing procedures that have occurred since publication of the 1982 data. Extensive tests for trace metals in CKD and finished cement from 97 kiln systems throughout North America reconfirmed that neither CKD nor cement have characteristics of hazardous waste as defined under the RCRA. The study represented 79 cement plants in the US (or 71 percent of the US plant sites) and 10 in Canada. Operating kilns decreased from 327 to 213 between 1980 and 1990.

The PCA (1992) included tests on CKD and cement for both total (acid soluble) and leachable trace metals (Tables 7 and 8). The amount of leachable metals in each sample was evaluated using the EPA toxicity characteristic leaching procedure (TCLP). Results of the tests showed no consistent correlation between the total concentration of a metal in CKD or cement and the amount of the metal brought into solution using the TCLP procedure. Interestingly, samples containing the highest metals levels did not necessarily produce the highest TCLP result. Moreover, samples producing the highest TCLP values often contained only moderate amounts of the metal of interest.

According to PCA (1992), Table 7 reveals that the number of data points available for computing the averages differed greatly for each metal and between cement and CKD, because of nondetectable values. Total antimony was below detection limits for most CKD samples; whereas, the total antimony, mercury, selenium, and thallium were below detection limits for most cement samples. The metals in Table 7 are grouped by their relative volatility, differentiated by the melting point of the pure metal. The refractory metals are listed in the last column by average cement-to-

Table 7. Total (acid soluble) Metals in Cement and CK.   (after PCA, 1992)

		Total in Cement, mg/kg				Total in CKD, mg/kg				Ratio of Avg.
Volatile		Min.	Avg.	Max.	No.	Min.	Avg.	Max.	No.	Cement/CKD
	Mercury	<0.001	0.014	0.039	21	0.004	0.660	25.500	68	2%
	Selenium	0.62	NM	2.23	6	2.68	28.14	307.00	54	NM
	Thallium	0.01	1.08	2.68	32	1.40	43.24	776.00	89	2%
	Cadmium	0.03	0.34	1.12	42	0.1	10.3	59.6	81	3%
	Lead	1	12	75	82	34	434	7390	95	3%
	Antimony	0.7	NM	4.0	2	0.3	NM	3.4	9	NM
	Silver	6.75	9.20	19.90	93	4.80	10.53	40.70	92	87%
	Arsenic	5	19	71	54	2	18	159	50	106%
	Nickel	10	31	129	85	1	22	60	65	141%
	Barium	91	280	1402	94	35	172	767	95	163%
	Beryllium	0.32	1.13	3.05	93	0.13	0.65	3.54	94	174%
	Chromium	25	76	422	94	8	41	293	95	185%
Refractory										

Notes:
1. Excludes non-detectable values
2. NM indicates average not meaningful because of large number of non-detectable values
3. No. indicates number of detectable values

Table 8. Leachable (TCLP) Metals in Cement and CKD.   (after PCA, 1992)

		TCLP-Cement, mg/L				TCLP-CKD, mg/L				Ratio of Avg.
Volatile		Min.	Avg.	Max.	No.	Min.	Avg.	Max.	No.	Cement/CKD
	Mercury	0.0001	0.0006	0.0050	32	0.0002	0.0018	0.0223	61	30%
	Selenium	0.001	0.011	0.025	17	0.006	0.152	1.711	38	7%
	Thallium	0.002	0.010	0.028	16	0.01	0.38	4.50	84	3%
	Cadmium	0.0003	0.0019	0.0123	29	0.0001	0.0288	0.2200	24	7%
	Lead	0.002	0.009	0.029	41	0.002	0.349	9.718	70	3%
	Antimony	0.003	NM	0.063	7	0.003	0.012	0.031	25	NM
	Silver	0.003	0.07	0.12	93	0.03	0.07	0.17	95	100%
	Arsenic	0.005	0.027	0.084	19	0.003	0.066	0.636	26	41%
	Nickel	0.06	NM	0.17	8	0.06	0.13	0.32	19	NM
	Barium	0.49	1.35	4.27	92	0.12	1.04	9.19	90	130%
	Beryllium	0.0001	0.0005	0.0030	61	0.0001	0.0004	0.0029	42	125%
	Chromium	0.07	0.54	1.54	92	0.01	0.10	1.29	78	540%
Refractory										

Notes:
4. Excludes non-detectable values
5. NM indicates average not meaningful because of large number of non-detectable values
6. No. indicates number of detectable values

CKD ratio. (Refractory materials are metals and their compounds, which have high melting points and are exceptionally stable at high temperatures.)

Table 7 illustrates that the more volatile metals (mercury, selenium, thallium, cadmium, lead, and antimony) tend to concentrate in the CKD, and the more refractory metals (chromium, beryllium, barium, nickel, arsenic, and silver) tend to concentrate in the cement. The PCA (1992) explained that volatile metals evaporate at the high kiln temperatures, and then condense and accumulate in CKD in cooler regions of the kiln system. The refractory metals are not as volatile at the high kiln temperatures, and thus tend to remain in the clinker.

Table 8 shows that TCLP values for antimony, arsenic, beryllium, cadmium, nickel, and selenium leachable from CKD were nondetectable for most samples. TCLP values for antimony, arsenic, cadmium, lead, mercury, nickel, selenium, and thallium leachable from cement were nondetectable for most samples. (PCA, 1992)

Figure 2 illustrates results from over 1100 TCLP tests for 12 different metals for CKD samples wherein the metals concentrations are normalized by dividing the measured concentration by the RCRA limit (PCA, 1992). A log-scale is used for the vertical axis to cover the wide range of concentrations measured in the tests. More than 99 percent of the CKD samples were below the RCRA limits. The PCA (1992) stated that one facility (but two different kilns) produced the only two CKD samples that exceeded the selenium RCRA limit, but this facility ordinarily recirculates all CKD back to the kiln system. Similarly, one facility (but two different kilns) produced two CKD samples that exceeded the lead RCRA limit. In each case, one of the kilns uses hazardous waste fuel and the other does not.
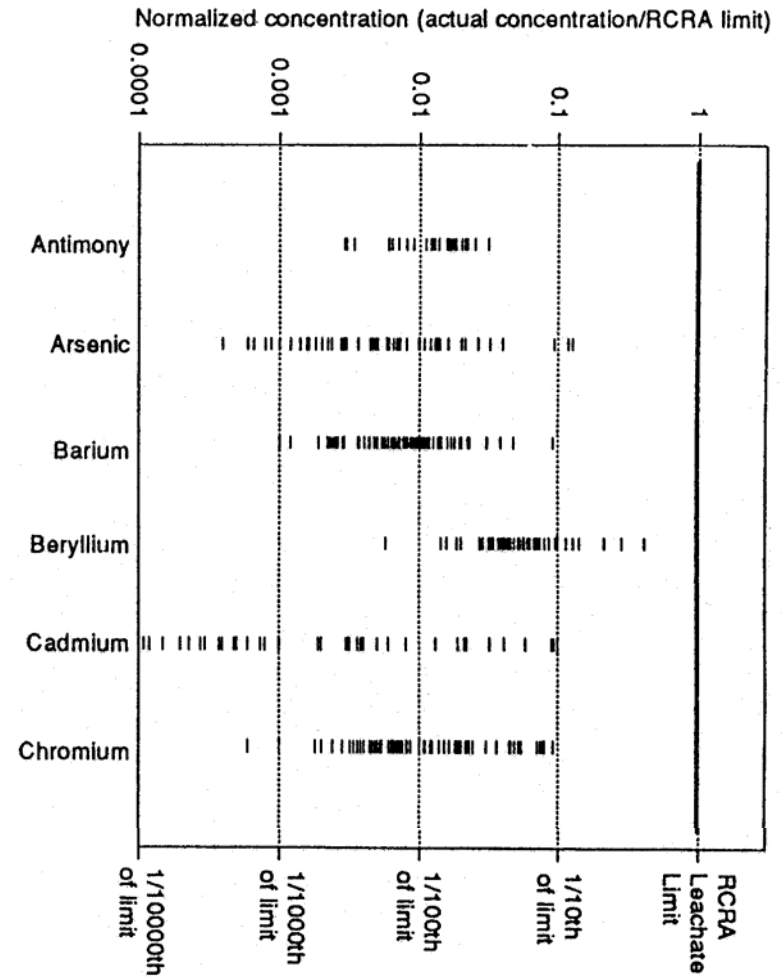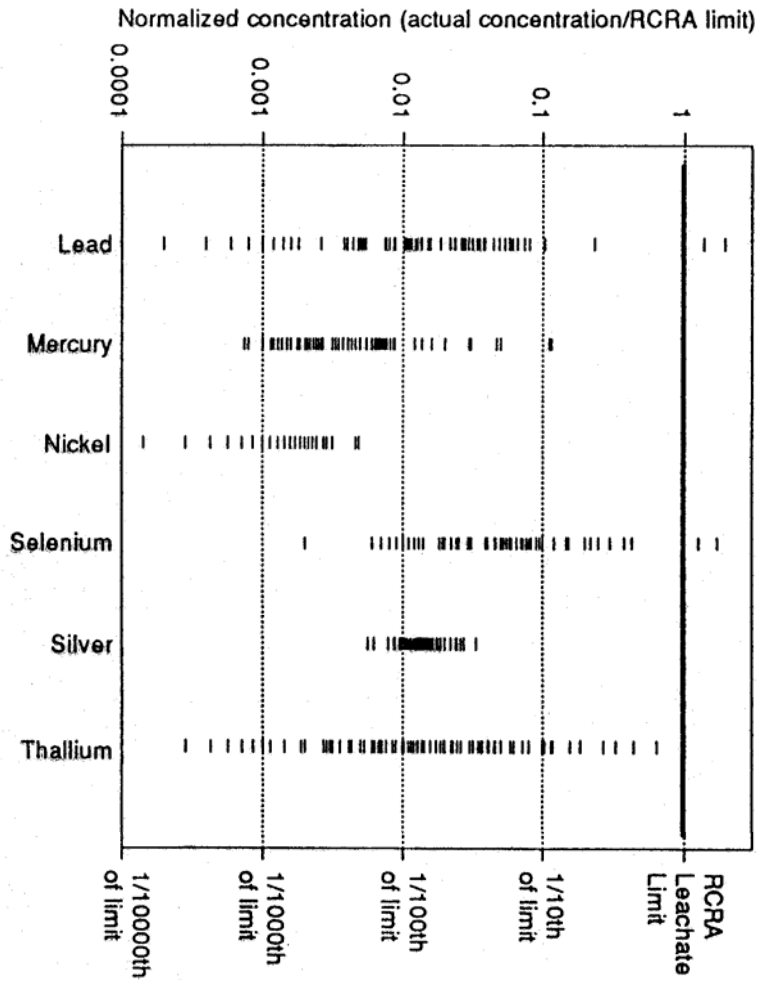
Figure 2. **TCLP Extracts from CKD (Only detectable values are shown).** (after PCA, 1992)

The EPA publishes regulations and findings related to CKD but apparently not for pavement layers stabilized with CKD. The following is excerpted from EPA (1995) located at http://www.epa.gov/fedrgstr/EPA-WASTE/1995/February/Day-07/pr-134.html:

In 1995, the EPA implemented a regulatory determination on CKD waste. The Resource Conservation and Recovery Act (RCRA) required this action. EPA concluded that additional control of CKD is warranted in order to protect the public from human health risks and to prevent environmental damage resulting from current disposal of this waste. The primary environmental concerns to be addressed through additional controls are documented damages to ground water and potable water supplies, and potential human health risks from inhalation of airborne CKD and ingestion via food chain pathways.

Federal statutes that potentially affect CKD management include the Clean Air Act (CAA), Clean Water Act (CWA), the Resource Conservation and Recovery Act (RCRA), and the comprehensive Environmental Response, Compensation and Liability Act (CERCLA). Regulations developed under authority of the CAA and CWA impose controls on releases of CKD to the air (via stack or fugitive dust emissions, 40 CFR Part 50) and water (National Pollution Discharge Elimination System (NPDES), 40 CFR Part 122, point source effluent discharges, and 40 CFR Part 411, effluent guidelines for cement manufacturing facilities), respectively. Under both RCRA and CERCLA, the Federal government can respond where the release of CKD or its constituents may present an imminent and substantial danger to human health or the environment. CKD that is not directly recycled is also subject to regulation under Subtitle D of RCRA as a solid waste. In addition, CKD generating facilities that burn RCRA hazardous waste in kilns are subject to the RCRA Boiler and Industrial Furnace rule (40 CFR part 266) and other RCRA requirements if the CKD from that combustion is "significantly affected" by the hazardous waste fuel. See 40 CFR 266.112.

For states with the highest cement production capacity (California, Michigan, Pennsylvania, and Texas), the EPA has found that CKD waste is subject to some regulation under State and local laws, but the requirements vary significantly from state to state. For example, California regulates CKD as a non-RCRA hazardous waste, but has suspended enforcement of the management requirements for CKD that fails the State's hazardous waste corrosivity test, pending the results of further study of CKD and other cementitious materials. Pennsylvania regulates CKD as a residual waste, requiring facilities to comply with site-specific disposal requirements and waste reduction strategies, which are both periodically updated by the State. In contrast, Michigan and Texas both consider CKD an industrial non-hazardous waste. Michigan requires permits, ground water monitoring, and regular reports of ground water sampling results; whereas, Texas issues non-enforceable guidance. Texas is in the process of developing on-site management standards for cement kiln dust and expects to propose them in 1995.

In addition, EPA's analyses of CKDs show that they do contain certain metals listed in Appendix A (Hazardous Constituents) of Part 261 of the RCRA. Table 9 presents the range of total concentration levels for a number of other toxic metals that the EPA has observed in CKD.

Table 9. Measured Metals Levels in CKD[1] [Mg/kg (parts per 10^6), total basis] (after EPA, 1995)

Metal	No. of Samples	Minimum	Mean	Maximum
Antimony	52	0.09	11.5	102
Arsenic	60	0.26	14.1	80.7
Barium	59	0.43	181	900
Beryllium	53	0.1	1.03	6.2
Cadmium	61	0.065	9.7	44.9
Chromium	61	3.9	31.2	105
Lead [2]	63	3.1	287	2,620
Mercury	57	0.003	0.33	2.9
Nickel	45	3	19.9	55
Selenium	52	0.1	12.2	103
Silver	56	0.25	5.9	40.7
Thallium	57	0.44	33.6	450

[1] Metals data sources include 1992 PCA survey, EPA sampling data, and public comments on the RTC.
[2] The median value for lead is 113 mg/kg.

A website located at http://66.216.42.132/HWFN0792.htm provides a comparison of existing TCLP characteristic leachate limits, Boiler and Industrial Furnace health-based leachate limits, and proposed Hazardous Waste Identification Rule leachate limits under both the CBEL and Expanded Characteristics Option alternatives. The State of Texas probably has its own leachate limits, therefore, those at this website were not imported into this report.

According to PCA (1992), new technologies to recover all of the CKD may become necessary as changes in kiln design and operating practices reduce the amount of CKD produced.

As the industry develops means to recycle more CKD to minimize waste, the character of the CKD may change.

Other Pertinent Findings Reported by the EPA

The following is excerpted from EPA, "Final Technical Support Document for HWC MACT Standards Volume III: Selection of MACT Standards and Technologies" U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C., July 1999. The website is located at http://yeehaw.state.ut.us/yeehaw?Query=specifications&submit2=go, then click on Item 3: EPA Document, "Final: Technical Support Document for HNC MACT Standards" .

EPA=s Report to Congress on CKD analyzed CKD data from five cement kilns burning hazardous waste. The data indicate that polychlorinated dioxins and furans (PCDD/PCDF) are present at very low concentrations in CKD generated by both hazardous and non-hazardous waste fuel burning facilities. (page 3-38, Report to Congress on CKD, Volume II: Methods and Findings, December 1993). Projecting these PCDD/PCDF concentrations in the CKD to the flue gas (assuming each cement kiln was emitting at a PM level of 0.030 gr/dscf (approximately equivalent to the MACT level)) shows that the stack gas PM-related level of PCDD/PCDF is also very low. The PM-related contribution of PCDD/PCDF to emissions is projected to range from only 0.00025 ng TEQ/dscm to 0.0000006 ng TEQ/dscm. Low PCDD/PCDF levels are in part because CKD has low carbonaceous content.

Mercury SREs (System Removal Efficiency; determined as one minus the ratio of the stack gas emissions to total input feed-rate of a hazardous air pollutant) in CKs range from 0 to more than 90 percent. However, Hg is generally regarded as "uncontrolled" once in the cement kiln system, regardless of the system type (long vs. short, wet vs. dry, etc.). Hg fed to the kiln volatilizes and primarily partitions to the stack gas. Mercury is generally volatile at typical air pollution control device (APCD) temperatures and is not typically contained in the clinker or CKD unless the CKD has elevated carbon content, which may adsorb mercury. Typical CKD has low carbon levels. The higher mercury SREs for some test conditions are likely due to measurement uncertainties associated with very low levels of mercury in the stack gas or feed streams. The most representative SRE for cement kilns appears to be from Source ID No. 306 (National Cement, which is no longer burning hazardous wastes) at about 10 percent, where well-characterized (and large) amounts of mercury were spiked.

For short kilns with alkali bypass stacks, the majority of the semi volatile metals (SVM) concentrate in the bypass CKD due to an internal recycle wherein metals vaporize at kiln temperature and condense in the preheater towers. Main stack CKD

has also been shown to be enriched with SVM, but to an 8-4 much lower degree than that of the bypass. Thus, bypass concentrations are higher than those in the main stack, as clearly demonstrated in the testing at Source ID No. 303. The internal recycle build-up is dependent on the bypass gas removal fraction and the constituent volatility. For high volatile metals such as mercury, discussed in Chapter 7, which generally do not tend to condense at APCD operating temperatures, no internal recycle is created. Similarly, an internal recycle is avoided for low volatile metals because they are largely released from the system through the clinker.

Note that, as discussed above in Chapters 2 and 6, a significant fraction of the low volatile metals (LVM) in cement kilns partitions into the clinker product. LVM does not tend to become concentrated in the bypass gases or build up an internal recycle to the same extent as SVM (i.e., LVMs are not enriched in the CKD in the bypass or main stack as SVMs are). Stack gas data from both bypass and main stacks are available for comparison for three kilns. For one facility (Source ID No. 321), bypass emissions concentrations are slightly lower than those from the main stack. For another (Source ID No. 301, no longer burning waste), the bypass is about five times higher than the main stack. For another (Source ID No. 315, also no longer burning waste), the bypass is about three times higher than the main stack. Differences may be due to different bypass gas ratios, different main and bypass stack APCD efficiencies, and different ratios of LVM feed rates in raw material and hazardous wastes. In any case, metals with low volatility are not expected to be enriched in the bypass gas. Additionally, LVM uncontrolled loadings in the bypass and main stack gases are not expected to be significantly different, although there may be some difference due to entrained raw materials LVM contributions in the main stack. There are no expected differences in the ability to control LVM in the bypass stack as compared to the main stack. There is also no strongly expected influence of in-line raw mill operational status on LVM emissions.

Commenters have argued that low alkali kilns have higher chlorine stack gas emissions levels and cannot meet the floor. However, chlorine is clearly being controlled in low-alkali kilns, due to the abundance of calcium-containing limestone, as well as the capture of alkali-chlorides as CKD in the particulate matter air pollution control device (APCD).

Indirectly Related Findings

Although kiln dusts were apparently not tested in NCHRP Project 25-9 (Nelson et al., 2001), the findings appear pertinent to this synthesis. The following was excerpted from the website located at http://www.tfhrc.gov/pubrds/julaug00/recycnat.htm. Additional information from the NCHRP study can be found at http://gulliver.trb.org/publications/nchrp/nchrp_rpt_448.pdf.

> The recently completed NCHRP Project 25-9, "Environmental Impact of [Highway] Construction and Repair Materials on Surface and Ground Waters," was directed to determine whether commonly used construction and repair materials might affect the quality of surface and ground waters. The objective was to evaluate the persistence of any toxic leachates of the selected materials and to estimate the possible impacts of these materials on surface and ground waters. The materials were evaluated considering the removal, retardation, and remediation that occurs as leached substances migrate from the material used in pavements, sub-bases, or fills toward surface or ground water. The study did not include materials deposited on the pavements, pavement-wear particles, and vehicle-wear and exhaust particles.

> Materials evaluated included municipal solid waste ash, coal fly ash, foundry sand, phospho-gypsum, blast furnace slag, steel slag, non-ferrous slags, roofing shingles, scrap tire rubber, reclaimed asphalt, mine tailings, and mining/smelter slags from various locations in the US and Canada.

> While leachates by distilled water from the "pure" materials were, in many cases, found to be toxic to the fresh water algae and/or to the macro-invertebrate Daphnia magna (water flea), the toxic impacts were reduced when these materials were incorporated into pavement materials. In almost all cases, the toxicity was removed by mixing the leachates with soils. Only a few waste or byproduct materials produced a toxic impact on nearby surface or ground water when they were placed into a pavement mixture, perhaps as part of aggregate. Also, leachates were generally non-toxic when passed through soils next to their placement in the highway materials, provided there was at least a nominal thickness (several centimeters) of a typical soil.

> Field observations and experiences from numerous states suggest that these laboratory results were correct. Under both laboratory and field conditions, the rates of leaching of toxic substances decrease with time as the ingredients are more tightly sorbed, modified, degraded, or removed.

> To evaluate these overall processes, the study developed a model that can be applied to each successive media through which the leachates may pass. Bioassay and other procedures were developed to test waste (recycled) materials for environmental impacts on surface and ground waters.

For many of the toxic metals, the concentrations detected in kiln dust were not significantly different whether the dust is generated from kilns that burn or do not burn hazardous waste. However, for lead, cadmium, and chromium, the mean concentration found in CKDs generated by kilns that burn hazardous waste is measurably higher than in CKDs from those kilns that do not burn hazardous waste; conversely, thallium and barium concentrations were measurably higher in CKD from kilns that did not burn hazardous waste.

In terms of potential constituent solubility and release, leach test results show that no significant distinction can be made between CKD generated from kilns that burn hazardous waste and those that do not burn hazardous waste. (This finding was corroborated for metals in CKD by leachate test results submitted to the Agency by the cement industry.) For example, laboratory analysis of CKD using the Toxicity Characteristic Leaching Procedure (TCLP) shows that trace metal concentrations rarely exceed RCRA toxicity limits, whether or not the CKD is generated at kilns that burn hazardous waste.

HANDLING KILN DUSTS

According to Dougherty and Funnell (1977), the characteristics of aged or stockpiled kiln dusts are more variable and inconsistent than those of fresh kiln dusts and are not usually as reactive as fresh kiln dusts. For best results, aged stockpiled CKD and LKD should not be used (due to hydration and consequent loss of reactivity) as a component of stabilized base or subgrade soil unless conditioned by the addition of commercial lime or other caustic material to enhance short-term strength development. There is very little, if any, free lime or free magnesia in stockpiled CKD and LKD that has been exposed to the environment for long periods. (Collins and Emery, 1983).

If fresh kiln dust is used, it must be stored in enclosed bins or silos to keep out moisture and prevent dusting. CKD and LKD can be used with fly ash, provided the dust is conditioned with moderate amounts of water. The use of moisture-conditioned kiln dust (to suppress dusting) and fly ash allows greater quantities of both materials to be set aside for future use without the need for enclosed storage. Such moisture conditioning will, however, cause full or partial hydration of the available free lime in the dust that may necessitate the later addition of a commercial hydrated lime to improve early strength development. (Chesner et al., 1998)

TYPICAL ENGINEERING PROPERTIES (This section modified after Chesner et al. [1998])

Some of the properties of kiln dusts that are of particular interest when kiln dusts are used in stabilized base or subgrade applications are particle size and specific gravity. The most important properties are, of course, the strength, stability, and durability of the stabilized soil/base system.

Particle Size: Maximum particle size of most kiln dusts is about 0.3 mm (minus No. 50 sieve). According to AASHTO T153-86 the Blaine fineness ranges from about 4,600 (coarser) to 14,000 (finer) cm^2/g (AASHTO, 2001). LKD is generally somewhat coarser than CKD, having a top size of about 2 mm (minus No. 10 sieve) and Blaine fineness ranging between about 1,300 and 10,000 cm^2/g. (Collins and Emery, 1983)

Specific Gravity: The specific gravity of CKD is typically in the range of 2.6 to 2.8, similar to Portland cement. LKD exhibits specific gravities in the order of 2.6 to 3.0. (Collins and Emery, 1983)

Strength: Kiln dust/fly ash stabilized base mixtures containing dolomitic limestone aggregates generally exhibit higher densities and compressive strengths than siliceous aggregate blends. Similarly, the strength of stabilized materials will be somewhat dependent upon the aggregate shape (higher strength with more angular crushed aggregates).

The effect of fly ash on strength development of kiln dust/fly ash/aggregate mixtures depends on the type of fly ash used in the mix. Table 10 lists typical 7-day compressive strengths that were achieved for kiln dust/fly ash-aggregate mixes (Chesner et al., 1998 and Collins and Emery, 1983). Mixes incorporating self-cementing fly ashes tend to have higher 7-day strengths than those containing pozzolanic fly ash. (Chesner et al., 1998)

Table 11 presents test results for splitting tensile strength and resilient modulus (i.e., modulus of rupture) versus comparative stabilized base mixes using commercial lime in kiln dust/fly ash/aggregate mixtures.

Durability: The durability of kiln dust/fly ash/aggregate mixtures assessed using the AASHTO T136 (AASHTO, 2001) procedure tends to be very good, with freeze-thaw losses of 2 percent or less measured (Collins and Emery, 1983). This compares favorably with conventional lime/fly ash/aggregate mixes. (Chesner et al., 1998)

Table 10. Compressive Strength of Kiln Dust/Fly Ash/Aggregate Mixtures.
(after Chesner et al., 1998)

Kiln Dusts /Fly Ash Mixes	7-Day Compressive Strength, lb/in^2
Kiln Dusts with Class C fly ash	1200 to 2000
Kiln Dusts with Class F fly ash	800 to 1200

Table 11. Splitting Tensile Strength and Resilient Modulus of Kiln Dusts/Fly Ash/Aggregate Mixtures. (after Chesner et al., 1998)

Base Mixture Type	Split Tensile Strength, psi	Resilient Modulus, psi
CKD/Class F Fly Ash/Aggr.	200 to 400	2.5 x 106
Lime/Fly Ash/Aggregate	--	1.9 x 106
LKD/Aggregate	200 to 300	--
Lime/Aggregate	210	210

Volume Stability: According to Collins and Emery (1983), most kiln dust/fly ash/aggregate mixtures are dimensionally stable (i.e., no volumetric expansion) over long periods of time, and are thus comparable to conventional lime/fly ash-aggregate mixtures. CKD that is high in sulfates and alkalis, and LKD that has higher free lime content tend to exhibit poorer dimensional stability.

Autogenous Healing: Kiln dust/fly ash/aggregate mixtures in field performance exhibit autogenous healing, although not to the same extent as commercial lime/fly ash/aggregate blends. However, kiln dust systems re-cement across crack boundaries and regain a significant portion of their initial compressive strength. (Collins and Emery, 1983)

DESIGN CONSIDERATIONS

Base/Soil Mixture Design

Kiln dusts have been used to modify subgrade soils and stabilize both subgrade soils and pavement base layers. Mixture designs for kiln dust/fly ash/aggregate mixtures for stabilized base should basically follow mix design procedures normally used for lime/fly ash/aggregate mixtures (Collins and Emery, 1983; Boles, 1986). Similarly, mixture designs for subgrade soils should follow established procedures.

A laboratory testing protocol on trial blends should establish the suitability of the particular kiln dust for stabilizing base/soil use. Typically, a CKD:fly ash ratio between 2:1 and 1:1 is recommended (Chesner et al., 1998). A LKD:fly ash ratio between 1:1 and 1:2 is recommended (Collins and Emery, 1983).

LKD added at 12 percent by dry weight of soil was found effective in stabilizing silty clay (Petry, 2001). Lesser amounts of kiln dusts or kiln dust blends have been used to modify subgrade soils to provide a temporary working platform to enhance constructibility of successive pavement layers (Heckel, 2001). Testing should always be performed to optimize mixture ratios for performance.

Chesner et al. (1998) recommends maintaining a condition of excess moisture for highly reactive LKD and CKD to permit complete hydration of any free lime. A separate slaking test can be conducted in advance to estimate the approximate amount of slaking water required.

Pavement Design

Pavement structural design procedures for stabilized base or subgrade soils containing kiln dust should be the same as those for conventional stabilized base materials (Chesner et al., 1998).

CONSTRUCTION (This section modified after Chesner et al. [1998])

Construction using kiln dust as a soil or base stabilizer is generally similar to that using lime or cement.

Handling and Storage

Fresh CKD and LKD are generally difficult to handle in bulk because of their fine, dry powdery nature and caustic characteristics. The addition of water to mitigate blowing and dusting problems during transport is common, but this practice causes hydration of the free lime or magnesia and significantly reduces the cementitious potential of the CKD or LKD. In situations where the CKD or LKD must be kept dry to preserve its cementitious potential, it must be handled in a fashion similar to conventional cement or lime.

Kiln dust/fly ash mixtures produced using self-cementing fly ash must be handled somewhat differently than mixes containing pozzolanic fly ash because self-cementing fly ash mixtures (especially those high in free lime) set up much more rapidly when exposed to water.

Due to the fine nature of kiln dusts, they may have a tendency to clump or bridge together at the feed opening when stored in silos. Consequently, bins or silos should be equipped with suitable vibration devices at the feed opening to mitigate this problem.

Mixing, Placing, and Compacting

Kiln dust/fly ash/aggregate mixtures are mixed and placed in uniform lifts and compacted using conventional construction equipment. The mixtures must be placed and compacted continuously and cannot be stockpiled for more than a couple of hours, after which time they will set.

Quality Control

The same test procedures used for conventional aggregate base courses or stabilized subgrade soils should be used for stabilized pavement layers containing kiln dusts. Materials stabilized with kiln dust should be held to the same standards as other similar stabilized materials.

PERFORMANCE OF KILN DUSTS AS STABILIZERS

General

CKD and LKD have been used alone and in combination with other materials (e.g., lime, cement, and/or fly ash) to stabilize soils and base materials. More than 25 years ago, Nebgen (1976) demonstrated that CKD can be an effective substitute for lime as a soil stabilizer. Laboratory investigation has shown that both clay soil and sand can be enhanced by addition of CKD (Bhatty et al., 1996; Zaman et al., 1999; Baghdadi and Rahman, 1990; Hopkins et al., 1995; Hunsucker et al., 1993). Similarly, several researchers have demonstrated that high quality base and subbase can be achieved through CKD stabilization in a ways similar to fly-ash stabilization or in combination with fly ash and/or lime (Nicholson, 1977; Nicholson, 1978; Nicholson and Goeb, 1982; Zenieris and Laguros 1988).

White and Bergeson (2001) conducted a long-term monitoring demonstration project on road base composed primarily of hydrated compacted Class C fly ash. They concluded that the high-volume application of CKD is an economical and suitable alternative when used with an appropriate calcium activator. Their rationale was that CKD activators increase cementitious and pozzolanic reactions in the hydrated fly ash material.

MacKay and Emery (1994) stated that more than 15 years of experience confirm that cementitious systems, including CKD and LKD, can be used to durably stabilize and solidify a wide variety of soils and that such systems can be designed using relatively simple laboratory procedures. The systems can be practically implemented using conventional, readily available materials and equipment. John Emery Geotechnical Engineering Limited of Ontario, Canada has probably done as much or more research on stabilization using kiln dusts than any other agency.

Laboratory Performance

Collins and Emery (1983) conducted a major laboratory study to determine the effectiveness of substituting kiln dusts for hydrated lime in lime/fly ash/aggregate road base systems. A total of 45 kiln dust samples, including 33 CKDs and 12 LKDs, were tested. In addition, 18 fly ashes (including 5 Class C ashes) and 6 aggregates were included. Kiln dust and fly ash samples were characterized to determine physical and chemical properties, as well as mineralogical, composition. Optimum kiln dust/fly ash ratios were developed for 66 mix combinations. Kiln dust/fly

ash/aggregate compressive strength tests were performed. Engineering properties (e.g., durability, volume stability) of optimum mix combinations were tested and compared with conventional lime/fly ash/aggregate blends. Most kiln dust/fly ash/aggregate mixes were comparable to, and in many cases demonstrated higher early strength than, lime/fly ash/aggregate mixes. Optimum mix strengths for kiln dust/fly ash/aggregate compositions were generally attained at kiln dust/fly ash ratios of 2:1 using CKD and 1:1 using LKD. By contrast, most lime/fly ash/aggregate mixes have lime/fly ash ratios of 1:3 or 1:4. Therefore, higher concentrations of kiln dust are required compared to hydrated lime. Mixes containing Class C fly ash developed higher strengths than comparable mixes containing Class F fly ash.

In a laboratory study, Miller and Azad (2000) found that increases in the unconfined compressive strength of soil occurred with the addition of CKD, which were inversely proportional to the plasticity index (PI) of the untreated soil.

Zaman et al. (1999) investigated the effect of wetting/drying and freezing/thawing on the resilient modulus values of limestone aggregate stabilized with up to 15 percent CKD. The limestone was considered to be substandard and therefore unsuitable for highway base courses. The layer coefficients of the stabilized aggregates were significantly higher than those of the raw aggregates. However, the layer coefficient of the stabilized aggregate base dropped significantly when the aggregate experienced freezing/thawing and wetting/drying cycles. When subjected to about eight cycles of freezing/thawing or wetting/drying, the layer coefficients of the CKD-stabilized aggregate base assumed values close to or lower than those of the raw aggregate base.

Zaman et al. (1992) investigated freezing/thawing and wetting/drying-induced durability of CKD-stabilized clay samples. Freezing/thawing tests were conducted by placing 56-day cured samples in a freezer for 12 hours and then thawing at room temperature (70°F) for 24 hours to complete one cycle. This was repeated 3 times to complete 3 cycles. Test results showed that the unconfined compressive strength decreased significantly due to the freezing/thawing or wetting/drying actions. It was observed that strength loss due to wetting/drying cycles reached 70 percent, while a 58 percent loss of strength was observed due to the freezing/thawing actions. In some cases, samples could not be tested because they broke during the wetting or freezing processes.

Nikraz (1998) found that either LKD or lime significantly improved the engineering

properties of fine-grained soil, from western Australia, with a clay fraction of 41 percent by weight. However, the LKD was not as effective as the lime.

Studying a limited number of CKDs and soils, Bhatty et al. (1996) concluded that CKD with high free lime and low alkalis resulted in compact clay soils of improved compressive strengths. However, CKDs with low free lime and high alkalis adversely affected the unconfined compressive strength. They stated that the higher alkalis could counter stabilization reactions because of the ionic interference. They also reported that CKD with low LOI and moderate alkalis reduced the plasticity index and improved unconfined compressive strength of clay soils but that CKD with high LOI and low alkali yielded significantly less improvements in compressive strengths and plasticity indices. Their study emphasized the importance of testing the actual kiln dusts and soils to be used in the field to verify their efficacy.

Freer-Hewish et al. (1999) reported the successful stabilization of desert sand with CKD for pavement structures. Although stabilization was achieved, large amounts of CKD were needed to meet pavement layer standards. Therefore, chemical additives (sodium metasilicate and calcium chloride) were used to reduce the CKD requirement.

Field Performance

In 1998, Chesner et al. (1998) stated that there is no widespread commercial use of kiln dusts in stabilized base mixtures in the United States. According to Collins and Ciesielski (1994), only four states had research data on the use of CKD for stabilizing base, however, they reported eight states (Il, Ks, Ky, La, Mo, NY, SC, Va) have tested CKD and LKD for stabilizing base and soil. Louisiana and South Carolina considered CKD unsuccessful for base stabilization due to poor performance or economics. Kansas considered CKD unsuccessful for soil stabilization for similar reasons.

The Illinois DOT constructed three experimental projects incorporating several materials for modification of various unstable (CBR < 6) subgrade soils (Heckel, 2001). In each location, sections were modified using high-calcium LKD. They found that LKD and the other materials were acceptable for subgrade modification and recommended mix design procedures and specifications (See Appendix A).

Kentucky researchers found that LKD performed better in stabilized base applications than CKD. Trial LKD sections constructed in Ohio and tested over a period of 6 months exhibited no cracking or surface damage, and deflections were observed to decrease with time as the pavement cured. (Chesner et al., 1998)

Miller et al. (1980) reported results from test pavements of six different mixes of pozzolanic concrete base courses that contained CKD and fly ash as the cementitious ingredients and crushed limestone as the aggregate. These were constructed on a concrete plant drive in Ohio. The fly ash/CKD/portland cement blends (percent by mass of dry ingredients) utilized in this study were: 6/6/0, 8/8/0, 10/10/0, 12/12/0, 8/8/0.5, and 8/8/1. Deflection measurements, monitoring of axle-load accumulations, and periodic compression tests of field samples were preformed. Laboratory test cylinders were prepared and tested. After about 26,000 ESALs during six months, no cracking or surface damage was visible except in one localized area. Deflection was found to decrease with curing time. Pozzolanic concrete containing CKD and fly ash as cementitious ingredients was found to have the property of autogenous healing. Anomalies were found in mixes that contained admixtures of portland cement. They concluded that pozzolanic concrete containing CKD and fly ash is potentially useful as stabilized base and merits further development. In apparently subsequent findings from this work but not published by Miller et al. (1980), Chesner et al. (1998) reported that the CKD sections in Ohio exhibited dimensional (i.e., volumetric) stability problems, which were attributed to the presence of sulfates and alkalis in the dust.

Miller and Zaman (2000) reported that a field (rural highway in Oklahoma) and laboratory study was conducted to evaluate CKD as a soil stabilizer. Performance of CKD from three different cement manufacturers was compared with that of quicklime. Observations were made to compare construction requirements for CKD and lime. Treated soil samples were collected from the field to prepare specimens for unconfined compression testing in the laboratory. In situ testing included dynamic cone penetration testing in the stabilized subbase and falling weight deflectometer testing after completion of the pavement. Chemical testing was conducted to determine the chemical makeup of each dust, and soil-CKD mixtures were tested for pH response. Chemical tests on the CKD and CKD-soil mixtures revealed aspects of the CKD composition that can be correlated with the degree of stabilization. Results showed that CKD from one cement plant performed significantly better than CKD from other plants or lime. Laboratory and field tests showed that, overall, CKD

28

was more effective than quicklime for stabilizing soil. Observations indicate that treatment with CKD can be cost-effective and that it requires less construction time than quicklime.

Cold in-place recycling (CIR) processes have successfully incorporated kiln dusts. After a 2-year performance period, a full-depth CIR in Saskatchewan indicates a blend of cement, fly ash, and kiln dust can be an effective subgrade soil stabilizer (Berthelot and Gerbrandt, 2002). CIR was used on a local road in Union, Pennsylvania last year (Landers, 2002). By pulverizing the old, thin asphalt pavement along with the base, a new 8-inch deep layer, stabilized using LKD, was constructed which was reported to be about 20 percent stronger, 90 percent of the cost, and completed in less time than the conventional method (removal and replacement with new materials). Early performance has been satisfactory.

Hunsucker and Sharpe (1989) summarized findings from an experimental road base utilizing lime kiln dust, fly ash, and aggregate. Observed performance was satisfactory. Compressive strength evaluations indicated exceptional early strength and continued strength gain. They concluded that the treated bases enhanced overall pavement performance and their use should be continued and that pavement life may even be extended at reduced costs.

Lin and Zhang (1992) evaluated of methods of rural road rehabilitation for Illinois DOT in 1987 using CKD, fly ash, and a recycling technique (in-place recycling of the base with a surface treatment) to rebuild the roadway base. Laboratory studies were conducted to develop the mix design for field demonstration. A 0.33-mi test road was constructed to evaluate the adequacy of the mix design and the practicality of the construction process. After about 4 years, performance of the test road was satisfactory. They concluded that CKD and fly ash can be used successfully for roadway base stabilization in the recycling process.

Two ongoing research projects to evaluate performance of CKD in soil stabilization were identified in Kansas and Oklahoma. The University of Kansas is conducting a study for Kansas DOT titled "Evaluation of cement Kiln Dust for Soil Modification and Stabilization," and it is due to be completed in September of 2003 (See http://rip.trb.org/browse/dproject.asp?n=7623). The objective is to evaluate the long-term performance of CKD for improvement of selected soils in conditions likely to occur in Kansas. The University of Oklahoma (G. A. Miller) recently completed a study for the Oklahoma DOT titled "Laboratory and Field Evaluation of Soil Stabilization Using Cement Kiln Dust," and the final report is available. The 5-year study began in the fall of 1997

(See http://rip.trb.org/browse/dproject.asp?n=3010). The objective is to provide additional scientific evidence regarding the effectiveness of CKD for stabilizing soils with low to moderate plasticity along a state route in Oklahoma.

Missouri DOT is exploring LKD for soil modification and stabilization at rates from 4 percent to 10 percent in silty clay soils. Little information was available at the following website: http://www.hwy63.com/images/documents/MO63ContractorMtgNotesFinal.pdf.

Findings from Canada and Oman are slated to be presented at the 8th International Conference on Low-Volume Roads in June of 2003 in Reno, Nevada. The two papers are (1) "Laboratory and Field Evaluation of the Use of Cement Kiln Dust and Lime to Stabilize a Silty Clay on Low-Volume Unpaved Roads" by G. Legere of Forest Engineering Research Institute and H. Tremblay of the Laval University, Canada and (2) "Evaluation of Cement Kiln Dust-Stabilized Reclaimed Asphalt Pavement Aggregate Systems in Road Bases" by R. Taha of the Sultan Qaboos University, Sultanate of Oman.

Supplementary Notes

Of note is that Collins and Ciesielski (1994) listed 18 industrial by-products that were included in state highway agency specifications and kiln dust was not among them.

Some CKD offers cementitious properties in and of itself. But, quite often, significantly greater compressive strength is attainable from a pozzolanic combination of CKD and fly ash. (Miller et al., 1980)

Report RP343, titled "Use of Cement Kiln Dust in Stabilizing Clay Soils," is available from the Portland Cement Association. This 36-page state-of-the-art report provides guidance on the use of CKD to stabilize clay soils, with and without being combined with portland cement, fly ash, or lime. Data on the type and level of CKD additions and the affects on the engineering properties of soil are presented. This report has been requisitioned by the author but was not available for this draft synthesis. Two additional reports available from the PCA are: "An Analysis of Selected Trace Metals in Cement" (SP109T) and "Kiln Dust and Detailed Illustration of Contingent Management Practices for Cement Kiln Dust" (SP115T).

CONCLUSIONS

This literature review was performed to provide TxDOT with a concise document on the state of the practice regarding the use of kiln dusts for stabilization of granular base materials and subgrade soils in highway pavements.

- Kiln dust (CKD or LKD) can be used to stabilize subgrade soils and pavement bases. But, quite often, significantly greater compressive strength is attainable from a pozzolanic combination of CKD and fly ash.

- Although there is no widespread commercial use of kiln dusts to stabilize pavement subgrade or base layers in the United States, CKD and LKD have been used successfully to stabilize both clay soil and sand. High quality base and subbase layers can be achieved through stabilization with CKD or LKD. However, as with any other pavement material, testing should be performed to optimize performance.

- Cold in-place recycling processes have successfully incorporated kiln dusts for stabilization of pulverized pavement material to produce a base layer.

- The same test procedures used for conventional aggregate base courses or stabilized subgrade soils should be used for stabilized pavement layers containing kiln dust. Materials stabilized with kiln dust should be held to the same standards as other similar stabilized materials.

- As one might expect from a by-product, the mineral content and thus quality of kiln dust, particularly CKD, is quite variable. The quantity of active ingredients related to soil stabilization varies substantially. Specifications should require minimum quantities of certain ingredients or certification thereof or warranty their performance.

- Depending upon the fuel source (e.g., coal containing sulfur), some kiln dusts may contain sulfur compounds. Soluble sulfates and alkalis have been attributed to undesirable swelling of pavement layers. Some cement plants may burn hazardous waste as kiln fuel, thus, some hazardous materials can end up in the CKD.

- In situations where the CKD or LKD must be kept dry to preserve its cementitious potential, it must be handled in a fashion similar to conventional cement or lime.

- There is very little, if any, free lime or magnesia in stockpiled CKD and LKD that has been exposed to the environment for long periods. Aged stockpiled CKD and LKD should not be used (due to hydration and consequent loss of reactivity) as a component of stabilized base or subgrade soil unless conditioned by the addition of commercial lime to enhance short-term strength development.

- Additional research is needed to assess the suitability of kiln dusts as a pozzolan activator in stabilized base/soil applications. Specifications are needed to define the physical and chemical requirements that will ensure acceptable field performance.

- Environmental-related properties of kiln dusts should be measured and management guidelines should be prepared to ensure that these products are managed in an acceptable manner.

- For materials similar to kiln dusts, leachates by distilled water from the pure materials were sometimes found to be present at toxic levels; whereas, in almost all cases, the toxicity was removed by mixing the leachates with soils or passing them through several centimeters of soil.

- Although CKD is not without some potential usefulness for purposes other than paving, the quantities of CKD that are generated are sufficient to present the cement industry with serious disposal or storage problems.

REFERENCES

Abeln, D.L., J.H. Rancy, R.J. Schreiber, and C Yonley, *Detailed Illustration of Contingent Management Practices for Cement Kiln Dust*, Serial No. SP 115 T, Portland Cement Association, Skokie, Illinois, 1993.

American Association of State Highway and Transportation Officials, Standard Method of Test, "Fineness of Portland Cement by Air Permeability Apparatus," AASHTO Designation: T 153-98, Part II, Tests, 21st Edition, 2001.

American Association of State Highway and Transportation Officials, Standard Method of Test, "Freezing-and-Thawing Tests of Compacted Soil-Cement Mixtures," AASHTO Designation: T 136-97 (1986), Part II Tests, 21st Edition, 2001.

Baghdadi, Z.A., and A. Rahman, "The Potential of Cement Kiln Dust for the Stabilization of Dune Sand in Highway Construction," *Journal of Building and Environment*, Oxford, England, 25(4), 1990, pp. 285-289.

Berthelot, C. and R. Gerbrandt, "Cold In-Place Recycling and Full-depth Strengthening of Clay-Till Subgrade Soils," *Transportation Research Record 1787*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 2002, pp. 3-12.

Bhatty, J.I., S. Bhattacharja, and H.A. Todres, "Use of Cement Kiln Dust in Stabilizing Clay Soils," RP 343, PCA Serial No. 2035, Portland Cement Association, Skokie, Illinois, 1996.

Boles, W. F., Fly Ash Facts for Highway Engineers, Report No. FHWA-DP-59-8, Federal Highway Administration, Washington, DC, July, 1986.

Boynton, R.S., *Chemistry and Technology of Lime and Limestone*, 2nd. Edition, John Wiley & Sons, Inc., New York, N.Y., p. 204, 1980.

Chesner, W.H., R.J. Collins, and M.H. MacKay, "User Guidelines for Waste and By-Product Materials in Pavement Construction," Report No. FHWA-RD-97-148, Federal Highway Administration, US Department of Transportation, Washington, DC, 1998.

Ciesielski, S. K. and R. J. Collins, *Recycling and Use of Waste Materials and By-Products in Highway Construction*, National Cooperative Highway Research Program Synthesis of Highway Practice 199, Transportation Research Board, Washington, DC, 1994.

Collins, R. J. and J. J. Emery, "Kiln Dust-Fly Ash Systems for Highway Bases and Subbases," Report No. FHWA/RD-82/167, Federal Highway Administration, Washington, DC, September, 1983.

Emery, J.J., personal communication with Mr. J. J. Emery, John Emery Geotechnical Engineering, Etobicoke, Ontario, Canada, April, 2003.

Emery, J.J., "Potential Uses for Kiln Dusts," paper prepared for ORF/CANMET Symposium on Mineral Fillers, Toronto, Canada, 1981.

EPA, "Regulatory Determination on Cement Kiln Dust," Environmental Protection Agency, Federal Register, 40 CFR Part 261, February 7, 1995.

Freer-Hewish, R.J., G.S. Ghataora, and Y. Niazi, "Stabilization of Desert Sand with Cement Kiln Dust Plus Chemical Additives in Desert Road Construction," Proceedings, Institution of Civil Engineers: Transport, Thomas Telford, Ltd., London, UK, 1999, pp. 29-36.

Haynes, W.B. and G.W. Kramer, "Characterization of U.S. Cement Kiln Dust," Information Circular No. 8885, U.S. Bureau of Mines, U.S. Department of Interior, Washington, D.C., 1982.

Heckel, G., "Alternative Materials for Subgrade Modification," Report No. IL-PRR-138, Bureau of Materials and Physical Research, Illinois Department of Transportation, Springfield, Illinois, 2001.

Hopkins, T.C., T. Beckham, and D. Hunsucker, "Modification of Highway Soil Subgrades," Report No. KTC-94-11, Kentucky University, Kentucky Transportation Center, College of Engineering, Lexington, KY, 1995.

Hunsucker, D.Q. and G.W. Sharpe, "Demonstration Project No. 59: The Use of Fly Ash in Highway Construction – Fayette County, Kentucky," Report No. KTC-89-32, Kentucky University, Kentucky Transportation Center, College of Engineering, Lexington, KY, 1989.

Hunsucker, D.Q., T.C. Hopkins, T.L. Beckham, R.C. Graves, "Construction and Performance of Highway Soil Subgrades Modified with Atmospheric Fluidized Bed Combustion Residue and Multicone Kiln Dust," Report No. KTC 93-4, Kentucky University, Kentucky Transportation

Center, College of Engineering, Lexington, KY, 1993.

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

Lander, K., "Building a Better Road for Less Money," *Better Roads*, James Informational Media, Des Plaines, Illinois, July, 2002.

Lin, C. and X. Zhang, "Use of Cement Kiln Dust, Fly Ash, and Recycling Technique in Low-Volume Road Rehabilitation," *Transportation Research Record 1345*, Transportation Research Board, National Academy of Sciences, Washington, DC, 1992, pp.19-27.

Little, D.N., personal communication with Dr. D.N. Little, Texas Transportation Institute, Texas A&M University, College Station, Texas, April, 2003.

MacKay, M. and J.J. Emery, "Stabilization and Solidification of Contaminated Soils and Sludges Using Cementitious Systems: Selected Case Histories," *Transportation Research Record 1458*, Transportation Research Board, National Academy of Sciences, Washington, DC, 1994, pp.19-27.

Miller, G.A and S. Azad, "Influence of Soil Type on Stabilization with Cement Kiln Dust," *Construction and Building Materials*, Vol. 14, No. 2, Elsevier Science, Ltd, Oxford, UK, 2000, pp. 89-97.

Miller, G.A., S. Azad, and B. Dhar, "Effect of Kiln Dust on the Collapse Potential of Compacted Shale," ASTM *STP 1275, Testing Soil Mixed with Waste or Recycled Materials*, M.A. Wasemiller and K.B. Hoddinott, Editors, West Conshohocken, Pa., 1997, pp. 232-245.

Miller, G.A. and M. Zaman, "Field and Laboratory Evaluation of Cement Kiln Dust," *Transportation Research Record 1714*, Transportation Research Board, National Academy of Sciences, Washington, DC, 2000, pp. 25-32.

Miller, C. T., D. G. Bensch, and D. C. Colony. "Use of Cement-Kiln Dust and Fly Ash on Pozzolanic Concrete Base Courses," *Transportation Research Record No. 754*, Transportation Research Board, Washington, DC, 1980.

Nebgen, J.W., J.G. Edwards, D.F. Weatherman, "Use of Waste Sulfate for Remedial Treatment of Soils," Report No. FHWA-RD-76-143, Midwest Research Institute, Kansas City, MO, 1976.

Nelson, P.O., W.C. Huber, N.N. Eldin, K.J. Williamson, J.R. Lundy, M.F. Azizian, P. Thayumanavan, M.M. Quigley, E.T. Hesse, K.M. Frey, and R.B. Leahy, *Environmental Impact of Construction and Repair Materials on Surface and Ground Waters, NCHRP Report 448*, National Cooperative Highway Research Board, National Research Council, Washington, DC, 2001.

Nicholson, J.P., *Mixture for Pavement Bases and the Like*, U.S., Patent No. 4,018,617, April 19, 1977.

Nicholson, J.P., *Stabilized Mixture*, U.S., Patent No. 4,101,332, July 18, 1978, Reissue No. 30,943, May 25, 1982.

Nicholson, J.P., E.O. Goeb, "1980's: The Pozzolanic Pavement Era in American Construction," *The Challenge of Change - Sixth International Ash Utilization Symposium Proceedings*, Morgantown Energy Technology Center, USDOE and National Ash Association, DOE/METC/82-52 (Vol. 1), pp. 358-368, 1982.

Nikraz, H.R., "Engineering Properties and Performance of Lime Kiln Dust for Subgrade Stabilization of Soft Clay," *Proceedings*, 3rd International Conference on Road & Airfield Pavement Technology, Vol. 2, Information Institute of Science and Technology, Ministry of Communications, P. R. China, 1998, pp. 1466-1472.

Petry, T.M., "Investigation of Agents of Practical use to Stabilize Slopes and Erosion Along the I-55 Corridor South of Sikeston, Missouri," Report No. RI-99-030, University of Missouri, Rolla, Civil Engineering Department, Rolla, Missouri, 2001.

PCA, *An Analysis of Selected Trace Metals in Cement and Kiln Dust*, Serial No. SP 109 T, Portland Cement Association, Skokie, Illinois, 1992.

Todres, H.A., A. Mishulovich, and J. Ahmad, "Cement Kiln Dust Management: Permeability," Research and Development Bulletin RD 130T, Portland Cement Association, Skokie, Illinois, 1992.

U.S. Environmental Protection Agency, *Report to Congress on Cement Kiln Dust,* Report No. EPA 530-R-94-001, December, 1993.

White, D.J. and K.L. Bergeson, "Long-Term Strength and Durability of Hydrated Fly-Ash Road Bases," *Transportation Research Record 1755*, Transportation Research Board, National Academy of Sciences, Washington, DC, 2001, pp. 151-159.

Zaman, M., J.G. Laguros, and A. Sayah, "Soil Stabilization Using Cement Kiln Dust," *Proceedings, 7th International Conference on Expansive Soils*, Dallas, Texas, pp. 1-5, 1992.

Zaman, M.M. and J.H. Zhu, J.G. Laguros, "Durability Effects on Resilient Moduli of Stabilized Aggregate," *Transportation Research Record 1687*, Transportation Research Board, National Academy of Sciences, Washington, DC, 1999, pp. 29-38.

Zenieris, P., and J.G. Laguros, "Fly Ash as a Binder in Aggregate Base Courses," *Proceedings, Symposium of the Material Resources Society*, Boston, Massachusetts, Vol. 113, , 1988, pp. 231-240.

Appendix A

Non-TxDOT State DOT Specifications that Include Kiln Dust

The following was extracted from Illinois DOT Materials Specifications, Section 1000.

SECTION 1012. LIME

1012.01 Hydrated Lime. Hydrated lime shall conform to the requirements of ASTM C 207, Type N. When used in pozzolanic aggregate mixture, the following modifications to ASTM C 207 shall apply:
(a) Total calcium and magnesium oxides (nonvolatile basis) min. percent ... 90
(b) Calcium oxide in hydrated lime (as received basis) max. percent 5
(c) Magnesium hydroxide (as received basis) max. percent 5
(d) Mechanical moisture in hydrated lime (as received basis) max. percent ... 4
(e) Residue - The sieve analysis of the lime residue shall be as follows:

Sieve Maximum Percent Retained
4.75 mm (No. 4) 0
600 μm (No. 30) 2.5
150 μm (No. 100) 15

1012.02 Hydrated By-Product Lime. Hydrated by-product lime shall conform to the following requirements:
(a) Total calcium and magnesium oxides
(nonvolatile basis) min. percent 65
(b) Available Calcium hydroxide (rapid sugar test,
ASTM C 25) plus total MgO content calculated to be
equivalent $Ca(OH)_2$, min. percent... 41
Note: Percent available $Ca(OH)_2$ + (%MgO) (1.828) =
percent equivalent available $Ca(OH)_2$. Where the available
$Ca(OH)_2$ is above the minimum indicating high calcium lime,
determination of the MgO is not necessary.
(c) Loss on ignition (carbon dioxide plus moisture, combined
and free) on as-received basis.
If sample is taken at the place of manufacture max. percent 35
(d) Free Water (as-received basis) max. percent 4
(e) Residue. The sieve analysis of the hydrated by-product
lime shall be as follows:

Sieve Maximum Percent Retained
4.75 mm (No. 4) 0
600 μm (No. 30) 2.5
150 μm (No. 100) 15
829
Art. 1012.03 Lime

1012.03 By-Product Lime for Lime Modified Soils. When used in lime modified soils, by-product lime (kiln dust) shall be either hydrated or non-hydrated conforming to the following requirements:
(a) Total calcium and magnesium oxides (nonvolatile basis) min. percent ... 60
(b) Available calcium hydroxide (rapid sugar test, ASTM C 25) plus
total MgO content calculated to be equivalent $Ca(OH)_2$
min. percent 30
(c) As received loss on ignition (carbon dioxide plus
moisture, combined and free), max. percent 40
(d) Free Water (as-received bases), max. percent 4

(e) Residue - The sieve analysis of the by-product lime shall be as follows:

Sieve Maximum Percent Retained
4.75 mm (No. 4) 5
600 μm (No. 30) 10
150 μm (No. 100) 25

1012.04 Non-Hydrated By-Product Lime for Lime Stabilized Soil Mixture.
When used in lime stabilized soil mixture, non-hydrated by-product lime shall meet the following requirements:
(a) Total calcium oxides (nonvolatile basis) min. percent 65
(b) Available calcium hydroxide (rapid sugar test,
as determined by ASTM C 25), min percent   35
(c) Loss on ignition (carbon dioxide plus moisture,
combined and free on as-received basis), max. percent   35
(d) Free Water (as-received bases), max. percent 2
(e) Residue - The sieve analysis of the by-product lime shall be as follows:

Sieve Maximum Percent Retained
4.75 mm (No. 4) 5
600 μm (No. 30) 10
150 μm (No. 100) 25